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Repeatability of Sheet Material Formation Results and Interchangeability of Processing Modes at Multi-Pass Laser Formation

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Abstract. Laser shaping of sheet materials is a flexible process and is carried out without force contact on the material, it allows forming, among other things, brittle, elastic and difficult-to-deformed materials. It is known that the main parameters of laser shaping are the beam power, the size of the focus zone and the speed of beam movement along the surface of the workpiece, however, the range of variation of these parameters is not unlimited, but due to the characteristics of a particular equipment. Therefore, it is necessary to develop an approach to selecting processing modes that can be selected from the range available on the equipment and at the same time obtain a predictable result. There is also a need to investigate a reproducibility of laser shaping results with a lot of pass-through processing.

Actually, this study is aimed at solving these issues. In particular, the article formulates a provision on complex formation parameters that allow determining interchangeable modes of laser molding processing and varying parameters in ranges available on equipment. For this, the basic processing mode was chosen, formation was carried out with a fixed number of passes, after which, using complex parameters, alternative modes were determined and formation was carried out under these conditions with the same number of passes. The article also presents the methodology and results of experimental studies of checking the interchangeability of formation modes and the repeatability of formation results during processing along parallel and multi-directional trajectories. It was experimentally found that the deviation of the strain value obtained in alternative modes, compared to the base, and did not exceed 2.46% for a three-pass cycle and 5.8% - for a nine-pass cycle. And the repeatability of the formation results during laser shaping is quite high; the discrepancy in the deformation value did not exceed 5%, and, preferably, was lower.

Introduction

Laser shaping is of interest to researchers, as it has a number of advantages. In particular, laser shaping is a contactless [1] flexible process, easily reconfigured. It does not require heavy metal-intensive equipment and tools, allows formation of rigid, elastic materials and brittle materials. In addition, among thermal forming methods, laser shaping is advantageously distinguished by the fact that laser beam as a thermal source, it is stable, dosed and can be clearly positioned.

Laser shaping can be performed with single or multiple irradiation. With multiple irradiation, the trajectories of the single passes can coincide, be arranged in parallel, or according to some law relative to each other or according to a combination of these variants. In general, the repeatability of laser formation processing results is quite high; however, under conditions of multiple irradiation, especially with mismatch of trajectories, the thermal front from the pre-treated zone can affect the formation results, changing the initial conditions. Therefore, there is a need to further study of the repeatability of processing results under such conditions.

In addition, an important factor that can hinder the use of laser shaping is the limited technological capabilities of the equipment. It is meant that equipment with the ability to widely vary the beam power, the speed of its movement and the size of the focus zone has a high cost. Therefore, there is a need to develop an approach, in which the user can vary processing modes (in the range possible in his/her equipment) in order to achieve the desired result.

Analysis of Publications

The analysis of the factors [2] of the laser shaping process shows that the most influential of them are the following: the laser radiation power, the speed of movement of the laser beam, the size of the focusing zone, the thickness of the processed sample and the properties of the processed material.

The properties of the processed material are initial conditions, so we can change them only before the formation, for example, thermal, mechanical or other types of processing. The thickness of the processed sample can also be attributed to the initial conditions. However, it should be taken into account that the mutual ratio of thickness of the sample to the beam diameter creates conditions for action of a particular forming mechanism. [3,4]

The most convenient parameters for control are the power of the laser beam, the speed of its movement and the size of its focusing zone. In general, the cross-sectional shape of the laser beam can be arbitrary, but the most common one is circular, so we take it for consideration, and then we talk about the diameter of the focus zone.

A potential user of laser shaping technology may not be able to process the variation of these three parameters over a wide spectrum. Moreover, laying such capabilities in equipment leads to its rise in price. The range of generated power and the step of its regulation characterize lasers presented on the market. Manipulators or tables provide a certain range of laser beam speeds, and focusing systems can change the size of the focus zone.

Based on this, it is necessary to develop a method for selecting of the process parameters (from the range provided by the user equipment), in which a guaranteed predicted generation result is obtained.

For this purpose, it is proposed to group the power of the laser beam, the speed of its movement and the diameter of the beam into the «energy load parameter» and the ratio of the beam diameter to the thickness of the sample - into the «geometric parameter.» The combination of these parameters will be a «complex generation parameter».

