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Hardening in laser forming under the temperature gradient mechanism

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Abstract. Laser forming is a contactless thermal forming process that can be applied for both single and double-curved geometries. When it comes to prototyping and small batch production, laser forming has the potential to compete with conventional sheet-metal forming processes; however, an investigation of the relationship between process parameters, hardness distribution and the bend rate is lacking. This study examines the influence of using different sets of processing parameters on the bend rate and the hardness distribution. ANSI 304 stainless steel samples of 1 and 3 mm thickness are laser formed up to 90° with a bend radius equal to their thickness. A theoretical discussion of the material's hardening kinetics is used to generalize the results. Micro-Vickers hardness test is used to measure the hardness distribution along the 3 mm samples to support the theoretical discussion. The results show that the bend rate increases when using different sets of process parameters; furthermore, the bend arc length has shown to have a significant influence over the bend rate. An increase of hardness is observed on the bottom side of the laser formed samples, indicating potential strain hardening.

1. Introduction

Laser forming is a contactless incremental thermo-mechanical forming process that uses a defocused laser beam to induce thermal stresses and strain into a workpiece. The process is highly flexible and can be used both for single and double-curved geometries. There are three main mechanisms in play during laser forming: temperature gradient mechanism (TGM), upsetting mechanism (UM) and buckling mechanism (BM) [1]. TGM is characterized with a steep thermal gradient along the material's thickness resulting in the material bending towards the laser beam [2,3]. The bend is a result of the initial material expansion during heating and the subsequent cooling of the surface layer which causes thermal contraction. TGM is one of the most reported mechanisms in laser forming, with an achievable bend angle up to 3° in a single pass [4,5]. BM is active when a negligibly small temperature gradient is developed through the material's thickness and the diameter of the beam is significantly larger than the material's thickness, resulting in a bend that can be either towards or away from the laser beam [4,6]. UM examines the same negligible thermal gradient as BM but with a laser diameter smaller than the material's thickness which results in material in-plane shortening [4]. In practice, laser forming is a complex interaction between the various mechanisms.

As stated, laser forming is an incremental process, meaning that if a bend larger than 3° is to be achieved using TGM, more than one laser passes will have to be utilized, this is called multi-pass laser forming. However, the issue with multi-pass laser forming is the bend rate decay, that is, with each laser pass the rate at which the bend develops decreases [3,7]. There are two major review studies on laser forming done in the recent years [4,8], and both reviews show an abundance of parameter studies, microstructural and control studies.

Shen et al. [9] performed a numerical study of two-scan laser forming with varying time intervals between laser passes along the same forming path; the lower the time interval between the passes the higher the peak temperature leading to a steeper thermal gradient which in terms results in a higher deformation. That said, the buildup of the peak temperature with every subsequent laser pass in multi-pass laser forming which may result in burning or melting the sample, needs to be taken into consideration. Lambiase et al. [10] examined both the productivity and necessity of multi-pass laser forming. The authors observe that even under same processing conditions, samples that are laser formed normal to the rolling direction tend to bend more. Moreover, Lambiase et al. [10] note that for passive air cooling the velocity of the laser is highly influential for the cooling time, with higher velocity resulting in highly reduced cooling time. The studies show both an influence of the process parameters over each other and over the bending rate.

An increase of hardness in the heat affected zone (HAZ) with each subsequent laser pass, either attributed due to strain hardening or phase transformation, has been observed in a multitude of studies [4,8] and cited as an influencing factor for the bend rate decay [3]. Edwardson et al. [3] made an overview of the factors influencing the bend rate in multi-pass laser forming using TGM. The investigated factors were strain hardening, section thickening, thermal effects, variation in absorption and geometrical effects. The authors observed that an increase of laser passes will result in an increase of micro-hardness in the HAZ; furthermore, with the increase of laser passes, the peak hardness will shift deeper into the materials' thickness. The geometrical factor, proposed by Edwardson et al. [7] and examined again by Edwardson et al. [3], refers to the geometrical distortion of the laser beam incident due to bend angle increase. Furthermore, at higher number of passes and higher bend angles, both strain hardening and the geometrical factor are dominant influencers for the bend rate decay [3]. Yang et al. [11] investigate the relation between the surface behaviors of the HAZ and the process parameters of pulse laser forming. The results show that both the depth of the HAZ together with the micro-hardness relationship between the HAZ and the hardening depth is dependent on process parameters. Moreover, the study shows that the micro-hardness decreases when moving away from the laser beam center, giving it a Gaussian distribution. However, a holistic investigation of the relationship between process parameters, hardness distribution and the bend rate seem to be missing.

