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A Laser Forming Study on Time and Energy Efficiency

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Abstract. Laser forming is a relatively slow process utilizing temperature differences in the material to cause plastic deformation. The process requires dwell time between laser passes to cool down the material, which results in a slow production rate. Not fully cooling the workpiece has been shown to give a higher bend rate per unit of time. This, coupled with the cooling rate at higher temperatures being more pronounced permits examining the efficiency of laser forming while working in different temperature ranges. The presented work experimentally explores different temperature ranges for AISI 304 from 20 to 1300°C using a thermal camera. Therefore, for each temperature range, the workpiece is heated and cooled to a achieve a constant peak temperature. The purpose is to compare the bend rate per unit of time with different temperature ranges and to examine overall time efficiency. Finally, since different power levels are utilized for each temperature range, the total energy used to achieve each bend will also be investigated. The results show that the increased formability and rate of cooling at higher temperatures increase efficiency in terms of total time. While efficiency in terms of the equipment is higher when allowing the workpiece to fully cool.

1. Introduction

Laser forming is an iterative, flexible, and contactless forming process, that works by creating plastic deformation from heating and cooling cycles. There are three main thermal mechanisms that govern the laser forming process: the temperature gradient mechanism (TGM), the upsetting mechanism, and the buckling mechanism. The presented work utilizes TGM as its forming mechanism. With each laser pass, the heating causes localized thermal expansion, that lead to thermal stresses. When the thermal stresses surpass the yield stress of the material, further expansion is converted into plastic deformation. Upon cooling, the thermal expansion is replaced by thermal contraction which results in bending towards the laser beam. Each subsequent laser pass under TGM contributes with up to 3° to the overall bend development; therefore, multiple laser passes are necessary to achieve any significant bend angle [1]. The cooling time between the laser passes is known as the dwell time, which depends on the material properties, part geometry, and forming parameters. When considering a complicated 3D part or a part with multiple bends requiring upwards to hundreds of passes, the accumulated dwell time will result in a significant decrease in process productivity. To increase process productivity, research has been focused in a number of approaches: the use of different cooling mediums, the effects of dwell times, and scheduling of laser forming.

The possibility of using a cooling medium, known as active or forced cooling has been investigated by multiple authors: Cheng and Yao [2] investigated the effects of forced air cooling on microstructure, tensile strength and bend angle. Shen et al. [3] numerically examined the effects of forced water cooling and found that forced water cooling could reduce the dwell time without affecting the bend angle per pass. Lambiase et al. [4] investigated the effect of partially submerged passive water cooling on laser forming. The authors found an increased cooling rate compared with calm air. Shen et al [5] investigated the effect of underwater pulsed laser forming. Paramisavan et al. [6] simulated the effect of bottom surface cooling on the bend angle and the heat affected zone.

Other works have investigated the effect of the dwell time. Shen et al. [7] numerically investigated the effect of dwell time and found that a shorter dwell time increased the total deformation due to an increased peak temperature of the second pass. Lambiase et al. [8] investigated the productivity given by different process parameters and trained a neural network to determine the optimum processing settings. The authors found that allowing the part to fully cool does not lead to the highest productivity. The authors used constant settings for all passes and sought to find the optimum settings by that strategy.

Noticeably less work has been done on scheduling of laser forming in order to increase productivity, with Hao et al. [9] and Hao et al. [10] being the primary contributions. The review by Bachman et al [11] and the review of recent advances by Safari et al [12] can be examined for a broader perspective of the recent literature of laser forming.

The current literature have examined the process based on constant process settings. This is an obvious choice from the process perspective; however it fails to address a question from the material perspective. If constant power is used without fully cooling the part, the peak temperature will increase which will change the material load and ultimately lead to melting of the surface. Thereby an open question is left: What if a constant peak temperature is maintained by use of variable process settings?

