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Published in:
Procedia CIRP

DOI (link to publication from Publisher):
10.1016/j.procir.2018.08.155

Publication date:
2018

Document Version
Publisher's PDF, also known as Version of record

Citation for published version (APA):
Thomsen, A. N., Kristiansen, E., Kristiansen, M., & Endelt, B. Ø. (2018). Influence of cooling on edge effects in laser forming. *Procedia CIRP*, *74*, 394-397. https://doi.org/10.1016/j.procir.2018.08.155

Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 74 (2018) 394–397

www.elsevier.com/locate/procedia

10th CIRP Conference on Photonic Technologies [LANE 2018]

Influence of cooling on edge effects in laser forming

Anders Noel Thomsen[a,]*, Ewa Kristiansen[a], Morten Kristiansen[a], Benny Endelt[a]

[a]Department of Materials and Production, Aalborg University, 9100 Aalborg, Denmark

* Corresponding author. *E-mail address:* ant@mp.aau.dk

Abstract

Edge effects in laser forming influence the possible tolerances that can be achieved with laser forming. Edge effects arise due to uneven temperature profiles along the laser scan line. It has been suggested that an increased cooling rate can minimize the occurrence of edge effects. This work will examine the effect of increased cooling to reduce edge effects. The height profile along the laser scan line is reported and compared for different levels of cooling using experiments and simulations. The results show that increased cooling has no impact on the edge effects.

Keywords: Laser forming; Edge effects; Active cooling.

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1. Introduction

Laser forming is a contactless forming method, which can be used for forming shapes with a laser. An advantage of laser forming is that it can be used for making small adjustments, and it can be applied to double curved geometries [1,2]. A limiting factor however, is the appearance of undesired edge effects that can occur during laser forming [3]. Edge effects are commonly described as a variation in the bending angle along the free end [3], but [4] describes that the laser bending can sometimes render a multi-curvature on a single linear laser scan path, defined as variation of the bending angle along one of the edges perpendicular to the scan line. The variation in bending angle should be minimized as it has a negative impact on the possible high tolerances.

Different studies on reducing the edge effects have been made and they were related to either the single scanning strategy or multiple scanning strategy. It has been documented that a number of input parameters has an impact on the variation in the bending angle and thereby the size of the edge effect. These input parameters were classified in [3] to the ones related to; the worksheet geometry, laser process parameters, mechanical constraints, laser beam geometry, cooling conditions and laser beam irradiation pattern. So far, no work has been reported on studies of all input parameters. Instead, only few input parameters were examined at a time and the remaining input parameters were kept constant. The state of the art results show that the constant input parameters also cause interaction, making it very difficult to create a model of the bending process to prevent or even minimize the edge effects. Existing examination methods include experimental work, *E*, simple analytical relationships, *A*, between few input and output parameters, a number of numerical models, *N*, and an empirical model, *Em*. The overview of the state of the art work is shown in table 1.

This research focuses on finding the dependencies between active cooling and the appearance of edge effects, treating all the other input parameters as constants. Active cooling is normally used for increasing the productivity in laser forming by reducing the dwell time [5,6]. The dwell time is an inactive time spent on waiting for the material to cool down between laser scans. If active cooling could not only increase productivity but also reduce edge effects, it would be very beneficial.

The use of active cooling in laser forming has already been investigated numerically in [5], where the authors found that the edge effects were reduced when cooling was applied. Contrary to that, the authors in [7] simulated the use of forced

10.1016/j.procir.2018.08.155

water cooling, but did not see any impact on the edge effects. The results in [5] and in [7] related to cooling were not validated experimentally.

Table 1. Overview of the state of the art work on appearance of edge effects in the laser bending process. P; laser power, V; scanning velocity, D; laser beam diameter, N_p; number of passes, W; width of the sheet, T; thickness of the sheet, N; nozzle offset, C; active cooling, Cs: cooling scheme; EBL/EFL; effective bend/free length, Δ α; variation in bend angle along the free edge; Δ β; variation in bend angle alongside edge.