Studies thus far have examined either the individual influence of parameters over the bending rate and hardness or finding optimal parameters for specific materials and sample thickness. This study attempts to investigate the correlation between the process settings and the hardening of the material and its influence on the bend behavior and bend rate decay. A theoretical analysis of the hardening kinetics under TGM, which is used to devise three hypotheses for the bend behavior will be presented in this study. Samples of 1 mm and 3 mm thick AISI 304 steel are bent up to 90° using different sets of parameters, hardness tests are made before switching parameters for the 3 mm samples.

2. Theoretical analysis

Laser forming is a highly dynamic process where thermal, mechanical and spatial aspects are closely coupled to create unique thermal and mechanical profiles all along the laser scan path [12]. The theory presented here is meant to give an overview of the possible paths of the transverse stress, perpendicular to the scanning direction, in relation to temperature and to demonstrate the complexity of the problem. The goal of the model is to make qualitative predictions on correlations. The theory has the following constraints:

1. Only considers TGM.
2. Neglect the influence of longitudinal, normal and shear stresses. This is purely for simplification as they are all bound to occur due to the non-uniformity of the transverse stresses and will change the deformation and hardening kinetics.

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3. Neglect the influence of position along the laser scan path and other geometric factors such as width and length of the part. The results of Thomsen et al. [12] showed that laser forming under TGM is suspect to differences in deformation and temperature profiles along the laser scan path.
4. Considers only the transverse stress and temperature through the thickness.

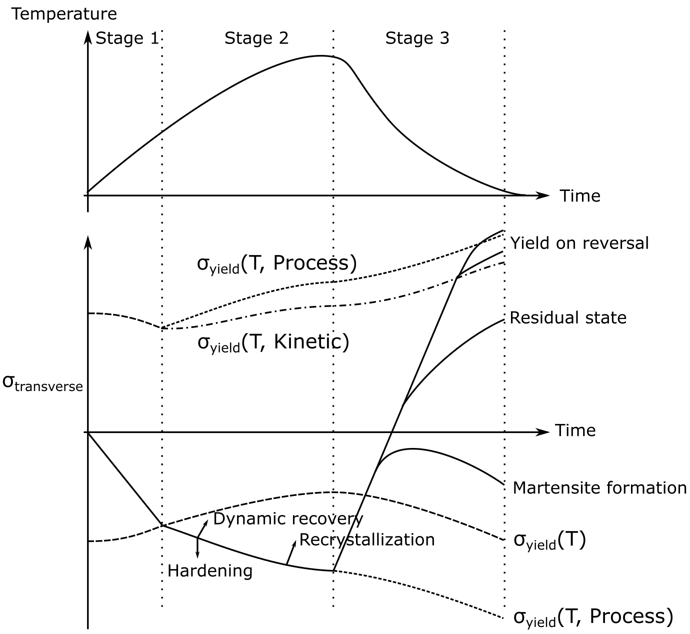

Figure 1. The temperature and transverse stress over time at a single material point. Note that a part can be in all three stages at different positions through the thickness at the same time.

The laser heats the material and as it is turned off, the material cools down, before the process repeats itself. This behavior is similar in shape albeit not in size throughout the thickness of the material. The peak temperature will be reached at different times through the thickness [13]. Figure 1 also shows the possibilities of the transverse stress over time and can be divided into several stages. Note that a part can be in all three stages at different positions during laser forming. Figure 2 shows how varying the speed will change the temperature profiles and their influence through the thickness.

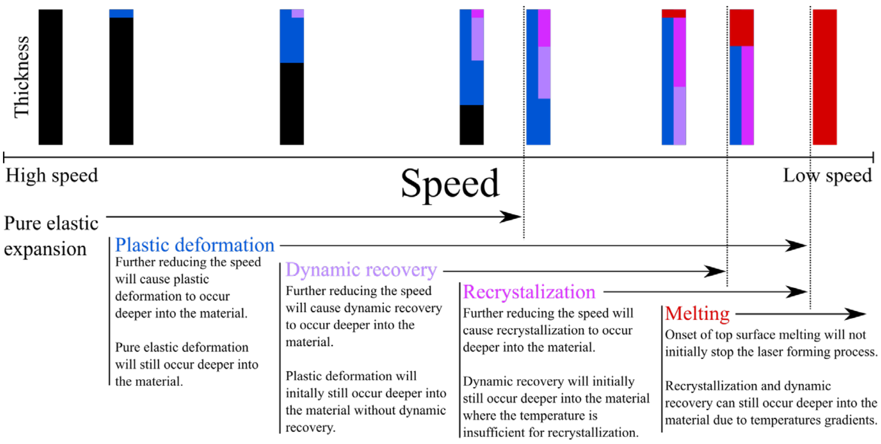

Figure 2. A one-dimensional model of the influence of the speed. Note that the position and occurrence of overlap between different factors is dependent on other process settings and the total thickness of the part. Similar models can be made for other process parameters as well.