That is: $\frac{P}{Vd}$ – is the «Energy load parameter» [W•s/mm^2], where P is the power of laser beam (LB), V is the speed of movement of LB, d – is the diameter of LB.

$\frac{d}{t}$ – is the «geometric parameter» [mm/mm], where it is the thickness of the sample.

$\frac{P}{Vd}\frac{d}{t}$ – is the «complex generation parameter».

It should be noted that the level of influence of the speed on the bending result may depend on the processed material, in particular Vollertsen F. [5] notes that the bending angle is directly proportional to v -0.63 for steel plates and Magee J. [6] says that the bending angle is directly proportional to v -0.54 for aluminum. However, as has been found [7], the speed of the beam movement can be changed not within arbitrary limits, but only within a certain range, beyond which there is either melting of the surface at silent speeds, or the absence of a significant molding effect.

For example, let us take the treatment mode from the cycle of experimental studies: power 0.8 kW, beam speed −1.2 m/min (20 mm/s), focal spot – 2 mm and sample thickness - 0.5 mm.

In this case, the geometric parameter is 4. Energy description parameter is 800/(20*2) = 20. And the complex generation parameter is 80 accordingly.

In case if the user laser is not able to generate such a power value, but outputs at a maximum of 600 W, in order to obtain a similar generation result, it is necessary to list the processing mode while maintaining the values of the energy load parameter and the geometric parameter. In this case, the power is reduced, and therefore, in order to maintain the value of the energy description parameter, it is necessary to reduce either the moving speed or the beam diameter. Since the change in speed is more variable and easier to implement, the beam diameter is left unchanged. Accordingly, the new speed will be: 600/40 = 15 mm/s (0.9 m/min).

If the user has limitations in the speed range, for example, the manipulator gives a constant speed of 25 mm/s (1.5 m/min), in order to maintain the formation results, either the power or the beam diameter must be varied. Let us list the power change while maintaining the diameter. If 20 = P/(25*2), the capacity will be 1000 W.

According to this approach, the results of regime formation are the following:

- power - 0.8 kW, beam speed -1.2 m/min (20 mm/s), focus area diameter - 2 mm and sample thickness - 0.5 mm;
- power - 0.6 kW, beam speed - 0.9 m/min (15 mm/s), focus area diameter - 2 mm and sample thickness - 0.5 mm;
- power -1 kW, beam speed -1.5 m/min (25mm/s), focus area diameter - 2 mm and sample thickness - 0.5 mm;

must be identical or close.

Similarly, if it is necessary to treat a sample of greater thickness, for example 1 mm, we list the processing mode while keeping the parameter values stable. The geometric parameter will be 4=d/1, the beam diameter will be 4 mm. Then the energy load parameter will be 20 =P/(20*4). And the power, accordingly, will be 20*20*4= 1600 W.

In the same way, substitute modes for smaller power values can be calculated, in particular, in Table 1 the irradiation modes are presented, the results of which were tested experimentally. Namely, mode No. 3 with a laser IAG beam power of 350 W. and a moving speed of 5 m/min was chosen as the base one, and the remaining substitute regimes were calculated according to the approach given above.

Table 1. Interchangeability check processing modes

	Power (P), [W]	Velocity (V), [m/min]
1	250	3.571428571
2	300	4.285714286
3	350	5
4	400	5.714285714
5	450	6.428571429
6	500	7.142857143
7	550	7.862457901

Research Methodology

To check the interchangeability of formation modes, based on the approach on complex formation parameters formulated above, a series of experimental studies was carried out. In particular, on steel 10 samples of 100x50mm in size, based on a reference processing mode with a power of 350 W and a laser beam speed of 5 m/min with a focus zone diameter of 3 mm, it was calculated that the complex parameter in this mode is 140. This made it possible to calculate other processing modes that should provide an identical generation result (Table 1.).

Moreover, the diameter of the focusing zone remained unchanged, only the speed of movement of the laser beam along the blank and the power of the laser beam varied. To take into account the influence of the number of passes, 3 passes were carried out on one edge of the sample, 9 - on the other. The distance from the edge of the sample to the irradiation zone was 30 mm. (Fig.1).