Ref.	Input	Output	Method
[3]	P, V, D	Δ α	*E*
[4]	P, V, N_p, W, EBL/EFL	Δ α, Δ β	*E*
[5]	P, V, N, C, Cs	Δ α	*N, E*
[7]	C, Cs	Δ α	*N*
[8]	P, V	Δ α	*A*
[9]	$\dot{V}$, EFL	Δ α	*N, E*
[10]	A new clamping strategy	Δ α	*A, N, E*
[11]	Scanning strategy	Δ α	*N, E*
[12]	P, V D, N_p; T, EFL	Δ α	*Em, E,*
Present	C	Δ α	*N, E*

This work revisits the use of cooling as a method for reducing edge effects and verifies the contradictory conclusions of [5] and [7]. The dependency between cooling and the edge effects is examined using simulations with increased levels of convection to simulate higher cooling at the surface. Experiments are conducted with increased levels of forced air-cooling and an attempt with forced CO_2 cooling is made.

The angle profile along the laser scan path is reported for simulations with different levels of convection as well as for experiments with different levels of forced air-cooling and forced CO_2 cooling. The simulations show that the effect of increased cooling is limited. The experimental work shows similar results; the variation of air-cooling levels and the application of CO_2 cooling has no significant effect on reduction of edge effect.

2. Numerical Model

A coupled thermal and mechanical model of the laser forming process is made in LS-DYNA. The heat input from the laser beam is simulated as a heat flux on the surface following a Gaussian distribution. The geometry is a flat plate of dimensions 55 x 50 x 0.5 mm. This corresponds to the flat plate used in the experimental model without the clamped length. The plate is clamped in one end with a constant temperature of 293 K at the clamp.

The process parameters are set to match the experimental parameters where possible. Convection is applied to all surfaces while radiation is considered negligible [10]. Natural convection is set at a convection coefficient of 10 W/m^2K. In order to simulate forced cooling, increased levels of convection are used.

3. Experimental method

3.1. Laser forming

The setup of the experiment is illustrated in Fig. 1. The purpose of the experiments was to determine the influence of cooling on the variation of bending angle.

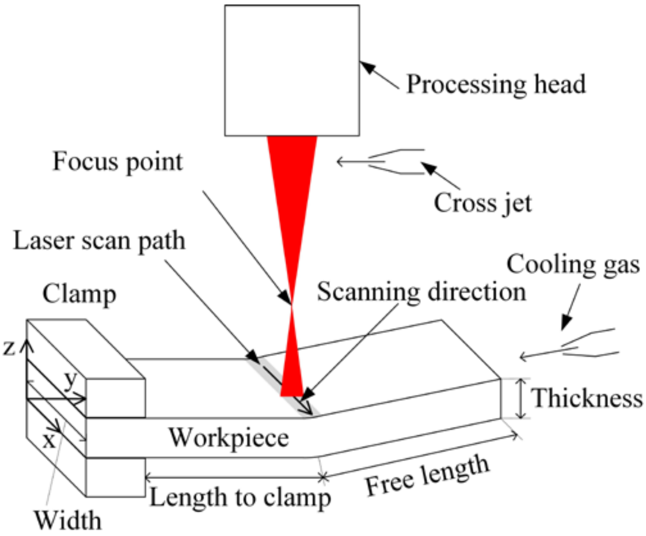

Fig. 1. Schematic setup. The laser follows the laser scan path by moving the workpiece on a xy-table. The width is 50 mm, the thickness is 0.5mm, free length is 25 mm and length to clamp is 30 mm. All the sheets used was made of AISI 304 / EN 1.4301.

A single laser scan pass was done at the workpiece with the equipment and values of parameters shown in Table 2 and 3.

Table 2. Equipment and its parameters used in all experiments.

Equipment	Manufacture	Equipment parameters	Unit	Value
Laser	IPG YLS-3000 SM	Focal length	mm	470
Processing head	HighYag (modified)	Collimated beam diameter	mm	11.05
XY-positioning	Q-sys	Beam quality factor	M^2	1.2
		Wave length	nm	1076

Table 3. Constant process parameters applied in all experiments.

Parameter	Unit	Value
Laser power	W	730
Scan speed	mm/min	6000
Laser Diameter	mm	3
Focus offset	mm	128
No. of scan paths	[ ]	1

The value of the input parameter, cooling, was controlled by applying different cooling methods. This was done according to Table 4. Air cooling was applied with an air flow delivered from a fish tale nozzle with different gas pressures. Furthermore, CO_2 cooling was applied from a fire hose nozzle, but a scientific quantification of the CO_2 cooling parameters for each experiment was impossible to state, which can cause variations between the experiments.

Table 4. Experimental plan for testing different levels of cooling.