The previous works have examined efficiency from a process perspective, i.e. what changes can be made to the process to improve efficiency. By use of advanced thermography, the perspective of the material can be explored instead. This work seeks to investigate different temperature profiles based on maintaining specific peak temperatures throughout processing. The purpose of these temperature profiles is to determine their effect on the overall efficiency in terms of bending rate over time and energy usage during forming.

2. Methodology

2.1. Experimental setup

The experimental setup can be seen in Figure 1. The laser is an IPG YLS-3000 SM fiber laser set in continuous mode. The laser has a beam quality of 1.2 M^2 and a wavelength of 1076 nm. The laser beam is directed using an ARGES Fiber Elephant 50 commercial galvanometric laser scanner system with dual galvanometric mirrors (+/- 10.5°) and a dynamic focus module at a focal length of 490 mm $\pm$25mm. The thermography measurements are performed with an InfraTec ImageIR 8380 having a measurement range of -10 to 1500°C using HDR operating at a combined 50 Hz. The detector is an inSb with a spectral range of 1.5 to 5.7 um and is cooled using a sterling cooler, with a resolution of 640 x 512 pixels.

2.2. Sample preparation

All samples are water jet cut workpieces of 100x50x1 mm from the same AISI 304 plate. To reduce variation in emissivity of the surface for the thermography measurements, the samples are laser marked in order to achieve a homogeneous and diffused surface. Note that this laser marking also greatly increases the absorption rate of the surface. The laser marking is performed with three out of six laser modules, power with average power output of 200W, speed of 25 mm/s, frequency of 5000 Hz, and a duty cycle of 15%. The galvanometric scanner system moves the

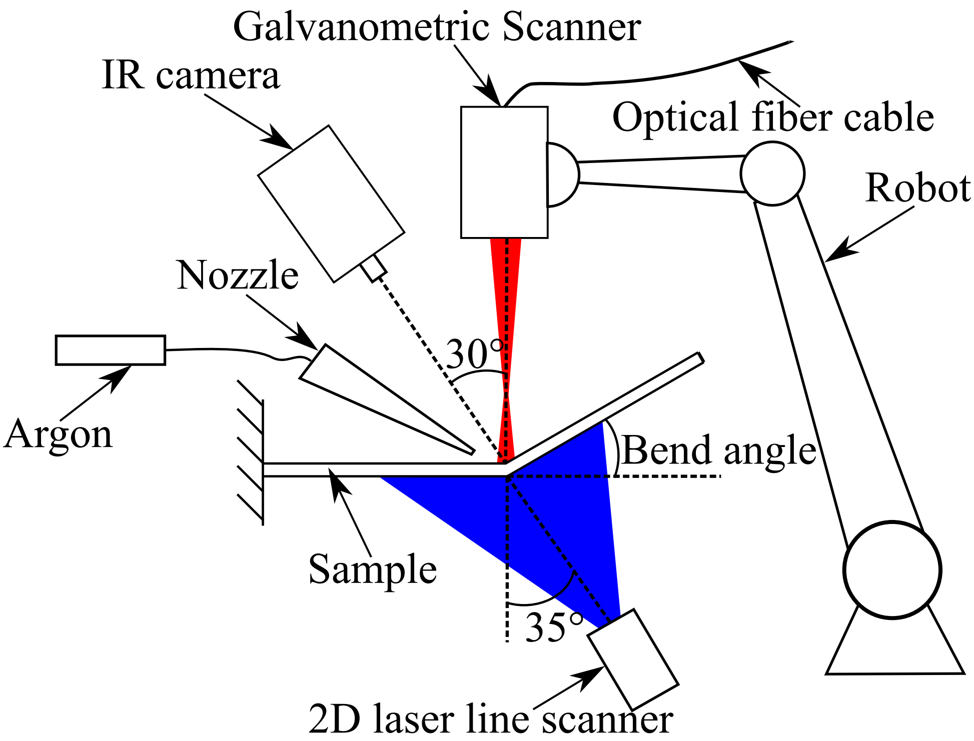

Figure 1. Schematic of experimental setup.

laser beam perpendicular to the plane of Figure 1. An overlap of 0.05 is made between the parallel passes and no height offset is applied.