Stage 1

The increasing temperature drives the increase in tensile thermal strains. As the thermal expansion is resisted by the surrounding material, the material experiences an elastic compressive response causing compressive elastic stresses and strains. No yielding occurs during stage 1.

Stage 2

As the thermal strains increases, the compressive transverse stresses increase to beyond the thermally reduced yield stress, resulting in plastic compressive stresses and strains. During this stage, depending on the temperature two mechanisms influence the hardening:

1. Increasing thermal strains cause increasing compressive stresses which leads to further work hardening of the material.
2. Increasing temperature leads to dynamic recovery and possible recrystallization, thus reducing hardening.

Stage 3

As the temperature starts to decrease, the thermal strains start to decrease as well. This leads to contraction, which in turn changes direction of the stresses to tensile. As the material contracts, the tensile stresses may increase to surpass the tensile yield strength. If one considers the kinetic hardening, the tensile yield strength may have been reduced by the compressive yield flow only moments before.

Another consideration is that the rate of cooling can lead to martensite formation. As martensite has a larger volume, the residual stresses can even remain compressive.

Hypotheses

The model in Figure 1 leads to several interesting hypotheses:

Firstly, traditional bending theory with an anti-symmetrical distribution of tensile and compressive strains around a neutral axis positioned halfway through the thickness cannot be applied. The position of the neutral axis is dependent on the depth of the heat affected zone i.e., what portion of the material is under stage 1-3. Furthermore, most of the plasticity occurs at elevated temperatures at the surface. This means that anti-symmetry cannot be expected. From a macroscopic point of view, limited stretching of the bottom surface may occur during TGM as part of the equilibrium during the cooling of the upper surface. An interesting consequence of this is that laser forming is primarily driven by thickening of the part even under TGM. The first hypothesis can be stated as:

1. *There is a significant top surface thickening in laser forming, especially when using smaller bend radii.*

Secondly, the most significant hardening will not necessarily occur at the surface despite this being the position of the most plastic deformation, because increasing temperatures can lead to dynamic recovery and recrystallization during stage 2. This in turn creates a question of where the limiting hardness does occur. As the temperature and especially the temperature profile, meaning gradients, can be modified through the process settings. It becomes apparent that the hardness distribution can be altered through the process settings. This leads to the second hypothesis:

2. *The through-thickness hardness distribution can be influenced by process parameters.*

Hardening of the material is known for influencing the bend rate decay [3]. Considering that the most plastic deformation occurs at the top surface, this would, without dynamic recovery, increase the top surface hardness; thereby, causing the bend rate decay. However, with dynamic recovery, the increase in hardness occurs at a shifted position through the thickness. As the plastic deformation is smaller at the shifted position; therefore, the effect on the bend rate decay is reduced. This leads to the third hypothesis:

3. *Shifting the hardness distribution affects the laser forming bend behavior.*

3. Experimental setup

The experiments were designed and conducted at Aalborg University's laser cell, the setup can be seen in Figure 3. The material used was AISI 304/ EN 1.4301 with thickness of 1 and 3 mm. All samples were 100 mm in length and 50 mm in width with clamping length of 20 mm and free length of 80 mm, as depicted in Figure 3**.**