Label	Repetitions []	Gas type []	Gas pressure mbar
Natural	3	Air	0
Air (2.5 bar)	3	Air	2500
Air (5.0 bar)	3	Air	5000
CO_2	3	CO_2	NA

3.2. Coordinate measurement

In order to quantify the effect of cooling effect on the achieved laser bends the measurements of the workpieces were done. For this purpose a Zeiss Contura 7/10/6 coordinate measuring machine was used. The measurement procedure is shown in Fig. 2. A step size of 0.5 mm was used.

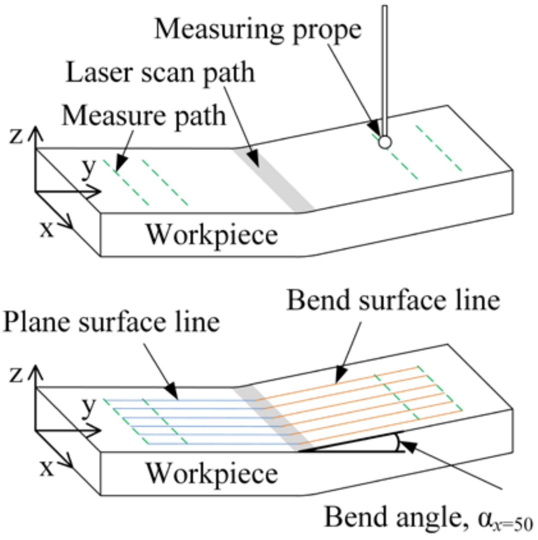

Fig. 2. Principle for measuring the bend angle, α. Top: The measuring probe makes two measuring paths on each side of the laser scan path. Bottom: Based on the measuring paths surface lines are constructed which follows the plane surface and the bend surface. The bend angle is determined as the angle between the plane surface lines and bend surface lines along the laser scan path.

The edge effects are calculated using the variance, σ, and ratios $R_{x=0}$ and $R_{x=50}$. $R_{x=0}$ and $R_{x=50}$ are introduced in this work to describe the known asymmetry in edge effects [9] and defined in equation 1 and 2.

$$R_{x=0} = \frac{\alpha_{x=0}}{\alpha_{x=25}} \tag{1}$$

$$R_{x=50} = \frac{\alpha_{x=50}}{\alpha_{x=25}} \tag{2}$$

4. Results and discussion

4.1. Simulated results

The angle profile from the simulated results can be seen in Fig 3. The profile of the angle is concave towards the laser beam. Examination of different profiles for the four different convection coefficients shows little difference in their shape. Thereby, the variation in convection coefficient has no impact on edge effects. The same conclusion can also been drawn from the analysis of the values of variance, σ, and the ratios $R_{x=0}$ and $R_{x=50}$, shown in Fig 4. In fact, the value of variance increases by a factor of almost three for increased convection compared to natural convection.

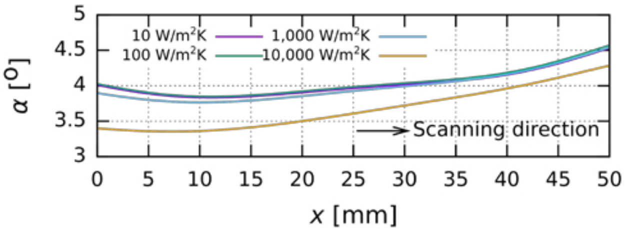

Fig. 3. Simulated angle profiles for different cooling levels.

The bend angle is similar for the three lowest levels of convection, but is reduced for a convection of 10,000 W/m^{2}K. The reduced bend angle is a result of a reduced heat effected zone (HAZ) from the high level of cooling.

The purpose of the simulations was to test whether increased cooling rate can decrease the edge effects. However, increasing the cooling in the simulations may lead to unnatural responses at the highest cooling rates. Therefore, a reduction in edge effects cannot be concluded based on the difference between simulations.