2.3. Laser forming

The laser forming is performed using six out of six laser modules for the 1000 and 1300°C samples while a single laser module is used for the 700°C . The laser paths are perpendicular to the rolling direction of the samples (along the width). Argon is used as shielding gas is in order to reduce further oxidation of the laser formed surface which can affect the thermographic measurements. Furthermore, the gas flow is set to 15 L/min, which also provides limited cooling to the surface. The bend angle is measured using a Wenglor MLWL 131 2D laser line scanner operating at 20 Hz. The 2D laser line scanner is positioned to measure the bottom surface at an angle of approximately 35°. All laser forming experiments are performed using a speed of 50 mm/s with a diffused laser beam with a diameter of 3 mm. Varying laser power and dwell time is applied to achieve different temperature profiles. The settings used for each experiment can be seen in Figure 2. The experiment is run with an open loop control and the number of paths are planned based on a target bend angle of at least 30° for each sample.

2.4. Thermography measurements

The measurements are performed at an angle of approximately 30° with respect to the measured surface normal. Validation experiments using AISI 304 and a thermal oven at 900°C show a measurement error due to angle (0-45° with respect to the normal) of less than 5°C. The output data from the thermography measurements consists of 640x512 pixel frames, 50 frames per second, where every pixel contains temperature information. The temperature analysis is performed using a 16x16 pixel region of interest (ROI) of the thermal scan that is along the laser path, depicted in red seen in Figure 3. Where Figure 3 a) is a single frame showing a