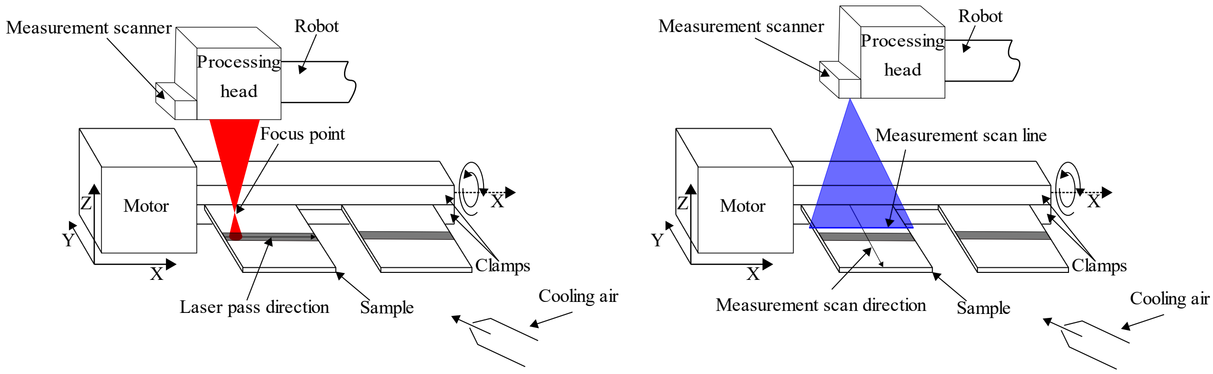

Figure 3. Experimental setup of the laser forming process. There are two moving parts in the setup, a Beckhoff AM8112 motor, and a KUKA KR 120. The motor provides rotation along the *X* axis with the intent of tilting the samples. The HighYang (modified) processing head is mounted on the robot which controls the motion of the laser beam. A Wenglor MLWL153 measurement scanner is mounted on the side of the processing head. The samples are air cooled from the bottom. The laser used is IPG YLS-3000 SM.

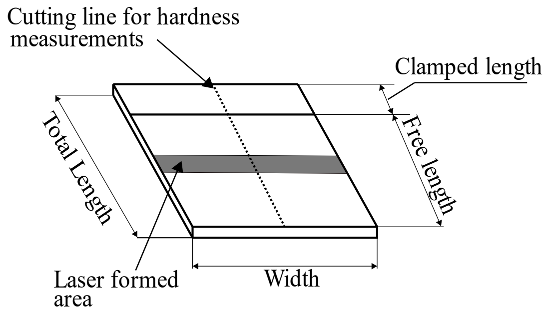

Figure 4. Dimensions for the samples. Total length is 100 mm, width is 50 mm. Clamped length is 20 mm and the free length is 80 mm. Sample's thickness is 1 and 5 mm.

All samples were laser formed, with the direction of the laser beam perpendicular to the sheet's rolling direction. Beam diameter is equal to the sample's thickness. For each thickness, several parameter sets were generated, the parameter sets can be seen in Table 1. Each parameter set consists of 30 laser passes and is repeated five times, after each iteration of the parameter set a measurement scan of the surface is performed to note down the bend angle. To reduce the influence of the geometrical distortion of the laser beam incident due to the developing bend angle, the samples are pre-tilted at 7.5°. For every 30° of bending, the sample will be tilted with an additional 15°; hence, from 0 to 30° bend angle the sample is tilted at 7.5°, from 30 to 60° the sample will be tilted to 22.5° and from 60 to 90° the sample will be at 37.5°.

After laser forming, three samples with 3 mm thickness will be cut midsection along the length, as seen in Figure 4, and prepared for micro-hardness testing. Three hardness measurements per sample were performed using Struers Duramin-40 and HV0.1 values were obtained with dwell time of 15 s and a load force of 0.9806 N. For reference measurements, the midsection of a non-laser formed sample was used. The midsection thickening of each sample was measured using a Wild Heerbrugg stereo microscope together with a AxioCam ICc 5 camera.

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Table 1. Process parameter sets. The naming convention is [sample thickness]-[parameter set number], 1-1 will be parameter set 1 for thickness of 1 mm.

Parameter set	Laser diameter [mm]	Power [W]	Scan speed [mm/min]	Number of passes per iteration	Dwell time between passes [s]
1-1	1	120	3461	30	30
1-2	1	90	1442	30	30
3-1	3	270	1154	30	60
3-2	3	180	320	30	60
3-3	3	180	240	30	60

4. Results and Discussion

In this section the results from the experimental part of the study will be presented and discussed. The bending rate for 1 and 3 mm samples can be seen in Figure 5. The results show that even though there is an increase in the overall bend, the more a parameter set is used, the lower the bend rate becomes. From Figure 5 it can also be seen that every time the parameter set is changed there is an initial increase in the bending rate. To investigate the change in the bending rate, the hardness distribution of the samples is investigated.

