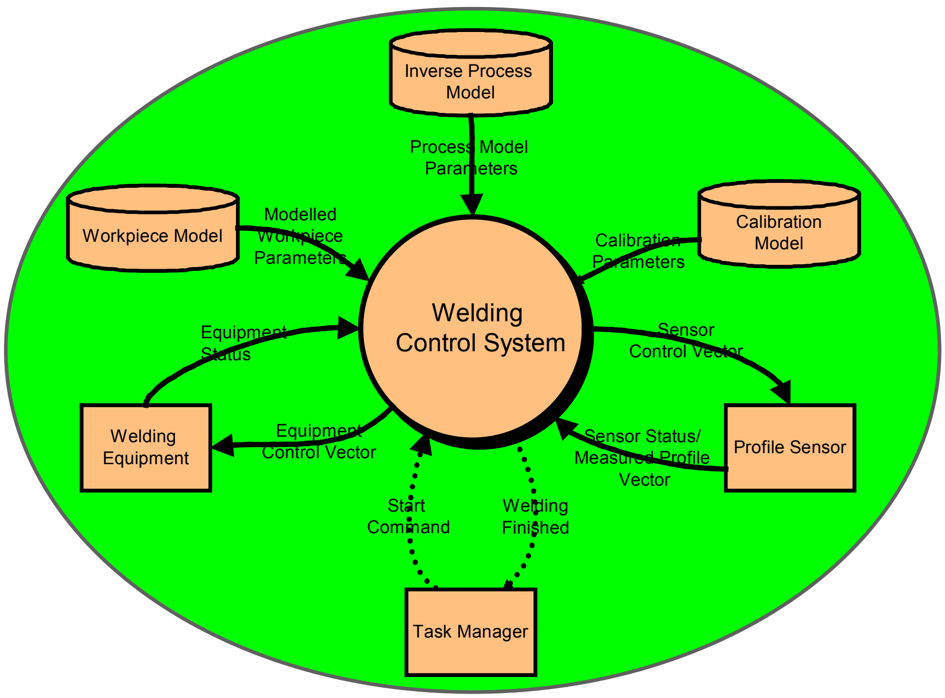
Sensor Based Robotic Laser Welding

Based on Feed Forward and Gain Scheduling Algorithms

Henrik John Andersen



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Preface

This thesis documenting research work carried out at Department of Production, Aalborg University, Denmark has been submitted to the Faculty of Engineering and Science for the fulfilment of the requirements for the Ph.D. degree within mechanical engineering.

The research work documented in this thesis was carried out in the period from August 1995 to January 1999 in connection with the national research programme ’The Laser Process in Heavy Industry’ (Laser processen i sværindustrien), and the follow-up project ‘Lasos-Control’ (Lasos-Styring). The work was carried out in co-operation with Odense Steel Shipyard Ltd. and the Force Institute, which is a Danish welding institute.

The report is written in English, and it includes a Danish and an English summary. The main report consists of the chapters 1 through 9, the appendixes A through E, and the annexes A through D. References are made within each chapter in such a way that referenced literature is listed at the end of the chapter.

The system developed and implemented during the working period is documented by the descriptions in the main report and by the source code in appendix C.

For readers without any knowledge of laser welding or laser technology in general, it is possible to get a basic introduction to these subjects by reading Appendix E.

Acknowledgements

I would like to thank Jens Klæstrup from the Force Institute and Michael Sellerup from Odense Steel Shipyard who made this project possible by inviting Department of Production to participate in the research programme ‘The Laser Process in Heavy Industry’. Additionally I wish to thank The Danish Agency for Trade and Industry and The Danish Technical Research Council who have funded the research work.

I would like to thank my supervisor Hans Holm, Department of Production, for his very enthusiastic participation during the project. I also wish to thank my additional supervisors Ole Madsen and Jan Lauridsen, Department of Production, for their support during the project.

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I wish to thank Lis Bach and Lone Corfixen, Department of Production for revising the English language in this report and in some of my scientific papers. This help was very useful.

Last but certainly not least I wish to express my very special thanks to my fiancée Bethina and to my daughter Mathilde for their great patience and tolerance in periods when holidays, weekends and evenings were spent at the university or at Odense Steel Shipyard.

Aalborg, 29 January 2001

Henrik John Andersen

English Summary

Parts of the Danish heavy industry are aiming at controlling advanced production technology in order to gain competitive power. For this reason they have shown interest in the laser process.

The laser technology has now been developed to such an extent that it is now possible to use it for both welding and cutting of thick metal sheets. This technology provides a possibility of reducing the heat-input to workpieces and additionally to increase processing speed and resulting workpiece tolerances.

The required workpiece tolerances for parts to be laser welded are significantly smaller than the required workpiece tolerances for traditional welding processes. However, in laboratory environment it has been shown that it is now possible to apply laser welding for thick metal sheets with a gap of 1.0 mm between the workpieces in the weld joint. Parts of the Danish heavy industry were willing to provide these tolerances in order to benefit from the advantages of the laser welding process.

The present thesis describes the work carried out for the development of a sensor based control system for laser welding. The system was implemented in a demonstration cell at Odense Steel Shipyard- Lindø.

A control theoretical description of the system and its surroundings was developed during the project. This description made it possible to specify the constraints and the output for the control system in both qualitative and quantitative terms.

Two generic classes of weld joints were specified, for which it is possible to quantify the workpiece parameters, quality parameters and control variables for the laser welding process.

The control system is categorised as a feedforward gain scheduling control system. The weld joint is measured by use of a profile sensor, which is positioned in front of the laser beam when seen in the welding direction. This sensor measures the position of the weld joint and the gap between the

workpieces. On the basis of these measurements, the control system calculates the control variables for the laser welding process. The control variables are calculated on the basis of an inverse process model. This inverse process model includes a set of control variables for the laser welding process for a number of discrete sizes of gaps.

A functional architecture was developed for the control system. The structure of the system is specified in this architecture. All data structures in the system are specified in this architecture. Also the communication interfaces to surrounding equipment are specified.

The implemented control system is tested in a demonstration cell at Odense Steel Shipyard. The portability of the control system is investigated with focus on the possibilities for applying such a system for laser welding in an industrial environment in heavy industry. The robustness of the provided quality parameters is investigated in relation to disturbances that are considered typical in heavy industry.

The implemented laser welding control system is able to provide satisfactory quality parameters for laser welding of joints in which a gap is present. The maximum size of this gap is 0.5 mm in order to achieve a satisfactory weld quality. An alternative laser welding control strategy is suggested for which the tolerances of gap are at least 3.5 mm for flange joints. For this strategy the welding speed will be increased to keep a constant speed corresponding to the maximum speed of the implemented control system. This will additionally reduce the heat-input to the workpieces.

Danish Summary

Danish Title: Sensorbaseret Robotiseret Lasersvejning

Baseret på Feed Forward Gain Scheduling algoritmer

Dele af den danske sværindustri har valgt at satse på højteknologi for at gøre sig gældende i den hårde internationale konkurrence. En af de teknologier, som har vakt interesse i sværindustrien, er laserteknologien.

Laserteknologien er nu udviklet i et sådant omfag, at den kan anvendes til både svejsning og skæring i store godstykkelser. Denne teknologi giver mulighed for at reducere varmeinputtet i emnerne og samtidig øge bearbejdningshastigheder og tolerancer.

For lasersvejsning gælder, at tolerancerne for svejsefugen er betydeligt mindre, end tilfældet er for traditionelle svejsemetoder. Under laboratorieforhold er det dog vist, at der kan anvendes lasersvejsning til sammenføjning af tykke plader, hvorimellem der er et gab på ca. 1 mm. I sværindustrien mener man, at sådanne tolerancer kan opnås, således at man kan blive i stand til at udnytte lasersvejseprocessens fordele.

Dette ph.d.-projekt omhandler udviklingen af en sensorbaseret styresystem til lasersvejsning. Styresystemet er implementeret i en demonstrationscelle på Odense Stålskibsværft – Lindø.

Gennem projektet er der udviklet en styreteknisk beskrivelse af systemet samt de omgivelser, det skal agere i. Dette har givet muligheden for at specificere forudsætningerne for, at styresystemet kan styre lasersvejse-processen på en sådan måde, at den specificerede kvalitet kan opnås.

Der er specificeret to generelle klasser af svejsefuger, hvortil det er muligt at kvantificere emneparametre af betydning for lasersvejseprocessen, kvalitetsparametre for svejsningerne samt styrevariable for lasersvejse-processen.

Styresystemet er kategoriseret som et feedforward gain scheduling system. Svejsefugen opmåles af en profilsensor, der er placeret foran laserstrålen. Denne profilsensor måler svejsefugens position samt gabet mellem emnerne. På baggrund af disse målinger beregner styresystemet styrevariable for processen. Styrevariablene beregnes på baggrund af en invers procesmodel, som for diskrete størrelser af gab har specificeret et sæt styrevariable og forstærkninger.

Styresystemet er dokumenteret ved en funktionel arkitektur, der angiver systemets strukturelle opbygning. Her er alle datastrukturer i systemet defineret sammen med kommunikationsgrænseflader med omgivende enheder.

Det implementerede system er testet i en demonstrationscelle på Odense Stålskibsværft. Herunder er systemets portabilitet undersøgt med henblik på at vurdere mulighederne for at anvende et sådant sensorbaseret realtidsstyresystem til lasersvejsning i et industrielt miljø. Systemets evne til at sikre robuste kvalitetsparametre er testet, når det udsættes for forstyrrelser, der anses som typiske i et industrielt miljø.

Det udviklede styresystem kan håndtere svejsefuger med et gab på op til 0.5 mm. Der er foreslået en alternativ styrestrategi, hvorved gabstolerancerne kan forøges op til 3.5 mm. Samtidigt kan hastigheden af lasersvejseprocessen sættes i vejret, og dermed vil varmetilførslen til emnerne mindskes.

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Chapter 1

Introduction

1.1 Industrial Background

Parts of the Danish heavy industry have chosen to aim at competitiveness through managing advanced production technologies. The main reason for this is that foreign competitors have lower expences for wages, and some of them have access to subsidies.

Some of the most frequently used processes in heavy industry are the cutting and joining of thick metal parts, together with handling and assembling of sub components such as sections into a container vessel. Besides material costs, these processes constitute a major part of the production costs in this particular industry.

Plasma cutting is one of the most frequently used cutting methods for thick metal parts, and joining of metal parts is usually performed by different arc welding processes. Some important characteristics for the above mentioned processes are that they induce a relatively high heat input to workpieces.

Moreover, the arc welding processes are quite slow processes. For some joint types (e.g. butt joints in thick plates) it is necessary to prepare the weld groove by machining in order to form a weld geometry that facilitates the required penetration of weld metal in the joint. This means that it is necessary to fill the weld groove with a number of weld beads. All of these beads contribute to distortions of the weld joint, and to consumption of production time.

The melting and solidification of the weld metal in the groove cause the workpieces to distort. These distortions mean that a lot of man hours have to be spent on fitting distorted parts into a superior structure of components. It is assumed, that approximately 25-33% of the man hours spent in shipbuilding industry are used for fitting together components [1].

In order to increase production rates during welding and assembling of components, heavy industry has become interested in laser welding and cutting processes. This Ph.D. work concerns control of the laser welding process in large plate dimensions.

1.2 Application of laser welding in heavy industry

The characteristics of the laser welding process differ significantly from the characteristics of arc welding processes. It is possible when using laser welding to provide a very deep and narrow input of heat into the weld groove. This heat input provides a shape of weld metal which is more concentrated than in traditional arc welding processes, which is illustrated in Figure 1.1.

The welding speed for laser welding is significantly faster than for traditional arc welding processes, even though penetration is deeper in this process. This is especially interesting, because it is thus possible at the same time to combine the possibility of minimising the number of passes with an increase in the welding speed.

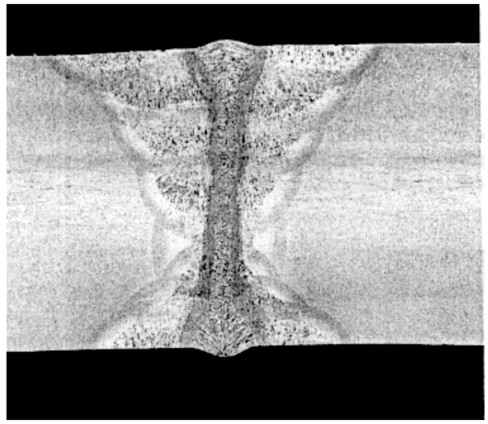

Figure 1.1: A single pass laser weld from both sides of a 25 mm thick steel plate superimposed on a multipass (11 passes) manual metal arc weld [2].

1.3 Practical Task of the present Ph.D. work

This Ph.D. project deals with design, implementation and test of a generic, sensor based control system for laser welding. This control system was tested in a demonstration work cell at Odense Steel Shipyard Ltd. The overall idea of constructing this demonstration cell was to investigate the possibility of applying the laser welding process to a production environment in heavy industry. The cell included both laser welding and cutting, though the cutting process is not treated further in this report.

The workpieces for this demonstration cell were production components for ship building with a maximum size of 16 metres times 4 metres, which is the maximum size of plates delivered from the steel mill. The plate thicknesses may vary between 4 and 25 mm.

Before describing the control system a review is made of work previously carried out within the area of control of laser welding. This is described in chapter 2 where a method for controlling arc welding processes will be examined in order to transfer this method to laser welding.

To control the laser welding process, a functional architecture was developed, which is described further in chapters 4 and 5. This architecture was implemented and tested in the demonstration cell at Odense Steel Shipyard Ltd.

For readers who are not familiar with laser welding technology or with laser technology in general it is possible to get a basic introduction to these technologies by reading Appendix E.

1.4 Scientific contribution

When studying literature about work within the area of applying laser welding in heavy industry, one may ask the question: What is missing in order to be able to control the laser welding process in an industrial environment? The laser welding process is well developed and tested in laboratory environments. Furthermore, a strategy is developed and tested for control of weld trajectory compensation for variations in the size of the gap between workpieces.

However, laser welding in heavy industry has never been performed in an industrial environment where a variety of manufacturing tolerances affects the welding process, and where the settings and the calibration of the laser welding equipment are not checked before each weld task.

The scientific contribution from this project is the description of these properties of a welding control system which enables portability of the laser welding control system, i.e. the ability to transfer this technology from one machine to another, or from one environment to another. To focus on the portability, these conditions, which have a significant effect on the ability to control the laser welding process in order to obtain a satisfactory weld quality, were investigated in an industrial environment. The work was particularly concentrated on the tolerances of equipment set-up and workpiece preparation, because these tolerances are known to have a significant effect on the result of a laser welding. Additionally, the addition of external materials such as gasses and wire was studied. Variations in the addition of filler wire and plasma control gas was tested in order to evaluate the significance on weld quality when these characteristics of the process are subjected to deviations.

References

[1] Sellerup Michael, Future Use of Lasers for Building Large Commercial Ships, Proceedings of Exploitation of Laser Processing in Shipyards and Structural Steelwork, 30-31 May 1996, Glasgow Moat House, UK, Arranged by TWI.

[2] Dawes Christopher, Laser Welding, a Practical Guide, 1992, Abington Publishing, ISBN 1 85573 034 0.

Chapter 2

Methodical Approach

The main purpose of this Ph.D. work is to establish and implement a generic method for controlling laser welding in an industrial environment. The environment is basically the production area in heavy industry. Here, quite large tolerances are traditionally found in the preparation and positioning of workpieces. Therefore, a generic method will be established for robotic laser welding of tasks in which the positioning and preparation tolerances require adaptation of the process to the actual conditions in order to maintain a satisfactory weld quality.

In this chapter a number of fundamental methodologies are evaluated to find a control method that seems sufficient for controlling the process. During this evaluation it is kept in mind that an important aspect of this particular project is the implementation of the system in order to test the theories for controlling the process in an industrial environment. Previous work in the field of controlling welding processes and especially the laser welding process is described and categorised with respect to the control method applied to the specific work.

The chosen control strategy for the present Ph.D. work is described shortly at the end of this chapter with the purpose of categorising this strategy in terms of control engineering.

2.1. Geometry based modelling approach

Laser welding processes are used for joining workpieces by fusion. The basic idea is to melt the edges of two workpieces and let the molten material from the two workpieces merge before it solidifies and join the workpieces. In case there is a gap between the workpieces it may be necessary to add filler material in order to obtain a desired geometry and strength of the welded joint.

2.1.1. Desired geometry of welded beads

Several reasons favour an optimisation of the welding process with regard to the weld metal[1] geometry. One reason why this is interesting is that the velocity of the welding process is dependent on the amount of heat, which must be induced into the workpieces per length unit. Another reason is that the solidification process causes a contraction of the molten material. This contraction causes the workpieces to distort as a function of the geometry and temperature of the molten material. To minimise these distortions the width of the melt zone has to be minimised in the individual weld tasks such that this zone is as narrow as possible but still able to provide a satisfactory fusion of the workpieces.

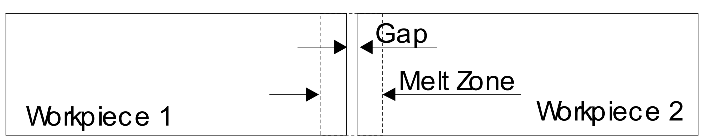

Figure 2.1: Cross section of workpieces to be joined by laser welding.

Figure 2.1 shows a cross section of two workpieces to be joined by laser welding with a gap between, and an indication of the desired melt zone. The melt zone is in this case illustrated by a constant width throughout the

[1] Weld metal is the area of metal, which has been molten during the welding process.

thickness of plates, which is the desired shape of the weld metal. This is because it is desirable that contraction, which will act in the transverse direction to the weld groove, is equally distributed throughout the plate thickness. Thereby angular distortions are significantly minimised. However, the characteristics of laser welded joints show that the geometry of the weld metal has a partial taper shape, as can be seen in Figure 2.2.

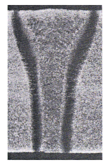

Figure 2.2: Thin section of laser welded joint

As can be seen from Figure 2.2, the width of the weld metal is varying from the weld surface to the bottom of the weld pass. This means that this width has to be controlled through the desired depth of penetration. The size and shape of the weld beads and heat-affected zones are dictated by the melting isotherms, whereas the final microstructure is related to the cooling rates of the welds. In the following section the physical processes that influence the melting isotherms and the cooling rate in laser welding will be described.

2.1.2. Physical process considerations

In order to control the geometry of weld metal in the weld joint the distribution of heat in the workpieces must be controlled. In this section it will be argued that a geometry based approach is to be applied for control of this distribution.

In this section these physical processes that occur during laser welding will be discussed. This discussion is limited to the processes which occur after the laser beam leaves the laser machine.

Energy radiation from the laser beam into the beam guidance system

Fibre optic (for Nd:YAG lasers) is the most simple and versatile beam guidance system because the beam is transported through a flexible path inside an optical cable. In this cable it is not necessary to align mirrors etc. The fibre optic is shown schematically in relation to the laser and focusing head in Figure 2.3. The optical fibre material is SIO_2 (quartz), and it is generally less than 1mm in diameter [2]. Because of energy transfer from the laser beam to the optical fibres and the optic system there is a loss of the laser power of a Nd:YAG laser. This loss is approximately 10-15% of the incoming beam energy. However, the efficiency of beam transmission may be impaired if the fibre is bent too tightly. A 0.5 mm diameter SIO_2 cable has an allowable bending radius of approximately 100 mm [2]. For a laser welding system it should be possible to control the bending radius in a way that minimises the loss as well as the variations in the loss of beam transmission efficiency. In this case it should be possible to regard this loss of energy as a constant parameter.

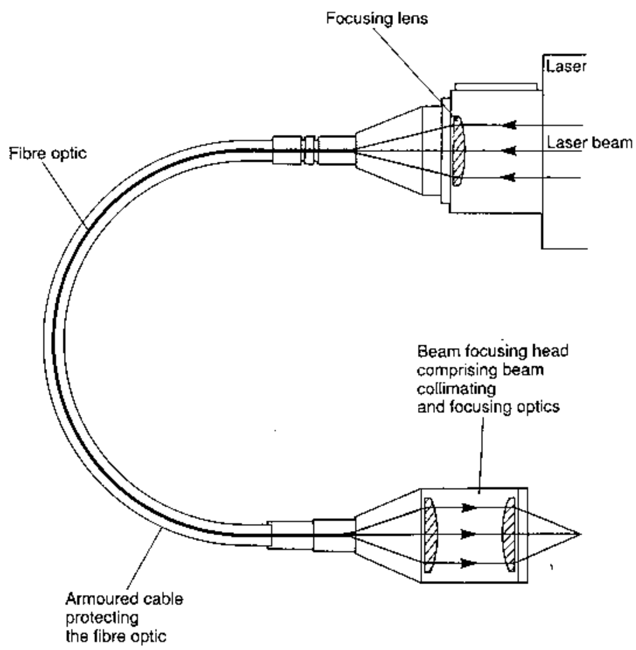

Figure 2.3: Concept of fibre optical beam transmission [2].

Reflective optic for transmission of the laser beam for CO_2 laser welding transmits the laser beam from one mirror to the next, as shown in Figure 2.4. Each mirror in a CO_2 beam transmission train absorbs approximately 3–5% of the incoming laser power, depending on the mirror conditions [2]. The mirrors may over time be covered with a layer of dirt from the surrounding air and from welding smoke. To minimise the mirrors' change in heat absorption it is possible to add a flow of cleaned air through the closed beam transmission train. This is also beneficial for keeping particles away from the free laser beam. Additionally, it is assumed that mirrors are cleaned within a certain interval in order to minimise the layer of dirt.

The mirrors in a beam transmission train may distort due to the absorbed energy. These distortions will change the directions of the outgoing laser beam unequally throughout the diameter of the mirrors. To minimise these distortions they are usually cooled by water.

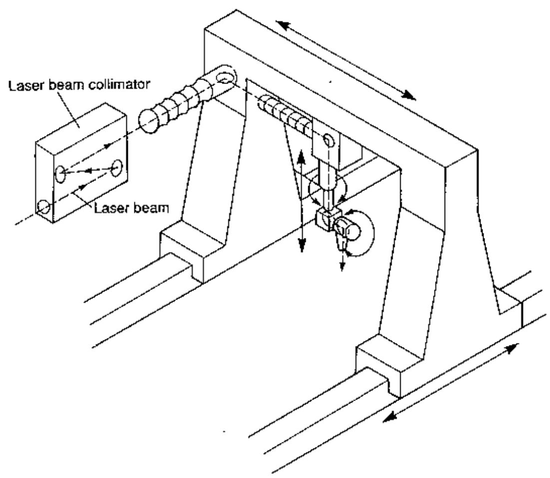

Figure 2.4: Concept of reflective optic beam transmission [2].

The loss of energy in the beam guidance system is caused by energy radiation from the laser beam into optical fibres, or into mirrors in the beam transmission train. The possibility of modelling this loss of energy is not investigated in the present Ph.D. work. The loss of energy for mirror based beam guidance systems would, however, involve chaotic parameters, such as the covering of mirrors by dirt. This parameter is influenced by spatter and smoke from the welding process, and by the supply of cleaned air to the system.

Instead of modelling the output power from the beam guidance system, it is quite simple to control it by measuring this output and by adjusting the output power of the laser machine. This is because the rate of change of the consumed energy in the beam guidance system is very small.

Thermal blooming may occur in the beam guidance system. This means that airborne particles and vapours obstruct the laser beam by absorbing beam energy, and by reflecting light waves from their normal path. Obviously, this also affects the absorption of energy in the beam guidance system. Thermal blooming may be avoided by supplying dry filtered air or nitrogen to the closed beam guidance system in order to avoid particles and vapours.

Considering the above mentioned types of energy losses, it is important to remember that a significant loss of energy may be unequally distributed throughout the diameter of the laser beam. This will additionally disturb the distribution of energy in the laser beam, because the energy density distribution has an influence on the focused spot size of the laser beam.

Heat radiation from the laser beam into the laser-induced plasma

During keyhole laser welding[2] some of the metal will evaporate and become ionised by the high power of the laser beam. This forms a brilliant blue/white plasma cloud just above the keyhole which is only partially transparent to the laser beam. This causes a reduction in the penetration of weld metal due to the resulting reduction in power density. However, the plasma helpfully increases the coupling of laser energy into the workpiece when the laser power is in the low intensity area of laser processing [3].

Protection gas is generally used in the laser welding process for protection of the weld keyhole and the molten metal from oxidation, and thus porosity and oxide inclusions are avoided. The type of protection gas has a significant effect on the formation of plasma. The most common shielding gasses are Ar, N_2, CO_2, He and mixtures of He and N_2. Helium is the best of common shielding and plasma control gasses because it has a higher ionisation potential [2]. This basically means that helium can absorb more energy before breaking down and before promoting an unacceptable plasma formation. The ability to transmit the laser beam without scattering and absorption is investigated by [3] for different protection gasses by establishing similar welding conditions for different protection gasses, and

[2] Keyhole laser welding is a process in which the intensity of the laser beam is very high when it reaches the workpieces (from approximately 10^3 W/mm^2 [2]). The laser beam penetrates into the workpiece surface and establishes a hole that is quickly filled with molten material before solidifying.

by measuring the resulting penetration depth. The results are shown in Figure 2.5.

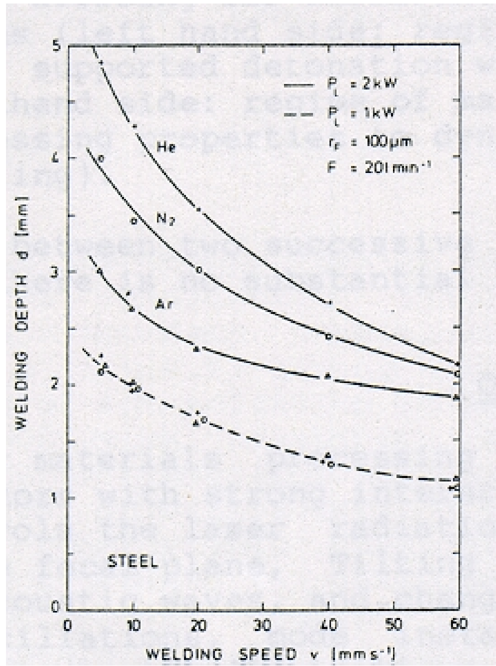

Figure 2.5: The effect of different protection gasses [3].

Heat radiation from the laser beam into the keyhole

The heat radiation from the laser beam into the molten weld pool depends on the initial laser power, on the losses of energy and energy density (which is described in the previous sections), and on the reflectivity of the material. The focused spot size which is influenced by the distribution of energy in the laser beam influences together with e.g. the welding speed the evaporation of material, and thereby the removal of material from the weld groove [2]. Additionally, these parameters are influential to the width of the welded joints. The wider weld joints the larger tolerances for gap and for displacement of the weld groove.

In the low range of laser intensity (below some critical value) the reflection of a given wavelength is independent of intensity but depends on various surface conditions like morphology and the state of oxidation of the workpieces. As the laser intensity at the surface of a workpiece approaches the critical value, the absorption instantaneously rises to nearly unity [3]. For high power laser welding the critical value for laser intensity will be exceeded. Further work in the modelling of absorption of the laser energy in the keyhole is described in [4].

Heat conduction and fluid dynamics in the weld pool

The shape of the weld pool is determined by the melting isotherm, which theoretically is influenced by the heat conduction, by the fluid dynamics in the molten weld pool, and by the heat conduction in the solid material. However, the fluid dynamics are shown to be insignificant [4].

Heat convection from the molten weld pool into the workpieces

The melting point of the workpieces and the latent heat energy, due to melting and solidification of material, influence the heat convection into the workpieces. However, the effect of latent heat due to melting is shown to be insignificant [4].

Heat conduction within the solid part of workpieces.

The heat conduction within the solid part of workpieces depends on the heat conductivity, on the geometric shape of the workpieces, as well as on the temperature gradient applied by the laser welding process (i.e. laser intensity and welding speed). The most important effect of this heat conduction is actually the cooling rate of the solid workpiece material. The cooling rate from 800°C to 500°C dictates the microstructure of the welded material and of the heat affected zone [5]. Therefore, this has a significant effect on the resulting quality of the laser-welded joints. Heat conduction in solid materials is well investigated, and models are established for this subject. But some of these models are non-linear with regard to the material temperature. This means that it is to be expected that thermal sensors must be applied to estimate the parameters of these models, if they are employed for controlling laser welding applications.

The design of steel alloys controls the metallurgical structure in welded joints. These alloys provide the desired metallurgical and mechanical characteristics in spite of a relatively fast cooling rate.

2.1.3. Controlling the process

The resulting quality of laser welded beads is dictated by the interaction of numerous physical phenomena of which the most important ones are mentioned in the previous section. However, the complicated physical processes of the laser machine have not been mentioned, because the output from this machine is regarded as a reliable controlled variable in the system. The influences of different parameters of the workpieces, such as variations in the gap between plates, material composition of the workpieces and special surface treatments of the workpieces have not been mentioned either. In the models of the physics of welding, above mentioned, these parameters are always fixed. As an example of this, no models are found which describe the variations of the absorption of heat in the keyhole as a function of varying gap or varying material composition. It is assumed that a model of the laser welding process, which is composed of the individual physical processes, will not be adequately developed for the purpose of controlling the process within the time horizon of the present Ph.D. project.

In this project the requirements from sponsors included an implementation of a laser welding control system for heavy industry. This system should serve as a tool for investigating the possibilities of controlling the laser welding process in an industrial environment and the problems that may occur there. Therefore, not only the ability to control selected physical phenomena of the laser welding process will be studied, but also the possibilities of controlling the unity of these processes in order to provide a specified and repeatably controlled quality of laser welded beads.

Never the less, it has been realised that the mentioned physical processes dictate the quality of the joints, and therefore an approach must be chosen which in some way includes these processes.

One approach which has shown to provide a repeatable weld quality is to adapt the welding control variables[3] to the geometric conditions of the weld joint [5], [6], [7]. This adaptation is performed by use of inverse process models. An inverse process model provides a set of welding control variables for a given workpiece geometry. It is possible to establish inverse process models that copes with variations in the weld geometry in such a way that the weld quality is held constant [8]. A number of workpiece

[3] Welding control variables are defined in chapter 4. For now, they may be regarded as these variables in the welding control system that are adjusted in real-time.

geometries and corresponding welding control variables must be included in these models.

In the present Ph.D. work this geometry based modelling and control approach is used and implemented at Odense Steel Shipyard Ltd. The modelling technique is based on inverse process models [9], [10], and on real-time measurement of the geometric preconditions for the welding process. The same modelling technique has previously been applied for intelligent automatic gas metal arc welding [11], [12], [13] and [14]. The concept of inverse process models is together with the structure of the control system described in details in chapter 4.

The quality of laser welded joints is dependent on a number of preconditions concerning the base material, the filler material, the preparation of workpieces, the surface treatment of workpieces, the welding equipment, the process variables etc. This Ph.D. work deals with the process control of the welding process. The preconditions for obtaining a specified weld quality by using the geometry based modelling and control system are additionally analysed. In literature a number of theories are applied for controlling the unity of the physical processes. These theories will be classified with regard to the type of control system used. However, initially the terminology for the types of control systems will be defined.

In addition to the type of modelling technique, it is important to be aware of which type of control system is feasible for adjusting the process by the chosen welding control variables. The control problem is considered in the next section.

2.2. The control problem

One of the most fascinating characteristics concerning control theories is that they can be applied to a wide range of systems, including systems for laser welding. Usually the object to be controlled is described by a system concept.

According to [15] a system is a number of components which are from a given point of view unified by some kind of interaction or inter-dependence.

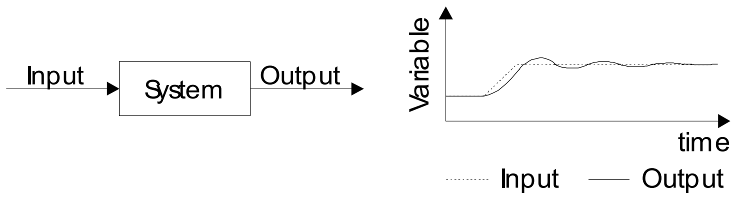

Figure 2.6: System represented as block diagram, and in time domain.

The systems upon which control theory can be applied are dynamic real-time systems, which means they are connected to our own dimension of time. They can be characterised by the fact that an input to the system will result in an output from the system. The time is in this sense considered as the independent variable.

The term ‘system’ may be used in the sense of a physical object, from which output can be observed by use of our senses. It may also be used in the sense of an abstract object that describes the relations between input and output by means of mathematics.

The output from a system may be described uniquely by the state and the input. The state of a system is any characteristic that relates input to output. For an abstract system the state variables may be defined as that collection of variables by which the output variables can be computed as a function of time, if the input to the system is known as a function of time together with the initial values of the state variables.

2.2.1. Open Loop Control

In case it is possible to describe the physical system and influences from the surroundings completely by means of mathematics, it will be possible to control the system in open loop. But, the system must be controllable, i.e. the influence of control variables on the system performance must be sufficiently strong to control the output. Figure 2.7 shows an open loop control system in which the desired output is specified through the input. In this figure the controller includes both a mathematical model of the controlled system and the influence from the surroundings, which enables the transformation from input variables to control variables. If the mathematical model is perfect the output will be exactly as specified by the input. The mathematical model of the controller is often called an inverse process model.

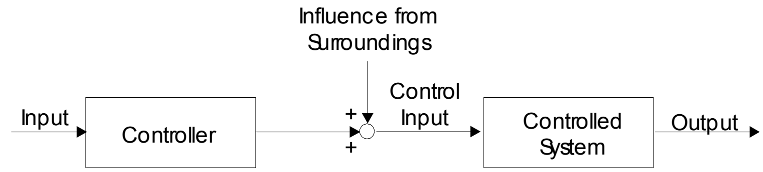

Figure 2.7: Illustration of an open loop control system.

2.2.2. Closed Loop Control

In laser welding, as in most processes, it is not possible to describe either the controlled system or the influence from surroundings sufficiently precise to control the output within the required accuracy. In this case influence from the surroundings is called disturbances, and a closed loop control system is applied in order to ensure that the achieved output is sufficiently close to the desired output of the system.

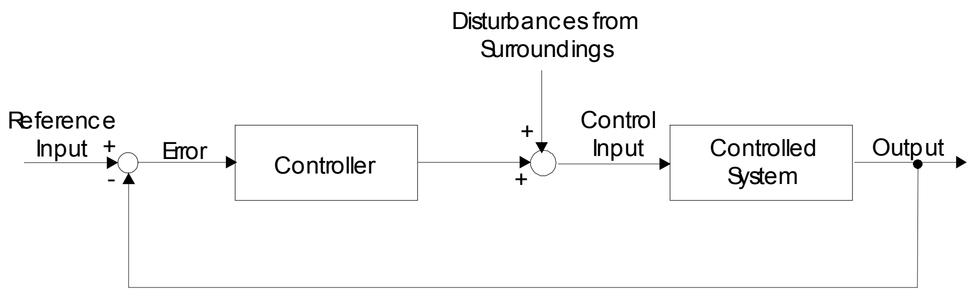

Figure 2.8: Illustration of a closed loop control system.

Figure 2.8 shows a closed loop control system in which the reference input specifies the desired output. The output is fed back and compared to the reference input, and in case a difference between the reference input and the output occurs an error is observed. In laser welding, as in many other systems, reference input and output in large numbers will exist. The system will be a multi input multi output system (MIMO). The controller includes a control law which provides the transformation of the error occurrence to the control input. This control law will ensure that the error is minimised or eliminated.

In terms of laser welding the reference input and the output are defined as the weld quality parameters, which are described in chapter 4. In order to establish a closed loop control system for laser welding, these quality variables would have to be measured in real-time during execution of the welding process. Furthermore, a control strategy for suppressing errors would have to be established, i.e. for transformation of the occurred error to a set of control input to the welding equipment.