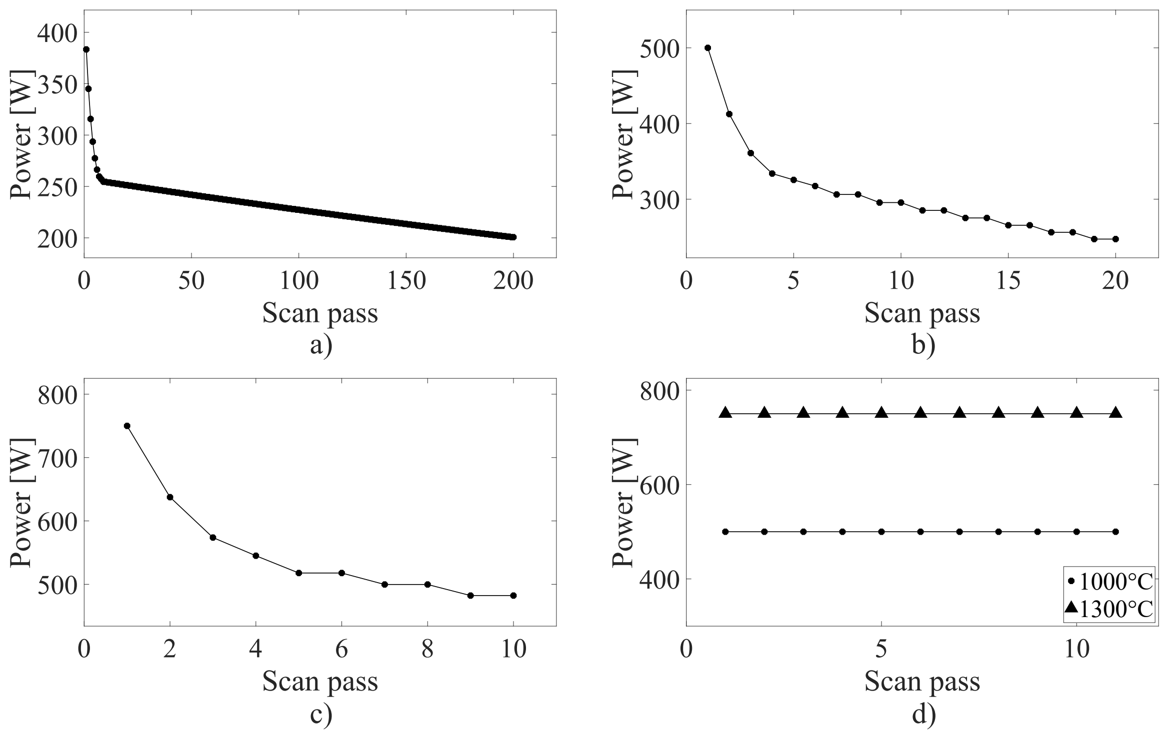

Figure 2. Power settings for temperature ranges of: a) 700°C , dwell time of 3.5 seconds. b) 1000°C , dwell time of 3.5 seconds. c) 1300°C , dwell time of 3.5 seconds. d) 1000°C and 1300°C , dwell time of 90 second.

measurement of the sample at room temperature, and Figure 3 b) shows a single frame of the same sample while its being formed. The temperature within the ROI is measured by taking the average of nine adjacent pixels. The pixels are chosen by checking how many times each individual pixel in all of the frames belonging to a single experiment have been above 600°C . The pixel that has been most often above 600°C together with it's eight adjacent pixels are chosen.

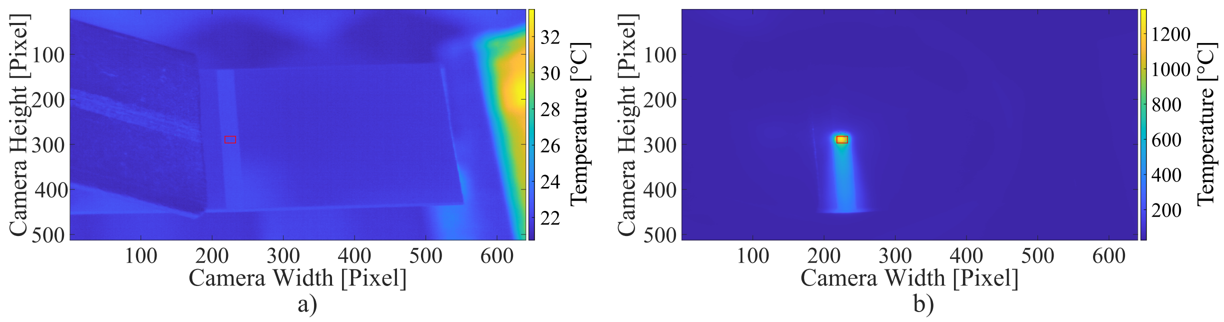

Figure 3. Thermographic measurement of a sample at: a) room temperature. b) while being formed. The highlighted region in red is the region of interest along the laser marked area.

3. Results and discussion

It should be noted that while recording the thermogrphic data, there were incomplete frames which resulted in noisy misreadings of the pixels; however the effect is limited compared to the amount of data captured and does not affect the investigated trends. The errors for each temperature profile experiment are shown in Table 1, with the total error being below 0.5% with the exception of the data for 1000°C which has an error of 0.87%. The incomplete frames are manually removed from the study.

Table 1. Number of incomplete frames in relation to the full amount of data.

Peak temperature Dwell time [s]	1000°C 90	1300°C 90	700°C 3.5	1000°C 3.5	1300°C 3.5
Total number of frames	51596	37908	52892	15150	17441
Number of incomplete frames	453	120	154	48	41
Error [%]	0.87	0.32	0.29	0.31	0.23

3.1. Bend angle

The bend development and temperature profiles for each sample can be seen in Figure 4. The results show that it was not possible to attain an angle above 25° with the current settings at 700°C . This is due to a pronounced bend rate decay, which is a result of geometrical distortion of the sample [13] and material hardening [14].

Furthermore, the results show that the fastest bend development occurs with a peak temperature of 1300°C. This is due to the elevated formability and higher gradients at higher temperatures. This is the case for both a long and short dwell time. However, it is more time efficient to form with a lower peak power than using a long dwell time.