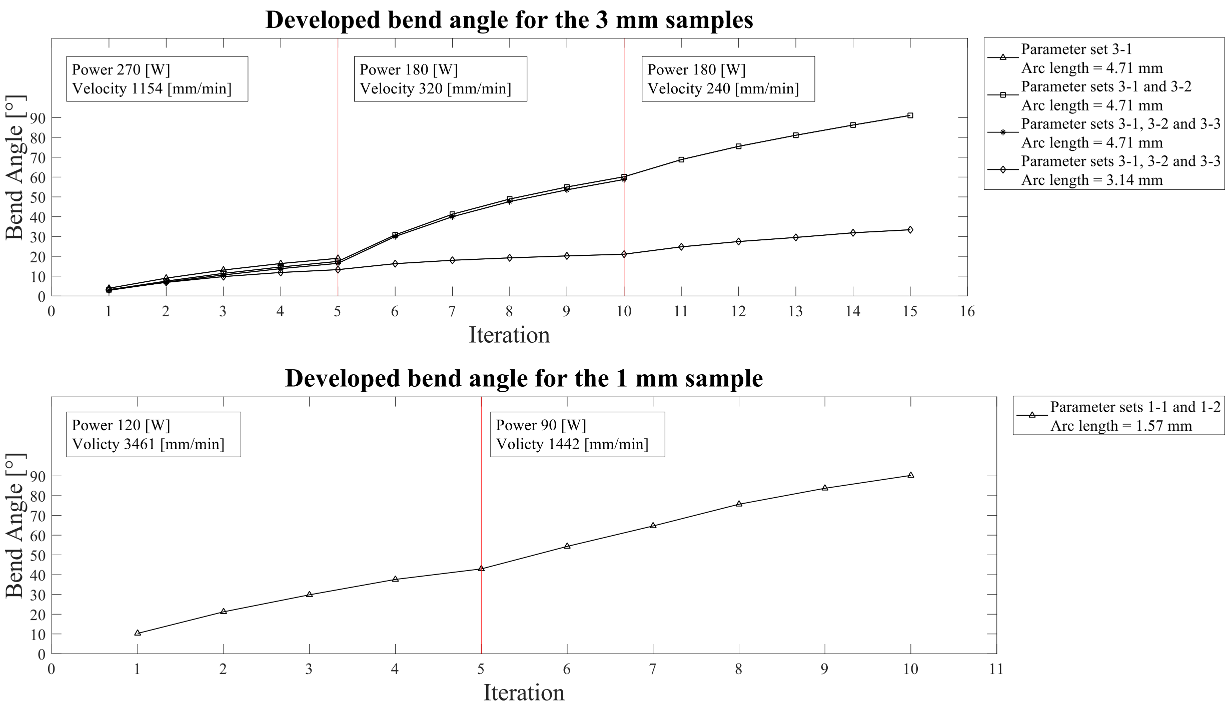

Figure 5. Developed bend for the 1 and 3 mm plates. The red vertical lines are separators for the parameter sets.

Furthermore, it is observed that the arch length has a significant influence over the bend rate and the maximum obtainable bend. When examining Figure 5, there are two samples that are being laser formed with parameter sets 3-1, 3-2 and 3-3; however, they exhibit vastly different final bend angles. The first sample has a final bend angle of 91.1°and the second has 33.4°. The difference between the two samples is the dwell time, 60 seconds and 30 seconds and the arch length, 4.71 and 3.14 mm, respectively. Of the two differences, only the decrease of 1.57 mm in arch length is deemed influential for the bend reduction. The only potential influences the lower dwell time might have is increased peak temperature with each subsequent laser pass. The increase of peak temperature will result in an increased bend rate or potentially burning the material, neither of which was observed for the sample with the 33.4° bend.

Figures 6 and 7 show the hardness distribution of both the reference and laser formed samples. There is good correlation between the hardness results and the theoretical section of the study, as the most significant hardening does not occur at the top surface, close to the laser incident despite the region having the most plastic deformation. Figures 6 and 7 show that the hardness distribution shifts deeper into the material, when changing process settings. This can explain the increased bend rate, the change of settings will result in modifying the temperature profile through the thickness, as it can be seen in Figure 8. The increased temperature in the upper midsection of the sample will lead into expanding the HAZ deeper into the sample's thickness which causes an increased bend rate.