Since some weld quality variables cannot be measured in real-time, such as e.g. the penetration depth[4], a full closed loop control of laser welding process cannot be established. But some state variables may be fed back. This is described later in this chapter.

2.2.3. Feed forward control

In a number of processes it turns out that it is not possible to control the output by applying a simple open loop control. Neither is it possible to measure the output or a sufficient number of state variables in real-time. Instead it may be possible to control the output sufficiently well by using feed forward control on condition that the influences from surroundings are well known.

In feed forward systems the control input for the plant is calculated by use of two different controllers, as shown in figure 2.9. The ordinary controller does not cope with changes (disturbances) in the surroundings. Only the normal condition of the controlled system and of the surroundings is considered (for closed loop systems this controller reacts to changes in the output, just like the controller in figure 2.8). The feed forward controller (see figure 2.9) establishes a feed forward control input (Yf) which is added to the ordinary control signal. The feed forward signal is calculated on the basis of predicted or pre-measured variations in the operating conditions.

In laser welding a number of parameters can be defined which may be included in a feed forward signal. These parameters are described in further detail and are categorised in chapter 4.

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[4] Penetration depth is defined precisely in chapter 6. For now, it may be considered as the depth of the weld metal when measured from top of the weld joint and in same direction as the laser beam.

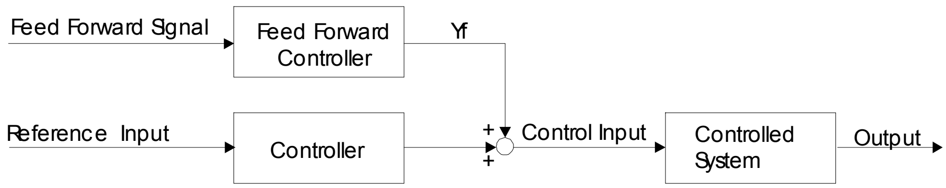

Figure 2.9: Feed forward control.

Feed forward control may be applied to closed loop systems. This changes the term 'feed forward control' to 'feed forward regulation'. Since the present and the previously performed work in the field of welding control does not imply feed forward regulation this is not described further in the present report.

Feed forward control may be categorised as static feed forward control, dynamic feed forward control or a combination of these control techniques. The static control method multiplies a constant gain factor to changes in the feed forward signal (see figure 2.10 and equation 2.1).

$$Y_f = K_{stat} \cdot (FF - FF_0)$$ **Equation 2.1**

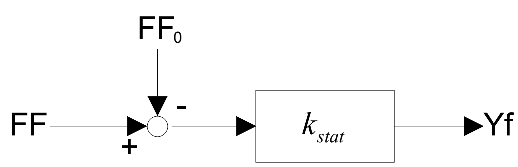

Figure 2.10: Transfer function for static feed forward control.

In dynamic feed forward control the feed forward signal is subject to an effect described by equation 2.2 and figure 2.11.

$$\tau \frac{dy}{dt} + Y_f = K_{dyn} \tau \frac{dFF}{dt}$$ **Equation 2.2**

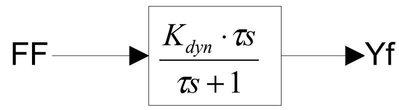

Figure 2.11: Transfer function for dynamic feed forward control.

The output from the dynamic feed forward controller only reacts to changes in the immediate feed forward signal.

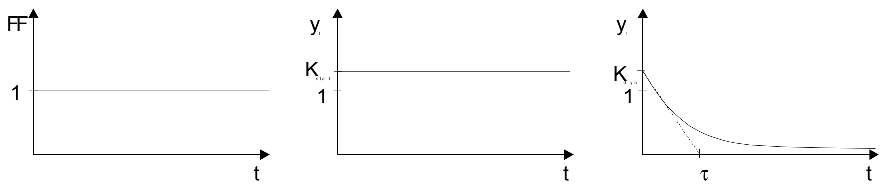

Figure 2.12: Step input (FF) and response (Y_f) from static and dynamic feed forward control, respectively. The initial feed forward signal (FF_0) is zero.

It is possible to establish a feed forward control system based on a combination of static and dynamic behaviour.

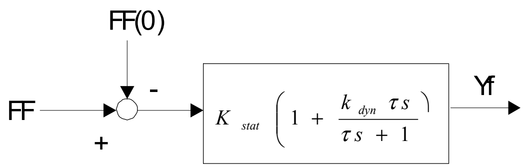

Figure 2.13: Transfer function for the combination of static and dynamic feed forward control.

Static and dynamic feed forward control methods are used in parts of the research, which is described later in this chapter. In this Ph.D. work feed forward control is used as well, but neither the static nor the dynamic methods give a precise description of the employed control method.

2.2.4. Adaptive control

One reason for discussing adaptive control in this report is that welding engineers use the term ‘adaptive control’ differently from that of most control engineers. Since this Ph.D. work applies control methods to laser welding the applied terms are obviously related to the terminology of control engineering.

Even though the term adaptive control has been used in the field of control theory for several decades, there is still no unique definition of this particular term. [16].

One definition [16] is to regard adaptive control as a special type of non-linear feedback control systems in which the states of the process can be separated into two categories which change at different rates. The quickly changing states are the ordinary process control feed back variables, and the slowly changing states are the regulation parameters of the controller. This introduces the idea of two time scales; a fast time scale for the ordinary feedback and a slower one for updating the regulator parameters. The regulator parameters are continuously adjusted due to optimisation of the system performance. This adjustment is based on measured changes in the control system performance.

2.2.5. Control gain scheduling

Control gain scheduling is easily confused with adaptive control because the regulation parameters may be changed during the process execution as in adaptive control. Instead of optimising the control parameters based on the evaluation of the system performance, the control parameters are pre-planned as a function of the operating conditions, as shown in Figure 2.14.

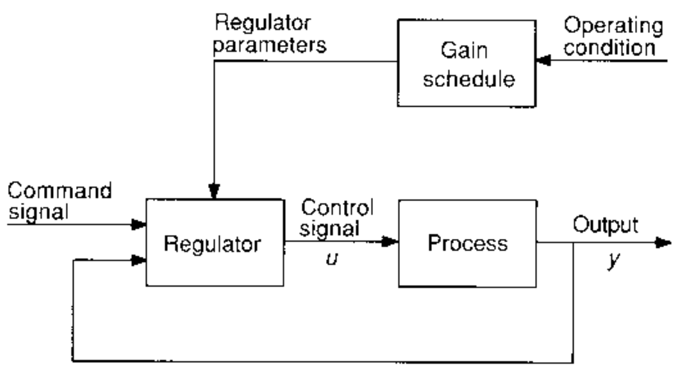

Figure 2.14: Structure of a gain scheduling closed loop control system [16].

The operating conditions may be measured by sensors or may be defined by pre-planning the process execution. It is possible to apply gain scheduling procedures for open loop as well as for closed loop control systems.

2.2.6. Definition of system limits

In the following sections some research on different methods for controlling the laser welding process with regard to joint quality will be outlined. In order to identify the types of control systems used for controlling the laser welding process the limits of the controlled system must be defined.

In the present report the controlled system consists of the equipment and materials used for executing the laser welding process. The controlled system consists of the workpieces, a laser machine, a beam transmission system, robotic manipulators, sensors and computers involved in the process and motion control. Moreover devices used for the supply and control of gas flows and wire additions are parts of the controlled system. Additionally, the applied gasses and filler wires are integrated parts of the system.

The input to the systems described in the following differs from one system to the next. This also applies for the measured output from the systems. However, a general trend is that the output is related to quality parameters in one way or another.

2.3. Previously performed research

In the following sections the described research copes implicitly with the physical processes mentioned earlier. However, these processes are not mentioned further in the following sections or in the rest of this report. The research is in the following sections categorised by the employed control methods.

2.3.1. Research in open loop welding control

Much research is performed in the field of open loop control of welding processes. Most of this research considers the influence of various welding control variables and parameters on certain quality parameters. The control system established during this Ph.D. work is partly based on the results of research in open loop control of laser welding.

[5] describes a number of welding control variables and their influence on certain quality parameters when applying CO_2 laser welding. The width and the depth of weld metal of a flat work specimen are investigated thoroughly with regard to welding speed variations, to the plasma control gas flow and to the mixture of helium and oxygen in the plasma gas at different welding

velocities. Also the hardness of the weld metal is investigated with regard to the composition of helium and oxygen in the plasma control gas, and to the plasma control gas flow.

In this work the maximum allowable size of gap between workpieces is investigated for butt joints with large plate thicknesses when welding without addition of filler wire. This investigation showed that the maximum allowable size of gap depends on the welding velocity. At a welding speed of 500 mm per minute, the gap was allowed to be maximum 0.5–0.6 mm. At a welding speed of 1500 mm per minute the gap was allowed to be maximum 0.2–0.3 mm.

This investigation also showed that the dynamics of the gap size had an influence on the acceptable size of gap. If welding in a weld groove in which the gap is decreased from a size larger than the maximum allowable gap size, the quality of the weld joint will not be satisfactory before the size of the gap is decreased to a level below the above mentioned 0.5–0.6 mm, corresponding to the chosen weld velocity of 500 mm per minute. When welding in a weld groove in which the size of gap increases from e.g. 0.0 mm to a size that is larger than the maximum allowable size, then the weld quality is satisfactory until the size of gap is a bit larger than the above-mentioned maximum allowable size.

A thorough investigation is made of the effects of applying filler wire to the laser welding process. The filler wire is in these investigations added from the front side and from the rear side of the laser beam, respectively, as shown in Figure 2.15. For high welding speeds (approximately 1000 mm/s) the depth of weld metal is bigger when adding the filler wire from behind the laser beam, compared to feeding wire from the front. At lower welding speeds a lack of material occurs in the surface of the weld when feeding filler wire from behind.

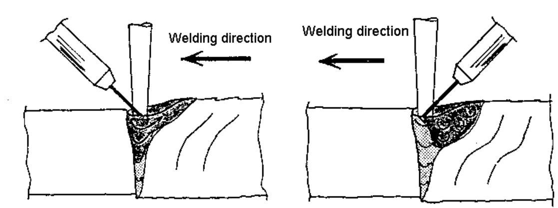

Figure 2.15: Addition of filler wire from the front and the rear side,

respectively [5].

The effects of feeding the wire from the front or from the back of the welding process, respectively, are described with regard to the depth of penetration of the weld metal. The conclusion is that for weld speeds above 625 mm per minute the penetration depth of weld metal is larger when adding the wire from behind the laser beam. For lower weld speeds the process tended to be more stable when adding the wire from the front.

2.3.2. Research in closed loop welding control

The application of on-line process control of the co_2 laser welding process with the aid of vision technology is investigated by [17]. These investigations are carried out for lap joints in mild steel and zinc coated mild steel. The size of the molten pool is monitored simultaneously by two CCD cameras from the top of the workpiece surface and from the backside of the workpieces, respectively. The aim of the investigation is to find a correlation between the signals from the CCD cameras (size of the molten pool), the position of the focus point and distance between the workpieces in the lap joint.

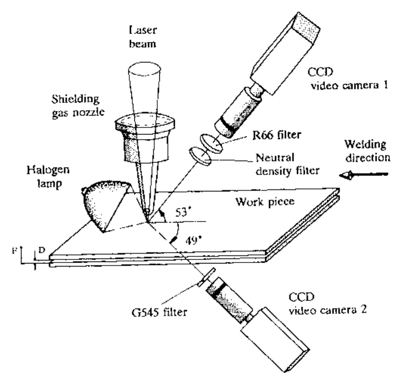

Figure 2.16: Experimental set-up [17].

It is found that variation of the position of focus point and distance beween the workpieces give different types of weld beads. These variations are also observed by analysing the signals from the CCD cameras. However, no unambiguous correlations are found for monitoring the influence of the variations on the width of the weld pool. It is not possible to tell if variations in the width of the weld pool are caused by changes in the distance between the workpieces or by change of the focus position relative to the workpieces.

2.3.3. Research in adaptive welding control

[18] establishes a model for adaptive control of the weld pool area for gas tungsten arc welding. The basic assumption of the control approach is that the pool width is proportional to the backside bead width in sheet welding, which is regarded as a direct specification of complete penetration of weld metal [18]. A vision measuring system is measuring the weld pool area in real-time, and a control algorithm is used for adjusting the welding current in order to control this width. The regulation parameters in this control algorithm are estimated on-line by using system identification. Therefore, the control method is a true adaptive algorithm in the sense of control terminology. The trajectory of the weld torch, the torch speed and the arc length are pre-programmed.

The adaptive control algorithm is tested in 1mm thick steel plates in which the heat transfer conditions are varied by changes in the workpiece geometry along the weld bead. The controller is able to track changes in the heat transfer conditions and to keep a relatively constant width of the weld bead.

2.3.4. Research in feed forward welding control

[8] establishes a feed forward control system for laser welding with filler wire. This system tracks the weld joint and adjusts the welding speed and the wire feed rate according to the size of the gap. The system uses a vision sensor for measuring the relative mutual positions of the workpieces and the gap between these in real-time. The control system is implemented with a look-up table for the parameters of the control gains for the welding speed and wire feed rate. These control parameters are in [8] described by a model which considers the size of the gap, the thickness of plates, the diameter of the applied filler wire, the angle between the incoming laser beam and weld groove, and the laser power.

The control parameters in the look-up table must be changed manually on the basis of known or expected operational conditions, which justifies that the system is categorised as a feed forward gain scheduling system.

2.4. Chosen control strategy

The control method developed during the present Ph.D. work is a feed forward control strategy based on a gain scheduling algorithm. The calculations of control variables were based on measurements of the gap between workpieces as described in [8]. The gap was measured by use of a laser sensor, and the calculation of control variables was based on a stationary feed forward algorithm which discretely changed the control parameters with regard to the actual size of gap. The control parameters were deducted from an inverse process model which described the welding speed, wire feed rate and position of focused spot size relative to the weld groove for a given set of quality parameters and pre-conditions for the process. This is described in detail in chapters 4 and 6.

The control strategy is quite similar to the one used by [5] and [11]. But some extra parameters were explicitly defined for the models, and an additional welding control variable was used compared to [5]. Considering [11], the type of modelling is the same as the one used in this Ph.D. project. However, the formalisation of the modelling approach is improved in terms of control theory (see chapter 4), and the functional architecture is extended in comparison with [11] (see chapter 5). The work carried out in [11] considered gas metal arc welding only. In the present Ph.D. project the modelling and control method is thoroughly tested for laser welding in production environment. In the present Ph.D. work the robustness and portability of the control strategy were investigated when transferring the control methods to an industrial environment.

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Chapter 3

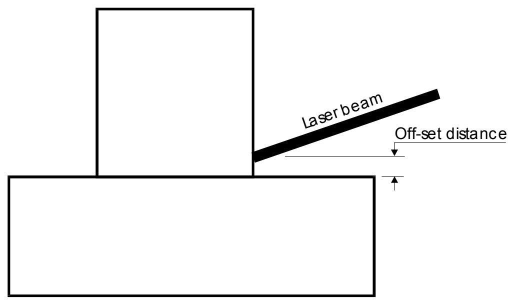
Problem Formulation

As described in the previous chapters, part of the danish heavy industry has shown interest in the possibilities for exploitation of laser welding technology. This technology has until now been developed and investigated to an extent which proves that it is applicable for welding of thick metal parts as the ones used in heavy industry.

It is shown that the manufacturing tolerances of the weld joint significantly influence the requested welding speed and the wire feed rate during the welding process, if a satisfactory weld quality must be achieved. It has in particular been shown that variations of gap size in the weld groove determine requirements regarding these welding control variables[1].

[1]Welding control variables are defined in chapter 4. For now, they may be considered as these controlled variables that may be changed in real-time by the welding equipment.

A system for measuring the gap and for compensating the weld speed and wire feed rate for laser welding is implemented at the FORCE institutes in Denmark. A human operator must initiate each weld task in this system. The operator must adjust the off-set distance manually by eye for each weld task (see figure 3.1). This adjustment is made by jogging the robot by manual input to a position where the laser beam hits the weld groove with a suitable off-set distance. The control system will then maintain this off-set distance during the weld task. The off-set distance is not a specified variable in the system, but is rather determined and adjusted for each weld task by the human operator.



Figue 3.1: Off-set distance of laser beam relative to weld joint.

The weld speed and the wire feed rate is in this system adjusted by using a look-up table in which the weld speed and the wire feed rate are defined for discrete sizes of gap in weld joints. The values for weld speed and wire feed rate in this table are based on steady state experiments. This look-up table may be considered a type of inverse process model[2] of the laser welding process. By using this strategy it is possible to obtain a satisfactory weld quality in a laboratory environment.

This Ph.D. project concerns the possibility of transferring laser welding technology into industrial production in heavy industry. The focus of work is described in the next few sections.

[2] Inverse process models are described in detail in chapter 4. For now, inverse process models may be considered as a type of process models for which the output is the welding control variables for the process.

The two main topics of this Ph.D. work were:

- To establish methods for implementation of a generic and fully automatic control system for laser welding of thick steel plates and to implement this system.
- To evaluate the portability of this system to industrial production environments by evaluating the robustness to typical tolerances.

3.1. Modelling and control strategy for laser welding

A control system for laser welding will be established and implemented in an industrial environment. The chosen control strategy will be described in terms of control engineering and block diagrams. The input and output of the system will be described thoroughly.

The control system will be partly based on the control principples that are implemented at the FORCE institutes, which has previously been mentioned [8], and on those which are developed in [12]. However, the system will include all necessary variables and parameters for fully automatic execution of laser welding without human interference for each weld task. The control of laser welding will in this work be based on steady state experiments, just as the work at FORCE institutes and of [12].

A method for applying inverse process models to the welding control system will be described thoroughly. This implies a method for stating the range of operation of these models.

In order to model the weld joint and significant parameters of the workpieces generic joint types will be established which cover the most common weld tasks in heavy industry. These joint types will provide a generic modelling terminology for both those weld joint and those parameters of the workpieces, which seem to be significant for control of the laser welding process.

3.2. Functional Architecture of control system

The control system described in the section above will be implemented in a software system. The functional architecture of this system will be described in chapter 5, where the system will be divided into logical sub-functions. The input and output will be described for both the superior system, and for the sub-functions of the system. In this way a generic controller for laser welding will be defined in terms of a functional structure. This structure will be divided into logical sub-functions for which the interfaces will be clearly defined. This will facilitate replacement of software routines or physical equipment in the system.

3.3. Test of control system in industrial environment

The implemented laser welding control system will be tested in a demonstration cell at Odense Steel Shipyard Ltd. These tests will include an investigation of the ability to provide a repeatable weld quality in an industrial environment.

It can be foreseen that some different types of disturbances to the weld tasks will be met when realising execution of these tasks in an industrial environment. This is because it is not considered profitable to make the same efforts to fine-tune set-up and to maintain equipment in an industrial production. It can be foreseen that requirements for fast production rates will influence the maintenance of equipment and equipment set-up. Additionally, it is to be expected that human operators in industrial production environments are less skilled than operators in laboratory environments, where experiments are often performed in co-operation with researchers. This means, that the understanding of the importance of tolerances and pre-conditions may not provide the human operator with the ability to interact immediately with machinery in case of poor calibration of welding equipment, exceeded production tolerances of the weld joints etc.

Disturbances that are foreseen to be typical in an industrial production are categorised and evaluated with regard to their influence on the weld quality. The robustness of the implemented welding control system will be evaluated in relation to these disturbances.

3.4. Evaluation of control strategy

A lot of experience was gathered during the Ph.D. work. The following chapters will be deal with the performed development work, and with implementation and testing of the welding control system. However, the descriptions of the system may differ from the implemented system in a way that would include better solutions based on the achieved experiences.

During development, implementation and testing of the welding control system, the control strategy will be evaluated and other possible strategies will be described.

References:

[8]: Nielsen Steen E., Seam Tracking and Adaptive Control Based on Vision Technology Used for High Power Laser Welding, Proceedings of 5th Nordic Laser Materials Processing Conference, September 6- 8, Oslo, Norway.

[12]: Madsen Ole et al., Model of Root-Bead Welding for Off-line Programming and Control, The 5th International Conference on Computer Applications in Production Engineering, Beijing, China, May 16 – 18 1995.

Chapter 4

Modelling and Control

The purpose of this chapter is to describe the strategy chosen for modelling and controlling the laser welding process in the present Ph.D. work. The components of the control system are categorised in order to facilitate the description of this system.

The structure of the established control system and the distinction between this system and traditional control systems are described in terms of control engineering.

4.1. Process Control Components

The characteristics that influence the quality of laser welded joints are in the following denoted as the process control components. These components are organised in six categories with respect to their ability to be controlled during preparation and execution of the process. This is in order to describe the components of welding control systems in generic terms. The categorisation is inspired from [14].

During categorisation the terms variables and parameters are used. The variables are the control components which are variable during the process execution. The parameters are the control components which are fixed during execution of weld tasks.

4.1.1. Equipment Parameters

The equipment parameters are chosen in relation to the specific equipment. They describe the equipment characteristics which cannot be controlled during process execution or preparation. Changing the equipment can only change them. The distribution of energy in the laser beam and the size of the protection gas nozzle are examples of equipment parameters.

4.1.2. Workpiece Parameters

The workpiece parameters are a result of the design and manufacturing of workpieces and of occurred process dependent heat distortions. These are e.g. the type of material and the geometry of workpieces.

4.1.3. Control Parameters

The control parameters are parameters which are chosen for a specific weld task, and which are not changed during execution of the laser welding process. These parameters are adjusted by equipment set-up and by choice of additional materials. Examples of control parameters are type of protection gas, plasma control gas and thickness of filler wire.

4.1.4. Control Variables

The control variables are characteristics which are adjusted by the process control system during process execution. Typical control variables for laser welding are the welding speed and the wire feed rate.

4.1.5. Process state variables

These variables define the states of the process during process execution. The values of the process state variables are functions of their initial state, and of the parameters and variables which are defined in sections 4.1.1

through 4.1.4. The distribution of temperature in the weld metal and in the heat-affected zone is an example of a process state variable. But since we do not either know the functional relationship or how to measure these variables, we will not make any attempt to monitor or control these variables explicitly.

4.1.6. Quality parameters

The quality parameters define the quality of the laser-welded joints, denoted by geometrical, mechanical and metallurgical characteristics. The process quality parameters are, like the process state parameters, functions of the first five categories in this section.

All of the above mentioned categories contain several parameters or variables. Therefore, a set of parameters or variables within a specific category is denoted as a vector such as a vector of control variables.

Some process parameters or variables may shift from one category to another, depending on the set-up of the manufacturing system. This can be illustrated by the angles between the weld groove and gravity. These characteristics are denoted as control variables if the workpiece is fixed at a workpiece positioner and the mentioned angles are manipulated during process execution. Whereas these angles are workpiece parameters if the workpiece position and orientation are constant during process execution.

4.2. Control System Structure

Using this defined categorisation of control components, it was possible to describe the established control system in generic terms.

The real-time[1] control system developed in the present work is categorised as an open loop gain scheduling feed forward control system. This categorisation is described further in the following sections.

The general structure of the control system is shown in Figure 4.1. The boxes describe physical and mathematical transformations of data, and the arrows describe the data that constrains and interfaces these transformations.

[1] Real-time: A data-processing system in which data are processed as it is generated and the data processing is completed in due time to ensure that the result of the data processing determines the trajectory of the process rather than the dynamic properties of the process itself.

Arrows entering the boxes from the left are input to the individual transformations, and arrows leaving the boxes from the right are output. Arrows entering the boxes from the top may be interpreted as the constraints, or as the requirements for the successful operation of the individual transformations.

4.2.1. Overall Structure

Figure 4.1 shows an overall structure of the control system which was established and implemented in connection with this Ph.D.-work. The reason for calling it an overall structure is that some of the components were only implicitly used in the actual real-time control system that is used for controlling the laser welding process, which is described further in section 4.2.2.

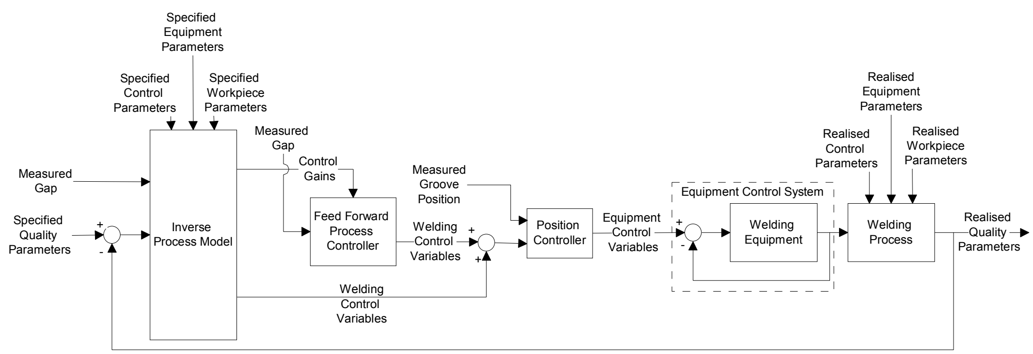


Figure 4.1: Overall structure of a process control system for laser welding.

The overall control system is not a typical real-time control system as normally described in control theory. Some of the shown data are not explicitly present in real-time, but rather during preparation of real-time execution. These are described in the following sections.

Specified quality parameters

The inverse process models (IPMs) are prepared to provide information concerning control variables corresponding to a given size of gap in the weld groove. These control variables will make sure that the vector of realised quality parameters corresponds to the vector of specified quality parameters. The vector of specified quality parameters for a particular IPM is constant, and thus not explicitly used during the real-time operation of the present process control system. Therefore, this input vector is only present during the establishment of the IPMs, which is further described later in this chapter.

Feed back of quality parameters

The overall system includes a feed back loop of the realised quality parameters of the laser-welded joints. Since these quality parameters include mechanical characteristics which are measured by destructive test methods, it was not possible to establish this feed back loop in real-time by direct measurements.

The feed back of quality parameters was performed during experimental preparation of IPMs for a specific type of weld tasks. During this preparation procedure the feed back was performed manually at the end of each experiment. The realised quality parameters were evaluated and compared to the specified quality parameters, and the parameters of the IPM were adjusted if necessary.

Inverse Process Models

The IPMs may be considered a generic tool for preparation of the control variables and the control gains for the process controller. The IPM would in the most generic form consist of a set of basic physical laws, from which exact control variables could be calculated for a given gap and for a specified set of quality parameters. However a sufficient amount of knowledge was not present for establishing this type of IPM, and therefore a type of experimentally established IPMs are employed.

In the present work IPMs were used for a linear open loop gain scheduling feed forward control strategy. The structure of an IPM is shown in Figure 4.2.

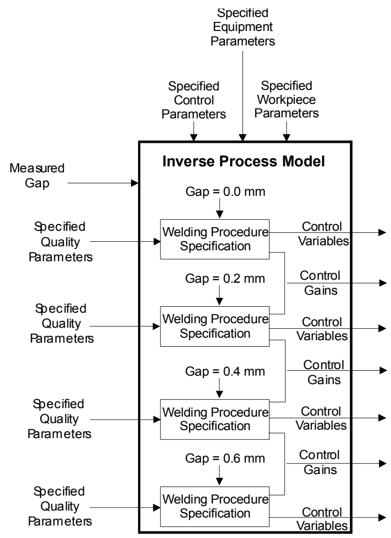


Figure 4.2: Structure of an IPM that covers gaps from 0.0 to 0.6 mm.

This IPM consists of a number of welding procedure specifications (WPS)[2]. Each of these specifications describes a vector of control variables. A WPS is established to provide a specific vector of realised quality parameters by using a specified set of control variables in the welding process. The WPS is established on the basis of a specific set of control parameters, equipment parameters and workpiece parameters. These specific parameters are required for a successful operation of the welding procedure and are therefore called the constraints of the WPS.

The IPM consists of a set of WPSs which all have the same constraints and which all provide the same quality parameters. The WPSs are all established for different sizes of gaps, which means that this particular workpiece parameter differs from one WPS to the next. Therefore, the control variables will differ from one WPS to the next as well, in order to provide the same quality parameters of the welded joints.

Within an IPM there must be a sufficient number of WPSs to cover the range of gaps that may occur in the weld tasks. The WPSs are valid for discrete sizes of gaps. In the present work a linear control strategy was

[2] A welding procedure specification is defined as the specification for execution of a weld task with a specific set-up of workpieces, equipment, additional materials and with a fixed set of control variables.

employed, which meant that the control variables changed linearly between two WPSs as a function of the gap. The density of the WPSs ensured that the weld quality was sustained for values of gaps that were in between two WPSs.

The input to the IPM was a vector of specified quality parameters that must be fulfilled by the welding control system, and it was the measured size of gap along the weld groove. The output is a number of discrete values of control variables and control gains. The mentioned control variables are in Figure 4.1 and Figure 4.3 denoted as welding control variables. This is because they are related to the welding process in general and not to the position of the weld groove.

The system is categorised as a gain scheduling control system because the control gains of the feed forward process controller were scheduled with respect to the operating conditions (gap). The IPM may be regarded as an advanced gain-scheduling algorithm, since the gains were scheduled as a function of the measured gap along the weld groove. Additionally, the control variables were scheduled as fixed values in the intervals in between the WPSs.

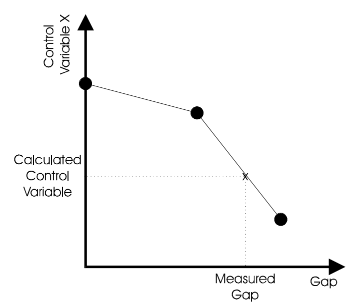


Figure 4.3: Control variable as function of gap.

Figure 4.3 shows a single control variable as a function of the measured gap. The dots represent the reference points at which the control variable is specified explicitly by WPSs. The slope of the lines connecting these reference points specifies the control gains for this specific control variable.

Basically the IPM concept may be applied to both steady state and dynamic control strategies. In the present work as well as in [14] the IPMs are basically applied for steady state control strategies. However, an algorithm was used in the present work for smoothing the measurements of gaps. The reason for this smoothing algorithm was that it filtered the measurements in order to avoid significant influences from noise in the measurements, but also to avoid abrupt changes in the executed control variables.

The mentioned smoothing algorithm affected the dynamics of the generation of control variables. The application of IPMs for true dynamic control strategies would require a thorough investigation of the dynamics of the welding process. These dynamics would involve procedures for starting and stopping the welding process as a function of workpiece geometry. This is not considered in the present work.

IPMs are applicable to linear as well as non-linear control strategies. But the application of IPMs in non-linear control strategies would require more advanced methods for the calculation of control variables than the application of quasi-stationary control gains as described later in this chapter.

IPMs are additionally applicable to both open loop and closed loop control systems. In the present work the IPM was applied to an open loop control strategy, which is described further in section 4.2.2. The closed loop strategy is possible in case the weld quality can be evaluated in real-time. It may also be possible to close the loop around a set of process states, such as the distribution of heat on the workpiece surface. But it would be necessary to know an unambiguous relation between these states and the realised quality of the welded joints. In this case the input would not be a vector of specified quality variables but rather the difference between specified and realised process quality parameters. The output structure of the IPMs might be the same as for open loop systems.

Feed Forward Process Controller

The input to the feed forward process controller is the measured gap along the weld groove. The output is a vector of welding control variables that must be added to the vector of welding control variables, which are specified by the IPM. The output is calculated as the product of the measured gap and the scheduled control gain for each control variable.

The control variables from the feed forward process controller ensure that the control variables change linearly as a function of change in gap in between the welding procedure specifications in the inverse process model.

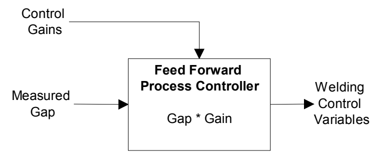


Figure 4.4: Establishment of welding control variables in the feed forward process controller.

The constraints of the feed forward process controller are the control gains that are scheduled by the inverse process model. These control gains are constant in the intervals in between the welding procedure specifications in the IPM.

Position Controller

The position controller relates the welding control variables to the position of the weld groove. The input is measured positions along the weld groove, and the output is a vector of equipment control variables.

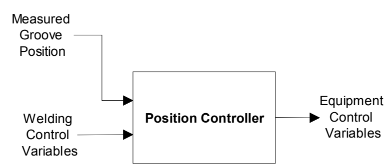


Figure 4.5: Position controller.

The equipment control variables correspond exactly to the welding control variables. However, they are adjusted in relation to the position of the weld groove, such that they are executed in the right positions. The equipment control variables are executed by the equipment control system, which is described in the next section.

Equipment Control System

The equipment control system is considered a sub system of the real-time control system. This sub system consists of laser machine, wire feeder mechanism and positioning robot. The equipment control system executes the equipment control variables that are calculated through the preceding functions.

Within the equipment control system a feed back of control variables is typically observed, e.g. as a position and velocity regulation in the positioning robot. Also the laser machine may include a feed back and regulation mechanism of the laser beam power. The wire feeder mechanism may as well measure and regulate the velocity of the wire.

Regulation by closed loop in the equipment control systems does not make the process control system a closed loop system because there is not feed back or regulation based on the process output.

Welding Process

The laser welding process is the physical result of the preceding functions. This process is basically the heating, melting, evaporation, condensing, fusion, solidification and cooling of the weld metal and heat affected zone. The physical processes mentioned in chapter 2 are deeply involved in these material processes.

The operating conditions that influence the welding process for a given set of control variables are described by the control, Equipment and workpiece parameters. As mentioned earlier, these parameters are specified for the weld tasks that are covered by a particular IPM. Small deviations in these parameters may occur because of tolerances in workpiece materials, in positioning of the laser beam etc. That is what makes the difference between specified and realised parameters.

The physical result of the welding process is described by a vector of realised quality parameters. This vector is intended to be similar to the vector of specified quality parameters, which is the input to the IPM in the overall structure of the control system (see Figure 4.1). However, the possible tolerances in the parameters mentioned just above may cause the realised quality parameters to deviate from the specified quality parameters. Therefore, it is extremely important to ensure that the value of the constraints of the IPM correspond to the actual value of the constraints of the physical welding process.

4.2.2. Real-time Structure

In control theory it is usual to categorise control systems with respect to the actual real-time algorithms and transformations. This categorisation is used to describe the control system throughout the rest of this report as well. The real-time structure of the control system is shown in Figure 4.6.

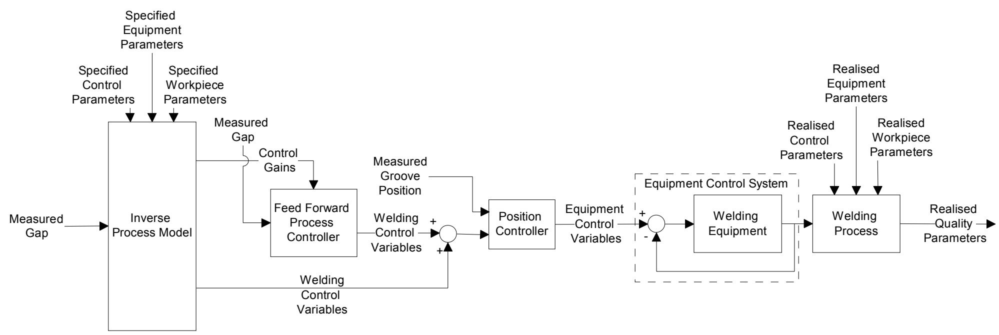


Figure 4.6: Real-time structure of the control system for control of laser welding.

The real-time control system may be categorised as a gain scheduling open loop feed forward control system.

The real-time control system differs from a traditional control system by including a model for the establishment of control variables. In traditional control systems these variables are established by use of control gains only, i.e. the output of the control system is subtracted from the input and the difference is multiplied with a gain factor. In real-time this welding control system has no input concerning reference quality parameters (see Figure 4.1). The input (specified quality parameters) is implicitly defined during preparation of the IPM.