Table 2 contains time characteristics from the processing such as total processing time, equipment time and equipment bend rate. Equipment time refers to time when the laser is on, and equipment bend rate is the ratio between the equipment time and the total developed bend angle. The results show that the fastest total processing time is with a short dwell time and a high peak temperature. This is due to the higher cooling rate at high temperatures. However the results also show that the equipment bend rate is highest when allowing a high dwell time. This is due to the higher temperature gradient. The results are notable from a scheduling perspective as it is 30-80% more efficient use of the equipment to allow the workpiece to fully cool. However, it is about three times more efficient considering the total time to allow the workpiece not to fully cool.

Table 2. Time characteristics of laser forming, where equipment time refers to work time of the laser and the equipment bend rate is the ratio between equipment time and the achieved final bend angle.

Peak Temperature Dwell time [s]	1000°C 90	1300°C 90	700°C 3.5	1000°C 3.5	1300°C 3.5
Total angle [°]	34.01	34.8	23.51	34.23	33.34
Total time [s]	988.00	727.00	879.00	242.00	217.00
Equipment time [s]	11.00	8.00	200.00	20.00	10.00
Equipment bend rate [$°/s$]	3.09	4.38	0.1175	1.71	3.33

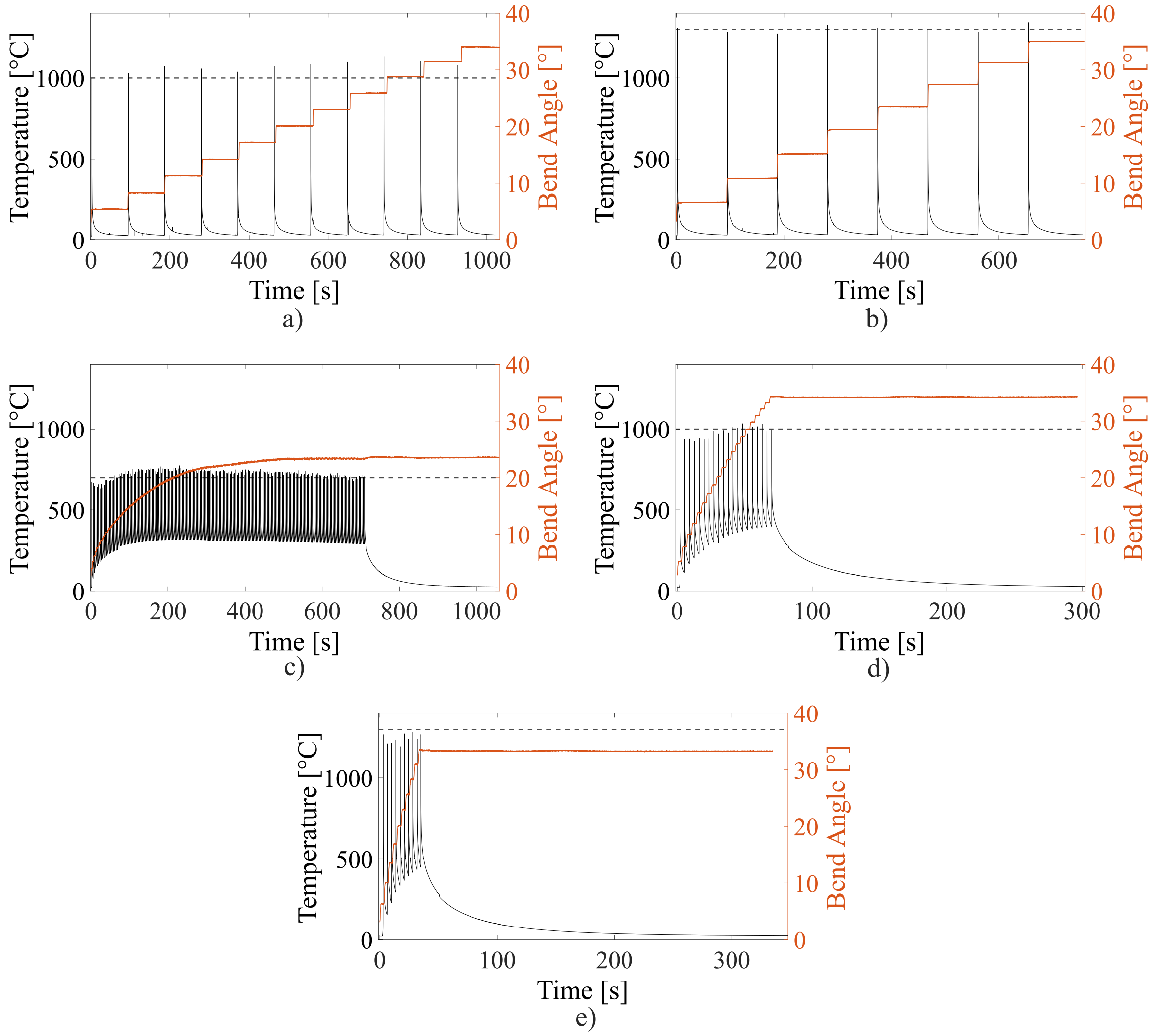

Figure 4. Temperature history for: a) 1000°C , 90 seconds dwell time. b) 1300°C , 90 seconds dwell time. c) 700°C , 3.5 seconds dwell time. d) 1000°C , 3.5 seconds dwell time. e) 1300°C , 3.5 seconds dwell time. The dashed lines indicates the target temperature.