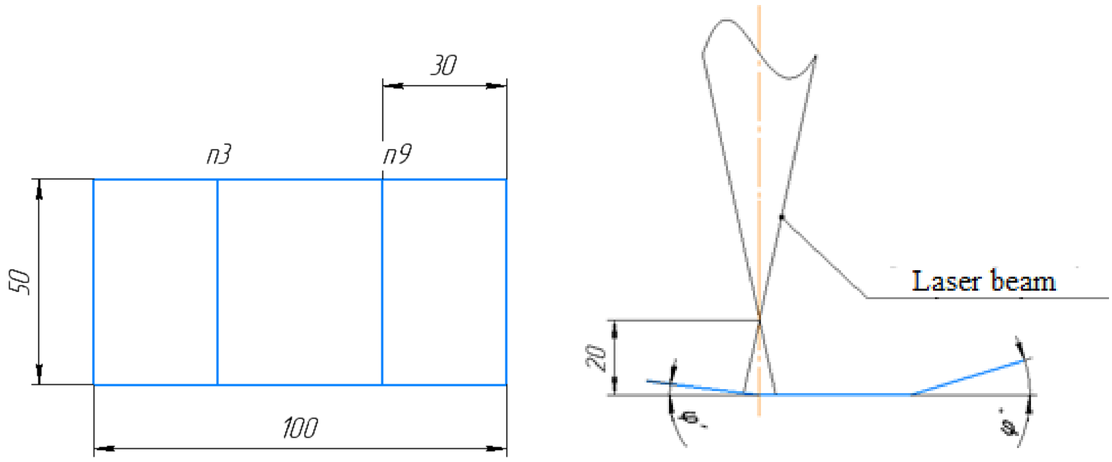


Fig. 1. Sample processing diagram for interchangeability check of formation modes

After the forming cycles, the bending angle was measured on an instrument microscope.

Determination of the repeatability of the formation results under multiple cyclic irradiation was carried out on austenitic stainless steel samples of 12X18N9T of size 200x50 mm and thick 0.5 mm. The choice of this steel is made in order to avoid influencing the results of formation of the mechanism of polymorphic transformations and, in general, structural changes in the processed material, which can significantly affect the formation results [8, 9]. The treatment was carried out in cycles of three passes, after three passes there was a transition to a new section and the cycle was repeated. Irradiation was carried out in one direction; movement without irradiation was carried out to reach the starting point.

The processing was carried out according to the diagrams shown on Figure 2 a-d. At the same time, the processing mode was as follows: laser beam on IAG with a wavelength of 1.06 micrometers, beam power - 350 W, beam speed - 5 m/min, focus zone diameter - 3 mm, number of passes on each trajectory - 3.

The value of the bending angle on each trajectory was made using an instrumental coutomere.

The Results of Experimental Research

Interchangeability of processing modes. The overall visual evaluation of the laser-irradiated area during laser shaping differed little from that of surface laser treatment without surface melting (Figure 3a).

A distinctive feature is thickening in the zone of laser passages (Fig. 3b). Such thickening is inherent in laser shaping using a temperature gradient mechanism [10, 11]. It is due to local changes in material volume because of thermal expansion of the material during heating and cooling.

A group of processed samples within the above procedure according to the modes shown in Table 1, had by default slightly different values in the bending angles of Figure 4.

The results of measurements of the bending angle of samples in absolute values and their deviation relative to the angle value obtained in the base mode are shown in Table 2. The base mode is marked in yellow.

It should be noted that the average deflection value in the bending angle value compared to the reference value for the three passes was 5.62%. And for nine passes there was a certain increase in this value to the level of 6.84%.

The increase in average deviation can be explained by the accumulation of heat in the preform after a larger quantity of passages.