The welding control system is operating in open loop, because there is no feed back from the output of the welding control system (quality parameters) nor from the states of the process (i.e. workpiece temperatures, weld pool shape and fluid energy flow).

The equipment control system has a feed back loop for control variables. This feed back is considered part of a sub system only and is no valid measure of the quality parameters or of the states of the process.

The established control system is a feed forward control system because the establishment of control variables is based on the measured size of the gap. This measurement is made at the position in which the control variables will be executed in the weld joint (see section 4.3).

The system is called a gain scheduling system because the gains are scheduled as a function of the operating conditions, as described previously.

4.3. Measuring and execution strategy

As described previously, the control variables are calculated to adapt the welding process to the varying gap in the weld groove. An optical triangulation sensor measures this gap during the process execution. The strategy for measuring the gap and for executing the control variables is described in this section.

The optical triangulation sensor is based on laser technology and has a resolution of 0.05 mm. This sensor is positioned at a fixed position related to the weld tool. The sensor is always in front of the weld pool during process execution, which enables real-time measurement of the weld groove before the weld pool reaches the measured position.

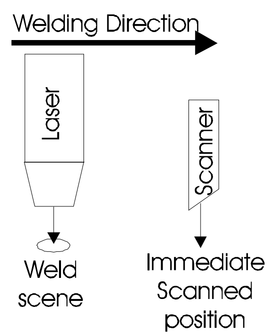


Figure 4.7: Set-up of weld tool and optical sensor.

The sensor measures positions of the workpieces, which forms the weld groove at discrete positions during execution of the welding process. Each measurement consists of a position of the weld groove and the size of gap at that particular position. No exact knowledge exists of either the positions of the weld groove or of the size of the gap in the positions between these measurements. However, the distance between two succeeding measuring positions is chosen so small that the gap can be considered constant and the weld groove is following a straight line between these.

As mentioned earlier, the control variables are calculated on the basis of gap measurements. This means that the control variables are established for discrete positions in the weld grove. This corresponds well with usual methods for programming positioning robots, since the movements of these are described in discrete terms. The movement from one of these positions to the next is linear and the control variables are constant.

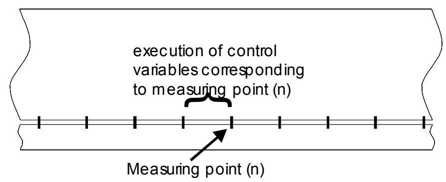


Figure 4.8: Illustration of the measuring points in the weld groove and the range in which the control variables corresponding to measuring point n are executed.

Figure 4.8 shows a weld grove with indication of the positions which are measured. The control variables corresponding to a measured position are executed in the area from the previously measured position to the actual, measured position.

4.4. Establishment and test of Inverse process models

In order to establish an inverse process model for a given type of weld task the constraints that apply to these tasks must be defined.

The equipment parameters do not have to be considered unless the welding equipment is changed. This is because these are implicitly defined for the specific equipment. But it is necessary to measure those parameters that may change over time.

The type of weld task for which the IPM is needed gives the workpiece parameters. These parameters (except the size of gap) are constant for the IPM.

A vector of quality parameters must be specified in order to evaluate when the realised weld quality resulting from experimental procedures is satisfactory.

Experimental procedures

Prior to establishing the IPM a number of workpieces which keep the defined workpiece parameters are prepared. The gap is kept at a constant size in each workpiece. Tack welds and spacer blocks fix the gap as shown in Figure 4.9.

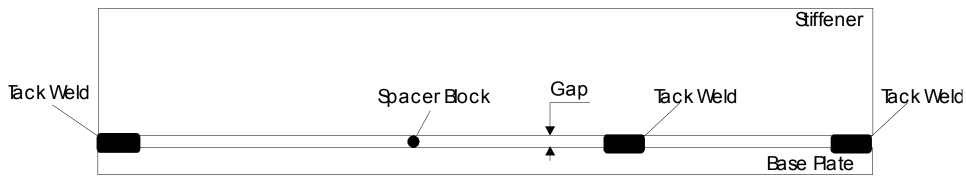


Figure 4.9: Test piece for establishing a welding procedure for an IPM.

The control parameters must be properly chosen in order to achieve the specified quality. One must keep in mind that the chosen control parameters are constant for the IPM, i.e. for all the WPSs within the IPM. Therefore, the chosen control parameters must ensure that the specified quality parameters can be achieved for all sizes of gap that are covered by the IPM by choosing appropriate control variables.

When a WPS is established for a given size of gap the operator chooses a vector of control variables for this particular size of gap. The finished weld bead is analysed with regard to the vector of realised quality parameters. In case the realised quality parameters correspond to the vector of specified quality parameters, the WPS is accepted for use in the IPM. If one or more of the realised quality parameters are not accepted, the operator adjusts the control variables and tries these variables on a new workpiece.

A suitable number of WPSs are established for an IPM in order to cover the sizes of gaps that may occur in the workpieces of the weld tasks.

References:

[14]: Madsen Ole, Sensor Based Robotic Multi-Pass Welding, 1992, Thesis within the research programme Integrated production Systems, Department of Production, Aalborg University, Denmark, ISBN 87-89867-02-5.

[19]: Holm Hans et. al, State modelling of Welding for Closed Loop Welding control, Proceedings of the tenth IPS Research Seminar held at Fuglsø, Denmark on 3 – 5 April 1995, ISBN 87-89867-29-7.

Chapter 5

Functional Architecture

This chapter describes the functional architecture of the '**Welding Control System**' established during the present Ph.D. work. The presented architecture is a generic architecture for automatic control of welding processes. However, the inverse process models and the 'Welding Control Vectors' are dedicated to laser welding.

The functions in the architecture are described as transformations, according to the employed modelling technique. This is because their tasks are to transform data from one state to another. The descriptions of transformations will provide a general view of the methods used for controlling the welding process. The input and output from the individual transformations are specified in appendix B. The implemented software is documented in Appendix C.

Experience from the Ph.D.work is taken into account in the presented architecture. This means that small improvements are included in this architecture compared to the implemented architecture.

The applied modelling method is the Yourdon modelling technique, which is shortly described in Appendix A. In the text below the names of data transformations (circles) are written in bold letters between apostrophes (‘**Name of Transformation**’, signals (dotted arrows) are written in italic letters between apostrophes: *‘Signal Name’* and data is written in normal letters between apostrophes (‘Name of Data).

5.1. Model of the Environmental Interface

The functional architecture of the ‘**Welding Control System**’ interfaces with the surroundings by exchanging data with surrounding equipment and with different models. An environmental model of the functional architecture is shown in Figure 5.1, where the interfacing data types are defined. The external measuring and processing equipment (terminators), and the models used by the ‘**Welding Control System**’ are briefly described below.

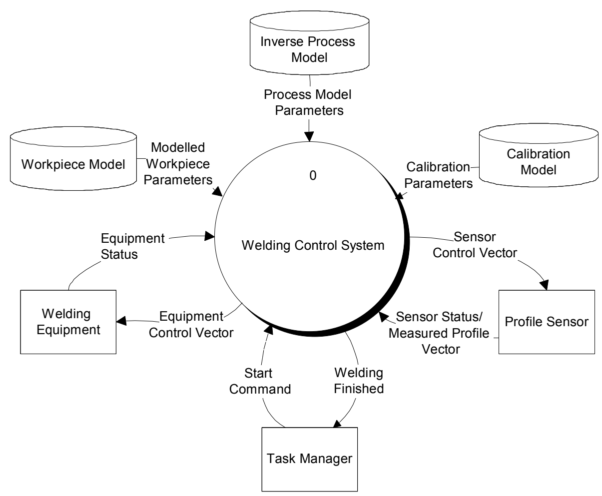


Figure 5.1: Environmental model of the functional architecture.

5.1.1. Environmental Terminators

The basic task of the '**Welding Control System**' is to provide the welding equipment with 'Equipment Control Vectors' that specifies the behaviour of the welding equipment. The terminators included in generation and execution of these 'Equipment Control Vectors' are the welding equipment, the profile sensor and the task manager.

Task Manager

The task manager has the very simple function of activating the '**Welding Control System**'. This function may be executed automatically or by an operator.

Profile Sensor

The profile sensor measures with a fixed frequency a set of points on the workpieces. The '**Welding Control System**' uses these measurements to identify the absolute position of weld groove and the absolute size of gap between the workpieces.

The '**Welding Control System**' controls the profile sensor by sending 'Sensor Control Vectors'. The sensor provides the '**Welding Control System**' with 'Sensor Status' and with 'Measured Profile Vectors'.

Welding Equipment

The welding equipment is the physical equipment which executes the process control components (see chapter 4). The welding equipment provides status messages which confirm the execution status of the equipment ('Equipment Status'). Additionally, the welding equipment provides the absolute 'Robot Locations' in real-time, i.e. the position and orientation of the end effector defined in the robot base frame. These 'Robot Locations' are included in the generation of 'Equipment Control Vectors'.

5.1.2. Environmental Models

In order to establish 'Equipment Control Vectors' which provide a specified quality in a robust way, it is chosen to use dedicated information about calibration of equipment, workpiece parameters and how to convert workpiece parameters to process variables. This information is included in inverse process models, workpiece models and calibration models, which are described below.

Workpiece Model

The workpiece model provides a description of workpiece parameters significant for choosing inverse process models and for controlling the profile sensor. Some of these parameters cannot be measured with the profile sensor, such as the thickness of plates, the type of workpiece materials etc. More detailed definitions are provided in appendix B.

Inverse Process Model

The inverse process models provide the '**Welding Control System**' with information about absolute values of process control variables corresponding to discrete values of workpiece parameters. The structure and contents of inverse process models are described in detail in chapter 4.

Calibration Model

The calibration model provides 'Calibration Parameters' to the '**Welding Control System**'. These parameters include information about the co-ordinate transformations from the sensor frame and the tool frame to the end effector frame. A more detailed definition is provided in appendix B.

5.2. Model of the Internal Architecture

The internal architecture describes the structure of the transformation of input data from terminators into output data for the welding equipment. This transformation is divided into 5 sub-transformations, as shown in Figure 5.2.

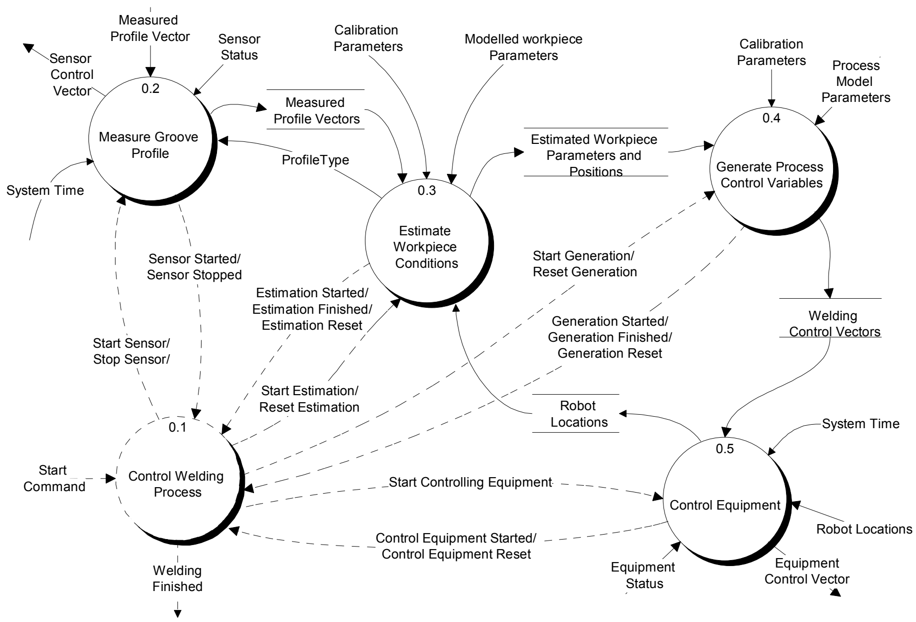


Figure 5.2: Model of internal architecture.

The division of the internal architecture serves the purpose of splitting the '**Welding Control System**' into a number of smaller functions that are easier to handle. These functions are divided into sub levels, which are described in the following sections. The dynamics of the '**Welding Control System**' is described in terms of the internal dynamics of the data transformations 0.2 through 0.5 in Figure 5.2 and the dynamics of the control transformation 0.1: '**Control Welding Process'**. The internal dynamics of data transformations are described in the sections belonging to the individual data transformation. The dynamics of the control transformation are described at the end of this chapter.

5.1.3. Transformation 0.2: 'Measure Groove Profile'

This function controls the external profile sensor, which is used by the '**Welding Control System**'. The measurements from the profile sensor ('Measured Profile Vectors') are acquired by this transformation and are transferred to other parts of the control system, where the data are used for estimation of the weld groove profile.

In the present Ph.D. project the profile sensor is a commercial laser based line scanner which is used for measuring and for extracting measured profile characteristics, which are organised in profile vectors. Since commercial sensor systems are available for this extraction, the Ph.D. work has not considered the low-level procedures for this topic, such as image processing algorithms.

This section describes the architecture for controlling the extraction of 'Measured Profile Vectors' from the profile sensor. The architecture for these transformations is shown in Figure 5.3.

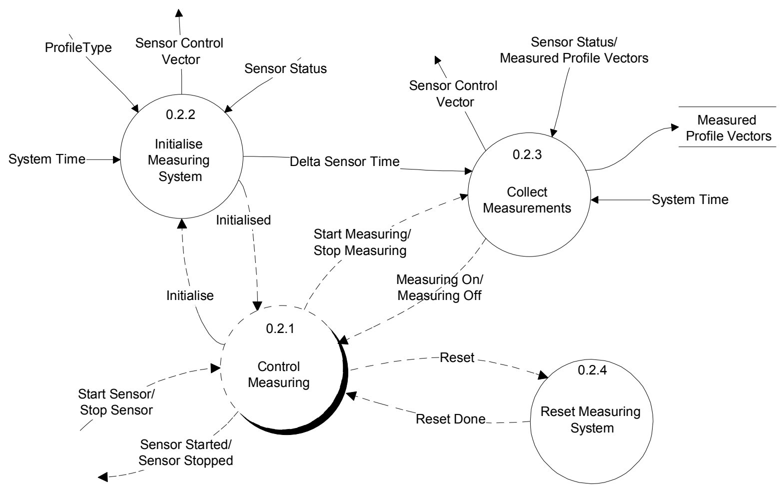


Figure 5.3: Decomposition of the transformation 0.2: 'Measure Groove Profile'.

The following sections provide a description of the transformations (functions) in the functional architecture for measuring the groove profile.

Transformation 0.2.2: 'Initialise Measuring System'

This transformation initialises the profile sensor before execution of a weld task. This includes providing information for the profile sensor about the 'Profile Type' to be measured. Additionally, this function calculates the parameter 'Delta Sensor Time' that specifies the difference between the values of the timer of the profile sensor and the timer of the '**Welding Control System**'.

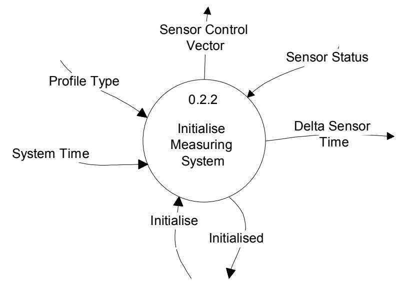


Figure 5.4: Sub transformation 0.2.2: 'Initialise Measuring System'.

The signal that activates the function is *'Initialise'*. The effect of *'Initialise'* is:

1) The function waits for the 'Profile Type' to be defined[1]. This must be defined within a specified timeout value.
2) The function establishes and sends a 'Sensor Control Vector' to the profile sensor. The command part of this vector is set to 'Set Profile Type*',* and the task specification part of the vector is 'Profile Type'.
3) The function waits for 'Sensor Status'.
4) If 'Sensor Status' is 'Success' the function establishes and sends a 'Sensor Control Vector' to the profile sensor. The command part of this vector is set to 'Reset Sensor Time'. The timer of the profile sensor will then start running from zero. 'Delta Sensor Time' is set to the actual value of the system time[2].
5) The function waits for 'Sensor Status'. This must be received within a specified time limit.
6) The function responds with the signal '*Initialised*'.

The time limit in point 5 has to be very small because the precision of time synchronisation between the profile sensor and the '**Welding Control System**' is significant for the geometric precision of the transformation of 'Measured Profile Vectors' from sensor frame to robot frame.

[1] The 'Profile Type' is defined by the transformation '**Estimate Workpiece Conditions**'.
[2] 'System Time' is the actual timer value in the '**Welding Control System**'.

Transformation 0.2.3: 'Collect Measurements'

This transformation controls the acquisition of profile measurements and sends these to the queue of 'Measured Profile Vectors'. The 'Measured Profile Vectors' are defined in the sensor frame. The time stamps in the 'Measured Profile Vectors' are converted to the time of the '**Welding Control System**' before the vectors are queued.

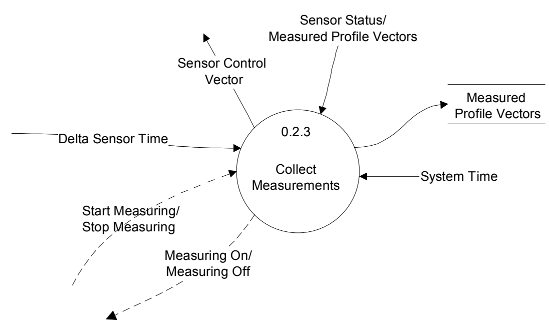


Figure 5.5: Transformation 0.2.3: 'Collect Measurements'.

The transformation is activated by the signals '*start measuring*' and '*stop measuring*', respectively:

The effect of '*Start Measuring*' is:

1) The function sends a 'Sensor Control Vector' 'to the profile sensor. The command part of this vector is set to *Start Profile Measurement*.
2) The function waits for 'Sensor Status'.
3) If the 'Sensor Status' is 'Accepted' the function will send the signal *'Measuring On'*.
4) The function will now start waiting for 'Measured Profile Vectors' from the profile sensor. Each time the profile sensor has established a new 'Measured Profile Vector' this vector is acquired and the value of 'Delta Sensor Time' is added to the time stamp of the 'Measured Profile Vector'. Then the vector is put into the queue of 'Measured Profile Vectors'. This continues until the signal *'Stop Measuring'* is received.

The effect of '*Stop Measuring*' is:

1) The function establishes and sends a 'Sensor Control Vector' 'to the profile sensor. The command part of this vector is set to 'Stop Measuring Profile'.
2) The function waits for 'Sensor Status'.
3) If 'Sensor Status' is 'Success' the function will emit the signal *'Measuring Off'*.

Transformation 0.2.4: 'Reset Measuring System'

This function cleans up the memory after the measuring system has performed measurements. The signal which triggers the function is *'Reset'*.

The effect of *'Reset'* is:

1) The function sets the value of 'Delta Sensor Time' to zero.

Transformation 0.2.1: 'Control Measuring'

This transformation is a control transformation and it only handles control signals for the sub-transformations in the transformation **'Measure Groove Profile'**

The connections between incoming and outgoing signals are presented in the state diagram shown in Figure 5.6.

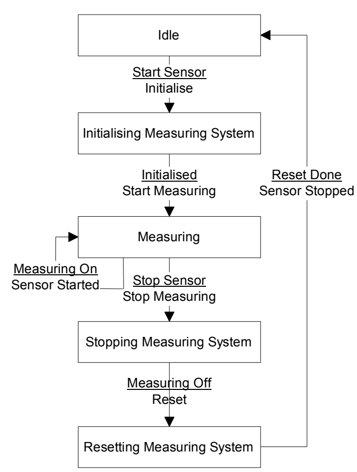


Figure 5.6: State Transition Diagram of transformation 0.2.1: 'Control Measuring'.

‘Idle’

Before a weld task is initiated and after it is finished the sub-transformation 0.2: ‘**Measure Groove Profile’** is in an idle state.

‘Initialising Measuring System’

When the signal *‘Start Sensor’* is received from transformation 0.1: ‘**Control Welding Process’**, the measuring system goes into the state ‘Initialising Measuring System’. The ‘Profile Type’ is now identified and sent to the profile sensor. The timer of the profile sensor is reset and the time in the ‘**Welding Control System**’ in this moment (system time) is copied into the parameter ‘Delta Sensor Time’. This is in order to synchronise the time stamps of the ‘Measured Profile Vectors’ with the ‘**Welding Control System**’.

‘Measuring’

Having received the signal *‘Initialised’,* the state machine transits into the state ‘Measuring’. In this state, the system orders the sensor to *‘Start Measuring’* the groove profile. The system acquires the ‘Measured Profile Vectors’, converts their time stamps to the time scale of the ‘**Welding Control System**’ and puts them into the queue of ‘Measured Profile Vectors’.

‘Stopping Measuring System’

When the signal *‘Stop Sensor’* is received the measurements are stopped and the profile sensor is turned off. After stopping the measuring system, the system can be reset.

‘Resetting Measuring System’

After the measurements have been stopped, which is signalled by the signal *‘Measuring Off’*, the system must be reset in order to clean up the memory. In this state, the system resets the ‘Delta Sensor Time’. Now the measuring system has finished the requested tasks and returns to the ‘Idle’ state. The queue of ‘Measured Profile Vectors’ may still be used by other transformations.

5.1.4. Transformation 0.3: 'Estimate Workpiece Conditions'

This transformation estimates workpiece parameters based on the workpiece model and 'Measured Profile Vectors'. The workpiece parameters may be divided into a set of fixed, constant parameters and a set of variable parameters that may vary continuously during each weld task. The fixed parameters are extracted directly from the workpiece model, and calculation of the variable parameters is based on the 'Measured Profile Vectors'.

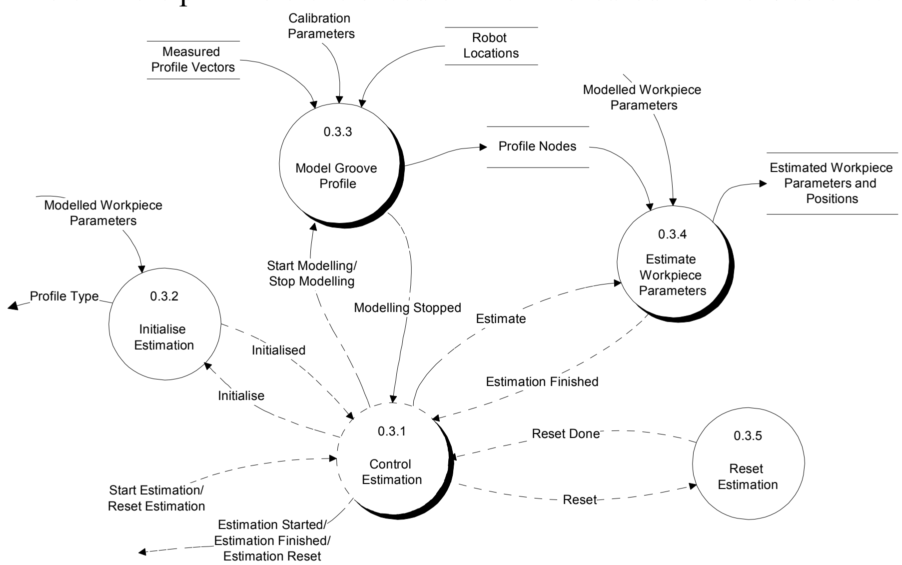


Figure 5.7: Transformation 0.3: 'Estimate Workpiece Conditions'.

The division of this transformation into logical functions is described in the following sections.

Transformation 0.3.2: 'Initialise Estimation'

This transformation initialises the estimation process. This function reads the workpiece model and specifies the 'Profile Type'. This information is used by the transformation 0.2.2: '**Initialise Measuring System**'. Additionally, the function allocates memory for the queue of 'Profile Nodes' and for the queue of 'Estimated Workpiece Parameters and Positions'. These data types are described later.

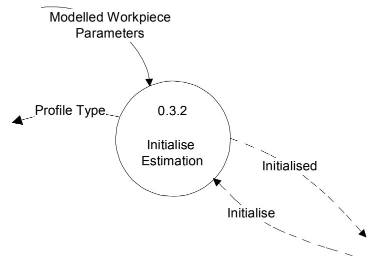


Figure 5.8: Transformation 0.3.2: 'Initialise estimation'.

The function is trigged by the signal *'Initialise'*.

The effect of *'Initialise'* is:

1) The function reads the 'Modelled Workpiece Parameters' from the workpiece model and identifies the 'Profile Type'.
2) The 'Profile Type' is made available for the transformation '**Initialise Measuring System**'.
3) The queues of 'Profile Nodes', 'Measured Profile Vectors', and 'Estimated Workpiece Parameters, and Positions' are instantiated in the memory. 'Profile Nodes' are described in the next section.
4) The signal *'Initialised'* is emitted.

Transformation 0.3.3: 'Model Groove Profile'

This sub-transformation transforms the 'Measured Profile Vectors' into 'Transformed Profile Vectors', which are defined in the robot base frame. The function establishes a model of the profile based on statistical analysis and filtration of the 'Transformed Profile Vectors'. The output of the function is a queue of 'Profile Nodes' that specifies the modelled profile at discrete positions. This modelling activity is in order to filter out noise from the measurements and to establish robust data for estimation of the workpiece parameters. The transformation is divided into the two sub-transformations, which are shown in Figure 5.9.

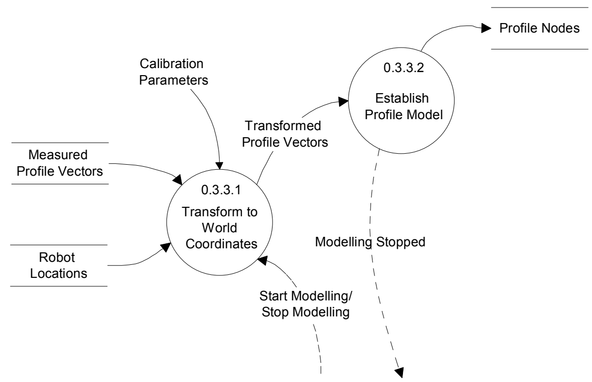


Figure 5.9: Decomposition of Transformation 0.3.3: 'Model Groove Profile'.

Transformation 0.3.3.1: 'Transform to World Co-ordinates'

The positions of 'Measured Profile Vectors' are specified in the sensor frame. Since the sensor frame moves continuously relative to the robot base frame, and since the workpiece is fixed relative to this frame, it is not possible to make a full analysis of the weld groove geometry in the sensor frame. Sudden changes in the measurements may be caused by sudden changes in the weld groove geometry, but sudden movements of the sensor may also cause this. The task of this particular transformation is therefore to transform the positions of the profile measurements from sensor frame to robot base frame.

The sensor is mounted on the end effector of the robot. Therefore the transformation from sensor frame to robot base frame consists of two successive transformations, i.e. the transformation from sensor frame to the end effector frame (${}^{sensor}T_{end\ effector}$), and the transformation from the end effector frame to the robot base frame (${}^{end\ effector}T_{base}$).

The transformation from end effector frame to robot base frame is also called the robot location and it changes as the end effector moves along the weld groove. The 'Measured Profile Vectors' must therefore be transformed according the actual robot location at the time when the measurement was made. The transformation matrix that specifies the transformation from sensor frame to end effector frame is specified in the 'Calibration Parameters'.

The function is triggered by the signals *'Start Modelling'* and *'Stop Modelling'*, respectively.

The effect of *'Start Modelling'* is:

1) The function reads the transformation matrix ${}^{sensor}T_{end\ effector}$ from the 'Calibration Parameters'.
2) The function reads the front element in the queue of 'Measured Profile Vectors'. The time stamp of this element is identified.
3) The function starts reading elements from the front of the queue of 'Robot Locations'. It searches until it finds the first element in which the time stamp value is higher than or equal to the time stamp value of the measured profile vector. This robot location is then measured later than or at the same time as the measured profile vector.

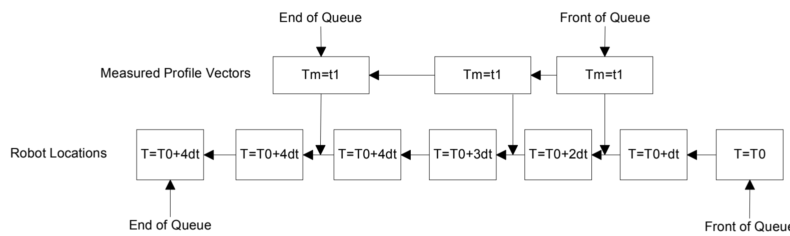


Figure 5.10: Interpolation of 'Robot Locations'.

4) An interpolated robot location is calculated that corresponds to the time stamp of the measured profile vector.
5) The positions in the 'Measured Profile Vector' are transformed from sensor frame to robot base frame according to the interpolated robot position.
6) The transformed positions are now organised into a transformed profile vector. This vector has no time stamp.
7) The front element of the queue of 'Measured Profile Vectors', which has just been processed, is deleted and the next element is now the front of this queue. The elements in the queue of 'Robot Locations' that are in front of the two elements used for interpolation are deleted. These elements are older than the first element in the queue of 'Measured Profile Vectors'.

The effect of the signal *'Stop Modelling'* is:

1) The status of the transformed profile vector being processed is set to end and no more elements from the queue of 'Measured Profile Vectors' are processed.

Transformation 0.3.3.2: 'Establish Profile Model'

This transformation establishes a model of the measured profile. This model is based on regression analysis of the positions in the 'Transformed Profile Vectors'. 'Profile Nodes' of R, S and T-points represent the model (see Figures 5.11 and 5.12).

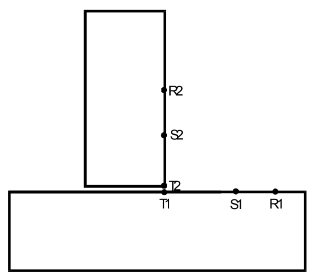


Figure 5.11: R, S and T points on a T-joint.

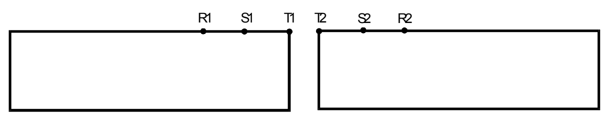


Figure 5.12:R, S and T points on a butt joint.

These 'Profile Nodes' are distributed with a fixed distance called the node distance (see Figure 5.13). When a tack weld is identified this function will establish a profile node at both ends of the tack weld. Nodes are additionally distributed along the tack weld with the same distance as mentioned (node distance).

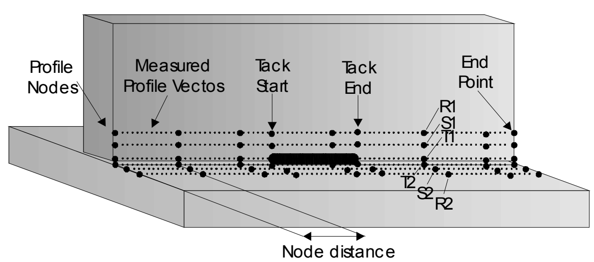


Figure 5.13: Expected distribution of 'Profile Nodes' in the weld groove.

This and the previous transformation are executed sequentially. The function is therefore executed in succession of the previous transformation.

The activities in the function are described below:

1) The 'Transformed Profile Vectors' are compared to the established model of the profile. Establishment of the initial model parameters are not considered in this report. The transformed profile vector is approved if the distances between the modelled and measured R, S and T points are within a specified tolerance. If the transformed profile vector represents a tack weld, the T1 and T2 points are positioned in the intersection between the surfaces of the weld groove, as shown in Figure 5.14. If the transformed profile vector represents a tack weld in a butt joint, the T1 and T2 points are positioned in the mid point between the intersection of the tack weld and workpiece surfaces on both sides of the tack weld, as shown in Figure 5.15.

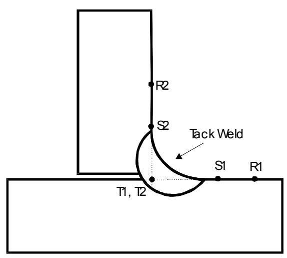


Figure 5.14: Position of R, S and T-points in case of tack weld in T-joints.

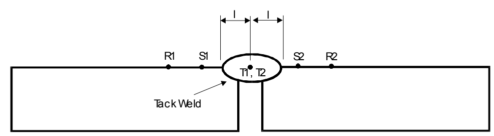


Figure 5.15: Position of R, S and T points in case of tack weld in butt-joints.

2) If the transformed profile vector is approved the function deletes the 'Transformed Profile Vectors' that are further away from the actual vector than the specified node distance. The model is then updated by linear regression of the remaining 'Transformed Profile Vectors'.

3) The function establishes new 'Profile Nodes' on the following conditions:

- The distance from the transformed profile vector, which is currently being processed, to the previously established profile node is larger than the specified node distance. Then if the transformed profile vector represents a point without tack weld, the new profile node has status of an ordinary profile node. If the transformed profile vector represents a tack weld, this profile node has status of a tack weld.

- The transformed profile vector, which is currently being processed, is the first measured position of a tack weld. Then the new profile node will be placed on the modelled weld groove, with the same distance to the previous profile node, as the measured profile vector. This node has status of a tack weld.

- The transformed profile vector, which is currently being processed, is the initial measured point after a tack weld. Then The new profile node will be placed on the modelled weld groove, with the same distance to the previous profile node, as the last 'Measured Profile Vector' that measured the tack weld. This node has status of a tack weld.
- The transformed profile vector is the initial point after the weld groove is ended. Then the new profile node will be placed on the modelled weld groove, with the same distance to the previous profile node, as the last 'Measured Profile Vector' that measured a position at the weld groove. This node has status of the last measured groove point.

The nodes established on the basis of the modelled weld groove are positioned as cross sections perpendicular to the weld groove. This means that the gap between the workpieces can be calculated directly as the direct distance between the points T1 and T2 in a particular profile node. In a butt-joint the T points are defined as the corner points of the two workpieces, as can be seen in Figure 5.12, and in a T-joint the T point on the free part of the joint is placed at the part corner. The T point of the flange is placed in the intersection between the R and S points of the two parts, which can be seen in Figure 5.11.

The difference between 'Measured Profile Vectors' and 'Profile Nodes' is that the profile vectors represent direct measurements of the weld groove positions, and the 'Profile Nodes' represent modelled positions in the weld groove. These positions are represented by R, S and T points for both types of entities. The 'Profile Nodes' have a fixed distance. However, the events listed below will trigger that a profile node is established no matter how close this may be to the previous one:

- Tack weld starts
- Tack weld ends
- Weld joint ends

The transformations '**Transform to World Co-ordinates**' and '**Establish Profile Model**' are repeated sequentially until the '**Transform to World Co-ordinates**' receives the signal *'Stop Modelling'*.

Transformation 0.3.4: 'Estimate Workpiece Parameters'

This function calculates the workpiece parameters which may change during process execution, and which are measurable by the sensor. The workpiece parameters that cannot be measured by the sensor are specified in the workpiece model. These data are then included in the estimated workpiece parameters. In this way the estimated workpiece parameters serve as an updated workpiece model which takes the geometrical variations and the absolute positions of the weld groove into account. This transformation is divided into the sub-transformations: '**Calculate Gap and Groove Angles**' and '**Establish Estimated Workpiece Parameters**'.

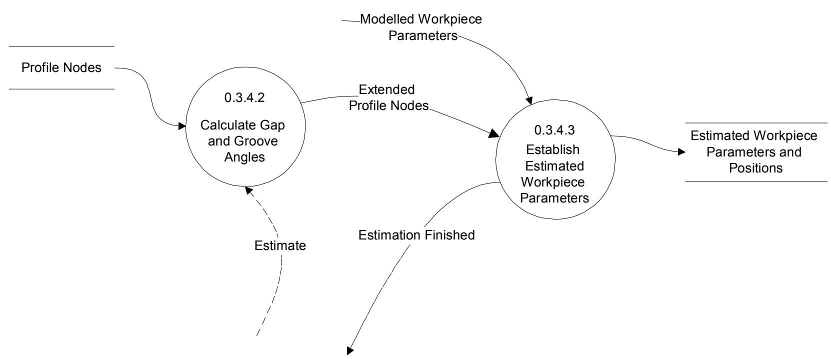


Figure 5.16: Decomposition of the transformation 0.3.4: 'Estimate Workpiece Conditions'.