When performing high temperature laser forming with insufficient dwell time, heat buildup in the part is bound to occur. The increased temperature affects the convection rate by reducing the thermal gradient as heat spreads through the part. The results here show that it is possible to avoid melting of the surface and maintaining a relatively constant peak temperature, but it requires careful manual work or automation with accurate prediction of the material's thermal behaviour. The advantage found here is in the order of three times faster; however, it should be noted that forced cooling will make the advantage smaller. This is because forced cooling will reduce the total time needed to bring the workpiece back to nominal temperature.

3.2. Temperature

The temperature histograms of the samples can be seen in Figure 5. It is noteworthy how little time is spent at temperatures above 800°C for all parts regardless of the settings used. The result is brief but important moments at high temperatures coupled with localized strain affecting the material kinetics. Table 3 is a summation of the time above specific temperatures

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for the different workpieces at a single pixel along the scan line. The results show how short lived and how influential the peak temperatures are. When comparing the 1000°C with the 1300°C sample with a dwell time of 3.5 seconds, the time above 1000°C goes from 0.30 seconds to 0.42 seconds; however this difference of about 0.12 seconds seems to contribute to an almost doubling in the equipment bend rate. The data also highlights that the process, albeit slow in the total processing time, is more dynamic when the actual changes occurs. Similarly when considering the samples with 90 second dwell time, the total time at elevated temperatures is short lived as well. In contrast for the 700°C sample, when considering the bending rate it is evident to see that although some bending occurs in the range of 400-700°C it is orders of magnitude smaller than what occurs above 800°C , which again is very different from what occurs at above 1000°C . This is interesting considering the very short time the sample actually spends above 1000°C .