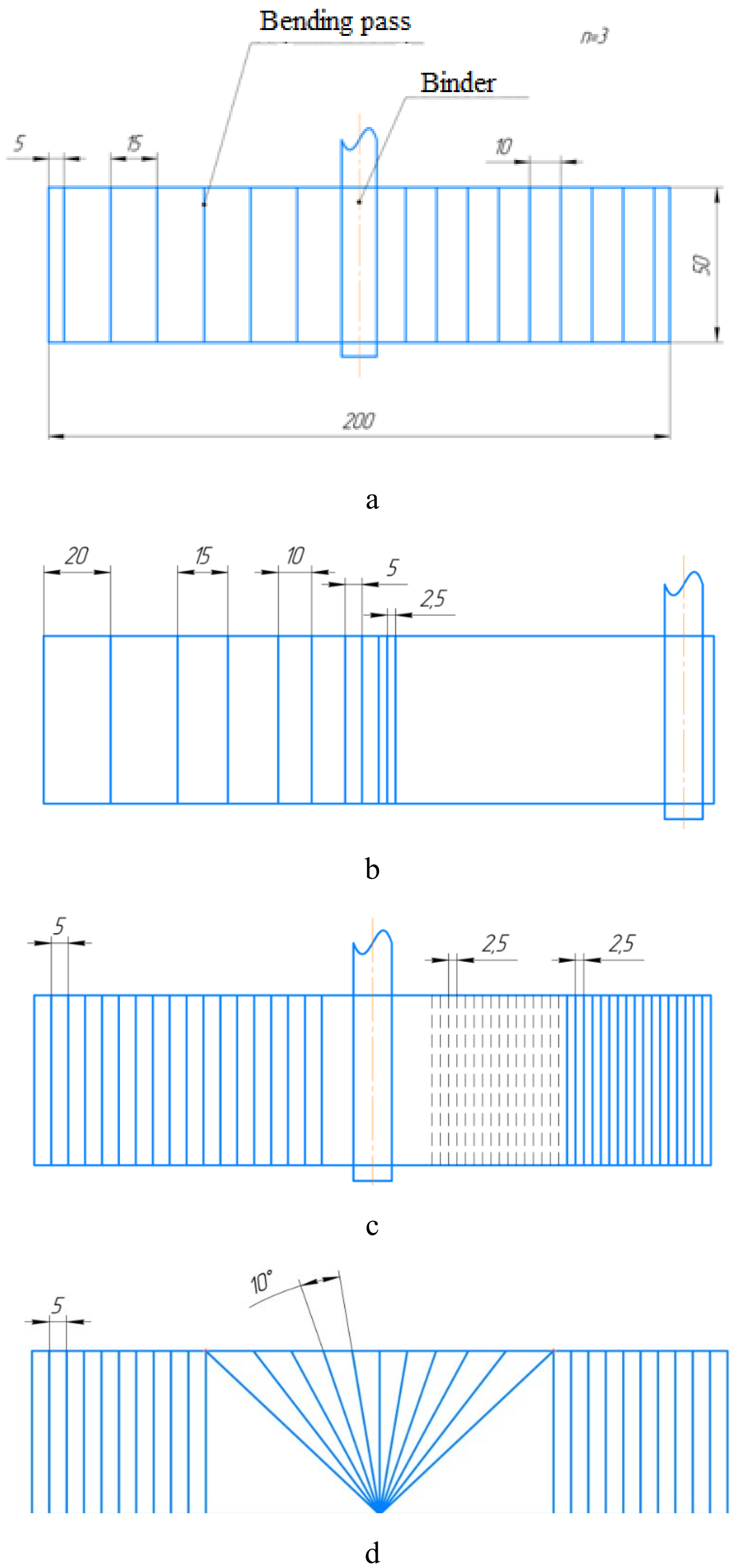
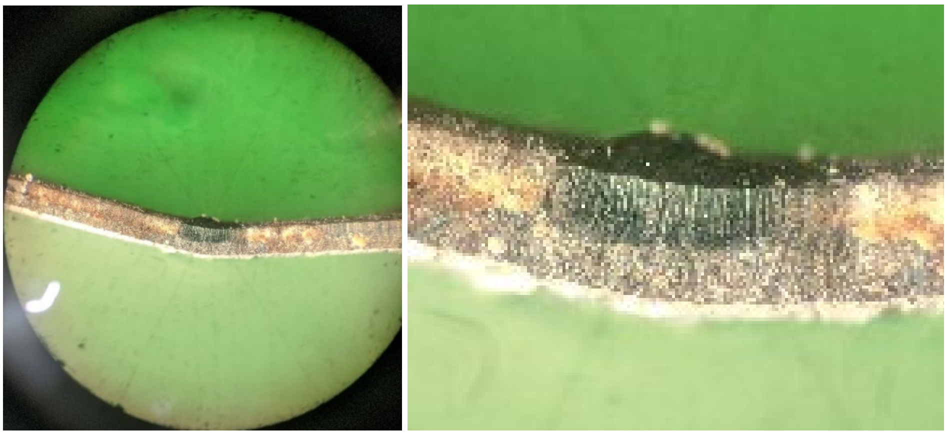