Transformation 0.3.4.2: 'Calculate Gap and Groove Angles'

This function extends the 'Profile Nodes' by calculating the gap and the angle between the workpieces in the weld groove. These operations are performed using ordinary geometric calculations based on the 'Profile Nodes'. This is not described further in the present report.

Transformation 0.3.4.3: 'Establish Estimated Workpiece Parameters'

This function integrates the 'Extended Profile Nodes' into the 'Modelled Workpiece Parameters'. The result of this is the estimated workpiece parameters, which include both 'Modelled Workpiece Parameters' and measured workpiece parameters at specific positions in the weld groove.

The structure of 'Estimated Workpiece Parameters and Positions' is specified in appendix B.

When an extended profile node with the status of groove end is converted to an element in the queue of 'Estimated Workpiece Parameters and Positions', this element inherits the status of an endpoint, and the function emits the signal *'Estimation Finished'*. No more 'Profile Nodes' are then transformed.

Transformation 0.3.5: 'Reset Estimation'

The estimation of workpiece parameters is reset when the order *'Reset Estimation'* is received from the transformation 0.1: '**Control Welding Process'**. The resetting includes termination of the queue of 'Measured Profile Vectors', the queue of 'Robot Locations' and the queue of 'Profile Nodes'.

Transformation 0.3.1: 'Control Estimation'

The estimation of workpiece parameters is controlled according to the state transition diagram in Figure 5.17.

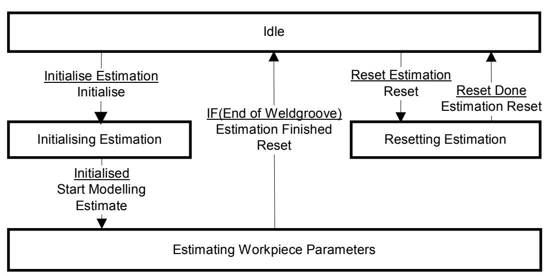


Figure 5.17: State transition diagram of transformation 0.3.1: 'Control Estimation'

'Idle'

The transformation starts in the idle state and goes into the state 'initialising estimation', when the signal *'Start Estimation'* is received from transformation 0.1: '**Control Welding Process'**.

'Initialising Estimation'

In this state the system initialises the memory segments used for establishing the estimated workpiece parameters. The 'Profile Type' is additionally identified for the weld task. After initialisation the function sends out the signal *'Estimation Started'* in order to indicate that the 'Profile Type' is established and may be used by transformation 0.2: '**Measure Groove Profile'**.

'Estimating Workpiece Parameters'

After initialisation the control system starts the estimation of workpiece parameters. In this transformation the weld groove is modelled on the basis of 'Measured Profile Vectors'. The modelled weld groove states the basis for calculating the gap and the angle between the workpieces in the weld groove. The measurements of the weld groove are in this manner filtered and combined with workpiece parameters from the workpiece model as described earlier in this chapter. This state is active until a profile node specifies the end of the weld groove. Then the signal *'Estimation Finished'* is emitted, and this transformation goes into an idle state.

'Resetting Estimation'

When the signal *'Reset Estimation'* is received from the transformation 0.1: '**Control Welding Process'**, the transformation removes the queues which are not in use any more. The queue of 'Estimated Workpiece Parameters and Positions' are still available for the transformation 0.4: '**Generate Process Control Variables**'.

5.1.5. Transformation 0.4: 'Generate Process Control Variables'

This transformation performs the transformation of estimated workpiece parameters into 'Welding Control Vectors'. A welding control vector is the set of welding control variables that enables a unique definition of robot motions and variable settings of the welding equipment. The 'Welding Control Vectors' are established for specific positions in the weld groove, which correspond to the positions of the estimated workpiece parameters.

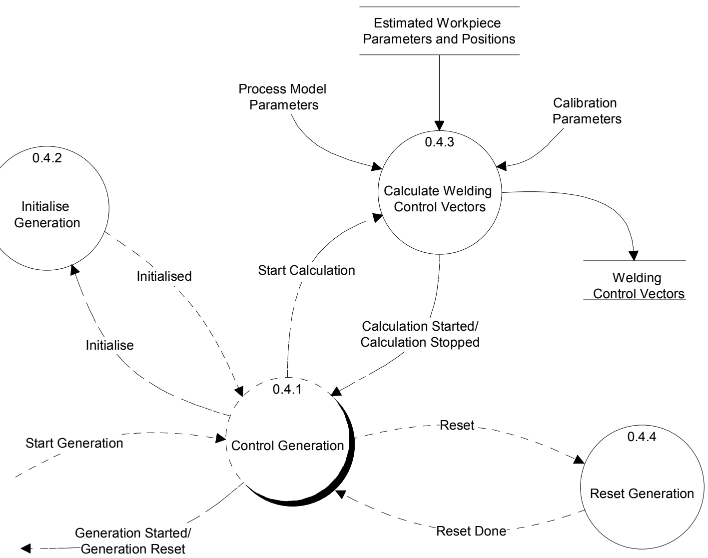


Figure 5.18: Decomposition of transformation 0.4: ‘ Generate Process Control Variables.

The transformation for generating process control variables is divided into the 4 sub-transformations 0.4.2,: ‘**Initialise Generation**’; 0.4.3: ‘**Calculate Welding Control Vectors**’; 0.4.4: ‘**Reset Generation**’; and 0.4.1: ‘**Control Generation**’.

Transformation 0.4.2: ‘Initialise Generation’

The sub-transformation is triggered by the command *‘Initialise’*:

The effect of *‘Initialise’* is:

1) The ‘Process Model Parameters’ and the ‘Calibration Parameters’ are instantiated in the memory. The function returns the signal *‘Initialised’*.

Transformation 0.4.3: ‘Calculate Welding Control Vectors’

This sub-transformation calculates ‘Welding Control Vectors’ based on the estimated workpiece parameters and the ‘Process Model Parameters’. The ‘Welding Control Vectors’ correspond to particular positions in the weld groove and are stored in a queue structure.

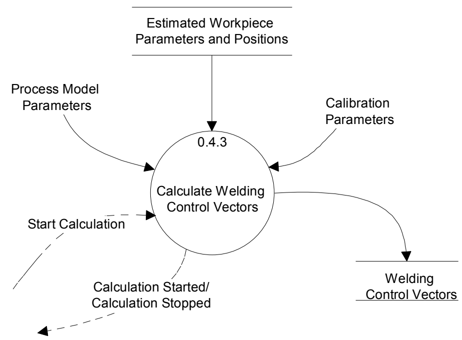


Figure 5.19: Transformation 0.4.3: 'Calculate welding control variables'.

The sub-transformation is activated by the command *'Start Calculation'*.

The effect of *'Start Calculation'* is:

1) The function extracts the front element from the queue of 'Estimated Workpiece Parameters and Positions'. If the queue of estimated workpiece parameters is empty, the function waits for new elements in this queue.
2) The fixed workpiece parameters[3] are compared to the constraints of the inverse process model in order to evaluate the validity of the inverse process model in the actual welding situation.
3) Based on the size of gap the function calculates the corresponding welding control variables and transforms these into a welding control vector. The calculation of control variables is described in chapter 4.
4) The points 1 through 3 are repeated until the 'Estimated Workpiece Parameters and Positions' indicate the end of weld groove. The signal *Calculation Finished* is then emitted.

The 'Calibration Parameters' specify the transformation matrix from tool centre frame to end effector frame. The tool centre frame specifies the position of focus point and the direction of the laser beam. The 'Welding Control Vectors' are specified using the end effector frame.

[3] The fixed workpiece parameters are the parameters which are not measured by the sensor system, such as material type, plate thickness etc.

Transformation 0.4.4: 'Reset Generation'

This transformation is executed on the command *'Reset'*. The effect of the signal *'Reset'* is:

1) The 'Process Model Parameters' and the 'Calibration Parameters' are removed from the memory of the present transformation, and the signal *'Reset Done'* is emitted.

Transformation 0.4.1: 'Control Generation'

The control transformation for generation of control vectors is decomposed into a state transition diagram, which is shown in Figure 5.20.

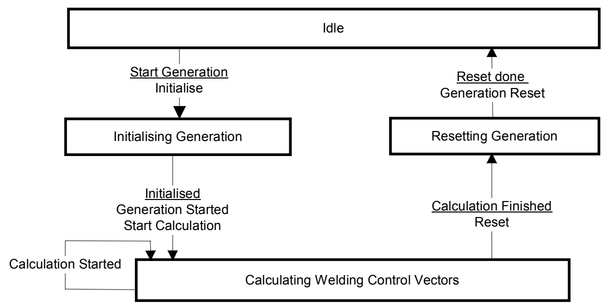


Figure 5.20: Decomposition of transformation 0.4.1: 'Control Generation'.

'Idle'

Before starting the generation of 'Welding Control Vectors', the transformation is in the Idle state.

'Initialising Generation'

When the signal *'Start Generation'* is received (see Figure 5.18) the system initialises the generation and starts the generation process. When the generation process is initialised the signal *'Initialised'* is generated and the signal *'Generation Started'* is sent to the superior transformation, transformation 0.1: '**Control Welding Process**'.

‘Calculating Welding Control Vectors’

In this state the function 0.4.3: ‘Calculate Welding Control Vector’ is initialised. It starts calculating ‘Welding Control Vectors’ and queuing these. This continues until the end of the weld task is reached. Then the signal *‘Calculation Stopped’* is emitted, see Figure 5.18.

‘Resetting Generation’

As soon as the generation is finished the generation process is finished. It is possible to reset this process immediately after the last welding control vector is queued, because the queue of ‘Welding Control Vectors’ is still available after the generation process is reset. Then the signal *‘Generation Reset’* (see Figure 5.18) is sent to the transformation 0.1: ‘**Control Welding Process’**, see Figure 5.2) and transformation 0.4: ‘**Generate Process Control Variables**’ returns to the idle state.

5.1.6. Transformation 0.5: ‘Control Equipment’

The transformation 0.5: ‘**Control Equipment**’, (see Figure 5.2) controls the execution of established ‘Welding Control Vectors’, and provides the ‘Robot Locations’ in real-time.

In order to provide the ‘Robot Locations’ in real-time the function must communicate with a real-time Cartesian interface in the robot controller. This interface is not a standard product for most robot manufacturers. The interface must enable the ‘**Welding Control System**’ to retrieve ‘Robot Locations’ with time stamps in real-time. Additionally, it must enable execution of ‘Equipment Control Vectors’ in real-time, which are sent from the ‘**Welding Control System**’.

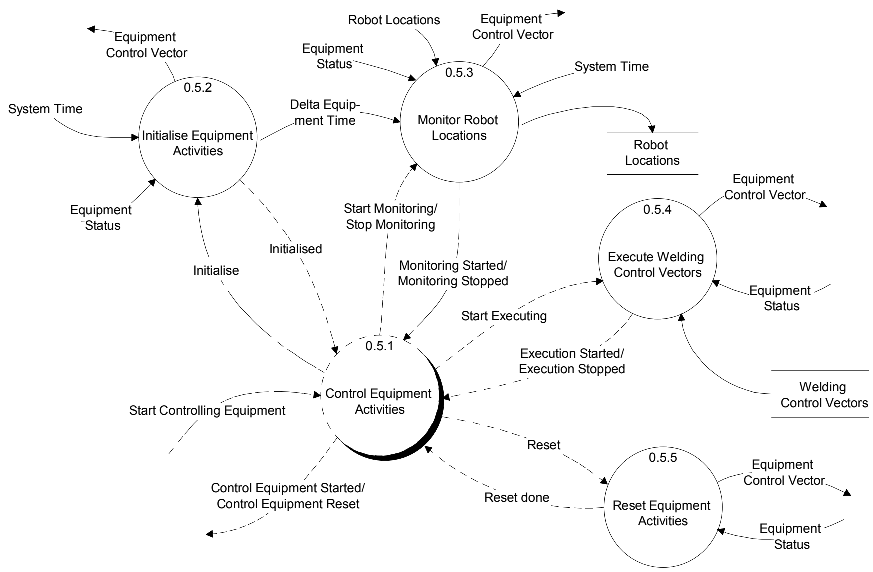


Figure 5.21: Decomposition of transformation 0.5: 'Control Equipment', (see Figure 5.2).

The architecture for the sub-transformation which interfaces the welding equipment with the '**Welding Control System**' is shown in Figure 5.21.

Transformation 0.5.2: 'Initialise Equipment Activities'

The sub-transformation 0.5.2: 'Initialise Equipment' sets the welding equipment in a *slave mode* relative to the global transformation 0: '**Welding Control System**' (see Figure 5.1). The timer of the welding equipment is reset in order to enable synchronisation of the welding equipment and the '**Welding Control System**'. The queues of 'Robot Locations' (see Figures 5.7 and 5.9 and transformation 0.3.3.1 on page 65) and 'Welding Control Vectors' (see Figure 5.19) are instantiated in the memory of the '**Welding Control System**'.

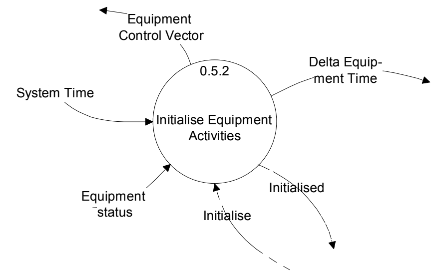


Figure 5.22: Transformation 0.5.2: 'Initialising Equipment Activities'.

The command activating this function is *'Initialise'*, and the effect of this signal is:

1) The function establishes and sends an 'Equipment Control Vector' to the equipment controller (see Figures 5.1 and 5.22). The command part of the this 'Equipment Control Vector' is 'Set Welding Equipment in Slave Mode'.
2) The function waits for 'Equipment Status' from the equipment controller (see Figures 5.1 and 5.22).
3) If the 'Equipment Status' is 'Success', the function establishes and sends an 'Equipment Control Vector'. The command part of this vector is 'Reset Equipment Time'. Then the timer of the welding equipment will start from zero.
4) The function waits for 'Equipment Status'.
5) If 'Equipment Status' is 'Success', the function sets the parameter 'Delta Equipment Time' to the actual value of the 'System Time' (time in the '**Welding Control System**').
6) The queues of 'Robot Locations' and 'Welding Control Vectors' are instantiated in the memory of the '**Welding Control System**'.
7) The function responds with the signal *'Initialised'*.

Transformation 0.5.3: 'Monitor Robot Locations'

This transformation monitors the 'Robot Locations'. These locations are synchronised with the '**Welding Control System**' before they are put in the queue of 'Robot Locations'. This is carried out by converting the time stamps of the ‘Robot Locations’ to the time scale of the ‘**Welding Control System**’.

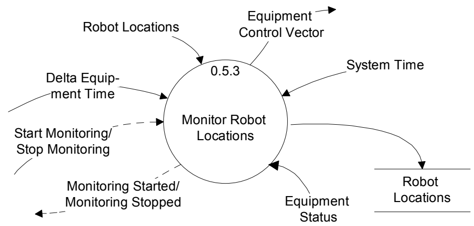


Figure 5.23: Transformation 0.5.3: ‘Monitor Robot Locations’.

The signals that trigger the transformation are *‘Start Monitoring’* and *‘Stop Monitoring’*.

The effect of *‘Start Monitoring’* is:

1) The function establishes and sends an ‘Equipment Control Vector’. The command part of this vector is ‘Start Sending Robot Locations’.
2) The function waits for ‘Equipment Status’.
3) If ‘Equipment Status’ is ‘Accepted’ the function emits the signal *‘Monitoring Started’*.
4) The function receives a robot location and adds the value of ‘Delta Equipment Time’ to the time stamp. Now the time stamp of the robot location is synchronised with the timer of the ‘**Welding Control System**’.
5) The synchronised robot location is added to the queue of ‘Robot Locations’. This queue is used by transformation 0.3: ‘**Estimate Workpiece Conditions**’ (see Figure 5.7).
6) The points 4 and 5 are repeated until the process is stopped by the signal *‘Stop Monitoring’*.

The effect of *‘Stop Monitoring’* is:

1) The function establishes and sends an ‘Equipment Control Vector’. The command part of this vector is ‘Stop Sending Robot Locations’.
2) The function waits for ‘Equipment Status’.

3) If ‘Equipment Status’ is ‘Accepted’ the function emits the signal *‘Monitoring Stopped’*.

Transformation 0.5.4: ‘Execute Welding Control Vectors’

This transformation converts ‘Welding Control Vectors’ (WCV) to instructions for the welding equipment and sends these instructions to the equipment as ‘Equipment Control Vectors’. This function may be regarded as a post processor which translates general welding control variables and positions received from transformation 0.4: ‘**Generate Process Control Variables**’ to equipment commands for the specific equipment.

The transformation is shown in Figure 5.24.

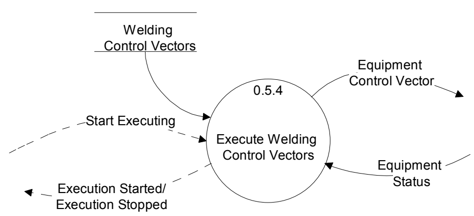


Figure 5.24: Transformation 0.5.4; ‘Execute welding control vectors’.

The command which activates the function is *‘Start Executing’*. The effect of this signal is:

1) The function reads the front element of the queue of ‘Welding Control Vectors’ and deletes this element from the queue. If the queue is empty, the function waits until an element enters the queue.
2) The welding control vector which is contained in this element is transformed into an ‘Equipment Control Vector’. The current state of the welding process affects the establishment of ‘Equipment Control Vectors’ in the following way:

- If the specified process state in the WCV is *process on* and the laser beam and wire feeding mechanism are currently off, the function will establish an ‘Equipment Control Vector’ which turns these on when the position of the WCV is reached.

- If the specified process state in the WCV is *process off*, and the laser beam and wire feeding mechanism are currently on, the function will establish an 'Equipment Control Vector' which turns these off when the position of the WCV is reached.

3) The 'Equipment Control Vector' is sent to the welding equipment. The command part of this vector is *Movement Command*. The task specification part specifies the position, orientation and velocity of TCP, the wire feed rate, laser power and gas flow rates.
4) The function waits for 'Equipment Status'.
5) If the 'Equipment Status' is 'Accepted', the function repeats the points 1 through 4 until the specified continuity type of the WCV is *End point*. Then an 'Equipment Control Vector' is established, that turns off the laser beam, gas flows and wire feeding mechanism when the specified end position is reached. The 'Equipment Control Vector' is sent to the welding equipment. The command part of this vector is *movement end command*.
6) The function waits for 'Equipment Status'.
7) If the 'Equipment Status' is 'Success' the function responds with the signal *'Execution Stopped'* and terminates the transformation.

The 'Equipment Status' is 'Accepted' if a movement command has a legal format for the equipment, and if there is currently no equipment errors. In this case the 'Equipment Status' is established as soon as the equipment controller acknowledges the 'Equipment Control Vector'. When command part of the 'Equipment Control Vector' is *movement end command*, the 'Equipment Status' is not established until the 'Equipment Control Vector' is executed. This is because no further 'Equipment Control Vectors' is planned to be executed in the present weld task, and the '**Welding Control System**' needs to know when the current weld task is finished.

Transformation 0.5.5: 'Reset Equipment Activities'

When the execution of 'Welding Control Vectors' is finished, the '**Welding Control System**' resets the welding equipment and the memory used by the transformation 0.5: '**Control Equipment**'.

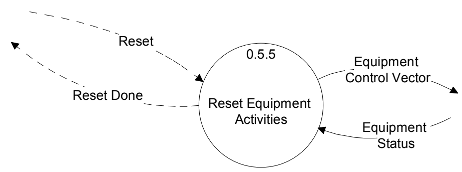


Figure 5.25: Transformation 0.5.5: 'Reset Equipment Activities'.

The transformation is triggered by the signal *'Reset'*. The effect of this signal is:

1) The function establishes and sends an 'Equipment Control Vector' to the equipment controller. The command part of this vector is 'Reset Welding Equipment'.
2) The function waits for 'Equipment Status'.
3) If 'Equipment Status' is 'Success', the function deletes the queues of 'Robot Locations' and 'Welding Control Vectors', and the signal *'Reset Done'* is emitted.

Transformation 0.5.1: 'Control Equipment Activities'

The state transition diagram of the transformation 0.5.1: '**Control Equipment activities**' is shown in Figure 5.26.

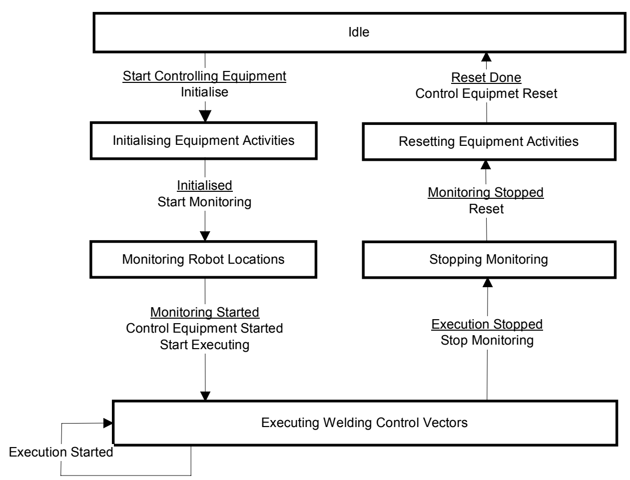


Figure 5.26: State diagram of the transformation 'Control Equipment'.

In the following the characteristics of the states in the diagram above will be defined. The description concerns normal operation of the system and no error handling is included in this description. The description contains references to numbered functions which are shown in Figure 5.21.

‘Initialising Equipment: Activities’

‘Start Controlling Equipment’ is received when the ‘**Welding Control System**’ is in the ‘Idle’ state. Upon receiving this command the system goes into the state: ‘Initialising Equipment Activities’. In this state the welding equipment is set in *slave mode*, and the ‘**Welding Control System**’ is set in master mode. The timer at the welding equipment platform is reset.

‘Monitoring Robot Locations’

The robot is ordered to ‘Start Sending Robot Locations’ to the ‘**Welding Control System**’. These locations are synchronised with the ‘**Welding Control System**’ by converting the time stamp to the corresponding time in this system. When this process is started it emits the signal *‘Control Equipment Started’* and it continues running until it is explicitly stopped.

‘Executing Welding Control Vectors’

This process extracts elements from the queue of ‘Welding Control Vectors’ and converts these into instructions for the specific welding equipment. These instructions are sent to the equipment controller as ‘Equipment Control Vectors’. The monitoring of ‘Robot Locations’ is still active during this process.

This process continues until a welding control vector has the continuity type: End Point. Then the command part of the corresponding ‘Equipment Control Vector’ is set to ‘Movement End Command’, and the process is stopped after execution of this particular ‘Equipment Control Vector’.

‘Stopping Monitoring’

The monitoring of ‘Robot Locations’ is stopped.

'Resetting Equipment Activities'

When the execution and monitoring is stopped the function will go into the state 'Resetting Equipment Activities'. Now the welding equipment return to *master mode* and is again able to execute ordinary NC programs. The queue of 'Robot Locations' is deleted and the signal *'Control Equipment Reset'* is sent to the transformation 0.1: '**Control Welding Process'**.

5.1.7. Transformation 0.1: 'Control Welding Process'

This transformation is the control transformation that controls the superior dynamics of the '**Welding Control System**'. The dynamics of this transformation is outlined in Figure 5.27. The control transformation controls the activation and deactivation of the four data transformations in the internal architecture (see Figure 5.2).

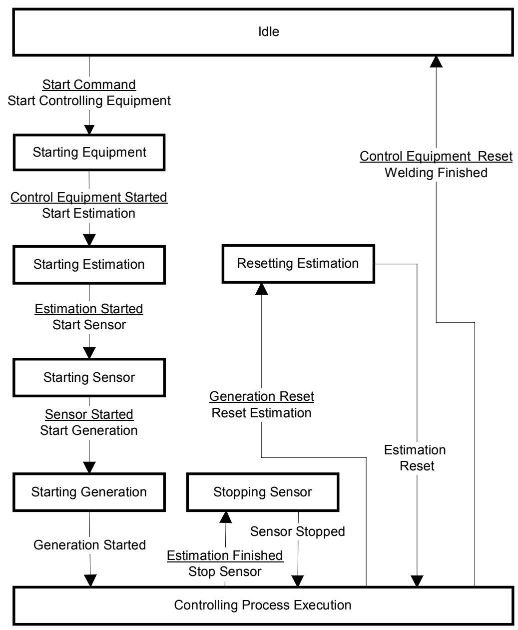


Figure 5.27: State transition diagram for the transformation 'Control Welding Process'.

'Idle'

When the welding equipment is controlled by previously prepared instructions or by manual operation, the '**Welding Control System**' is in an 'idle' mode. This is e.g. the case when the robot moves the welding equipment from one weld task to the next.

The '**Welding Control System**' establishes the 'Equipment Control Vectors' on the basis of measurements of the weld groove. Therefore, the '**Welding Control System**' is depending on the ability to make measurements on the weld groove in order to control the welding equipment. Before initialising the '**Welding Control System**', the welding equipment must be in a position where the laser sensor can measure the initial point on the weld groove, as shown in Figure 5.28. This will be the starting point of the welded joint.

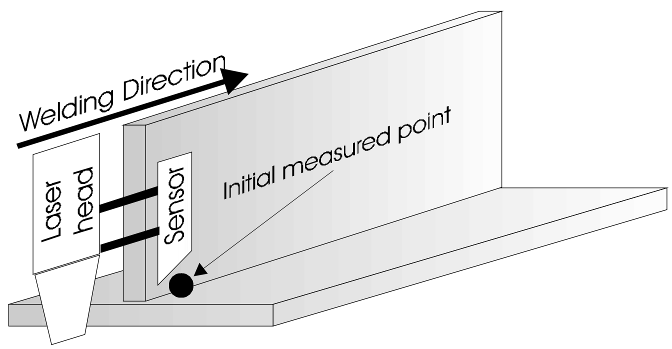


Figure 5.28: Initial position of welding equipment.

The situation shown in Figure 5.28 enables the '**Welding Control System**' to calculate the 'Equipment Control Vector' for this initial point. New measurements are made during movement of the welding equipment, and these provide the basis for generation and execution of the following 'Welding Control Vectors'.

'Starting Equipment'

When the '**Welding Control System**' receives the *'Start Command'*, the four data transformation processes are started. The transformation 0.5 '**Control Equipment**' is started first in order to set the welding equipment in *slave mode,* and to start establishing 'Robot Locations' for the estimation of workpiece parameters. In this state, the queues of 'Welding Control Vectors' and 'Robot Locations' are instantiated in memory.

When this transformation is started it will start executing 'Equipment Control Vectors', when these are generated.

‘Starting Estimation’

When the transformation for control welding equipment is started the ‘**Welding Control System**’ is receiving ‘Robot Locations’ continuously. The transformation 0.3: ‘**Estimate Workpiece Conditions**’ is now started. This transformation reads the workpiece model and defines the ‘Profile Type’. In this state the queues of ‘Measured Profile Vectors’ and ‘Estimated Workpiece Parameters and Positions’ are instantiated in the memory of the ‘**Welding Control System**’. The system starts waiting for ‘Measured Profile Vectors’ in order to estimate workpiece characteristics.

‘Starting Sensor’

Now the groove profile is known and it is possible to specify which type of profile to look for. The transformation 0.2: ‘Measuring groove profile’ is started now and it will start establishing ‘Measured Profile Vectors’. Since the transformation 0.3: ‘**Estimate Workpiece Conditions**’ is already initialised, it is ready to establish estimated workpiece parameters as soon as ‘Measured Profile Vectors’ are available.

‘Starting Generation’

The data transformation 0.4: ‘**Generate Process Control Variables**’ is now started. This function uses the ‘Estimated Workpiece Parameters and Positions’ to calculate ‘Welding Control Vectors’. These variables provide a generic specification of the process variables that are required in order to obtain the specified weld quality for steady state conditions.

‘Controlling Process Execution’

When the generation of ‘Welding Control Vectors’ is started, all data transformations are started and the measurements from the laser range scanning sensor are continuously compared to the related ‘Robot Locations’ and transformed to ‘Equipment Control Vectors’, which are sent to the welding equipment and executed. Or in other words, the system is automatically controlling the execution of the weld task.

The welding process is controlled until the task is finished. The weld task is finished if the pre-programmed length is welded or if the weld groove ends. The length of the weld groove is specified in the workpiece model. If the weld groove ends it will be realised by the transformation 0.2: '**Measure Groove Profile'**.

The state 'Controlling process execution' (see Figure 5.27) is active when the transformation 0.5: '**Control Equipment**' transforms elements from the queue of 'Welding Control Vectors' to 'Equipment Control Vectors' and executes these on the welding equipment. During this execution the transformation 0.1: '**Control Welding Process'** will jump to other states of resetting data transformations as these are finished dealing with the particular weld task. After these resetting states, the system will return to the state 'Controlling Process Execution'. This state is finally ended when the welding equipment has executed the last 'Equipment Control Vector' in the weld task.

When the last element in the queue of 'Welding Control Vectors' is executed on the welding equipment, the control transformation receives the signal *'Control Equipment Reset'*. Now the transformation '**Control Equipment**' is in an 'Idle' state and no more activities are needed from the '**Welding Control System**', before the next weld task is initiated.

'Stopping Sensor'

When the '**Welding Control System**' has estimated the workpiece parameters and positions at the end of the weld groove, the signal *'Estimation Finished'* is received by the control transformation **'Control Welding Process'**. Now the estimation needs no more profile measurements in the actual weld task, and the profile sensor is stopped.

'Resetting Estimation'

When the last element of the estimated workpiece conditions and positions is transformed to a welding control vector, the signal *'Generation Finished'* is received by the transformation 0.1: '**Control Welding Process'**. Then the transformation 0.4: 'Generate welding control variables' (see Figure 5.2) needs no more 'Estimated Workpiece Parameters and Positions'. The transformation 0.3: '**Estimate Workpiece Conditions**' is then reset. Now the queue of 'Estimated Workpiece Parameters and Positions', and the queue of 'Measured Profile Vectors' are deleted, and so is the memory segment that contains the 'Modelled Workpiece Parameters'. After this transformation is reset the transformation 0.1: **'Control Welding Process'** receives the signal *'Estimation Reset'*.

Chapter 6

Geometric Constraints

The methods of the welding control system are generic, i.e. the welding control system is able to convert workpiece parameters to welding control vectors for any weld task. However, it is necessary to map the structure of workpiece models as well as inverse process models to different types of weld joints. In this chapter two categories of weld joints for which generic structures of workpiece parameters are specified. The chosen categories cover most configurations of workpiece geometries for laser welding in heavy industry.

6.1. Basic Joint Types

The basic joint types in welding are butt-joints, corner-joints, edge-joints, lap-joints and T-joints. These joint types are shown in figure 6.1.

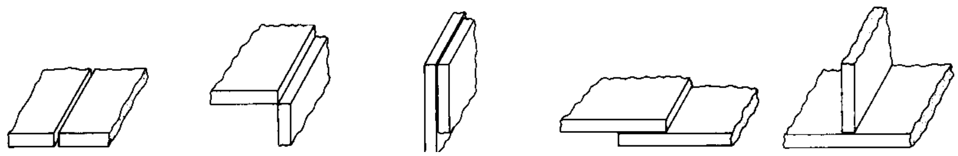


Figure 6.1: Basic joint types in welding [20].

The butt-joints are joints for which the workpieces are approximately in the same plane.

The corner-joints are joints for which two parts are located approximately at right angles to each other.

The edge-joints are joints between the edge faces of two or more parallel plates.

The lap-joints are defined as the class of joints in which the workpieces have an overlap at the position of the weld bead. Differently from the edge-joints lap-joints are joining the edge face of one plate to the main face of another plate.

The T-joints are joints for which the parts are at approximately right angles, in the form of a T.

The mentioned classification of weld joints is based on traditional welding terminology, which is mainly aimed towards manual welding processes. In the present Ph.D. work the method of inverse process models is applied, which is based on geometric specifications of the weld joint and the parts to be welded. Since the workpiece parameters are constraints and input for the inverse process models, it is necessary to quantify these. This quantification is not dealt with in traditional classification and specification of joint types.

6.2. Generic Joint Types

In this section two classes of joint types will be specified, which are generic and which covers most weld applications in heavy industry (see figure 6.2). For these joint types it is possible to quantify all workpiece parameters, control variables and quality parameters. This enables handling of the included joint types in an automatic welding control system.

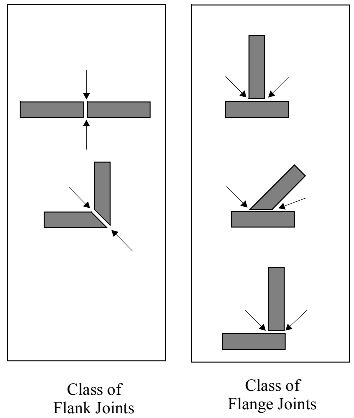


Figure 6.2: Class of flank-joints and class of flange-joints.

The classes of flank-joints and flange-joints cover the classes of butt-joints, corner-joints, edge-joints and T-joints which are described above. Generic specifications of workpiece parameters, quality parameters and control variables (see chapter 4) for flank-joints and flange-joints are described in the following sections. The class of lap-joints represents these types of weld joints in which the adjacent surfaces are the flat side of both workpieces. Since lap-joints are relatively unusual in heavy industry it has been chosen to delimit this project from any further analysis of these profile types.

6.2.1. Class of Flank-joints

The range of flank-joints covers the traditional class of butt-joints plus any angular configuration of the parts to be welded – as long as edges of the workpieces constitute the joint. The geometric workpiece parameters of this joint type are shown in figure 6.3. The workpiece edges at the groove was assumed to be parallel for cross sectional areas in this type of joints.

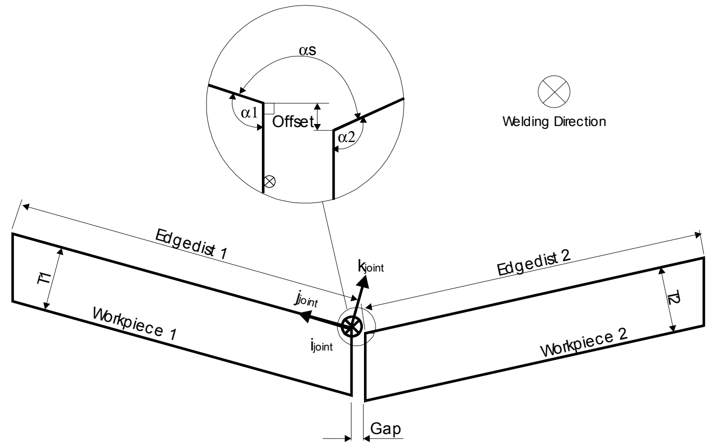


Figure 6.3: Flank-joint and corresponding geometric workpiece parameters.

Workpiece Parameters for Flank-joints

Workpiece 1 is always defined as the workpiece which is at the left hand side of the weld groove when looking in the welding direction. Position and orientation of workpiece 1 are specified by a joint frame ($F_{joint} = i_{joint}, j_{joint}, k_{joint}$). The origin of the joint frame is placed in the joint at the upper corner of workpiece 1, i_{joint} is directed in the welding direction, j_{joint} is directed along the surface of workpiece 1 and k_{joint} is calculated by use of the right hand rule.

- α_1 specifies the angle between surface and joint edge of workpiece 1.
- α_2 specifies the angle between surface and joint edge of workpiece 2.
- α_s specifies the angle between surfaces of workpiece 1 and workpiece 2.
- Edgedist 1 specifies the distance from the joint edge to the opposite edge of workpiece 1.
- Edgedist 2 specifies the distance from the joint edge to the opposite edge of workpiece 2.
- T1 specifies the thickness of workpiece 1.
- T2 specifies the thickness of workpiece 2.
- Off-set specifies the off-set between surfaces of the workpieces (see figure 6.3).