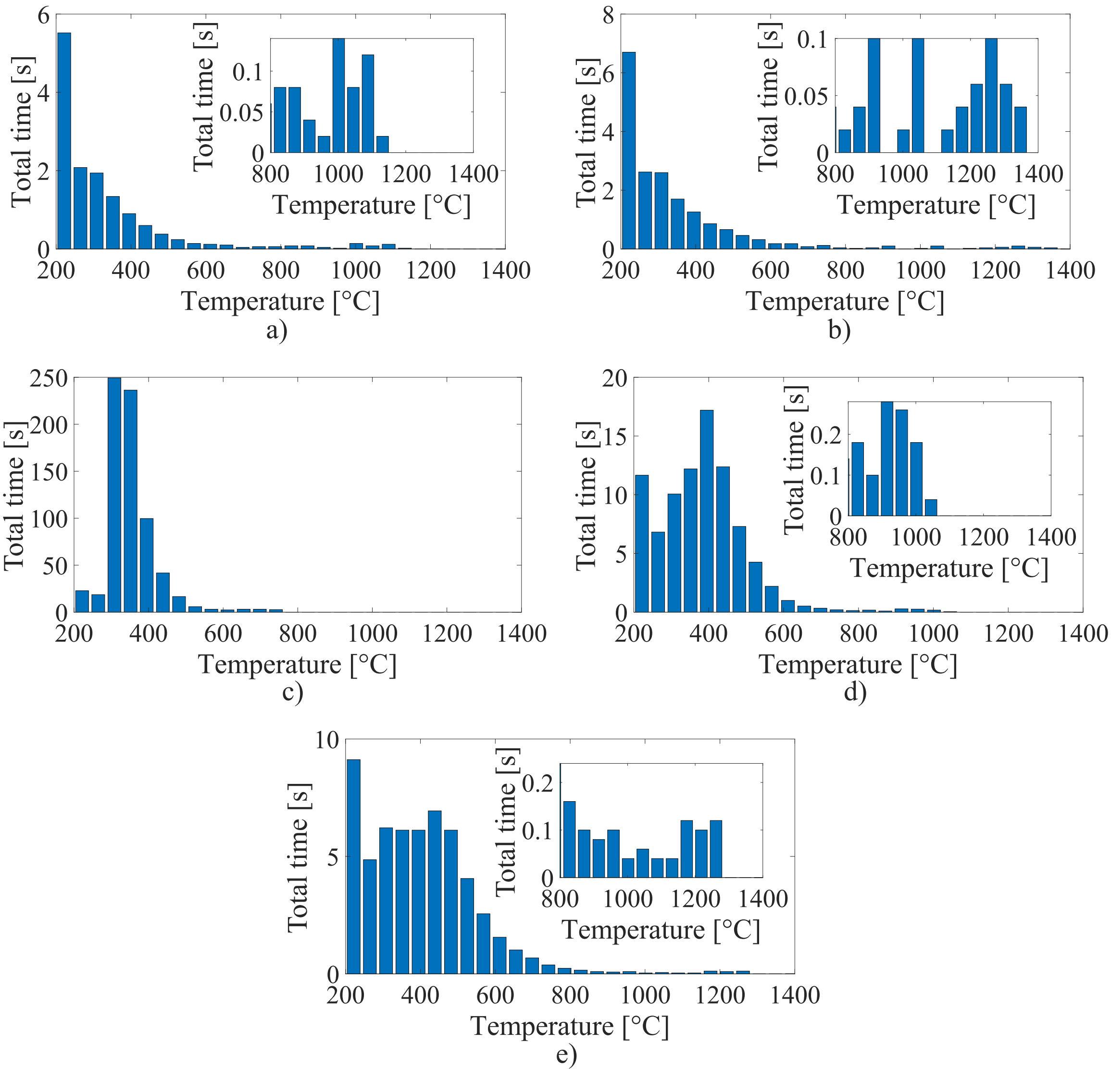

Figure 5. Total temperature history for: a) 1000°C , 90 seconds dwell time. b) 1300°C , 90 seconds dwell time. c) 700°C , 3.5 seconds dwell time. d) 1000°C , 3.5 seconds dwell time. e) 1300°C , 3.5 seconds dwell time.

Table 3. Time above certain temperatures for each of the samples, measured by the averaging the selected nine pixels in the ROI.

Peak Temperature Dwell time [s]	1000°C 90	1300°C 90	700°C 3.5	1000°C 3.5	1300°C 3.5
Time above 400°C	2.64	3.98	106.94	36.28	26.94
Time above 600°C	0.96	1.16	11.12	3.00	4.38
Time above 800°C	0.58	0.62	0	1.04	0.98
Time above 1000°C	0.30	0.42	0	0.12	0.50
Time above 1200°C	0	0.26	0	0	0.22

3.3. Energy

The total energy used to form each part can be seen in Table 4 along with the energy efficiency. This contains only energy output of the laser and does not account for energy usage of the system under operation. It is interesting to note that while the 700°C sample is about 10 times more inefficient compared to higher temperature forming, there is less difference between the other samples. It can appear that the higher temperatures are more efficient with a lower dwell times in comparison to longer dwell times. However, the difference is of a size that warrants more experiments before anything conclusive can be determined. Nonetheless, it is interesting to note that as it stands, it does not appear that there is a significant difference, allowing time constraints to be dominant during process planning.