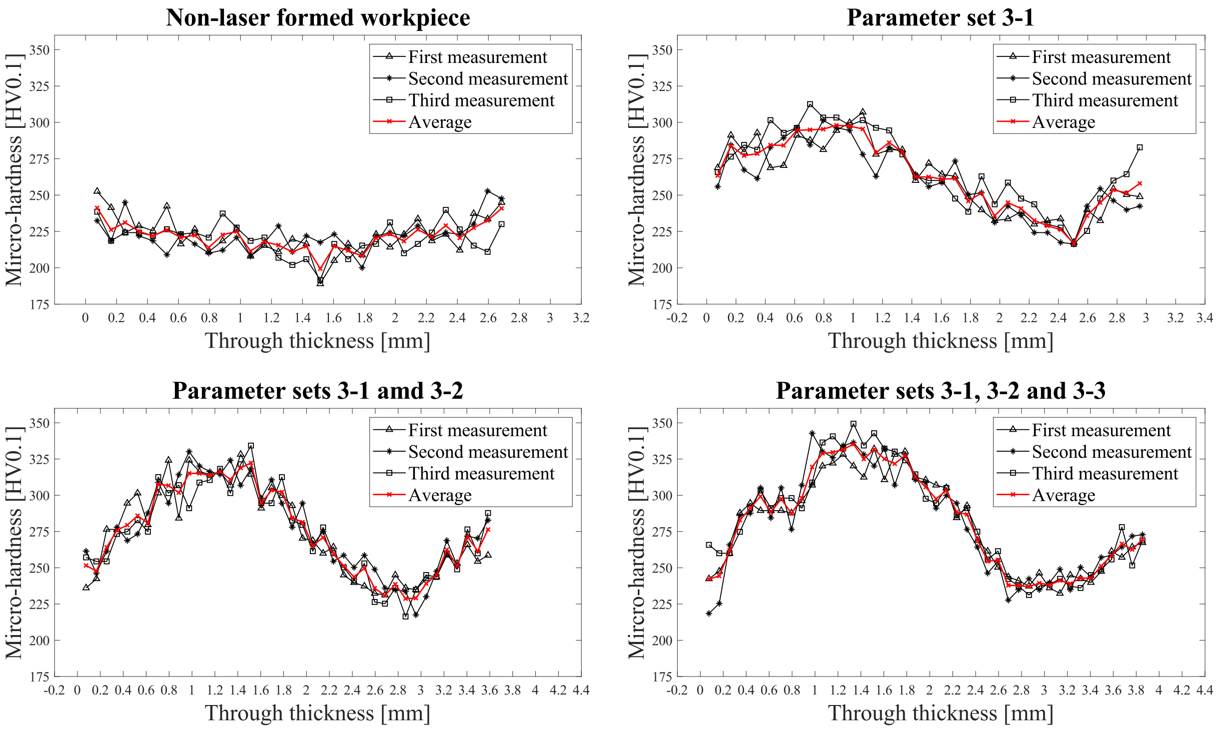

Figure 6. Micro-hardness measurements of the 3 mm samples with arch length of 4.71 mm. Parameter set 3-1 power 270 W, scan speed 1154 mm/min. Parameter set 3-2 power 190 W, scan speed 320 mm/min. Parameter set 3-3 power 190 W, scan speed 240 mm/min.

In both Figure 6 and Figure 7, all samples seem to follow the same hardness distribution trend. From the top surface, the hardness increases and peaks away from it, it then drops to levels similar to the reference material before slightly increasing again towards the bottom surface. The drop in hardness can be an indication of a neutral axis, that seems to shift deeper into the material when changing process settings. Thereby, the increase in hardness at the bottom surface would be from strain hardening, induced by the bending moment during laser forming. This bending moment is believed to occur during cooling of the HAZ, when the material contracts and the modulus of elasticity and yield strength of the HAZ begins to increase again. If the flow stresses have surpassed the yield strength of the material, flow may begin to occur on the bottom side. This would mean that the yielding was tensile in nature. None of the samples exhibit any significant oxidation on the bottom surface that might indicate elevated temperatures which could result in hardening due to either phase transformation or grain refinement.