- Gap specifies the distance between workpiece 1 and workpiece 2 in the weld joint. As mentioned on page 91 the workpiece edges at the groove was assumed to be parallel for cross sectional areas in this type of joints. Therefore, the gap was considered constant through the thickness of plates.
- Tack welds are not shown in figure 6.3. However, the start and stop positions of tack welds in the weld joint are workpiece parameters as well.

Quality parameters for flank-joints

The quality of welded joints may be categorised into mechanical and geometric quality parameters.

The following parameters belong to the class of mechanical quality parameters for flank-joints:

- Hardness of the welded joint.
- Elongation ability of the welded joint.
- Impact resistance of the welded joint.

These parameters are strongly influenced by the cooling rate of the welded joint during the welding process, the shape of the welded joint, and the composition of base material and filler material.

The following parameters belong to the class of geometric quality parameters for flank-joints (see figure 6.4):

- Binding depth of the welded joint.
- Penetration of weld metal.
- Size of notches.
- Cracks and inclusions in the welded joint.

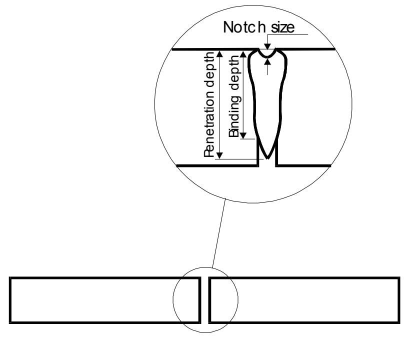


Figure 6.4: Geometric quality parameters for flank-joints.

Possible Control Variables for Flank-joints

The possible control variables are variables which may be changed during process execution. Normally as few control variables as possible are utilised when using empirically established process models. This is in order to minimise the experimental preparations of inverse process models. In case the inverse process models were based on generic physical models, such as mentioned in chapter 2, it may be advantegous to utilise as many control variables as possible. This is because then it would not be necessary to consider experimental work for preparation of weld tasks.

It is possible to employ the following control variables for the class of flank-joints:

- Laser power.
- Weld speed.
- Defocus length is the distance from the focus point of the laser beam to the top of the weld joint. The defocus length is positive if the focus point is above the weld joint.
- Travel angle is the angle between the laser beam and the welding direction.
- Work angle is the angle between the laser beam and the bisector plane of the weld joint.

- Displacement from the joint centre is the displacement of the laser beam from the bisector plane (see figure 6.5). This variable is positive when the laser beam is displaced in the direction away from workpiece 2.
- Wire feed rate.
- Work angle of wire.
- Travel angle of wire.
- Plasma gas flow rate.
- Work angle for plasma gas flow.
- Travel angle for plasma gas flow.
- Protection gas flow rate.
- Angle between welding direction and gravity.
- Angle between bisector plane and gravity.

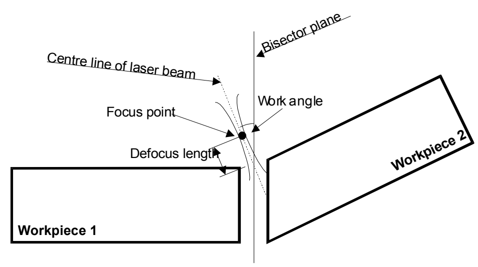


Figure 6.5: Control variables for flank-joints.

6.2.2. Class of Flange-joints

The class of flange-joints is characterised by joining the edge face of one plate to the surface of another plate.

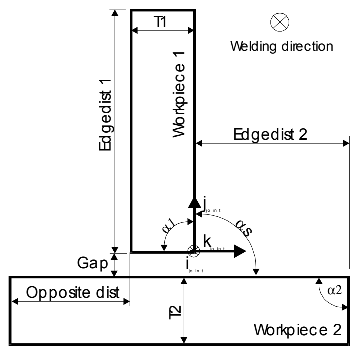


Figure 6.6: Geometric parameters in the estimated workpiece parameters for T-joints.

Workpiece Parameters for Flange-joints

Workpiece 1 can be characterised as the workpiece jointed by its edge face to the surface of workpiece 2. Position and orientation of workpiece 1 are specified by a joint frame ($F_{joint} = i_{joint}, j_{joint}, k_{joint}$). Origin of the joint frame is placed in the joint at that corner of workpiece 1 which is closest to the heat source. i_{joint} is directed in the welding direction, j_{joint} is directed along the surface of workpiece 1, and k_{joint} is calculated as the last unit vector of a right hand co-ordinate system.

It is assumed that the adjacent edge face of workpiece 1 and surface of workpiece 2 are parallel, i.e. the gap is constant in a cross sectional area.

- α_1 specifies the angle between surface and edge face of workpiece 1.
- α_2 specifies the angle between surface and the edge face of workpiece 2, which is at the same side of workpiece 1 as the joint.
- α_s specifies the angle between surfaces of workpiece 1 and workpiece 2.
- Edgedist 1 specifies the distance from the edge face at the weld joint to the opposite edge face of workpiece 1 (see figure 6.6).
- Edgedist 2 specifies the distance from the surface of workpiece 1 which is closest to the weld joint, to that edge face of workpiece 2 which is on the same side of workpiece 1 as the weld joint (see figure 6.6).

- Opposite dist specifies the distance from the surface of workpiece 1 which is not closest to the weld joint, to the edge face of workpiece 2 which is on the same side of workpiece 1 (see figure 6.6).
- T1 specifies the thickness of workpiece 1.
- T2 specifies the thickness of workpiece 2.
- Gap specifies the distance between workpiece 1 and workpiece 2 in the weld joint.
- Tack welds are not shown in figure 6.6. However, the start and stop positions of tack welds in the weld joint are workpiece parameters as well.

Quality Parameters for Flange-joints

The quality parameters for flange-joints are the same as for flank-joints, but some of them are measured differently, which is shown in figure 6.7.

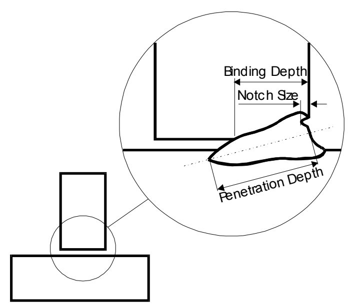


Figure 6.7: Geometric quality parameters for flange-joints

The penetration depth was in this Ph.D. work measured in the same angle from the bisector plane as the work angle of the laser beam. This choice was made in order to establish equal measuring conditions for all experiments. Another possibility would be to measure the longest direction of weld metal, which has shown to deviate slightly from the measure mentioned above.

Control Variables for Flange-joints

The control variables for flange-joints are much like the control variables for flank-joints. Actually, the only difference is the configuration of these, since the bisector plane for this joint type is parallel to the surface of workpiece 2 (see figure 6.8).

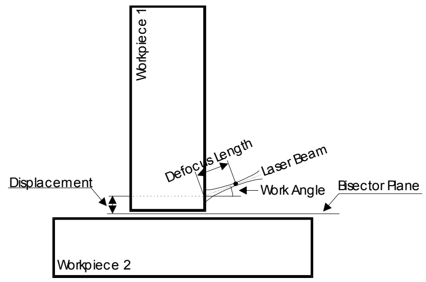


Figure 6.8: Control variables for the flange-joints type.

6.3. Preparation of Generic Joint Types

For the class of flange-joints an automatic control system was implemented which is able to generate control variables for the welding equipment in real-time. This work has thrown light on some necessary pre-conditions for controlling the welding process using the planned method.

As described in chapter 4, it was chosen to assume that all workpiece parameters except size of the gap are fixed. The control system is based on measurements of the gap between the workpieces. A laser sensor that scans a line of the surface provides these measurements. The configuration of the profile sensor relative to a flange-joint is shown in figure 6.9.

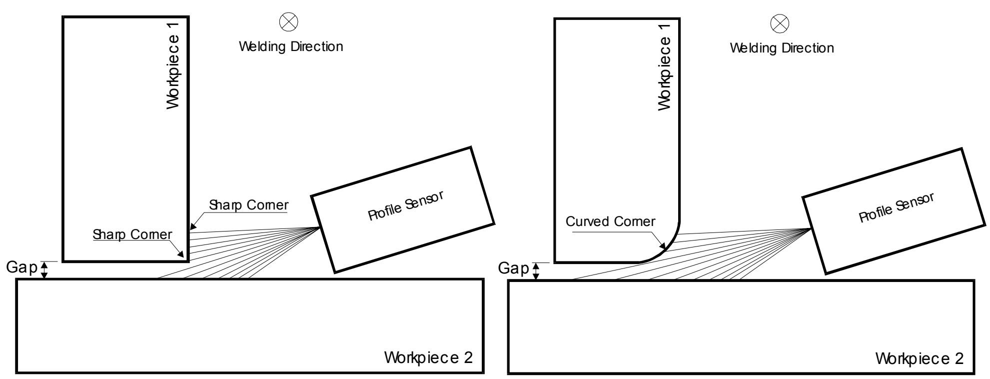


Figure 6.9: Configuration of laser sensor during measurement of flange-joints. In the figure to the left, workpiece 1 has a sharp corner at the weld joint. In the figure to the right, workpiece 1 has a curved corner towards the weld joint.

In order to obtain robust measurements of the surface of workpiece 2, it is necessary to keep an angle between workpiece 2 and the sensor. In the present project this angle varied between 17° and 45°. The measurements seemed to be more robust when keeping the angle at 45° than at 17°.

The radius of curvature of the workpieces seemed to vary randomly between 0.0 and 1.0 mm when receiving steel plates ordered with sharp corners from the steel mill (see curved corners in the right hand side of figure 6.9). This curvature is due to the rolling process at the steel mill.

In order to measure the gap when radius of curvature is present, the sensor system must provide sophisticated methods for deciding the end position of workpiece 1. In the applied sensor system this method was based on an algorithm for which a straight line was fitted to the measurements. When the distance between this line and a measured position exceeded a certain value, the measurement was no longer considered being part of the line. Using this method made it possible to measure the gap if the radius of curvature was constant. However, the radius of curvature was stochastic within the mentioned limits.

In order to delimit the system from the mentioned measuring tolerances all workpieces corresponding to workpiece 1 were milled on the edge towards the joint. Also this may cause problems since the corners must be sharp and free of burs.

Another problem for measuring the gap was when some of the surfaces on the workpieces were shining. This was especially a problem if only part of a surface was shining, because some parameters describing the workpiece surface were setup in the measuring system. These parameters included conditions like reflectivity, which is considered constant for the entire surface. The sensor gets problems if the reflectivity changes stochastically over the surface.

One reason for shining surfaces may be that burs from the milling process is removed by grinding the corner of workpiece 1. Another reason may be that the primer removal process caused the surface of workpiece 2 to be extremely smooth and shiny.

The primer removal process is necessary before laser welding in most heavy industries. The reason for this is that the primer is usually based on zink. The zink vaporises during the welding process and causes gas inclusions in the weld metal because the gas cannot get through the weld metal before it solidifies. In the present project the primer was removed by laser burning. The laser beam was transformed into a straight line on the surface of the workpieces. This line was moved over the workpieces with a laser intensity that caused the primer to vaporise. This is possible because the zink has a lower boiling temerature than the base metal. Figure 6.10 shows a base plate (workpiece 2) before workpiece 1 is placed at the weld joint.

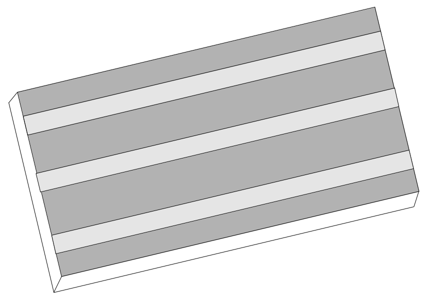


Figure 6.10: The figure shows workpiece 2 before workpiece 1 is positioned. Primer is removed for 3 weld joints.

During the primer removal process it may happen that the laser beam melts a small layer of the base material, which means that the surface gets very smooth when this base material floats together before solidification. The smooth surface gives a shining surface, which caused problems for the sensor system in the project, as described above.

One way to avoid that the primer removal process causes the surface of workpiece 2 to disturb the measuring system is to only burn a track that corresponds to the thickness of workpiece 1. However, workpiece 1 must be positioned very precisely on top of the burned track.

6.4. Geometric Constraints in Steady State Versus Dynamic Systems

The geometric constraints specified in this chapter were used in the Ph.D. work for a steady state welding control system. This system did not take the dynamics of the welding process or of the welding equipment into account. The geometric constraints specified were sufficient for successful operation of the developed steady state welding control system. Experimental work was only carried out using the class of flange-joints in this project. Furthermore, not all of the specified workpiece parameters were used in the welding control system. The workpiece parameters edgedist 1, edgedist 2 and opposite dist (see figure 6.6) were not used.

The reason for not using edgedist 1 was that the size of edgedist 1 in the experiments was so big that the edge face of workpiece 1, which was away from the weld joint, was not heated significantly during the laser welding process. Therefore, changes in this workpiece parameter would not change the heat conduction away from the weld joint significantly. The reason for not using opposite dist was the same as for edgedist 1. For edgedist 2 the same argument could be used. However, it should be mentioned that edgedist 2 varied from a few millimetres up to more than one meter. This showed that the welding process was not very sensitive to this particular workpiece parameter.

The workpiece parameters start and stop position of tack welds, were used in the Ph.D. project. A special inverse process model was applied for welding through tack welds. This process model was utilised from the starting point of the tack welds and de-activated at the end point of the tack welds.

Principles for a dynamic welding control system described in [21] explicitly takes the dynamic temperature of the weld zone actually being processed into account. In this system the heat conduction is explicitly calculated by use of generic physical process models, such as described in chapter 2. The physical models in this system are simulated using finite element methods, which enables a more optimised utilisation of the workpiece parameters for flange-joints and for other joint types.

The definition of flank-joints and flange-joints are considered sufficient for establishing the geometric conditions for dynamical welding process models. It is assumed that all relevant workpiece parameters are included in the definitions of these flange types. Even though the mentioned definitions include workpiece parameters that were not used in the present Ph.D. work, these are considered necessary for a generic description of the joint types. According to the principles of [21] these workpiece parameters will be used in a dynamic welding control system based on generic physical models.

References

[20] Cary, Howard B., Modern Welding Technology 4th. ed., Prentice Hall, ISBN 0-13-241-803-7.

[21] C.B. Terp et al, Welding Process Control Based on a Numerical Model and State-Space Techniques, Proceedings of the eighteenth IASTED International Conference on Modelling, Identification and Control, Innsbruck, Austria, February 15-18, 1999, ISBN 0-88986-239-7.

Chapter 7

Experiments

The conditions for performing welding experiments in laboratory is usually fine-tuned in order to ensure that results of experimental work correspond to well known conditions. For laser welding this fine-tuning consists especially of accurate set-up of welding equipment, workpieces and additional materials such as filler wire, protection gas and plasma control gas. In case sensor equipment is used for seam tracking or for feed forward control of the laser welding process, this equipment is usually thoroughly calibrated.

The careful fine-tuning of experimental set-up is typical and necessary for work carried out by researchers and developers or for work carried out in co-operation with these. Most important aspect of their work is to obtain such results of their experiments that conclusions may be drawn.

When moving laser welding processes into industrial environments it must be expected that less time is spent on preparation of each individual weld task than in laboratory. Industry is expected to focus on the throughput at the laser welding plant in order to keep costs at a low level. A typical requirement from industry is that the skills of human machine operators may be limited, since it is expensive to keep highly skilled operators in daily production. Furthermore it is not easy to find highly skilled machine operators for laser welding.

The result of the above-mentioned is that less fine-tuning and calibration of laser welding equipment must be expected in industrial environments. This chapter deals with work carried out in order to investigate the portability of laser welding into industrial environments when the above-mentioned fine-tuning is expected to be minimised.

In this chapter robustness to disturbances of the laser welding system will be investigated. This robustness is basically with regard to disturbances to the workpiece parameters and to the calibration and set-up of equipment, since these are most likely to occur in an industrial production. Initially the chapter deals with repeatability of quality parameters for the normal condition in which no disturbances occur.

Documentation of experiments can be found in appendix D and test results of magnetic powder inspection can be found in annex D. The experiments are limited to concern the class of flange joints only (see chapter 6).

7.1. Experimental set-up

The experiments were carried out at Odense Steel Shipyard Ltd., where the laser welding control system was implemented in a demonstration cell for laser welding and cutting. The laser welding equipment and the implemented control system were used during the experimental work.

Most of the experiments were performed with no gap between the workpieces. However, some experiments were carried out on a weld joint with an artificially established gap between the workpieces. This was done in order to simulate a production situation in which a gap occurs.

Because of manufacturing tolerances of the workpieces it was difficult to obtain a gap between the workpieces, which had a specified constant value throughout the weld joint. This yields both for weld joints with a gap size of zero and for workpieces with a gap size of another specified value. This is mainly because gap sizes were measured in tenths of millimetres. The gaps were constructed using tack welds and spacer blocks as shown in figure 7.1.

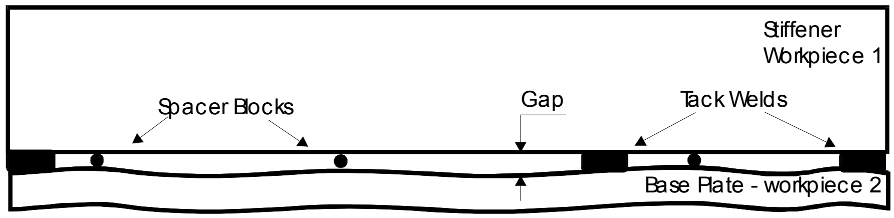


Figure 7.1: Sketch of workpieces set-up for workpieces with an artificially constructed gap. The manufacturing tolerances make it impossible to obtain a constant gap throughout the weld joint.

In situations where the gap size was specified to be zero the workpieces were fixed by tack welds only.

7.2. Inverse Process Model

An inverse process model was established for laser welding flange-joints. The inverse process model and the constraints of this model are described in this section. The inverse process model was approved for laser welding of flange joints for deck components in ship constructions by the classification societies Lloyds Register of Shipping and American Bureau of Shipping. This approval was based on procedure tests carried out using the local laser welding equipment including the implemented welding control system and the established inverse process model. The procedure test and the approval are documented in Annex C.

Work Piece parameters

The workpiece parameters for the established inverse process model are: α_1 = 90°, α_2 = 90°, α_s = 90°, Edgedist 1: Not used, Edgedist 2: Not used, Opposite dist: Not used, T1: 10 mm, T2: 10 mm, Gap: Varied. The material composition is specified in Annex B. Explanations to the mentioned workpiece parameters are made in chapter 6, section 6.2.2.

In addition to the mentioned workpiece parameters, it should be mentioned that workpiece 1 was milled at the edge face near the weld joint. This was in order to avoid curved corners such as shown in chapter 6, figure 6.9. This milling process was performed after primer was added to the surfaces of the workpieces. Therefore the milling process ensured that no primer was on the edge face of workpiece 1 during welding.

The primer of workpiece 2 was removed by laser burning as described in chapter 6.

The inverse process model was primarily used on workpieces as the one shown in figure 7.2. This figure illustrates the size of test pieces used for the experimental work described in this section.

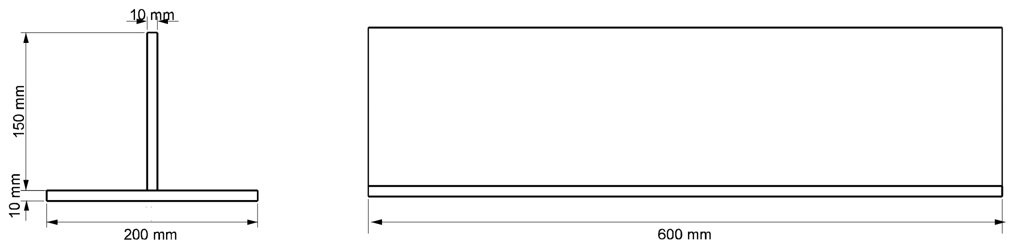


Figure 7.2: Sketch of standard workpiece used for experiments during the Ph.D. work.

However some production parts with different dimensions were welded using the same inverse process model. A sketch of one of these production parts is shown in figure 7.3.

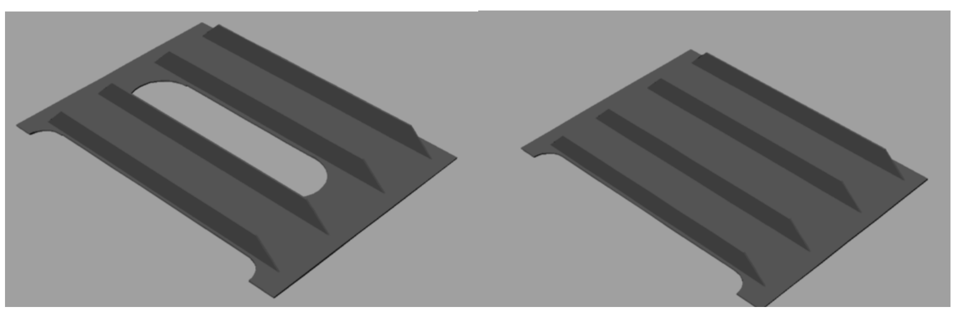


Figure 7.3: Sketch of typical production parts that were welded using the inverse process model.

It can be seen in figure 7.3 that the distance from the weld joint to the edge faces of workpiece 2 (horizontal workpiece) varied significantly for some of the production parts. This distance varied from a few millimetres to more than one metre. These production parts were approved by the classification Society, American Bureau of Shipping (ABS) on the basis of visual inspection and ultrasonic tests of all production parts in full length. This indicated that the significance of the influence of weld quality of 'edgedist 2' and 'opposite dist' are relatively small.

Equipment Parameters

The laser used for the experiments was a 12 kW CO_2 laser from Wegmann Basel. However, due to problems with the laser power was reduced to approximately 11 kW from the resonator. The laser beam was transported through a system of 11 water cooled mirrors. The distance between two successive mirrors was varied at three different locations in the beam train, corresponding to three positional degrees of freedom (X, Y and Z). The distance between two successive mirrors could vary approximately 1 m in the X and Z directions, and approximately 4 m in the Y- direction.

The equipment had the following equipment parameters near the weld scene:

- Focus length: 400 mm.
- Diameter of focus point: 0.6 mm.
- Diameter of the protection gas nozzle: 14.5 mm.
- Diameter of the plasma control gas nozzle: 2 mm.
- Distance between profile sensor and laser beam: 100 mm.
- Distribution of energy in the focus point – See figure 7.4.

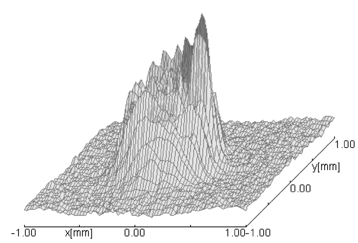


Figure 7.4: relative distribution of energy in the laser beam measured in the focus point.

The laser range sensor was positioned 100 mm in front of the laser beam, the travel angle of this sensor was 0° and the work angle of the sensor was 45°.

The equipment parameters that correspond to the inverse process model were given implicitly by the specific equipment, and will therefore not be described further. As described in chapter 4, section 4.1.1

Control Parameters

The control parameters are these parameters, which are controlled by manual or automatic adjustment of the laser welding equipment before execution of the weld tasks, such as described in chapter 4, section 4.1.3.

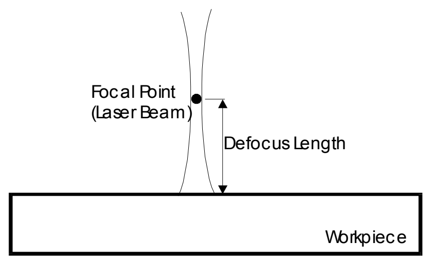
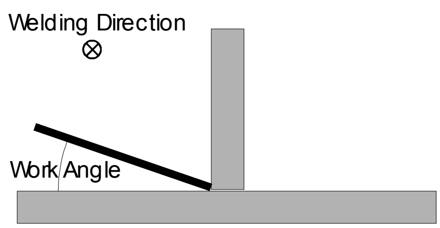
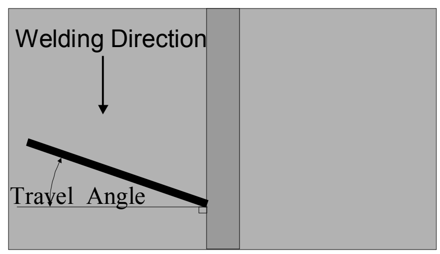


Figure 7.5: Defocus length is the distance from the focal point of the laser beam and the surface of the workpiece/weld joint. If the focal point is under the surface of the weld joint, the defocus length is negative.

The control parameters corresponding to the inverse process model were: Plasma control gas type: Helium, plasma control gas flow rate: 6 l/min, protection gas type: Helium, protection gas flow rate: 86 l/min, welding wire type: OK Autrod 12.51, diameter of welding wire: 1.0 mm, work angle for laser beam: 19°, travel angle of laser beam: 0°, defocus length: -15 mm (see figure 7.5), work angle for addition of welding wire and plasma control gas: 23° (see figure 7.6), travel angle for addition of welding wire and plasma control gas: 45°. The control parameters are additionally specified for each experiment in appendix D.



End view



Top view

Figure 7.6: Work angle and travel angle for laser beam, welding wire and plasma control gas, respectively.

Quality Parameters

As mentioned in chapter 4, the quality parameters can be split into metallurgical, mechanical and geometrical parameters.

<u>Metallurgical parameters</u> of the welded joints and of the heat affected zone are mainly determined by the composition of base material and filler wire material. Also the added protection gas and plasma control gas affect these parameters slightly, as the rate of cooling from 800°C to 500°C during the welding process. However, it is possible to establish a set of work constraints for the welding process by choosing a proper composition of base material and filler wire material. The work constraints are basically a maximum cooling rate from 800 to 500°C. In practice it is possible to stay within these working constraints by setting a maximum welding speed.

<u>Mechanical quality parameters</u> comprise hardness, ductility, and impact strength. The mechanical quality parameters were tested by the internal quality department at Odense Steel Shipyard and approved by the

classification company ABS. The requirements for the mechanical quality parameters were specified as follows:

- Hardness of welded joints, measured by the Vickers method should be less than 380 HV.
- Ductility of welded joints should be at least 22%.
- Impact strength of welded joints, measured by charpy testing should be at least 47 j.

This Ph.D. work was focused on the geometrical quality parameters of laser welded joints, because the control variables will affect these directly. The geometrical quality parameters for flange joints are described in chapter 6, section 6.2.2. The requirements for the geometrical quality parameters were:

- No heat cracks were allowed in the welded joints.
- The binding depth should be at least half the thickness of workpiece 1 in order to obtain full fusion between the workpieces (see figure 7.7).
- Visual approval of notch size.

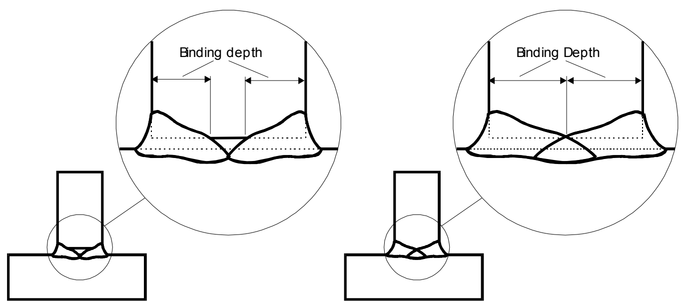


Figure 7.7: The welded flange joint at the left hand side has a lack of fusion between the weld joints. The flange joint at the right hand side has full fusion between the workpieces.

The welded joints were tested for surface cracks by magnetic particle inspection of the entire length of all weld joints. The fusion between workpieces was tested for all production workpieces by use of ultrasonic inspection of all weld joints in full length.

The binding depths, penetration depths and notch sizes presented in this chapter and in appendix D were measured at sections of the experiments using a profile projector of the type Nikon V12. This profile projector has a X-Y-Z table controlled manually by spindles. The X, Y and Z positions of the table are measured by encoders connected to a digital display. The tolerances of this measuring system are so small that they are considered irrelevant for the measurements. However, the tolerances of the measurements are influenced by the eye-measure of the operator, since the operator measures the distance between the boundaries of the individual parameters. By repeated measuring geometric quality parameters on weld joints, it was concluded that the measuring tolerance was in the range of one tenth of a millimetre.

Control Variables and Control Gains

The control variables and the control gains which correspond to the inverse process model are described in this section. The control variables for this particular inverse process model comprise welding speed, wire feed speed, and displacement (see figure 6.8 and table 7.1). In table 7.1 the inverse process model is shown in the format of specific welding procedure specifications for discrete sizes of gap, which is also described in chapter 4, section 4.2.1.

	Welding Control variables		
Gap [mm]	Displace-ment [mm]	Speed [mm/min]	Wire Feed Rate [mm/min]
0.0	0,2	900	400
0.3	0,5	750	500
0.6	0,7	750	1300
0.9	1,1	700	1650

Table 7.1: Inverse process model consisting of four welding procedure specifications for the gap sizes 0.0 mm, 0.3 mm, 0.6 mm, and 0.9 mm.

The inverse process model can be converted to the format shown in table 7.2. In this format the control gains are explicitly specified for use in the feed forward process controller, such as described in chapter 4, section 4.2.2.

			Welding Control variables			Control Gains		
Gap [mm]			Displace-ment [mm]	Speed [mm/min]	Wire Feed Rate [mm/min]	Displace-ment []	Speed [min^{-1}]	Wire Feed Rate [min^{-1}]
0.0	to	0.3	0,2	900	400	1,00	-500	333
0.3	to	0.6	0,5	750	100	0,67	0	1333
0.6	to	0.9	-0,1	850	-600	1,33	-167	2500

Table 7.2: Control variables and control gains specified in the inverse process model.

The control gains in table 7.2 represents the slope of the control variables as function of gap. In the feed forward process controller (see section 4.2.1) the control gains are multiplied with the absolute gap size. This value is added to the value of control variables. Therefore the off-set of control variables is adjusted in table 7.2.

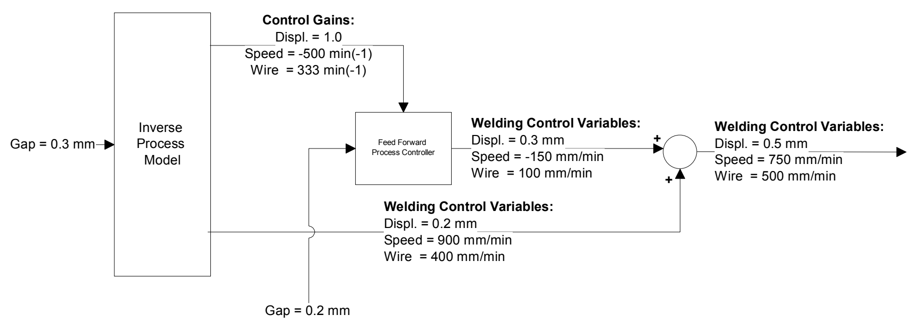


Figure 7.8: Example on calculation of welding control variables for a measured gap size of 0.2 mm.

The inverse process model specified in tables 7.1 and 7.2 is used in figure 7.8.

7.3. Repeating the Normal Conditions

The normal conditions are defined as the set of workpiece parameters in which the size of gap is 0.0 mm (see figure 7.9), and for which the equipment is calibrated in accordance with the specified control parameters for the inverse process model.

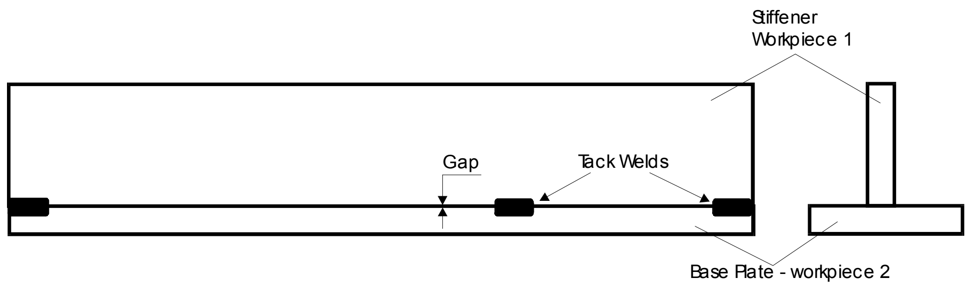


Figure 7.9: Set-up of workpiece for normal conditions, in which no gap occurs.

The experiments 6b5, 6b6, 6b7, and 6b8 (see appendix D for documentation of experiments) were carried out using normal conditions. The specified size of gap for the weld joints were 0.0 mm, and the welding control variables and parameters were set to the normal values, as described previously. The measured sizes of gap in the weld grooves are shown in figures 7.10 through 7.13. The curve length indicates the distance from starting point of the weld joint.

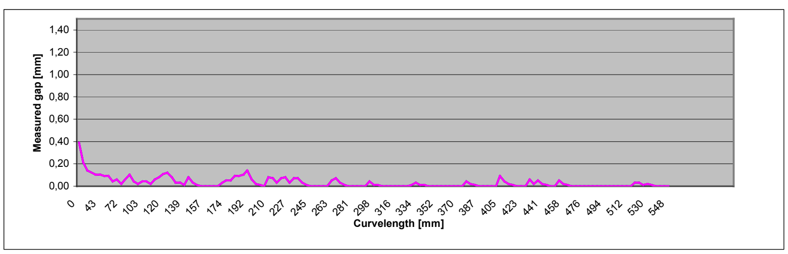


Figure 7.10: measured gap size in experiment 6b5.

The laser scanner made 143 measurements while executing experiment 6b5. The average size of gap in these measurements was 0.03 mm.

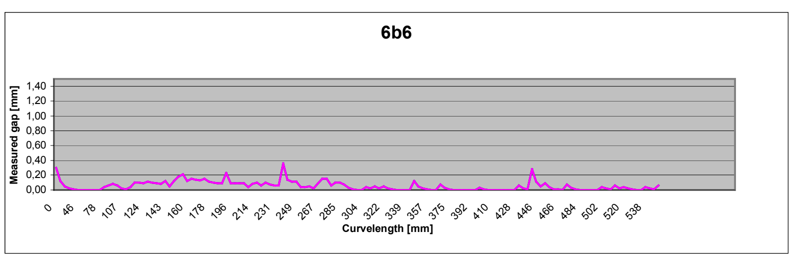


Figure 7.11: measured gap size in experiment 6b6.

The laser scanner made 141 measurements while executing experiment 6b6. The average size of gap in these measurements was 0.06 mm.

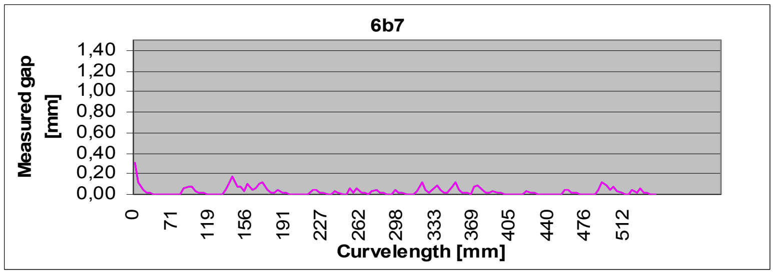


Figure 7.12: measured gap size in experiment 6b7.

The laser scanner made 141 measurements while executing experiment 6b7. The average size of gap in these measurements was 0.03 mm.