Table 4. Energy consumption of the output of the laser during laser forming. Not including efficiency of laser and energy consumption of support equipment.

Peak Temperature Dwell time	1000°C 90	1300°C 90	700°C 3.5	1000°C 3.5	1300°C 3.5
Total angle	34.01	34.8	23.51	34.23	33.34
Total energy [kJ]	5.50	6.00	45.89	6.11	5.51
Efficiency [kJ/°]	0.16	0.17	1.95	0.18	0.17

4. Conclusion

Laser forming samples have been made using different peak temperatures validated using thermographic measurements. The results have been used to compare the total processing time, equipment time and energy applied.

- Bending with a long dwell time (90 seconds) creates a 30-80% more efficient use of the equipment depending on peak temperature during processing.
- Bending with a short dwell time (3.5 seconds), requires adjustments of the power used per pass but can reduce the total processing time by a factor of three.
- Bending to almost 30 degrees uses almost 10 times more energy at a peak temperature of 700°C compared with above 1000°C due to a more pronounced bend rate decay.
- There is a limited difference in the total amount of energy used when comparing long and short dwell time.

The results lastly indicate that scheduling can be used to achieve a much faster process by efficient use of the equipment either in the form of long dwell times or short dwell times depending on how many simultaneous bends can be performed.Furthermore, it would also be an interesting study to compare the metallurgical properties depending on the thermal history of the workpiece.

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References

[1] Lawrence J, Schmidt M J and Li L 2001 *International Journal of Machine Tools and Manufacture* **41** 967–977 ISSN 08906955
[2] Cheng J and Lawrence Yao Y 2001 *Journal of Manufacturing Processes* **3** 60–72 ISSN 1526-6125 URL `https://www.sciencedirect.com/science/article/pii/S1526612501700345`
[3] Shen H, Hu J and Yao Z Q 2011 *Materials Science Forum* vol 663 (Trans Tech Publ) pp 58–63
[4] Lambiase F, Ilio A and Paoletti A 2013 *International Journal of Advanced Manufacturing Technology* **64**
[5] Shen H, Ran M, Hu J and Yao Z 2014 *Optics and Lasers in Engineering* **62** 1–8
[6] Paramasivan K, Das S, Marimuthu S and Misra D 2018 *The International Journal of Advanced Manufacturing Technology* **94** 2137–2147
[7] Shen H, Shi Y and Yao Z 2006 *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science* **220** 507–511
[8] Lambiase F, Di Ilio A and Paoletti A 2016 *The International Journal of Advanced Manufacturing Technology* **86** 259–268
[9] Hao Y and Lien J M 2019 *Proceedings of the 3rd Annual ACM Symposium on Computational Fabrication* pp 1–11
[10] Hao Y, Guan W, Hernandez E A P and Lien J M 2021 *2021 IEEE International Conference on Robotics and Automation (ICRA)* (IEEE) pp 7788–7794
[11] Bachmann A L, Dickey M D and Lazarus N 2020 *Quantum Beam Science* **4** 44
[12] Safari M, Alves de Sousa R and Joudaki J 2020 *Metals* **10** 1472
[13] Edwardson S P, Abed E, Bartkowiak K, Dearden G and Watkins K G 2006 *Journal of Physics D: Applied Physics* **39** 382 URL `https://dx.doi.org/10.1088/0022-3727/39/2/021`
[14] Nikolov G N, Thomsen A N and Kristiansen M 2021 *IOP Conference Series: Materials Science and Engineering* **1135** 012006 URL `https://dx.doi.org/10.1088/1757-899X/1135/1/012006`