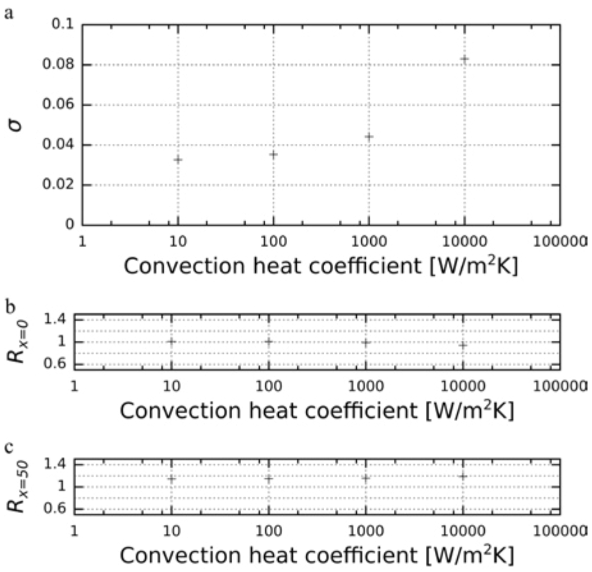

Fig. 4. The values of (a) σ, (b) $R_{x=0}$, (c) $R_{x=50}$ for the simulated angle profiles.

4.2. Experimental results

The experimental angle profiles can be seen in Fig 5. Each experiment was repeated three times. As with the simulated results, the angle profiles are mostly concave towards the laser beam.

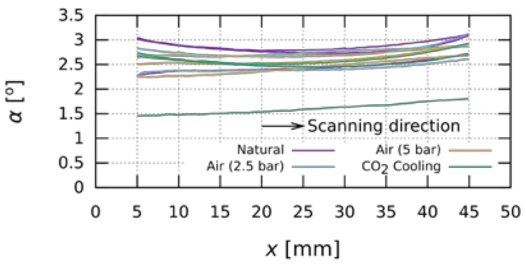

Fig. 5. Experimental angle profiles for different cooling methods.

Examination of the profiles shows the relatively low repeatability of the experiments. A single profile for CO_2 cooling is almost half the bending angle compared to the other samples. It is unclear if this is due to outside disturbance or large variation between samples. This sample might also be effected by lack of process control when applying CO_2 cooling.

Regardless low repeatability of experiments, there is no apparent effect of the different cooling methods. This conclusion is drawn from the experimental results analyzed for the values of σ, $R_{x=0}$ and $R_{x=50}$ shown in Fig 6.

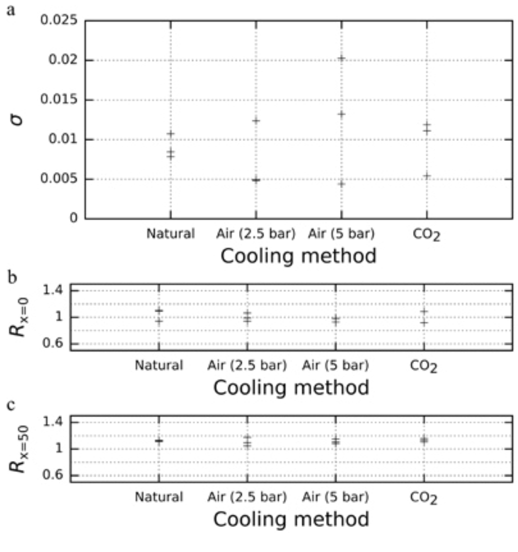

Fig. 6. The simulated (a) σ, (b) $R_{x=0}$, (c) $R_{x=50}$ for the simulated angle profiles.

The experimental and simulated results show no impact on the edge effects, neither beneficial or detrimental, which is in agreement with the results of [7]. However this conclusion is contrary to the results of [5] who reported a decrease in edge effects of 54% and 17%, for two different settings of laser power and scan speed, with active cooling. The contradiction can be explained by possible couplings between cooling and other process parameters. The work of [12] found coupling between several parameters in an attempt to minimize edge effects, however cooling was not included in their study.

Work presented in this article shows that cooling is not the simple solution to reduce the edge effects. There are still unresolved questions related to the effect of cooling on edge effects, such as whether there are coupling effects between several process parameters and whether the localization of cooling can affect the results. From the conducted experiments, it is apparent that a study into these topics must include several repetitions, due to the natural variations between samples.

5. Conclusion

Simulations of the laser forming process with varying level of convection have been made and proved no reduction in edge effects. The same conclusions were drawn from the analysis of experimental results. The experiments were repeated three times, which showed that the natural variability in the samples are relatively large.

Acknowledgements

Support for this project under work package 3 by the Manufacturing Academy Denmark (MADE) is gratefully acknowledged. This work was supported by the Innovation Fund Denmark project “INTERLASE” number 7050-00024B. The numerical work was supported by the following private foundations: Det Obelske Familiefond, Ole Kirk’s fond, Tranes fond, Fabrikant Mads Clausens Fond. The experimental equipment used for this project was supported by the Poul Due Jensen Foundation.

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