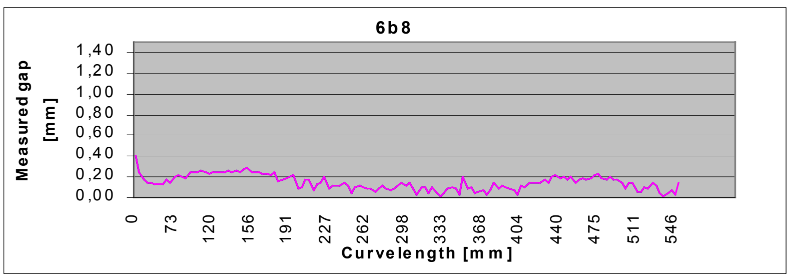


Figure 7.13: measured gap size in experiment 6b8.

The laser scanner made 144 measurements while executing experiment 6b8. The average size of gap in these measurements was 0.15 mm.

For all the mentioned experiments the control variables were compensated for changes in the gap size according to the inverse process model. The welded joints were inspected for cracks in the surface by magnetic particle inspection in full length of the joints. The geometric quality parameters binding depth, penetration depth, and notch size were tested by destructive inspection. Sections were made at three positions of the weld joints.

The results of magnetic particle inspection is presented later in this chapter, and the focus will be put on the binding depth, penetration depth and notch size in the following sections. The values of these parameters for a repeated normal situation are shown in figure 7.14 and can be seen in appendix D.

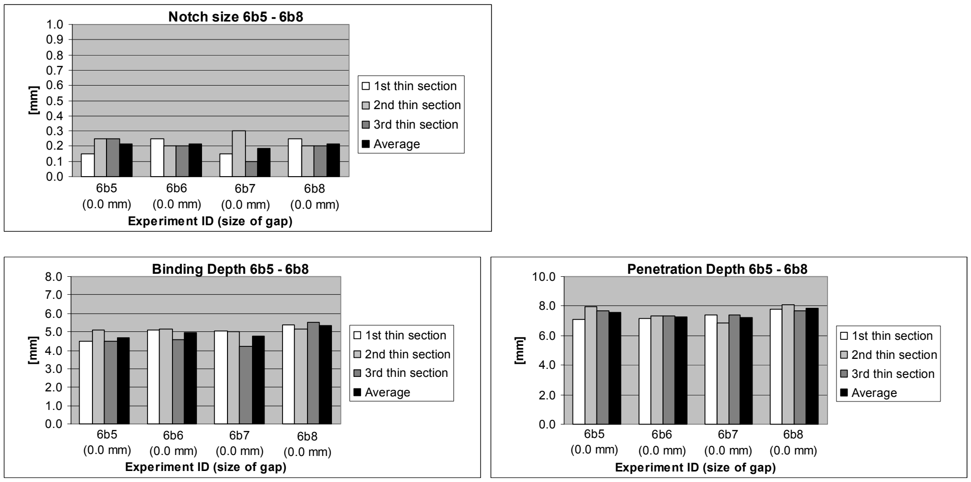


Figure 7.14: Notch sizes, binding depths and penetration depths for the experiments 6b5, 6b6, 6b7 and 6b8.

The average size of binding depth for the four experiments was 4.9 mm. The smallest size was 4.2 mm as the largest binding depth was 5.5 mm. The largest deviation in binding depth within one experiment was seen in experiment 6b7, in which the smallest value was 4.2 mm in section 6b7C[1] where as the largest was 5.1 mm in section 6b7A.

The average size of penetration depth for the four experiments was 7.5 mm. the smallest penetration depth was 6.9 mm and the largest was 8.1. Within a single experiment the largest deviation in penetration depth was found in experiment 6b5, in which the smallest value was 7.1 mm whereas the largest was 8.0 mm.

The average size of notch for the four experiments was 0.2 mm. The smallest and largest notch sizes were 0.1 mm and 0.3 mm, respectively. The largest deviation of notch size in a single experiment was in experiment 6b7, in which the notch size was 0.3 mm in section 6b7B, whereas it was 0.1 mm in section 6b7C.

[1] The suffixes A and B refers to different sections in the welded joint. The quality parameters for each section can be seen in appendix D.

Discussion about Repeatability

It can be seen from the measurements of gap in figures 7.10 through 7.13 that the measured gap was always larger in the beginning of the weld joint. This is because of the starting procedure, by which the gap is always overwritten in the sensor system with a value of 1.9 mm. The initial measurements are not included in the graphs, but a filtering procedure in the software causes that the following measurements are affected by the initial gap measurements. Starting and stopping procedures was not investigated thoroughly during the Ph.D. work .

The measured gap in experiment 6b8 was slightly larger than the measured gaps in the experiments 6b5 to 6b7. This was mainly caused by uncertainty of the profile scanner, since sizes of gaps were checked by measuring blades before process execution. Locally the gap may have varied slightly but not more or less continuously as shown for experiment 6b8. The accuracy of sensor measurements may have been affected by small burrs left from the milling process. (workpiece 1 was milled at the face edge, such as described in chapter 6).

It can be concluded that the binding depth varied 1.3 mm in the four experiments and up to 0.9 mm within a single experiment (6b7). Additionally the binding depth was larger for all sections in experiment 6b8, in which the measured gap was slightly larger than in the experiments 6b5 through 6b7.

As it can be seen in the figures 7.10 through 7.13 the gap varies throughout the weld joints in all of the experiments. It is not possible to find any coherent connection between the binding depth and the size of measured gap at the precise positions[2] of the sections. However, this was not expected either, since binding depth is strongly affected by heat distribution in the workpieces, which is a dynamical function of the heat input and the geometry of workpieces. Therefore it must be concluded that the tolerances of binding depth is approximately 1.3 mm for a weld groove with a gap size of 0.0 mm.

The binding depths in experiment 6B8 were larger than in the experiments 6B5 through 6B7. This is assumed to be caused by the fact that the measured gap was larger in this experiment. Even though the actual gap had approximately the same size as in the other experiments the control variables were calculated on the basis of the measured gap. Therefore the welding

[2] The precise position of the sections are specified in appendix D for each section.

speed was lower, the wire feed rate and the displacement was larger in this experiment, which caused a slightly larger binding depth than in the previous experiments. The same tendency was seen in experiment 6B10, which is presented in section 7.4.

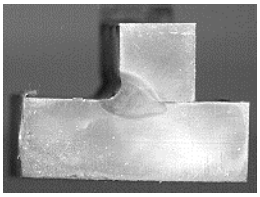
The penetration depth varied 1.2 mm in the four experiments and up to 0.9 mm within a single experiment (6b5). The penetration depth was generally slightly larger in experiment 6b8 than in the rest of the experiments. However, this difference was less significant than for the binding depth. The same arguments can be used for penetration depth as for binding depth.

The notch size varied 0.2 mm in the four experiments and also 0.2 mm within a single experiment (6b7). For the other experiments the notch size varied only 0.1 mm within the experiments.

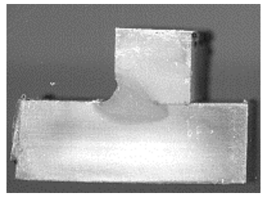
Comparison to Normal Condition Experiments at Force Institutes

The inverse process model was established especially for the laser welding equipment at Odense Steel Shipyard, where the experiments were performed. The result of the experiments may be compared to pilot experiments performed on laser welding equipment at the Force Institutes, which is a Danish welding institute. The reason for this comparison is that the geometry of weld metal[3] in the experiments was significantly different from one equipment to the other.

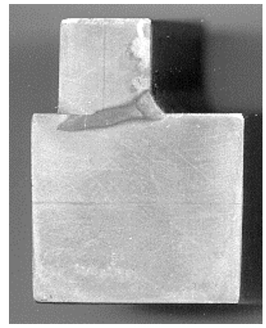
[3] Weld metal is defined as that part of the material, which has been molten during the laser welding process.



Exp. 6b7, OSS,
Gap: 0.0 mm.
Speed: 886 mm/min (av.)
Wire feed: 409 mm/min (average)



Exp. 6b8, OSS,
Gap: 0.0 mm.
Speed: 829 mm/min (av.)
Wire feed: 447 mm/min (average)



Pilot experiment p-08,
Force, Gap: 0.0 mm.
Speed: 1000 mm/min (fixed)
Wire feed: 449 mm/min (fixed)

Figure 7.15:Sections from experiments performed on Odense Steel Shipyard and on the Force Institutes, respectively. Plate thickness for exp. 6b7 and 6b8 was 10 mm for both plates. For exp. p-08 the plate thickness was 12mm for the body plate (workpiece 1) and 30 mm for the flange plate (workpiece 2).

It can be seen in figure 7.15 that the geometry of the weld metal deviates significantly from the experiments made on Odense Steel Shipyard (OSS) to the pilot experiments made on the Force Institutes. The main reason for this deviation is different power and the intensity of the laser beams at the two facilities.

The power of the laser beam at OSS was approximately 7.5 kW at the weld scene, as it was approximately 9.0 kW at the Force Institutes. In order to avoid too much spattering during the welding process at OSS, the defocus length was decreased to 15 mm (see figure 7.5). This may have affected the geometry of weld metal. At Force Institutes the focal point was positioned in the surface of weld joint.

The welding speed varied from 820 to 881 mm/min as average values for the individual experiments at OSS, whereas it was fixed throughout the experiment at Force, where it was 1000 mm/min.

When calculating the amount of wire added per meter of the weld joints, these values were approximately the same for the experiments at OSS and Force.

One parameter that deviated significantly from the experiments performed at OSS and at Force Institutes, respectively was the size of notch in the welded joints. In the experiments 6b5 through 6b8 at OSS the average notch size was 0.2 mm. In the experiment p-08 performed at Force Institutes no notch was found. Three additional pilot experiments were carried out at Force Institutes with a gap size of 0.0 mm and with different control variables. None of these welded joints included a notch.

The above comparison of laser welded joints from two different facilities shows that equipment parameters have a very significant influence on the geometry of weld metal. When a company invests in laser welding equipment it is therefore important to make sure that the welding equipment is able to generate joints with an acceptable shape of the weld geometry. This test is considered de-coupled from the adjustment of control variables.

7.4. Preparation of Workpieces

Influence of workpiece preparation on geometric weld quality is described in this section. The investigated disturbances to workpiece preparation concern the shape and the set-up of the workpieces. Experiments in the present Ph.D. work indicate that the thickness of primer material close to the weld joint affects the crack formation significantly in the surface of the weld joints. This is described at the end of this section.

Weld Joints Including a Gap

One of the characteristics for weld joints in industry is that a gap usually is present between the workpieces in a weld joint. The gap is caused by manufacturing tolerances of individual workpieces and by inaccurate fixation of the weld joint e.g. by tack welding. The experiment 6b10 was performed in order to evaluate how well the welding control system copes with this situation.

The weld joint was prepared to have a gap size of 0.5 mm. However the preparation of an accurate gap size different from zero is quite difficult, and therefore the gap varied a bit throughout the weld joints. The measured gap size for this experiment is shown in figure 7.16.

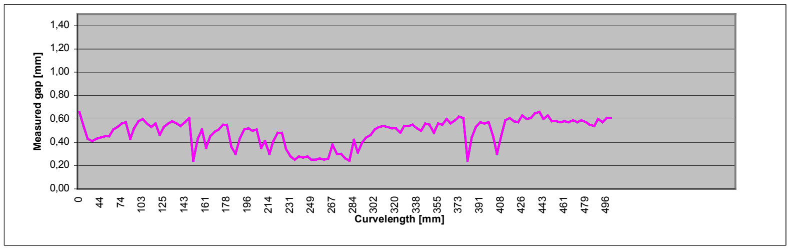


Figure 7.16: Measured gap size in experiment 6b10.

During experiment 6b10 the profile sensor made 129 gap measurements and the average measured gap size was 0.49 mm.

The geometric quality parameters binding depth, penetration depth, and notch size for the experiment are measured at three different positions in the weld groove, sections 6B10A, 6B10B and 6B10C. The parameters for each of the three sections are documented in appendix D, and shown in figure 7.17.

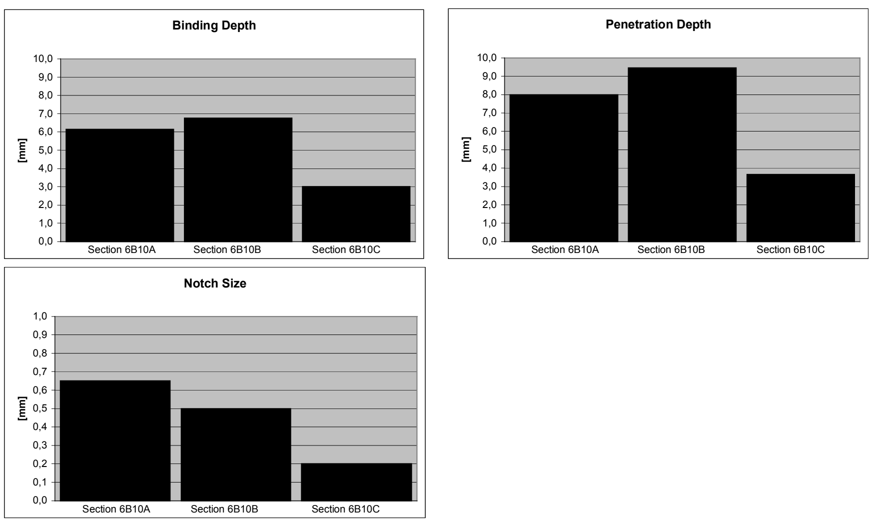


Figure 7.17: Geometric quality parameters measured at the three sections of experiment 6B10.

The geometric quality parameters of section 6B10C deviates extremely from the quality parameters of sections 6B10A and 6B10B. It is possible that the plasma formation from the welding process has increased exceptionally at this particular position, preventing part of the laser beam to penetrate the plasma cloud. However, visual variations of the plasma formation was not observed during the experiment. Another possibility is instability of the equipment, such that the output power from the laser cavity has decreased for a short moment. Anyway the deviation is too large to be explained by ordinary process deviation and therefore section 6B10C is omitted in the interpretation of experiments.

The average, maximum, and minimum values of binding depth, penetration depth, and notch size for the experiment are shown in figure 7.18, together with the average, maximum and minimum values for experiments 6B5 to 6B8 (normal conditions).

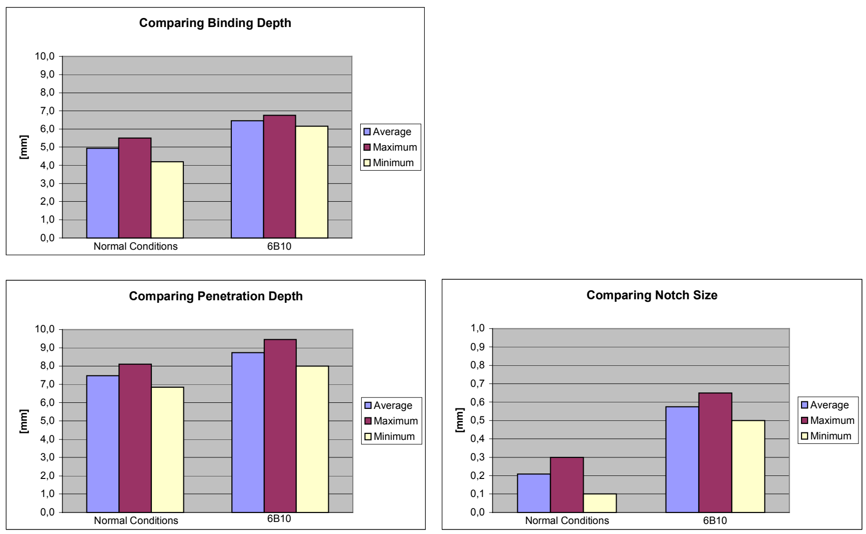


Figure 7.18: Diagrams of geometric quality parameters from experiment 6b10, in which an artificially constructed gap was present in the weld groove.

Discussion of the influence of gap size on geometric quality

As shown in figure 7.18 the binding depth, penetration depth, and notch size are significantly larger for experiment 6B10 (with a gap of 0.5 mm) than for the normal conditions. This was mainly because of the parameters of the inverse process model. As shown in the inverse process model (table 7.1) three control variables were changed when a gap was present in the weld groove.

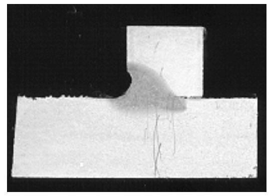
When the gap between workpieces was increased the wire feed rate was increased in order to compensate for the missing base material. The welding speed was decreased as function of increasing gap size, in order to melt the additional filler wire at the weld scene. Additionally the displacement (see chapter 6, figure 6.8) was increased as function of increasing gap size in order to keep a satisfactory binding depth, and in order to provide a satisfactory visual quality of the weld joint.

It is to be expected that at least one of the quality parameters could be kept constant as function of varying gap size. During establishment of the inverse process model it was attempted to keep the binding depth constant and at the same time to keep the notch size at an acceptable level. Especially the notch size gave a lot of problems during the experimental work. A lot of pilot experiments were made in order to keep the notch size at an acceptable level for weld joints with a gap of both 0.0 mm and 0.5 mm. As described in section 7.3 it was not even possible to avoid a notch even when no gap was present in the weld groove. However, when the gap size was approximately 0.5 mm, as in experiment 6B10, it was not possible to keep the notch size at the same level as when no gap was present. The parameters of the inverse process model is strongly reflecting the attempts to keep the notch size at an acceptable level. Therefore the binding depth for weld joints including a gap size of 0.5 mm is larger than for weld joint with a gap size of 0.0 mm.

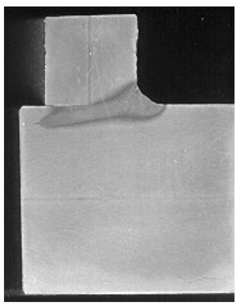
The penetration depth for weld joints in which a gap is present is depending on the parameters of the inverse process model as well. This quality parameter is not important for the mechanical properties of the weld joint, and was therefore not considered during establishment of inverse process models for flange joints. However it can be expected that the binding depth and the penetration depth are proportional. This is conditioned by the displacement (see figure 6.8), which should be adjusted to provide the largest possible binding depth with the given penetration depth and shape of weld metal.

Comparison to Gap Experiments at Force Institutes

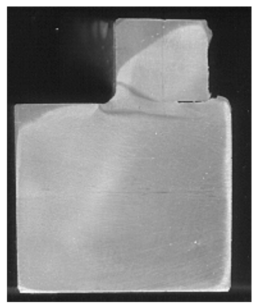
The pilot experiments performed at the Force Institutes included three experiments on weld joints with a gap size of 0.5 mm. Section regions are shown in figure 7.19 for experiment 6B10 performed at OSS and for the experiments performed at Force Institutes, respectively.



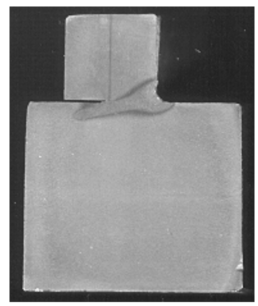
Exp. 6b10, OSS,
Gap: 0.5 mm.
Speed: 748 mm/min (av.)
Wire feed: 754 mm/min (average)
Filler area/Gap area = 1.3



Pilot experiment p-01,
Force, Gap: 0.5 mm.
Speed: 750 mm/min (fix)
Wire feed: 2444 mm/min (fixed)
Filler area/Gap area = 3.4



Pilot experiment p-06,
Force, Gap: 0.5 mm.
Speed: 1000 mm/min (fix)
Wire feed: 2147 mm/min (fixed)
Filler area/Gap area = 2.2



Pilot experiment p-18,
Force, Gap: 0.5 mm.
Speed: 1000 mm/min (fix)
Wire feed: 2150 mm/min (fixed)
Filler area/Gap area = 2.3

Figure 7.19: Experiments in which the gap size was 0.5 mm, performed at the laser welding facilities at OSS and Force Institutes, respectively. The plate thicknesses are the same as in figure 7.15.

The geometry of weld metal for weld joints in which the gap was 0.5 mm varied significantly from the experiment performed at OSS to the experiments performed at the laser welding facility at Force Institutes. In figure 7.19 it can be observed that the tendency to notch formation is significantly more evident in the section from the OSS experiment than for in the sections from Force experiments.

When a gap is present in the weld joint the filler material must substitute the missing material between the workpieces. Since the binding depth of the weld joints at OSS was approximately 5 mm and at Force Institutes was approximately 6 mm, the area of the gap, i.e. the area of missing material was defined as the gap size multiplied by 5 and 6 mm, respectively. The gap area is shown in figure 7.20.

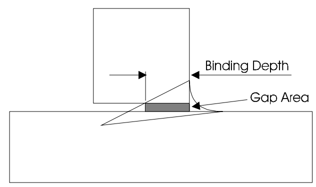


Figure 7.20: Illustration of gap area.

By comparing the Wire feed rate and the welding speed it is possible to calculate the area of applied filler material at a cross section of the weld joints. The area of applied filler material relative to the gap area was calculated for the experiments at OSS and at Force Institutes, and specified for each experiment in figure 7.19. The area of added filler material relative to the gap area was approximately twice as big in the Force-experiments as in the OSS experiments.

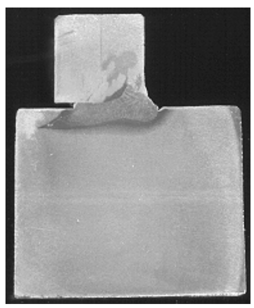
It should be mentioned that these calculations are made on the basis of average values for measured gap, welding speed and wire feed rate for the experiments performed at OSS. For the Force-experiments the values are calculated on the basis of the artificially established gap size, measured before process execution and of fixed values for the welding speed and wire feed rate, which were constant during processing.

The control parameters were different in the experiments at OSS and Force, respectively. The work angle was 12° at Force and 19° at Force. Also the displacement varied a few tenth of a millimetre.

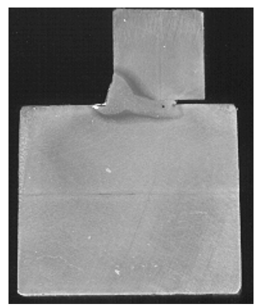
At OSS welding of joints in which the gap sizes were above 0.5 mm was abandoned because of a critical notch formation for these gap sizes. It was in these experiments necessary to decrease the welding speed in order to provide sufficient power to keep the binding depth and additionally melt the increased amount of filler material. When the speed was below 500 mm per minute, the heat around the nozzle for wire feeding nozzle was so intense that the nozzle at several occasions reached the melting point.

During the attempts to weld larger gap sizes than 0.5 mm it was observed that the width of weld metal at the joint surface increased, which implied that the size of the keyhole increased in the laser welding process. This was assumed to facilitate the notch formation because further freedom for fluid dynamics in the keyhole and in the molten pool was obtained. Therefore the increased width of weld metal and of the keyhole are considered to be a strongly influencing factor for the increased notch formation.

The pilot experiments at Force Institutes included weld joints with a gap size of 1.0 mm as well. The results of these experiments were more successful than the OSS-experiments. Two sections from these experiments are shown in figure 7.21.



Pilot experiment p-14, Force,
Gap: 1.0 mm.
Speed: 400mm/min (fixed)
Wire feed: 3300 mm/min (fixed)
Filler area/Gap area = 4.3



Pilot experiment p-16, Force,
Gap: 1.0 mm.
Speed: 600 mm/min (fixed)
Wire feed: 4500 mm/min (fixed)
Filler area/Gap area = 3.9

Figure 7.21: Sections of pilot experiments performed at the Force Institutes on weld joints with a gap size of 1.0 mm. The plate thicknesses are 12 and 30 mm, respectively.

It can be seen in figure 7.21 that the weld material was wider for the sections in which the gap was 1.0 mm than for the sections in which the gap was 0.0 mm and 0.5 mm (see figures 7.15 and 7.19). Additionally it can be seen from the figure text that the area of added filler wire relative to the gap area was larger for these experiments. Anyway these sections show a notch formation which, however, is significantly different from the notch formation in the OSS-experiments. In the sections in figure 7.21 the notch formation followed the bottom of the weld joints and had a relatively small radius, compared to the notches of the OSS-experiments (see figure 7.19).

The two series indicate a general trend to increased notch formation when the weld speed decreases and the width of the keyhole therefore increases. The influence of various control variables and control parameters will be presented later in this chapter.

It should be noted that the thickness of workpieces are different in the pilot experiments performed at Force Institutes and the experiments performed at OSS. The influence of this difference is hard to evaluate. However, the concentrated heat input in laser welding generally causes a lower heat absorption from surrounding material, which reduces the influence of different material thicknesses in the two series of experiments.

Curvature of Corners at the Weld Joint

As described in chapter 6 the corners of workpieces from the steel mill have a curved shape that can be associated with a radius of a quarter of circle. The radius of this circle is caused by the rolling process at the steel mill. The radius of this curvature varies between 0.0 and 1.0 mm, according to the steel supplier.

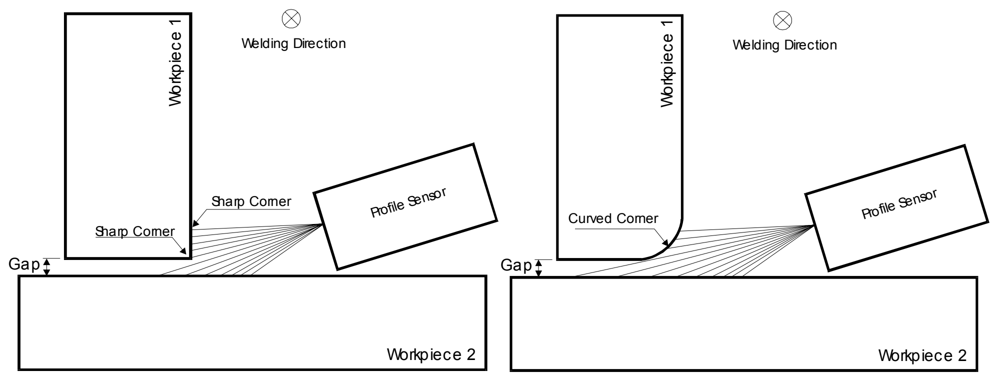


Figure 7.22: Workpiece with sharp corner and workpiece with curved corner, respectively.

For two reasons it was chosen to mill the edge face of workpiece 1 for all production parts that were welded in the laser welding cell.

One reason for milling workpiece 1 was to remove the primer from the section between the workpieces. Since the primer contains zinc and since the boiling point of zinc is lower than the melting point of the weld metal, the weld metal solidifies earlier than the zinc ceases to boil during the welding process. The concentrated heat input into the workpieces causes a fast cooling rate of the weld joint. Therefore the evaporated zinc will not reach the surface of the welded joints before the weld metal is solidified. This will provoke inclusions and crack formation in the welded joints.

Another reason for milling workpiece 1 was that the curved corner affected measurements from the laser scanner. The measured gap size was strongly affected by the radius of the corner at the weld joint, such as shown in figure 7.22. The influence of curved corners was investigated by the following two types of experiments:

The experiments given the names 72b1, 72b2, 72b3, and 72b4 (see appendix D) were performed on workpieces with a controlled corner radius of curvature of 1.0 to 2.5 mm. The weld joints were carefully prepared to keep a fixed gap size of 0.0 mm for all workpieces. The radii of the workpieces were confusing the profile sensor in such a way that the measured size of gap would be larger than 0.0 mm for all experiments. However, the measured size of gap were overruled by a special procedure in the welding control system, which specified the measured gap to be 0.0 mm, regardless of the measurements from the profile sensor. In this way the process control variables were calculated on the basis of a specified gap size of 0.0 mm which corresponded to the actual gap size. The geometric quality parameters of the experiments are shown in figure 7.23, and in appendix D.

The measured size of gap for these experiment are not shown because the measured gaps were overwritten by the value 0.0 mm before the system made a dump of the measurements into the log-file. The influence of curved corners on measured gap size is shown for the next experimental series, which is described later in this section.

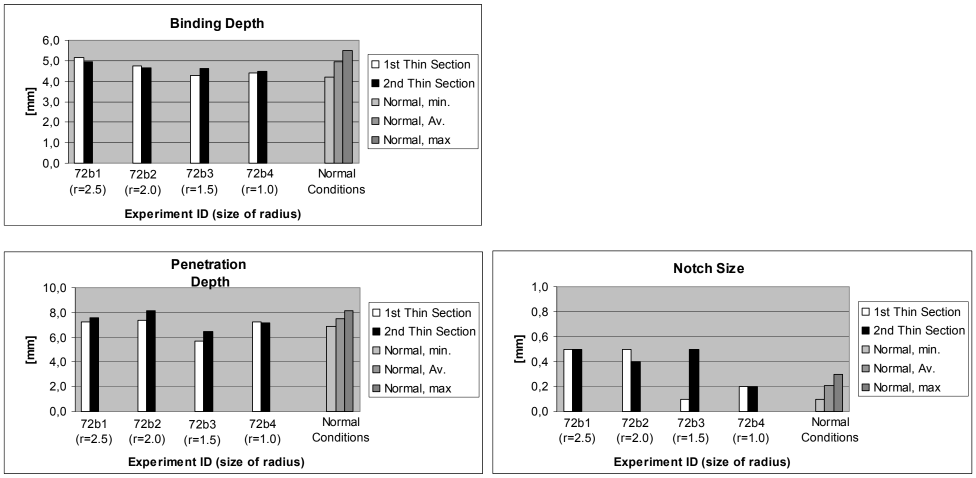


Figure 7.23: Geometric quality parameters from the experiments 72b1 to 72b4, in which the corner radius of the workpiece had controlled variations. The white blocks represent the parameters from the first and the black blocks the parameters from the second section from each experiment. The corresponding quality parameters from normal conditions (exp. 6B5 through 6B8) are shown in the graphs as well. These are represented by the minimum, maximum and average values for the experiments.

The quality parameters of the experiments 72b1 to 72b4 can be compared to the quality parameters of the experiments for normal conditions. Since the system has responded to a size of gap, which was 0.0 the deviation of quality parameters for these experiments, compared to the quality parameters for the normal conditions must primarily be explained by the corner radius of workpiece 1.

It is expected that missing material in the corner of workpiece 1 would enable the laser beam to penetrate deeper into the weld joint and thereby provide a larger penetration depth and binding depth. Additionally it would be expected that the notch size would be larger because of lack of material in the joint.

As it can be seen in figure 7.23 not all of the expected results was observed in the experimental results. The binding depth was close to the average binding depth for normal conditions, and all of the measured binding depths were within the interval between minimum and maximum values for the normal conditions, measured in experiments 6B5 through 6B8.

Also the measured penetration depths were in the same range as for normal conditions, although the penetration depth for 72B3 (corner radius = 1.5 mm) were slightly smaller. Since smaller penetration depth is only seen for exp. 72B3, and not for the experiments with larger and smaller corner radii than this one respectively, it is not considered a general trend that a corner radius within 2.5 mm influences the penetration depth significantly.

The assumption of increased notch size can be verified by looking at figure 7.23. The notch size for the experiments 72B1 and 72B2 (corner radius 2.5 and 2.0 mm) have a larger notch size than the weld joints welded with normal conditions. The two sections of experiment 72B3 (corner radius = 1.5 mm) shows a large difference between the notch sizes, and no certain conclusions is drawn from this experiment. However, experiment 72B4 (corner radius = 1.0 mm) which was the experiment that was closest to the normal conditions had a notch size which corresponds to the notch sizes in experiments performed with normal conditions.

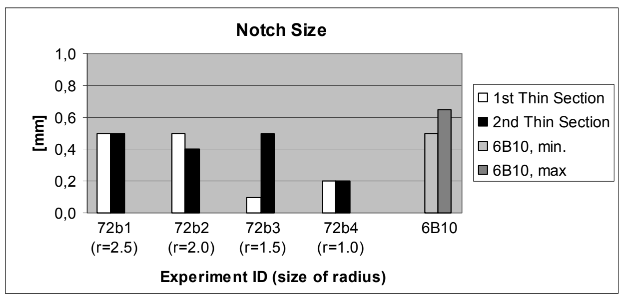


Figure 7.24: Comparison of notch size from the experimental series 72B1 through 72B4 and experiment 6B10, in which the actual gap was 0.5 mm.

As it can be observed in figure 7.24 the sizes of notches were smaller for the experimental series 72B1 through 72B4 than in experiment 6B10 in which the actual gap size was 0.5 mm. Two different effects are assumed to cause the increased notch sizes (compared to normal conditions) in these different types of experiments. In the experiments 72B1 through 72B4 the notch was caused by lack of material in the weld groove when the corner radii were increased to a level above 1.0 mm. In experiment 6B10 it was assumed that the width of the molten weld pool facilitated the extended notch formation caused by reduced welding speed when the measured gap was 0.5 mm (see page 125).

When corner radius is within the range of 2.5 mm and both the actual and the measured gap sizes are 0.0 mm, the notch size is at the same level as when both the actual gap size and the measured gap size is 0.5 mm.

It is concluded that curved corners of workpiece 1 does not affect the geometric quality parameters significantly when the corner radius of curvature is maximum 1.0 mm, and as long the measured gap corresponds to the actual gap size. If the corner radius exceeds 1.0 mm the control variables must be adapted to the corner radius in order to avoid additional notch formation.

When measured gap size is disturbed by curved corners

The experiments given the names 73b1, 73b2, 73b3, and 73b4 (see appendix D) were made for investigation of the effect of curved corners when the gap measurements were influenced by radius of curvature. The inspection of geometric quality parameters were made from two sections of each experiment and from magnetic powder inspection.

The corner radius of workpiece 1 in experiment 73b1 was 2.5 mm. The measured gap during the welding process is shown in figure 7.25.

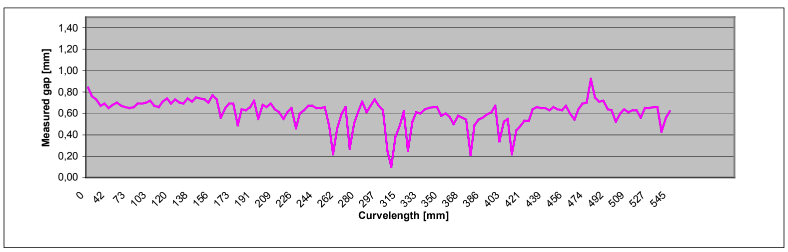


Figure 7.25: Measured gap during welding in experiment 73b1. The actual size of gap was 0.0 mm throughout the weld joint and the corner radius of workpiece 1 was 2.5 mm.

The laser scanner made 143 measurements while executing experiment 73b1. The average size of gap in these measurements was 0.61 mm.

The corner radius of workpiece 1 in experiment 73b2 was 2.0 mm. The measurements of gap are shown in figure 7.26

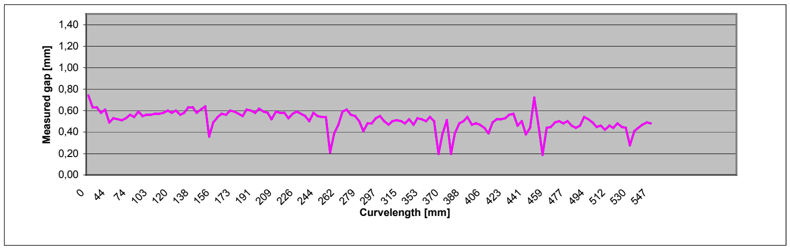


Figure 7.26: Measured gap during welding in experiment 73b2. The actual size of gap was 0.0 mm throughout the weld joint and the corner radius of workpiece 1 was 2.0 mm.

The laser scanner made 138 measurements while executing experiment 73b2. The average size of gap in these measurements was 0.51 mm.

The corner radius of workpiece 1 in experiment 73b3 was 1.5 mm. The measured gap during the welding process is shown in figure 7.27.

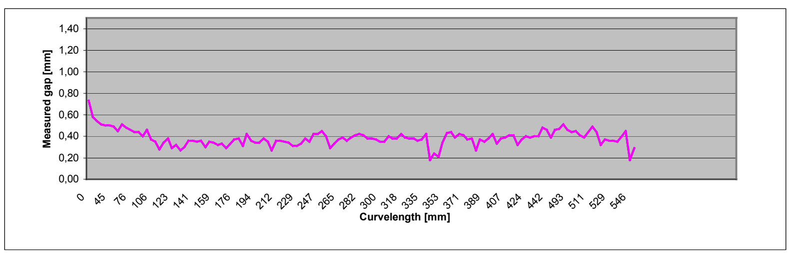


Figure 7.27: Measured gap during welding in experiment 73b3. The actual size of gap was 0.0 mm throughout the weld joint and the radius of curvature was 1.5 mm.