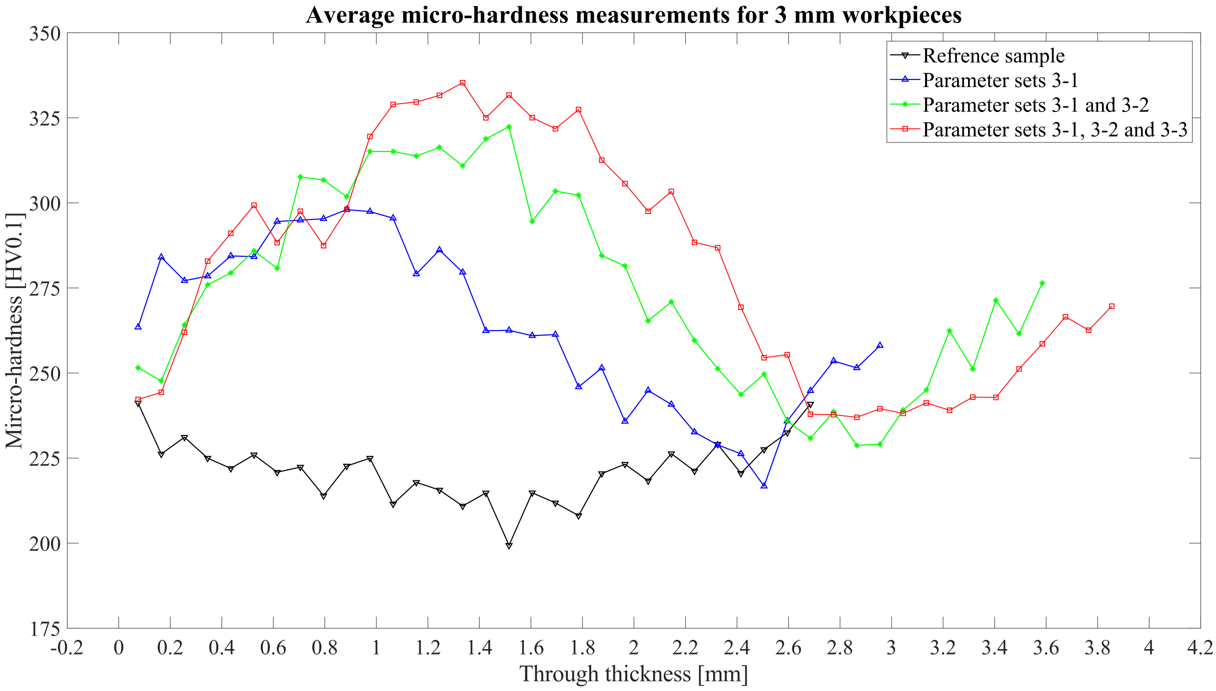

Figure 7. Average micro-hardness measurements for the 3 mm samples. Parameter set 3-1 power 270 W, scan speed 1154 mm/min. Parameter set 3-2 power 190 W, scan speed 320 mm/min. Parameter set 3-3 power 190 W, scan speed 240 mm/min.

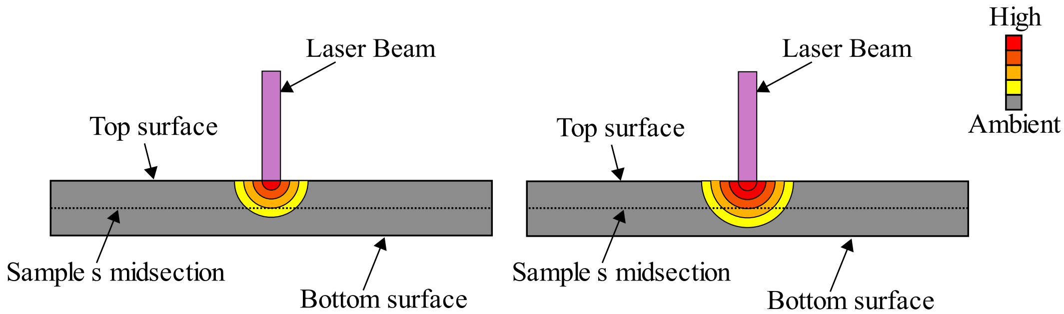

Figure 8. Change of the temperature profile through the sample's thickness when using different process parameter sets. For example, left side can be the temperature gradient using parameter set 3-1 and on the right parameter set 3-2.

Significant section thickening is observed in the laser formed 3 mm samples that were cut for the hardness measurements, with thickness increasing by 34% in the sample formed with parameter sets 3-1, 3-2 and 3-3. The section thickening can be seen in Figure 9 and the measurements can be seen in Table 2. The increased section thickening needs to be taken into account when considering process parameters, as settings for a 3 mm thick section may not work as intended for a 4 mm thick section. Furthermore, this can lead to some unintended consequences when designing part tolerances and may require machining.

Table 2. Section thickening of the HAZ for 3 mm samples.