The laser scanner made 134 measurements during this experiment and the average size of measured gap was 0.38 mm.

The corner radius of workpiece 1 in experiment 73b4 was 1.0 mm. The measured gap during the welding process is shown in figure 7.28.

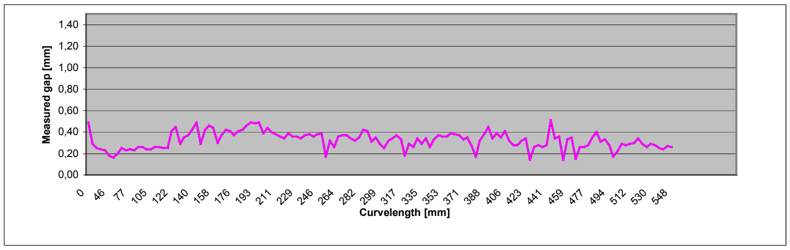


Figure 7.28: Measured gap during welding in experiment 73b4. The actual size of gap was 0.0 mm throughout the weld joint and the radius of curvature was 1.0 mm.

The sensor made 143 measurements during the experiment and the average size of gap was 0.32 mm.

The measured size of gap for the experiments 73b1 through 73b4 show the influence of curved corners on estimated gap size. This is obtained because all of these weld joints were carefully prepared to keep a fixed gap size of 0.0 mm throughout the joints. The measured gaps are influenced significantly by the corner radii. It would be possible for the vendor of the profile sensor, Modular Vision Systems inc., to adjust internal parameters of the sensor and thereby achieve more precise gap measurements for a specified corner radius. Though the corner radius is normally not specified because it varies stochastically between 0.0 and 1.0 mm.

The geometric quality parameters corresponding to the measurements above is illustrated in appendix D and in figure 7.29.

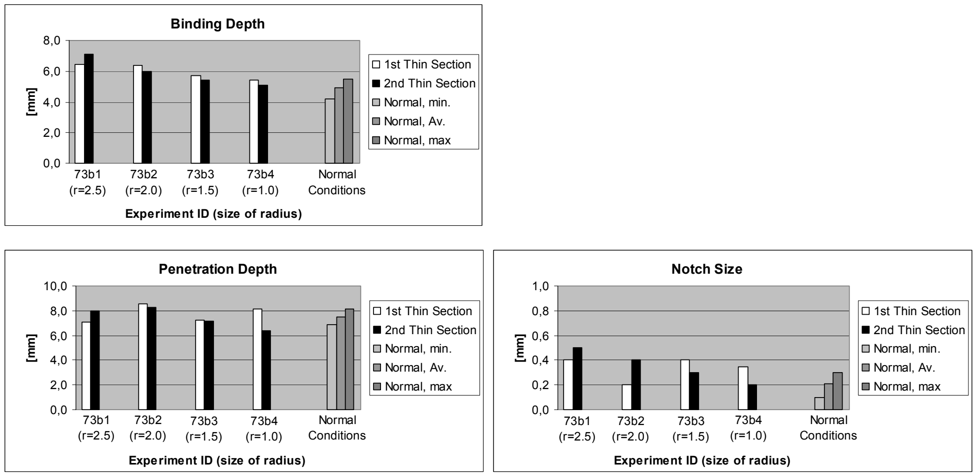


Figure 7.29: Geometric quality parameters for the experiments 73b1 to 73b4, in which the radius of workpiece edges were varied from 2.5 to 1.0 mm, and the gap measurements were not compensated for the disturbances of these radii. The white blocks represent the parameters of the first, and the black blocks the parameters of the second section of each experiment. The corresponding quality parameters for experiments in which normal conditions for welding (6B5 through 6B8) is shown in the graph. The minimum, average and maximum values are represented for these experiments.

When the gap measurements are disturbed by curved corners it is to be expected that the measured gap increases as function of the missing material in the region close to the joint. This assumption is satisfied in the experimental results (see figures 7.25 through 7.28).

The above described disturbances will affect the control variables in such a way that the displacement (see figure 6.8) and the wire feed rate will change proportional to the measured gap size, whereas the welding speed will change inversely proportional to this.

It was expected that the binding depth would increase as consequence of the larger displacement. However, this increased displacement may cause a lack of fusion between the weld metal and workpiece 2. The relation between increased heat input (due to decreased welding speed) and increased addition of filler material is strongly influencing the ability to avoid lack of fusion. One have to remember that the increased heat input must melt both additional filler material and the base material, since the measured gap is caused only by the missing material in the round corner of workpiece 1 (see figure 7.22).

As it can be seen in figure 7.29 the binding depth was actually increased in the welded joints of experiments 73B1 through 73B3 in which the corner radii were 2.5, 2.0 and 1.5 mm, respectively. Though, the binding depth of experiment 73B4 (corner radius 1.0 mm) had the same level as for normal conditions, and for experiment 73B3 (corner radius 1.5 mm) the binding depth was only slightly above the level of normal conditions. No lack of fusion were found in any of the sections, and the fusion was not near the critical level for any of the sections either.

It was expected that the penetration depth would be unchanged or slightly smaller than for normal conditions. Mainly because the additional heat-input must be used for melting both base material (because the actual gap was 0.0 mm) and an increased amount of filler material.

The experimental results (see figure 7.29) showed that the penetration depth was at the same level as for normal conditions. Only the penetration depth measured in experiment 73B2 (corner radius = 2.0 mm) exceeded the maximum level of the experiments 6B5 through 6B8 (normal conditions) with 0.1 mm.

The reason why the level of the penetration depth for these experiments corresponds to the level of penetration depth for normal conditions is that the process had a reserve of power when the measured gap increased compared to the normal conditions. This reserve of power came from the reduced welding speed relative to the added amount of filler material. This reserve of power was additionally observed during welding of experiment 6B10, in which the actual gap size was 0.5 mm. In this experiment it was seen that the penetration depth and the binding depths were increased compared to the normal situation.

The conclusion on influence from curved corners of workpiece 1 on the penetration depth was that no significant influences were observed.

It was expected that the notch sizes would be smaller in the experiments 73B1 through 73B4 because additional filler material was added to the weld joint (see table 7.1) even though the actual gap was 0.0 mm. The smallest notch size was expected in experiment 73B1 (corner radius = 2.5 mm), in which the measured gap was largest (see figures 7.25 through 7.28).

It can be observed from figure 7.29 and from Appendix D that the notch sizes of the sections from experiments 73b1 to 73b4 were generally slightly larger than for normal conditions.

The larger notch sizes are assumed to be caused by the decreased welding speed in the experiments, which causes the size of the keyhole to increase. As described earlier in this chapter (in the sections above figure 7.21) the tests described in this thesis indicates a trend towards stronger notch formation when the size of keyhole and thereby the weld metal increases.

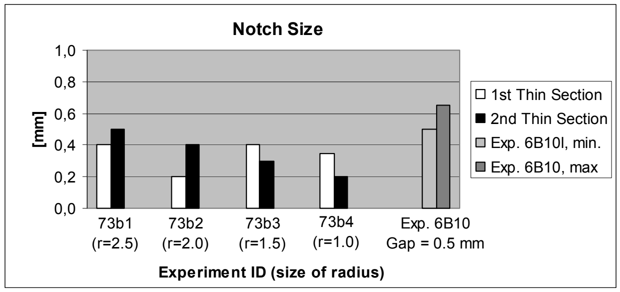


Figure 7.30: Comparison of notch size from exp. 73B1 through 73B4 with the notch size from exp. 6B10 in which the actual gap was 0.5 mm.

As it can be observed in figure 7.30 the sizes of notch in the experimental series 73B1 through 73B4 were slightly smaller than in experiment 6B10, even though the measured gap was approximately the same (see figures 7.16 and 7.25 through 7.28). The latter means that the control variables for these experiments were within the same range. The reason why the notch sizes were smaller for 73B1 through 73B4 is that the reduced welding speed had approximately the same effect on the notch formation in this series as in 6B10, but the filler material only had to cover the missing material caused by the rounded corner. In exp. 6B10 the filler material had to compensate for missing base material throughout the entire gap-area.

Conclusion on corner radius

For laser welding weld joints with a corner radius it can be concluded that it is necessary to compensate for the missing material in the rounded corner when the corner radius exceeds 1.0 mm (see figure 7.23). This is based on the assumption that it is possible to measure the actual gap size in spite of the corner radius, which was not possible with the profile sensor used in the present project.

If the measured gap deviates from the actual gap size because of the corner radius, the notch formation is affected towards a larger notch size because the welding speed is decreased. This trend is observed already at a corner radius of 1.0 mm (see figure 7.29). The increased amount of filler material does not have to cover a full sized gap corresponding to the measured gap size, but only a small area of missing material at the rounded corner. Therefore the observed notch sizes caused by corner radii, where the profile sensor responds to these radii by larger gap measurements, are smaller than notch sizes caused by an actual gap in the weld groove, when the profile sensor is not affected by curved corners.

As shown in figure 7.19 the possibilities to weld joints including a gap, without obtaining a notch in the welded groove, varies for different types of laser welding equipment. In other words the robustness of weld quality regarding notch formation as consequence of gap in the weld joint may vary significantly from one laser welding plant to the next. Considering the robustness of weld quality with regard to notch size as consequence of curved corners may be considered proportional to the robustness towards gap variations. The main argument for this is that notch formation due to curved corners is mainly caused by the decreased welding speed, which is the same for notch formation caused by an actual gap in the weld groove.

Primer removal

One difference between laboratory and industry is that experiments in laboratory may be performed on clean metal sheets without any paint or primer. In industry and especially in off-shore industry the protection of parts against corrosion is very important. The quality of laser welded joints may easily be affected by paint or primer in the weld groove. Therefore paint and primer must be removed before laser welding is started.

It is described in chapter 6 how primer was evaporated and removed from workpiece 2 by use of a special laser line in the present project. A workpiece from which three lines of primer have been removed is shown in figure 7.31. The workpiece in this figure corresponds to workpiece 2 in figure 7.22. The primer on the edge-face of workpiece 1 was removed by milling.

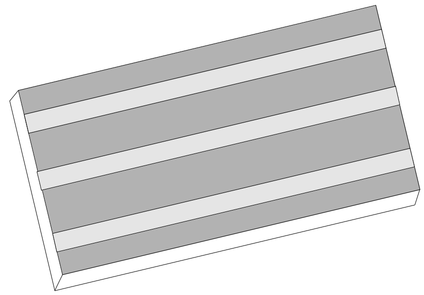


Figure 7.31: Workpiece 2 from which 3 lines of primer has been removed

During the Ph.D. project experiments were carried out in which the primer removal was done by use of a spinning wire brush. The magnetic powder inspection of these experiments revealed a critical crack formation in most of the welded joints. Even though no visible primer was present on the workpieces, further investigations of workpieces revealed that particles from the primer were pressed into the surface of the workpiece by the spinning wire brush. These particles were devastating for the quality of weld joints.

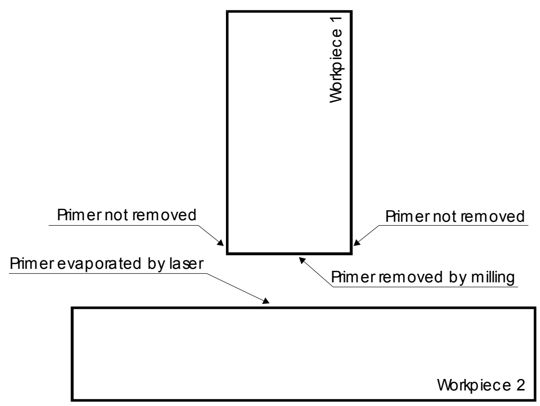


Figure 7.32: Illustration of the areas with and without primer.

The presence of primer on flange joints is shown in figure 7.32 for weld joints in the project, including the joints of experiments presented in this chapter. As indicated in this figure the primer was not removed on the main faces of workpiece 1. In the final experimental series the magnetic powder inspection of weld joints indicated that the thickness of primer on these faces had a significant influence on crack formation.

The experimental series were performed using a total of 28 test pieces with a length of approximately 600 mm each. The stiffeners (workpiece 1) were provided from three different profiles (profile 2, 3 and 6). The workpieces were marked with the identification of the used profile for workpiece 1.

25 out of 28 welded joints were inspected by magnetic powder inspection (MPI). The MPI was performed by the Force Institute, and the report of this inspection is provided in Annex D. The MPI revealed that cracks were present in 8 out of the 24 inspected joints. Cracks in connection with start and stop of the weld joints was not counted, since no work has been done in this Ph.D. work to provide procedures for starting and stopping the laser welding process. The classification societies American Bureau of Shipping and Lloyds Register of Shipping approved that cracks could be present in the starting and ending points of the laser welded joints in deck components. However, this was on the condition that these ends would be overlapped by TIG or MIG welding.

Profile	No. 2	No. 3	No. 6	Cracks	No Cracks	No MPI	Crack in 2	Crack in 3	Crack in 6
6b5			X	X			0	0	1
6b6			X		X		0	0	0
6b7			X	X			0	0	1
6b8			X	X			0	0	1
6b10			X		X		0	0	0
71e1	X					X	0	0	0
71e2	X					X	0	0	0
71e3	X					X	0	0	0
72b1		X		X			0	1	0
72b2		X			X		0	0	0
72b3		X			X		0	0	0
72b4		X			X		0	0	0
73b1		X			X		0	0	0
73b2		X			X		0	0	0
73b3		X			X		0	0	0
73b4		X			X		0	0	0
73c1		X			X		0	0	0
73c2		X			X		0	0	0
73c3		X			X		0	0	0
73e1			X	X			0	0	1
73e2			X		X		0	0	0
73e3			X	X			0	0	1
73f1		X			X		0	0	0
73f5			X	X			0	0	1
73f6			X	X			0	0	1
73f7		X			X		0	0	0
73g1		X			X		0	0	0
73g2	X				X		0	0	0
Total	4	14	10	0	0	0	0	1	7

Table 7.3: Summary of appendix D with regard to profile used as workpiece 1 in the test and the presence of cracks, except for cracks at the start or the end of the joints.

For each experiment documented in appendix D the information about profile number for workpiece 1 is provided. Additionally it is described whether or not one or more cracks were present (except for cracks in connection with start and stop of the weld joints). Table 7.3 shows a summary of crack formations in the welded joints. From this table it can be observed that 4 experiments were carried out using profile number 2. Out of these 3 welded joints were not tested by MPI and the remaining joint had no cracks. 14 welded joints were carried out using profile number 3, and all of these were tested by MPI. Only one of these joints had a crack formation, corresponding to 7% of the 14 joints. Ten experiments were carried out using profile number 6, and all were tested by MPI. 7 of these joints corresponding to 70% of the 10 joints had crack formations between the starting and the ending point.

After the experimental series the thickness of primer on remaining parts of the three profiles were tested. This test revealed that the thickness of primer was 25 to 30 micrometres on the profiles no. 2 and 3. On profile no. 6 the thickness of primer was approximately 50 micrometres near the weld joint.

The conclusion of this is that the thickness of primer and paint in the area near the weld joint must be very accurately controlled, if primer or paint has to be present at all. Primer or paint must not be present between the parts in a flange joint, not even in so small quantities that cannot be observed by human eye.

7.5. Tolerances of control parameters

The control parameters are these parameters which are adjusted prior to the laser welding process, i.e. they are not changed during processing (see chapter 4, section 4.1.3). As described in chapter 4, section 4.2.1, the inverse process model is constrained by a specified set of control parameters. The inverse process model is only expected to provide the specified quality parameters if these constraints are kept. In a production situation it is easy to imagine that one or more control parameters can deviate from the specified value because of inexact adjustment or calibration.

In this section two series of experiments are described. The experiments concern variations of the plasma control gas flow and of the laser beam power. The objective for doing these experiments were to investigate the robustness of geometric quality parameters of laser welded joints with regard to precision of these parameters. The robustness to these parameters influence the necessity of monitoring these parameters strictly during the laser welding process.

Variation of the plasma control gas flow

When using high power lasers for welding and the welding speed is below 1000 mm/min vapour will be ejected from the keyhole[4] and can form a very dense plasma cloud just above the keyhole, such as shown in figure 7.33.

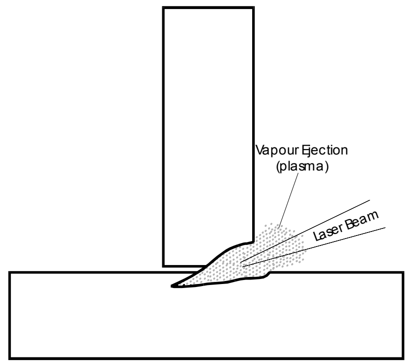


Figure 7.33: Laser welding process with plasma formation.

The plasma cloud is not completely transparent to the laser beam, which means that part of the laser beam is re-radiated in all directions. Thereby the laser energy can be spread before it reaches the metal surface. In order to reduce this spreading of the laser beam, plasma control gas is added to the laser welding process. The plasma control gas nozzle was positioned above the wire nozzle behind the laser beam relative to the welding direction, such as shown in figure 7.34.

[4] The laser beam establishes a keyhole in the workpiece during welding. The base material in the keyhole is evaporated and the edge of the keyhole consists of molten material.

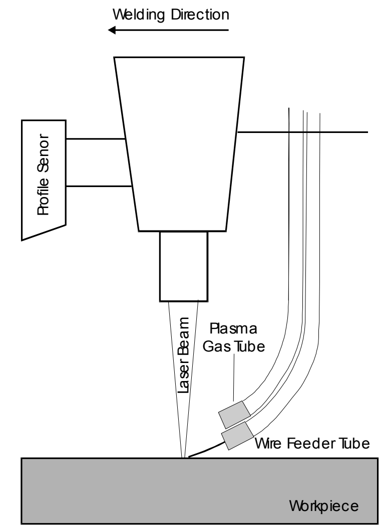


Figure 7.34: Sketch of equipment set-up at the weld scene.

The wire was aimed by the wire feed tube/nozzle towards the point of the laser beam that intersect the workpiece surface. The plasma control gas was aimed in the same direction as the welding wire. The work angle and travel angle of the wire feeder nozzle and of the plasma control gas nozzle is specified in appendix D.

The experiments 73E1 through 73E3 were carried out with different values of plasma control gas flow rate. The constraints for the inverse process model includes a plasma control gas flow rate of 6 l/min, i.e. this flow rate was used during the experiments 6B5 through 6B8, in which the normal conditions were maintained. The flow rates for the experiments 71E1 through 71E3 were as specified below.

71E1: Plasma control gas flow rate was 0 l/min.

71E2: Plasma control gas flow rate was 16 l/min.

71E3: Plasma control gas flow rate was 29 l/min.

It was expected that the binding depth would decrease slightly and the penetration depth would increase proportional to increasing plasma control gas flow, since the re-radiation of the laser beam due to plasma formation above the keyhole would decrease. This was expected to contribute to a more narrow laser beam. Additionally it was expected that the notch size would decrease with increasing plasma control gas flow. This is because the plasma is extremely warm and will give off heat radiation to the weld joint, which contributes to widen keyhole and the molten pool. Widening these is discussed in section 7.4.

The geometric quality parameters of the sections from the experiments 71E1 through 71E3 are shown in figure 7.35 and in appendix D.

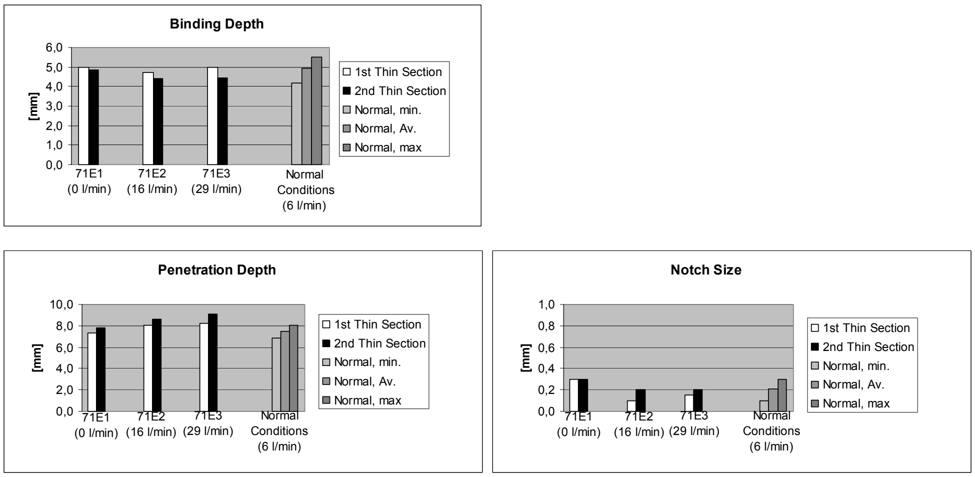


Figure 7.35: Experimental results from the series 71E1 through 71E3, in which the plasma control gap flow rate was varied.

One section from each of the three experiments are shown in figure 7.36.

Exp. 71E1 Plasma gas flow: 0 l/min | Exp. 71E2 Plasma gas flow: 16 l/min | Exp. 71E3 Plasma gas flow: 29 l/min

Figure 7.36: Sections of the experiments 71E1 through 71E3.

The shape of the welded joint surfaces changes as function of the plasma control gas flow rate (see figure 7.36). A characteristic ridge is observed in the welded joint of experiment 71E3, in which the plasma control gas flow rate was quite high.

It can be observed in figure 7.35 that the binding depths were approximately the same for the three experiments, and at the same level as for the experiments 6B5 through 6B8 (normal conditions). The small decrease in binding depth for experiments 71E2 and 71E3 is not sufficiently significant to draw any conclusions from them. The reason why the binding depth was not decreased significantly is probably that even though scattering of the laser beam due to plasma formation is decreased the energy from the laser beam, which is no longer re-radiated by the plasma cloud, was directed into the keyhole and contributed to maintaining the width of the keyhole.

The expectations for increased penetration depth as function of increasing plasma control gas flow rate was satisfied.

The notch sizes measured in experiment 73E1, where no plasma gas was added, are larger than the average of notch sizes for normal conditions. Though, they are not exceeding the corresponding maximum values for normal conditions. The notch sizes for exp. 71E2 and 71E3, in which the plasma control gas flow was larger than for normal conditions, the notch sizes were between the minimum and the average values for notch size during normal conditions. These variations are not sufficiently significant for making any conclusions, even though they slightly indicate the expectations mentioned previously. However, figure 7.36 shows that the geometry of the welded joint surface tends to vary as function of plasma control gas flow rate.

Variation of the laser beam power

For different reasons the power of the laser beam may vary during time. These variations can be caused by dirt on mirrors in the beam transmission train (see chapter 2, section 2.1.2). Also disturbances to the laser cavity may cause variations of the laser beam energy. A possible disturbance that may affect the laser power is the supply of fresh laser gas to the laser cavity (see appendix E, Chapter 3).

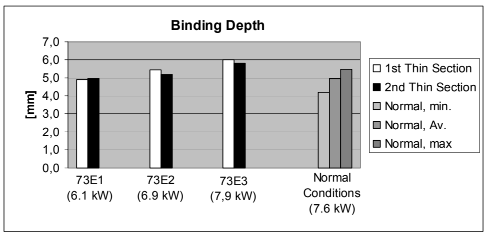
The experiments 73E1 through 73E3 were carried out with different levels of laser beam power. The power was constant during the experiments, but was adjusted and measured before each experiment. The laser beam power was set as follows.

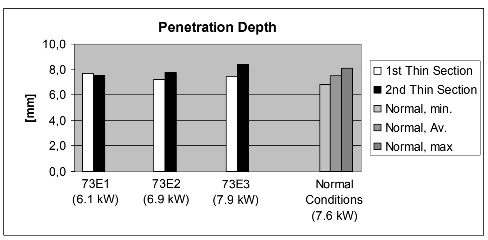
73E1: The laser beam power was 6.1 kW.

73E2: The laser beam power was 6.9 kW.

73E3: The laser beam power was 7.9 kW.

It was expected that the binding depth and the penetration depth would change proportionally to the variations of the laser beam power, since they are directly dependent on the energy put into the weld groove. The notch size was expected to change inversely proportional to the change of laser beam power because the keyhole and molten pool was expected to increase. It is earlier in this chapter indicated that the notch size seems to increase when the keyhole widens.





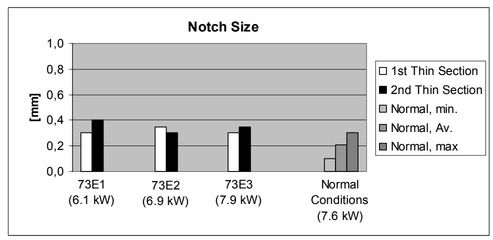


Figure 7.37: Geometric quality parameters for experiments 73E1 through 73E3, in which the laser power was varied.

The geometric quality parameters for the three experiments are shown in figure 7.37 and in appendix D.

From figure 7.37 it can be observed that the above mentions expectation for binding depth was satisfied in the experiments. The binding depth increases proportionally to increasing laser beam power. The experimental results showed that the penetration depth only varied slightly as function of the variations in laser beam power.

The tendency towards increased penetration depth caused by increased laser beam power is not significant. In fact all the measured penetration depths for experiments 73E1 (6.1 kW) and 73E2 (6.9 kW) are within the corresponding minimum and maximum values for the normal conditions (7.6 kW). Only one of the measured penetration depths in experiment 73E3 (7.9 kW) exceeds the maximum value for penetration depth during normal conditions, and this is with no more than 0.3 mm.

The reason why the penetration depth did not change significantly is probably that increased laser beam power contributes to increased plasma formation, which causes scattering of the weld beam throughout the plasma cloud and the keyhole. This will have a counteraction on the tendency to increase penetration depth in favour of widening the keyhole and thereby contribute to increasing binding depth.

The notch size did not decrease as function of decreased laser beam power as expected. Actually it was increased 0.1 mm for one section in all of the experiments, compared to the maximum value for notch sizes during normal conditions. No arguments can be found for the notch size to increase in experiment 73E1 when the laser beam power was decreased 1.0 kW. However it should be noticed that it is very difficult to make conclusions on the basis of variation of one tenth of a millimetre, especially since no general trend was observed.

7.6. Tolerances of control variables

The control variables are these variables that are controlled by the implemented welding control system (see chapter 4, section 4.1.4). Calibration of the equipment has an influence on these variables. Therefor the robustness of quality parameters with respect to variations of these variables is examined in this section. Three control variables are used in the system; The welding speed, the wire feed rate, and the displacement of the laser beam.

Variation of Welding speed

Laser welding is always carried out using mechanical manipulators. In the present Ph.D. project the manipulator was numerically controlled. Even for numerically controlled manipulators deviations from the programmed welding speed can occur. Usually the calibration of manipulators provides a relatively high accuracy of the welding speed. However many numerically controlled manipulators have an override possibility, which enables manual override of the speed. The speed can normally be set to a specified percentage of the programmed speed by manual activation of the override button. Experience from the project showed that it was important to check the actual position of the override button before each experiment in order to keep the planned speed.

The experiments 73F1 through 73F7 were carried out with varied welding speed in order to investigate the robustness of the geometric quality parameters with respect to these variations.

The speed deviated from the normal conditions as follows.

73F1: The speed was decreased 50% compared to normal conditions.

73F5: The speed was increased 50% compared to normal conditions.

73F6: The speed was increased 25% compared to normal conditions.

73F7: The speed was decreased 25% compared to normal conditions.

The experiments 73F2 through 73F4 are not considered because the laser beam power dropped during process execution, caused by disturbances to the supply of laser gas to the laser cavity.

It was expected that the binding depth, penetration depth and notch size would vary inversely proportional to the variation of welding speed because the heat input varies proportional to the welding speed. The geometric quality parameters are shown in figure 7.38 and in appendix D.

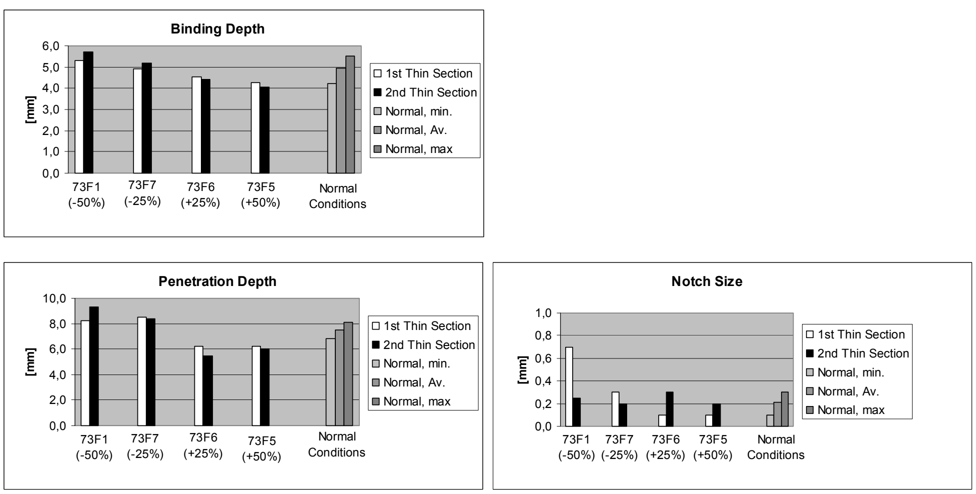


Figure 7.38: Geometric quality parameters of the experiments 73F1 through 73F7, in which the welding speed was varied. The experiments 73F2 through 73F4 are left out because of too low laser beam power.

The binding depth observed from the experiments satisfies the expectation for this particular parameter. The tendency that binding depth decreased as welding speed was increased was consistent throughout the experimental series.

The Penetration depth showed the expected trend for welding speed decreased 50%, decreased 25% and increased 25%. Also when the normal conditions were compared to these experiments the trend was consistent. However continuation of the trend was not observed for experiment 73F5 in which the welding speed was increased 50%. One possible explanation to this is that the welding speed were increased to a level at which the plasma formation may have been reduced significantly, and thereby a larger percentage of the laser beam energy were let into the joint. However, the binding depth did not seem to be influenced by a more narrow weld zone, such as described in the section concerning the experimental series 71E1 through 71E3 in which the plasma control gas was varied. No consistent conclusion can therefore be drawn why the penetration depth does not seem to continue decreasing when the welding speed is varied from 125% to 150% of the planned welding speed. However, when considering the interval of penetration depths for normal conditions, this interval may explain the interruption of the described trend.

The variation of notch size as function of increasing welding speed does not show a significant trend throughout the experimental series. It can be observed that the notch size for experiment 73F1 (welding speed reduced 50%) differed 0.4 mm from 0.3 to 0.7 mm in the two sections. This indicates that there was an instability in the welding process causing this large deviation in notch size. The notch sizes for experiments in which the welding speed was varied from 25% below to 50% above the welding speed for normal conditions were all within the same range as for normal conditions.

Variation of wire feed rate

It was observed during the experimental work that the wire feed rate was typically affected by three different types of errors:

The driving wheels of the wire feeder mechanism could be slipping on the welding wire because of resistance between the wire and the tube and nozzle for steering the wire to the right position (see figure 7.34). Therefore the wire feed rate could differ from the planned value. In this case the wire was usually stopped.

The welding wire could be stopped because the heat radiation from the welding process melted part of the wire feeding nozzle.

The calibration of the wire feeding mechanism could be inaccurate.

In order to investigate the robustness of quality parameters with respect to significant changes of the wire feed rate the experiments 73G1 and 73G2 were carried out. In experiment 73G1 the wire feed rate was set to zero and in experiment 73G2 the wire feed rate was increased 50% compared to the normal situation.

It was expected that the binding depth and the penetration depth would be inversely proportional to the wire feed rate since an increased wire feed rate would increase the laser beam energy used for melting the filler wire.

The notch size was expected to be inversely proportional to the wire feed rate because additional material is added to the joint when the wire feed rate is increased.

The geometric quality parameters measured at the sections of the experiments 73E1 and 73E2 are shown in figure 7.39 and in appendix D.

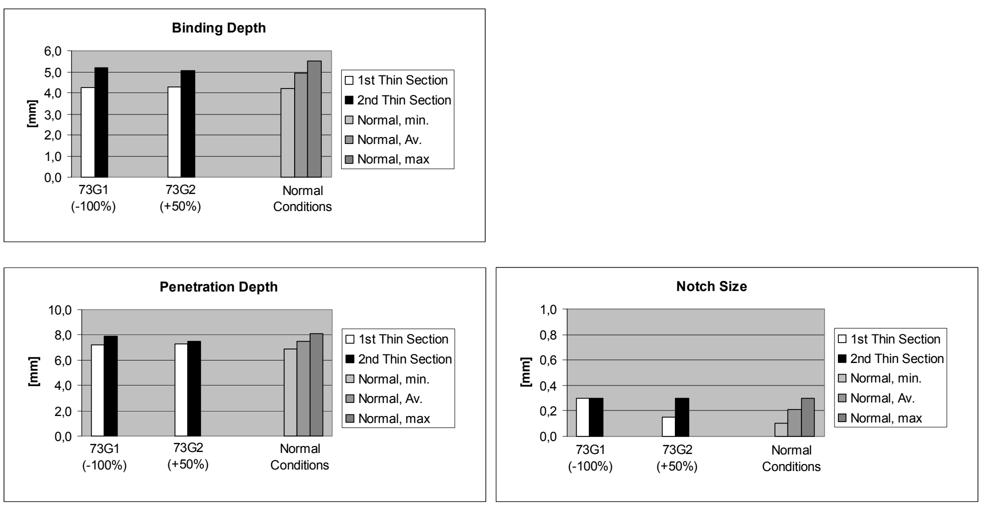


Figure 7.39: Geometric quality parameters for the experiments 73E1 and 73E2 in which the wire feed rate was varied from the normal conditions.

It can be seen from the measured geometric quality parameters that the binding depth was at the same level for both experiments. Compared to the normal conditions these binding depths were within the range between the corresponding minimum and maximum values for binding depths of experiments performed using the normal conditions.

The penetration depth was like the binding depth at the same level for both experiment 73E1, 73E2 and for the normal conditions. The variations of wire feed speed did not affect the penetration depth significantly.

The notch size for experiment 73E1 was 0.3 mm for both sections in this experiment. This corresponds to the maximum value of notch size observed in the experiments using normal conditions. The notch size was 0.2 and 0.3 mm, respectively for the sections of experiment 73E2. This difference is neglectable since all notch sizes were within the limits of notch sizes for normal conditions.

It can be concluded that the variations in wire feed rate in these experiments were too small to make a significant difference to any of the three geometric quality parameters. The experiments were carried out using a weld joint in which the gap was 0.0 mm. Therefore the quality parameters are more robust to variations of the wire feed rate than if the wire had to compensate for missing material in a weld joint including a gap.

Variation of displacement

The displacement (see figure 6.8) was controlled automatically as function of the measured gap size. The displacement specifies the elevation of the laser beam relative to the bisector plane, positioned in the middle of the joint. The wire feeder nozzle and the plasma gas nozzle (see figure 7.34) was fixed to the laser supply system. Therefore the position of plasma gas and wire addition followed the position of the laser beam. Inaccurate calibration of equipment can lead to deviations of the actual displacement of the laser beam relative to the planned displacement. Therefore the robustness of quality parameters are investigated with respect to such deviations.

The experiments 73C1 to 73C3 were carried out with variations in the displacement relative to the normal conditions. The variations from normal conditions were as follows.

73C1: The displacement was varied –0.3 mm (i.e. lowered towards the joint).

73C2: The displacement was varied +0.3 mm (i.e. elevated from the joint).

73C3: The displacement was varied +0.5 mm (i.e. elevated from the joint).

The binding depth was expected to change proportional to the displacement because the inner point of the weld metal would be lifted in direction of workpiece 1. However, there is a risk that lack of fusion will occur between the weld metal and workpiece 2 when the displacement is increased. The penetration depth was expected to remain unchanged when the displacement is changed since the heat-input into the workpieces are the same. The notch size was expected to remain unchanged.

The experimental results for the experiments 73E1 through 73E3 are shown in figure 7.40 and in appendix D.

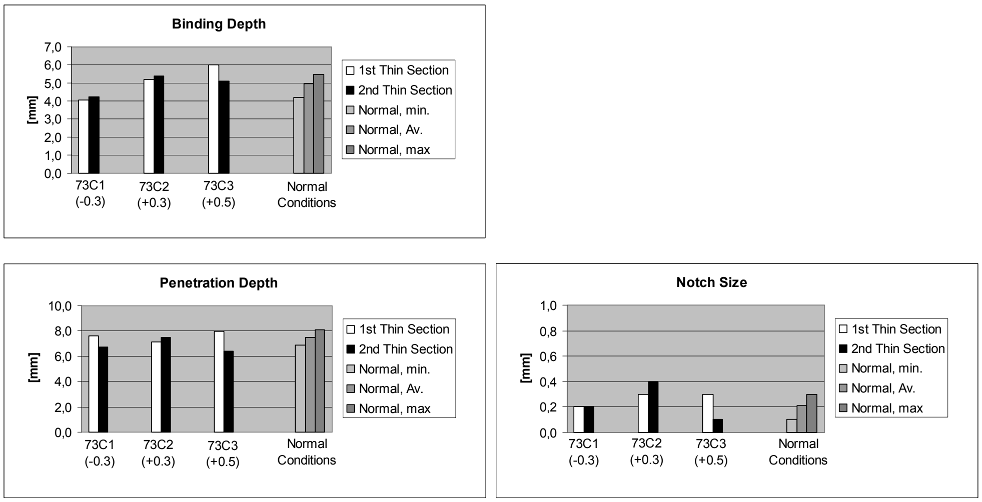


Figure 7.40: Geometric quality parameters for the experiments 73C1 through 73C3, in which the displacement of the laser beam relative to the joint centre was varied.

The expectations for binding depth and penetration depth were satisfied by the experiments, also when compared to the normal conditions. No lack of fusion was observed in any of the experiments. The notch size was 0.4 mm in one of the sections of experiment 73C2. This notch size is the only one that exceeded the limits of notch sizes for the normal conditions, and only with one tenth of a millimetre.

Based on the experimental results of the experiments 73C1 through 73C3 it is concluded that binding depth changes proportionally to changes in displacement of the laser beam. Though this is depending on the absolute displacement specified for the inverse process model. The penetration depth and the notch size are relatively unaffected by changes of the displacement.

Chapter 8

Extension of Tolerances for Laser Welding

The methods developed and described through the previous chapters, and the methods of the studied literature indicate that the laser welding process should only be applied when the workpiece tolerances are very small. According to chapter 7, the size of gap must not exceed 0.5 mm. Though [5] and [8] indicate that gaps up to 1.0 mm can be welded by using laser welding technology. These tolerances are based on an artificially created gap that is prevented from responding naturally to the laser welding process. Therefore, an experiment is presented which indicates that these tolerances can be extended by allowing the workpieces to respond naturally to the heating and contraction caused by the laser welding process. This experiment was carried out while welding a T-joint, joining two workpieces with a plate thickness of 10 mm.

A tendency was observed for contraction of the weld groove. Contraction was observed in the area near the weld scene during the laser welding process. The problems caused by this contraction during the establishment and validation of welding procedures are described. Additionally, an opportunity to utilise this contraction for extension of the allowable workpiece tolerances for laser welding of T-joints in large plate thicknesses is described in the present chapter.

8.1. Identification of contraction effect

In order to get permission to perform automatic laser welding in shipbuilding industry, it is necessary to validate the inverse process models (IPMs) with respect to the output quality of the laser welded joints. The inverse process models are validated experimentally by first welding workpieces with the smallest gap provided by the IPM, then workpieces with the largest gap provided by the IPM.

These gap sizes for IMP validation are purposely created during the tack welding procedure. When the largest gap to be tested was 0.5 mm, a workpiece with this gap was created in order to validate the IPM. This gap was created by using spacer blocks between the base plate and the stiffener. A sketch of the workpieces used for the validation tests of inverse process models is shown in figure 8.1 below.

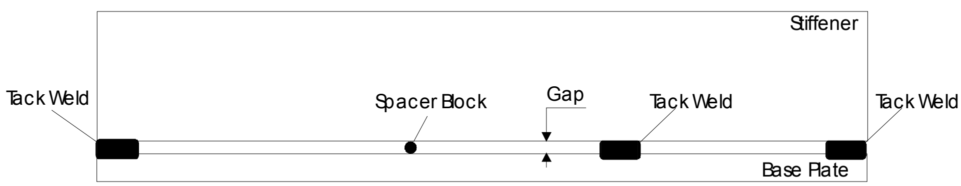


Figure 8.1: Sketch of the workpieces for validation of inverse process models.

The gap is intended to be constant along the entire length of the weld groove and throughout the welding process. When performing these experiments it was found that the laser welding process itself is able to change the gap size during execution of the welding process. One example of this is shown in figure 8.2. In this figure a gap has been established by using spacer blocks, which can be seen in figure 8.2 between the scanner and the laser. As shown in the figure, this gap is contracted at the position of the laser beam and the base plate is tilted around the spacer block, whereby the gap is widened at the scanner position.

During execution of the laser welding process it was identified that the gap tended to change continuously during the process execution. This was especially apparent when a difference was discovered between the measurements, which were made when the profile sensor and the laser welding system followed the weld groove with the laser beam switched off, and afterwards measurements which were made afterwards with the laser beam turned on.

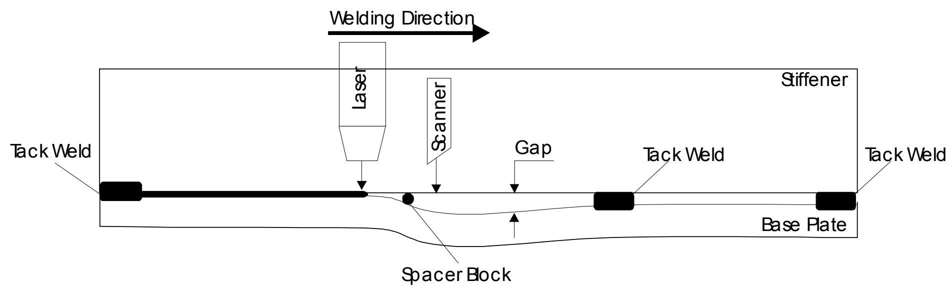


Figure 8.2: Sketch of distortions in the weld groove caused by heat contractions.

The experiments indicated that the groove was contracting at the weld scene during the welding process. Because of the distance between the vision sensor and the laser beam, the actual above-mentioned contraction caused the gap to change between the time of prior measurement and the time of welding at a specific position in the weld groove. This means that when the control system calculates the welding control variables based on the gap size at a specific position as determined by the scanner, this gap may have changed before welding is executed according to these variables at that position.

8.2. Extension of the tolerances

The contraction effect described above was allowed to occur in an experiment in which there were no mechanical spacer blocks to prevent the gap from contracting due to the welding process. The workpieces in this experiment had a length of 1400 mm and were tack welded with no gap at the starting point of the weld run and with a 4 mm thick spacer block at the opposite end. There were no tack welds or spacer blocks between the starting point and end point. The welding control system was programmed to start welding at the end with no gap, and to stop 200 mm before the end of the workpieces.

The welding control system was programmed to follow the weld groove, at first without the laser beam on and then afterwards with the beam on and the weld executed. During these two runs the control system saved a log-file containing the measurements from the vision camera. In figure 8.3, the measurements registered when the system was following the weld groove without the laser beam turned on are illustrated by the thin line, and the measurements registered during the welding run with the laser beam turned on are illustrated by the thick line. These measurements show that contraction of the weld groove closes the gap, even at the precise position where the vision camera is making measurements. This camera was located approximately 150 mm in front of the welding scene. Additionally, it was seen that the gap contracted from an opening of 2.8 mm to an opening of only about 0.2 mm at the immediate scanned position.

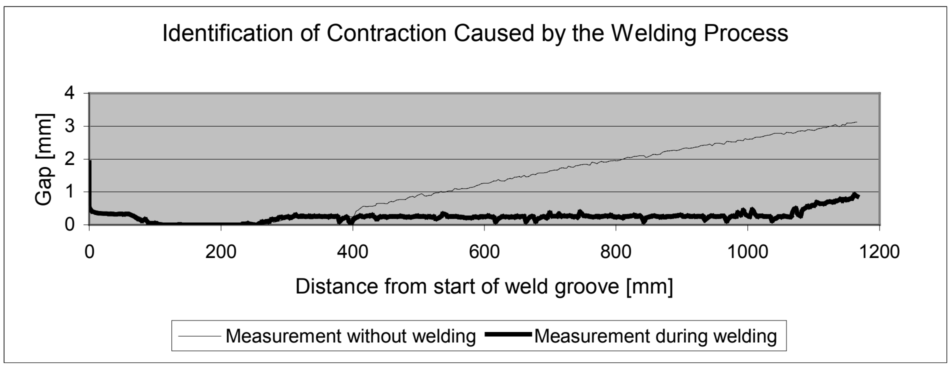


Figure 8.3: Measurements recorded by the welding control system when following the weld groove with and without the laser beam turned on.

The reason why the gap seems to increase after 1050 mm of the welding is that the profile sensor is getting closer to the spacer block in the end position as shown in figure 8.4 below.

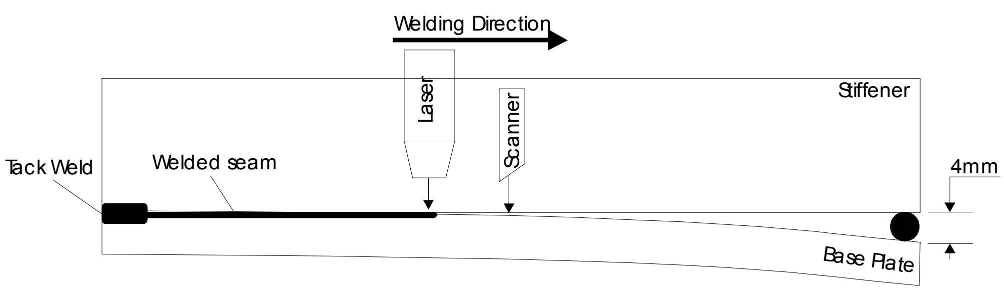


Figure 8.4: The weld groove is contracted by the heating and cooling from the welding process. The contraction is significant at the position of the line scanner.

The welding control variables used in the experiment described above were the same as used for a weld groove without an intentionally created gap. The resulting visual weld quality was the same throughout the weld joint, and it was characterised as satisfactory.

In the experiment, the control variables were not controlled. Instead, the control variables were set constant to fit a weld groove with no gap between the workpieces. Here, the control system only acted as a seam tracking system. After the experiment, a number of micro sections of the weld joint were made. These were visually judged, and it was found that no significant difference existed between the micro sections throughout the weld groove.

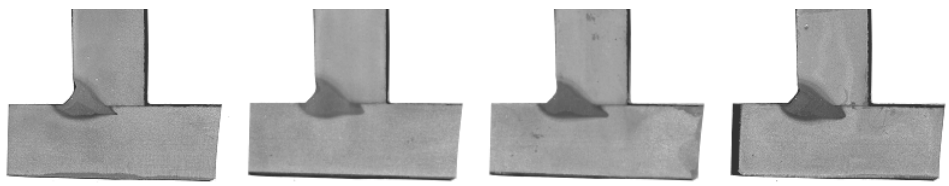


Figure 8.5: The thin sections in this figure are taken from the workpiece of the described experiment. The original gap was (shown from left to right) 0.5 mm, 1.5 mm, 2.5 mm and 3.5 mm at the positions where these thin sections are taken.

From figure 8.5 above, it can be seen that the gap is totally contracted after execution of the weld task. There is no significant difference in the shape or the penetration of weld for the thin sections removed from regions where the original gap was 0.5 mm, 1.5 mm, 2.5 mm, and 3.5 mm, respectively.

8.3. Changes to Tack Welding Procedures

Traditional tack welding procedures in heavy industry describe only the maximum size of gap in the weld grooves. Additionally, there may be a maximum distance between tack welds and a minimum length of the individual tack welds.

In order to extend the tolerances for laser beam welding in industrial applications by utilising the described contraction effect, it is necessary to apply a suitable tack welding procedure. A suitable tack welding procedure is suggested in the following section, based on the characteristics of the contraction effect.

The contraction effect works like a zipper and therefore it has a point of origin, which is moving along the weld joint at the same position as the laser beam. One condition for the contraction is that the gap size in this point of origin is zero, and that it is possible to contract the weld groove in front of the laser beam. Therefore, the tack welding procedure must ensure that the gap size at the starting point of the joint is zero and that there is no mechanical obstacles preventing the gap to contract throughout the joint. This means that the gap size must be zero at all positions in which tack welds are present. However, the gap size between the tack welds is allowed to be at least 3.5 mm (see figure 8.5).

8.4. Discussion of Utilisation of the Contraction Effect

It has been shown that the heating caused by the laser welding process and the subsequent solidification of the weld metal causes contraction of the gap in an area near the weld scene. Measurements indicate that the size of the gap will be close to zero when there are no physical obstacles preventing the gap from contracting. It is shown that T-joints with gap sizes of at least 3 mm can be welded by utilising the contraction effect. Since the contraction effect is a dynamic process that zips up the gap smoothly, it seems that the size of gap has only a minor influence on the contraction effect. However, the gradient of an increasing gap during the welding process is significant and must be investigated and specified for each individual type and dimension of material.

By utilising the contraction effect, the tolerances of the gap may be increased considerably compared to the tolerances obtained so far. A condition for increasing these tolerances is that no obstacles must be placed in the weld groove because these would keep the weld groove from contracting. Additionally, it has to be ensured that tack welds do not afix a gap between the workpieces.

Since the contraction effect provides a weld groove with a very small gap between the workpieces, feed forward control of the welding process is not needed with regard to variations in the gap size. Only a seam tracking system for execution of a set of fixed welding control variables throughout the welding process. This makes it considerably easier to establish and to validate models or welding procedures for the weld tasks.

The contraction of the weld groove is identified for laser welding of flange joints in 10 mm plate thicknesses and with a laser power, which was approximately 8 kW at the weld scene. It will be necessary to investigate the contraction with respect to different thicknesses of plates, for different levels of laser power, and for different gradients of changing gap size. Additionally it must be noticed that the contraction effect has to be shown for other joint types as well, such as for flank joints (see chapter 6, section 6.2.1).

8.5. references

[5] Nielsen Steen E., Svejsning med højeffekt Laser, 1992, Force Institutes, Report 92.80, ISBN 87-7784-009-7 (In Danish).

[8] Nielsen Steen E., Seam Tracking and Adaptive Control Based on Vision Technology Used for High Power Laser Welding, Proceedings of 5th Nordic Laser Materials Processing Conference, September 6- 8, Oslo, Norway.

Chapter 9

Conclusion

This chapter is the conclusion on the research carried out during the Ph.D. project and documented in the present thesis. The project was initiated with the purpose of investigating the possibilities for applying laser welding in heavy industry.

The project was part of a national research programme 'The Laser Process in Heavy Industry'. The purpose of this programme was to carry known experiences of laser welding and cutting into industry and to evaluate the possibilities for heavy industry to benefit from the laser technology. The basic task of this research programme was to implement a demonstration cell for laser welding and laser cutting in an industrial environment at Odense Steel Shipyard. Based on this demonstration cell the research should focus on the possibilities for implementing laser welding and cutting in a large scale industrial production and to evaluate the benefits for applying these technologies.

At the beginning of this project it was already proven that laser technology could be applied for welding workpieces with large thicknesses of the metal sheets. It was also proven that laser welding was possible for joints in which the gap sizes were up to approximately 1 mm. Additionally it was known that the welding speed and the wire feed rate had to be varied for different sizes of gap in the joint. In addition to this it was known that weld joints with variations in the size of gap could be welded by using a seam tracking system, which additionally adjusted the welding speed and the wire feed rate as function of the size of gap [8].

The above mentioned experiences were obtained during laboratory work, during which the weld joints were carefully prepared to meet conditions required for laser welding.

The Ph.D. work presented in this theses was part of the research programme 'The Laser Process in Heavy Industry' with the purpose of establishing a fully automatic process control system for laser welding and to implement this system in the demonstration cell at Odense Steel Shipyard. Additionally the Ph.D. work should describe the portability of this welding control system with focus on operating conditions in an industrial environment.

The two main tasks carried out in the presented research work were:

1) To establish methods for a generic and fully automatic control system for laser welding of thick steel plates and to implement this system.
2) To evaluate the portability of this system to industrial environments by evaluating the robustness to typical disturbances.

The result of the first main task is primarily documented in the chapters 4 through 6. The results of the second main task is documented in chapter 7. An additional possible strategy for controlling the laser welding process for the class of Flange joints was tested and is described in chapter 8.

9.1. Establishment of welding control system

A sensor based control system for laser welding was established and implemented as described in the chapters 4 through 6. This control system is based on inverse process models which includes a number of welding procedure specifications with common constraints but for different discrete sizes of gap. The inverse process models are described in detail in chapter 4.

In chapter 4 the welding control system is additionally described with respect to the applied control methods in terms of control theory.

The welding control system is based on feed forward and gain scheduling algorithms such as described in chapter 4. The inverse process model (IPM) is considered a gain schedule because the gains are implicitly specified in the IPM and since these are pre-planned for different intervals of gap sizes of the weld joints.

The parameters and variables used in the welding control system are categorised into the categories: equipment parameters, workpiece parameters, control parameters, control variables, and quality parameters (see chapter 4, sections 4.1.1 through 4.1.6). This categorisation helps providing a generic understanding of the input, output and constraints of the welding control system, such as described in chapter 4.

The Yourdon modelling technique is applied for description of the functional architecture of the welding control system. This method facilitates the definition of data transformations in real-time systems because it distinguishes between data transformations and control transformations, such as described in appendix A. The control transformations are subdivided into state transition diagrams, which facilitates specification of event-based real-time operations.

The functional architecture of the welding control system is described in chapter 5. In this section the structure of the implemented system is described thoroughly, including the data structures used for this system.

The system is described by data transformations and control transformations on different levels. In this way all transformations of data are described thoroughly for the system. The event based operations of the system are described in terms of control transformations and state transition diagrams.

Communication interfaces between the welding control system and external equipment are described by the data structures and events of these interfaces. Descriptions are made in Chapter 5 and in Appendix B.

The welding control system is considered a general process control system for the range of welding processes. However, if the laser welding process is substituted with another type of welding process, the structure of process model parameters and welding control vectors (see appendix B) must be changed. Additionally the transformation 0.5.4 ‘Execute Welding Control Vectors’ (see chapter 5, section 5.1.6) must be changed in order to translate the new structure of welding control vectors to equipment control vectors (see chapter 5, section 5.1.6 and appendix B).

The fully automatic welding control system calculates well-defined control variables for the welding process. Also the quality parameters (see chapter 4, section 4.2.1) obtained by the welding control system have to be well defined in order to evaluate the possibilities for using the individual inverse process models for specific weld tasks. The welding control system is additionally constrained by a set of control parameters, which has to be kept in order to provide the expected quality of laser welded joints.

In order to quantify quality parameters and control variables two generic joint types were established during the work. This is the types of flange joints and flank joints, which are described in chapter 6, section 6.2. These joint types are stated to include the most usual weld joints in heavy industry. By establishing these relatively generic joint types it is possible to quantify workpiece parameters, quality parameters and control variables for these specific joint types.

The welding control system is implemented in the demonstration cell at Odense Steel Shipyard. The system is implemented in the robot controller of this cell. This robot controller has an open event based interface, which allows developers to implement software routines in the robot controller and to read data from and write data to the robot controller at several states in the controller software.

9.2. Evaluation of Portability

The portability of the welding control system was investigated with focus on the general ability to apply the system for laser welding components in heavy industry. In order to evaluate the portability of the welding control system the robustness of quality parameters were evaluated in relation to typical operating conditions in heavy industry. The quality parameters were subdivided into metallurgical, mechanical and geometric quality parameters.

The metallurgical quality parameters were assumed to be influenced primarily by the metallurgical structure of the base material and filler material. Additionally the cooling rate from 800 to 500° was assumed to be significant for the metallurgical composition of laser welded joints. By applying constraints for the composition of base material and filler material and for the welding speed it was assumed that desired metallurgical quality parameters could be kept. Anyway the classification societies did not set any explicit criterias for metallurgical quality parameters for laser welded joints. Therefore these parameters are not considered in the present thesis.

The classification societies has set explicit criterias for the mechanical quality parameters maximum hardness, minimum ductility and impact resistance. These criterias were met for the normal conditions, i.e. when no gap was present and the laser welding process were carried out in accordance with the inverse process model and the constraints of this. They were also met when a joint was welded, in which the size of gap was 0.5 mm. It was assumed that the mechanical quality parameters were directly related to metallurgical and geometric quality parameters. Therefore the mechanical parameters were not treated further in the presented research.

The classification societies has set explicit criterias for the geometric quality parameters, fusion of the welded joints. Potential notch formations in the welded joints has to be approved by the classification societies.

For a laser welded joint no lack of fusion must be present in the weld joint. The fusion is directly dependent on the binding depth specified in chapter 6, section 6.2.2. No explicit maximum size of notch is specified, but the welded joints has to be approved by visual inspection. In this inspection notch formation is considered a critical geometric quality parameter.

For investigation of portability the robustness of the three geometrical quality parameters binding depth, penetration depth and notch size were investigated in relation to the operating conditions in an industrial environment.

repeatability

The repeatability of geometric quality parameters were investigated for normal conditions, i.e. for the conditions in which no gap was present in the weld joint and in which the welding process were carried out in accordance with the inverse process model and the constraints of this.

It was revealed that the tolerance of the measured gap in the weld joint was approximately 0.15 mm even though the edge face of workpiece 1 was milled (see chapter 7, section 7.3). It was additionally observed for that the tolerance of binding depth for flange joints was 1.3 mm and the corresponding tolerance of penetration depth was 1.2 mm. This is considered quite large tolerances in comparison with the average values for binding depth and penetration depths, which were 4.9 and 7.5 mm, respectively.

The conclusion on this is that in order to control the penetration depth robustly it is necessary to take these tolerances into account during establishment of the inverse process model. Either a number of experiments must be carried out in order to ensure that no binding depths are below the minimum limit, or the binding depth for one experiment must be so large that deviations of 1.2 mm can be accepted.

Even though no gap was present in the experimental series for normal conditions it was not possible to establish welding procedures at the demonstration cell, for which no notch formation occurred. Corresponding procedures established at the Force Institute showed no tendency to notch formation when the gap was 0.0 mm. Indications showed in chapter 7 that the width of the weld metal (caused by the size of the keyhole) had a significant influence on notch formation.

Robustness to gap

The quality parameters were measured for a weld joint in which a gap of 0.5 mm was present. It was characteristic for this experiment that both the binding depth, the penetration depth and the notch size were significantly larger in this experiment than in the experiments for normal conditions. The main reason why the binding depth and the penetration depth were larger than for normal conditions must be found in the parameters of the inverse process model. It should be possible to establish an inverse process model that keeps at least one of these parameters constant even though gap is varied.

The effort for establishing the inverse process model was primarily focused into the attempt for minimising the notch size, since this was a major problem at this particular laser welding facility. The parameters of the inverse process model reflects this effort strongly. Even though quite an effort was made for minimising the notch size it was increased significantly compared to the experiments for normal conditions.

When comparing the experiment made at a weld joint with a gap of 0.5 mm to corresponding experiments performed at the Force Institute the same trend was seen as for the normal conditions. The notch size from the demonstration cell was significantly larger than the notch sizes from the Force Institutes. Also the weld metal was significantly wider at the welded joint from the demonstration cell than at the welded joints from the Force Institutes. This supports the theory of proportionality between the width of weld metal (and keyhole) and the tendency to notch formation.

At the Force Institutes it was possible to establish welding procedures for laser welding of joints in which a gap of 1.0 mm was present. At these joints a tendency to notch formation was observed. However the width of weld metal in these joints were significantly larger than the width of weld metal in joints where gaps of 0.0 and 0.5 mm was present.

At the demonstration cell it was not possible to establish procedures for laser welding of joints in which a gap size larger than 0.5 mm was present. The reason was that the notch size increased significantly for these sizes of gap.

It can be concluded from the above mentioned experiences that when implementing a laser welding control system for heavy industries it is of the greatest importance that the laser welding equipment to be controlled is thoroughly tested before implementation of the control system. It must be ensured the required quality parameters can be met when using the specific laser welding equipment for weld joints including the expected sizes of gap.

Robustness to curvature of corners

When purchasing steel plates from the steel mill it can be observed that what is usually considered sharp corners actually has a curvature. The radius of this curvature varies stochastically between 0.0 and 1.0 mm. The robustness of geometric quality parameters in relation to a radius of curvature that varied from 1.0 to 2.5 mm was investigated.

The conclusion to this was that if the size of the gap in the joint could be measured correctly in spite of the curvature of corners the binding depth and penetration depth were relatively unaffected of the curved corners. As long as the radius of curvature did not exceed 1.0 mm the size of notch was unaffected. However when the radius of curvature exceeded 1.0 mm the notch size increased.

The measured size of gap will usually be disturbed by the curvature of corners because it is very difficult for the profile sensor to estimate what is missing material caused by this curvature, and what is missing material caused by an actual gap in the joint. It was observed that for radius of 1.0 mm the profile sensor measured a gap of 0.32 mm, even though the actual size of gap was 0.0 mm. For radius of 2.5 mm profile sensor measured a gap of 0.61 even though the actual gap was 0.0 mm.

When the measured gap increased because of the mentioned curvature, the control variables were affected by this variation. In the presented work the penetration depth was unaffected of curved corners but the binding depth changed proportionally to the variation of corner radius. This tendency was seen because the inner end of the weld metal was lifted in such a way that a larger part of the weld metal actually covered the area between the workpieces. If the inverse process model had been more thoroughly optimised this lift of weld metal could have caused lack of fusion in an area between the weld metal and workpiece 2.

Because of the changed control variables the notch size was increased when the radius of curvature exceeded 1.0 mm. However, the notch sizes for these experiments were less significant than notch sizes for experiments in which the measured gap had a similar size but was caused by an actual gap in the weld joint. Since the notch formation is obviously dependent on the equipment parameters it can be concluded that the notch size caused by curved corners are proportional to the notch size caused by presence of an actual gap in the weld joint for a specific laser welding equipment.

Robustness to primer near the weld joint.

It was already before initiation of this Ph.D. work known that no primer must be present between the workpieces in the joint, since this was devastating for the weld quality. Through this project it was additionally observed that the method for removal of primer between the workpieces is important for the weld quality. When removing primer with a spinning wire brush part of the primer is pressed into the surface of the base material and may cause crack formation, which is devastating for weld quality. This was observed even though no primer could be seen by human eye.

It was additionally indicated that primer at these surfaces near the weld joint which are not between the workpieces may cause a devastating crack formation in the welded joints. This was especially seen when the thickness of primer was increased from 30 to 50 microns. Therefore it is of the greatest importance that the area of the workpiece surfaces that will be included in the weld joints is thoroughly cleaned before welding. Another possibility may be to investigate the maximum thickness of primer in order to avoid crack formation. This maximum thickness must then be obeyed for all parts to be laser welded.

Robustness to variation of control parameters

As described in chapter 4 the inverse process model is constrained by a set of control parameters. In case these control parameters are changed the quality parameters may be affected. The robustness of quality parameters was investigated in relation to variations of the plasma control gas flow rate and the beam power.

The conclusion of this investigation was that variations of the plasma control gas flow rate did not affect the binding depth. The penetration depth was however influenced slightly by these variations. The binding depth was increased as function of increased plasma control gas flow rate. It was observed that the notch size was not affected, but the geometry of the joint surface was significantly affected by the variations of plasma gas flow (see figure 7.36).

The changes of the joint geometry and of the penetration depth indicates that it is important to control the plasma gas flow. However, the rates of plasma control gas flow was varied from 0 to 29 l/min, which indicates that the tolerances of this control parameter are relatively large.

The robustness of geometric quality parameters in relation to variations of the laser power was investigated and showed that the binding depth varied as function of laser power. The penetration depth and the notch size were only slightly affected by the applied power variations. The applied laser power for these experiments varied from 6.1 to 7.9 kW and the variations of binding depth were no more than approximately 1 mm for this interval.

The conclusion for robustness of geometric quality parameters in relation to disturbances of the laser power is that small variations of laser power within 2-3 tenths of a kilo watt will not influence the quality parameters significantly. However, larger deviations in laser power may cause lack of fusion in the welded joints. Such variations may occur in case of missing supply of laser gas to the laser cavity.

Robustness to variation of control variables

The inverse process model specifies a set of control variables and control gains for execution of the welding process for a given size of gap within the range of the inverse process model. Accurate execution of these control variables is of course of greatest importance for the validity of the inverse process model and thereby for the fulfilment of the specified quality parameters. The control variables of the inverse process model are welding speed, wire feed rate and displacement of the laser beam. The robustness of quality parameters in relation to disturbances of these control variables were investigated.

Based on this investigation it is concluded that the welding speed has a significant influence on both binding depth and penetration depth. When lowering the welding speed to 50% of the normal speed an unstable size of notch was observed. The conclusion of this is that the welding speed must be controlled thoroughly for fully automatic laser welding. It must be made sure that the programmed speed cannot be overruled by an override possibility when welding according to the inverse process model.

The robustness of geometric quality parameters in relation to deviations of the wire feed rate was investigated for a gap size of 0.0 mm. It can be concluded that variations of the wire feed rate at this size of gap did not have any significant influence on the measured quality parameters. However, this investigation ought additionally to be performed for weld joints in which the maximum size of gap was present as well. In this type of weld joints the influence of filler wire would be more critical. Therefore no conclusion is drawn for this particular control variable.

Displacement of the laser beam may vary in case the calibration of equipment is not sufficiently accurate. The influence of this displacement on geometric quality parameters was investigated in the project. It was concluded that especially the binding depth was influenced by this control variable. Since the binding depth varied approximately 2 mm when the displacement was only varied 0.8 mm, it is obvious that the calibration of the welding equipment with respect to the position of the laser beam focus point must be very accurate. It is additionally important to monitor frequently that this calibration is kept.

9.3. Additional control strategy

During the implementation and testing of the welding control system for the class of flange joints (see chapter 6, section 6.2) it was realised that establishment of artificially constructed gaps was very difficult, especially when tolerances of one tenth of a millimetre should be kept. The distance between spacer blocks applied for obtaining the specified gap for procedure tests should be small in order to avoid changes of the gap size caused by contraction of the solidifying weld metal.

A control strategy for laser welding of flange joints is suggested (see chapter 8), in which the contraction of the weld joint is utilised for automatic closing of the gap between workpieces by use of this contraction effect. The gap is practically closed by using this approach, which means that laser welding of the entire weld joint can be carried out using a set of fixed control variables. Only seam tracking is then necessary in order to compensate for variations in the position of the weld joint.

This strategy was tested at the demonstration cell by a single experiment. The results of this experiment showed that a gap size of at least 3.5 mm could be contracted to approximately 0.0 mm by the solidification process. The tolerances for gap in weld joints are in other words extended considerably. The control variables used for welding a workpiece in which the gap varied from 0.0 to 3.5 mm were the same as used for normal conditions. This means that the speed of the laser welding process was as high as the maximum speed applied in the control system presented earlier. Also the heat input was as low as the minimum heat input used for this system and the use of filler materials corresponded to the minimum value.

When utilising this methodology it will not be necessary to establish inverse process models for more than one gap size. This gap size is approximately 0.0 mm, which means that problems with critical notch formation are reduced significantly. However, it is of greatest importance that the gap can be contracted by the solidifying weld material. In case e.g. a tack weld is present in a position in which the gap size is larger than 0.0 mm, the contraction is disabled and the control strategy will fail.

The described strategy is only tested for the class of flange joints and only in one set of workpiece parameters. The strategy should be tested thoroughly with regard to different thicknesses of material and also for the class of flank joints in order to finally evaluate the potentials for applying this strategy for heavy industry.

9.4. Contribution and Perspectivation

The contribution of the presented research included the establishment and classification of a fully automatic welding control system, that was implemented in a demonstration cell at Odense Steel Shipyard for laser welding of flange joints.

The classes of flange joints and flank joints were specified in order to establish a generic method for quantification of workpiece parameters, control variables and quality parameters.

The portability was investigated for the welding control system by evaluation of the robustness of geometric quality parameters in relation to typical deviations from the normal conditions when applying the control system for laser welding in an industrial production environment.

The results of experiments performed using the implemented control system in the demonstration cell at Odense Steel Shipyard were compared to the results of experiments carried out at the Force Institute. It was observed that especially the tendency to notch formation was significantly more evident for the experiments carried out at Odense Steel Shipyard than for the experiments carried out at the Force Institute. This difference is assumed to be cased by different equipment parameters of the two facilities.

The author of the present thesis is not aware of any investigations, which unambiguously define a relation between equipment parameters and the resulting geometry of welded joints. Therefore the following advice is given to future users of laser welding equipment in heavy industry: The laser welding equipment must be tested in order to prove the ability to perform laser welding of joints in which the requested gap is present, with acceptable quality parameters. This test has to be approved before the implementation of the specified control system makes any sense.

It was found that standard profiles from the steel supplier included a stochastic curvature of the corners. This curvature contributes to inaccuracies of the measured gap, since the profile sensor is not able to compensate for this curvature as long as it is stochastic. These inaccuracies causes the welding control system to apply control variables that correspond to welding a larger gap than is actually present in the joint. Therefore the welding speed is decreased which reduces the efficiency of the laser welding installation. Additionally there is a risk of critical notch formation caused by the decreased welding speed.

It was found that primer in the area between workpieces was devastating for the weld quality because it contributed to critical cracks in the welded joints, even though the primer was not visible. Therefore primer removal must be performed with tools that with 100% certainty remove all of the primer between the workpieces before they are put together.

It was found that primer in the area close to the intersection of the workpieces could cause heat cracks if the layer is too thick. Before implementing laser welding of flange joints in heavy industry methods should be developed to remove primer from these areas. At least the thickness of primer should be controlled in such a way that it does not exceed a specified maximum level, which then has to be approved for laser welding.

It was found that a very accurate calibration of the laser position of the laser beam focus point is very important. Robust calibration routines must ensure that the laser beam focus point can be positioned very precisely.

In order to provide robust geometric quality parameters, the tolerance of the binding depth and penetration depth must be taken into account. This can be done during establishment of the inverse process model. The model can provide binding and penetration depth measured in one section that allows deviations of approximately 1.3 mm. Otherwise a number of sections must be measured in order to make sure that none of the binding depths or penetration depths are below the minimum values.

The mentioned strategy for utilising the contraction of solidifying weld material was found during the project. This strategy is considered extremely potential for laser welding in heavy industry. It enables at the same time an extension for tolerances of laser welding and an increased efficiency of the laser welding equipment due to the fixed high welding speed. Additionally it reduces the heat-input to the joints. However this strategy has to be further investigated. It is therefore recommended that a serious effort is put into investigation of this particular welding control strategy.

The welding control system was implemented for welding of the class of flange joints. Additionally the methods for laser welding of flank joints are developed but still not implemented. This work is considered limited in the scope of the generic functional architecture of the implemented system

references

[8] Nielsen Steen E., Seam Tracking and Adaptive Control Based on Vision Technology Used for High Power Laser Welding, Proceedings of 5th Nordic Laser Materials Processing Conference, September 6- 8, Oslo, Norway.