Bend Angle [°]	Section thickness	Increase compared to nominal thickness [%]
19.00	3.27	9
57.40	3.75	25
91.10	4.04	34

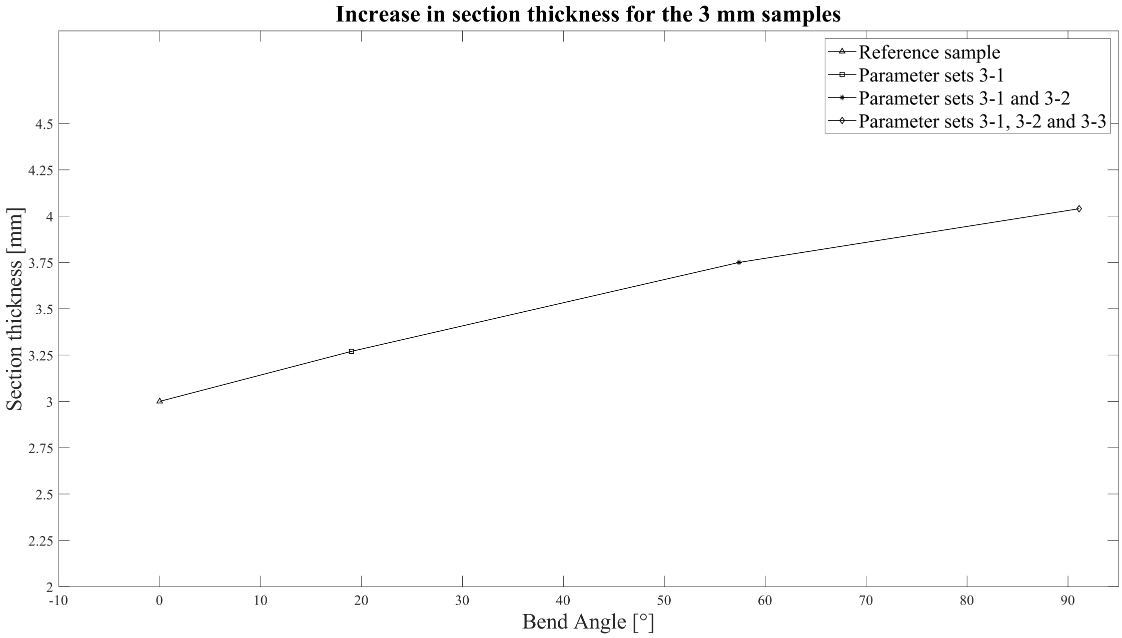

Figure. 9. Cross section thickness for the 3 mm samples laser formed using parameter sets 3-1, 3-2, 3-3. Parameter set 3-1 power 270 W, scan speed 1154 mm/min. Parameter set 3-2 power 190 W, scan speed 320 mm/min. Parameter set 3-3 power 190 W, scan speed 240 mm/min.

5. Conclusion

This study has examined the hardening kinetics of the laser forming process using TGM. ANSI 304 stainless steel samples of 1 and 3 mm thickness have been laser formed, using different sets of parameters, up to 90° and the cross-section hardness distribution of the 3 mm samples has been examined. From the results and discussion section of the study, several things can be concluded:

- The most significant hardening does not occur close to the top surface. The hardening distribution shifts deeper into the material due to the change of the temperature profile in result of changing the process parameter.
- Changing process parameters to gradually increase the amount of energy introduced to the sample will result in increase of the bend rate, which can translate into higher maximum bend angles. The hardness is responsible for the bend rate decay, by altering the hardness distribution, the bend rate decay is influenced. By reducing the bend rate decay, higher bend angles can be achieved.
- There have been a significant section thickening in the 3 mm samples when the bend radius is equal to the thickness. This needs to be taken into consideration when planning process parameters for higher bend angles, e.g., the for the 90° 3 mm sample, the section thickness has increased to 4 mm; hence, using the parameters designed for 3 mm cross section might not work as well for a 4 mm one due to the through thickness temperature gradient not being the same.
- Hardness increase have been observed close to the bottom surface, this can be an indication of strain hardening which can be a result of limited stretching occurring in the region while cooling.
- The hardness drop between the top and bottom surface can be an indication of a neutral axis, similar to the one described in conventional sheet metal forming.
- The arc length of the bend has shown a significant influence over the bend rate. Decreasing the arch length for the same bend angle and processing parameters, will result in increased local hardening, due to heating a smaller area.

This study has taken a more holistic approach to show that there is a correlation between the process settings and the hardening of the material and its influence on the bend behavior and bend rate decay. The study has shown that there is a potential of examining different processing schemes and their time cost effectiveness based on bend development.

For future work, it will be of interest to examine samples with varying arc lengths and its influence over the hardness distribution, section thickening and bending rate. Another topic of interest can be to investigate the bend development rate when using multiple parameter sets, as done in this study, and compare it to the bend rate of a sample that is only formed using the last parameter set. The focus here will be to see if the maximum obtainable bend is influenced by the chosen processing scheme. Lastly, the change in material strength, in the bend, due to section thickening compared to conventional sheet-metal forming could a topic of investigation.

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