Fig. 2. Stainless Steel Sample Processing Diagrams 12X18N10T



a b

Fig. 3. General view of the irradiation zone from the end of the sample (steel 10, thick - 0.5 mm): a) general plan, b) laser passage zone

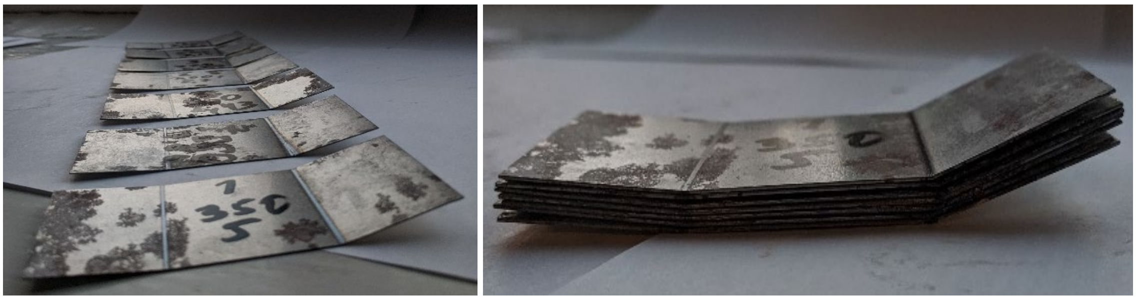


Fig. 4. Visual evaluation of formation results

Table 2. Measurement results of formed angles and deviation from reference value

№ sample	passes 3			deviation	passes 9			deviation
	[deg]	[min]	[decimal]	[%]	[deg]	[min]	[decimal]	[%]
3	6	46	6.766667	0	18	16	18.26667	0
1	6	35	6.583333	2.70935961	17	27	17.45	4.47080292
2	6	1	6.016667	11.0837438	17	56	17.93333	1.824817518
4	5	42	5.7	15.7635468	16	31	16.51667	9.580291971
5	6	52	6.866667	-1.47783251	17	36	17.6	3.649635036
6	6	38	6.633333	1.97044335	16	4	16.06667	12.04379562
7	6	31	6.516667	3.69458128	16	32	16.53333	9.489051095

It should also be noted that values that differ significantly from the others, in particular 15.76 and 11.08 for a three-pass cycle and 12.04 for a nine-pass cycle, are due to basing errors or the influence of non-system factors. Excluding these peaks, the average deviation is 2.46% for the three-pass cycle and 5.8% - for the nine-pass cycle.

In general, summing up the results obtained, it can be argued that using the provision on complex formation parameters allows us to find alternative processing modes, at which a close value of the formation result can be obtained. This may be useful for adapting the recommended processing mode to the capabilities of existing equipment.

Repeating of the Processing Results. In the case of working the sample on one side with a pitch between adjacent paths of 15 mm and on the other 10 mm (Figure 5), different values of the outbound curvature of the surface were obtained. However, the deformation at each individual site was proportionate and close in magnitude. In particular, the results shown in Table 3 were obtained for the 15 mm area irradiated.

Fig. 5. Sample shape at irradiation with 15 mm pitch (right side) and 10 mm pitch (left side)

Table 3. Formation results with 15 mm pitch

№ of pass	Step, [mm]	Angle,		decimal	average	deviation from average, [%]
		[deg]	[min]			
1	15	10	20	10.33333	10.33333	0
2		10	20	10.33333		0
3		10	30	10.5		-1.612903226
4		10	30	10.5		-1.612903226
5		10	10	10.16667		1.612903226
6		10	10	10.16667		1.612903226

In this case, the deviation from the average value of the bending angle on each trajectory did not exceed 1.62%, which is a good result.

For 10 mm pitch, the strain values were slightly different, as was for the deflection value (Table 4). The difference for deformation on a separate trajectory, compared to the previous case, is explained by the installation error, because of which the irradiation conditions were slightly changed, in particular the size of the beam-focusing zone. However, the amount of deformation in each section was repeated quite well, and if the value on the 7th lane (which could be caused by the influence of a non-system factor) is excluded, then the discrepancy of the results does not exceed 4.77%.

In the case of a variable pitch sample between adjacent passages (Figure 6), a similar pattern was obtained (Table 5).

In this case, the largest deviation was 3.5% and all the others were less than 1%.

Obviously, the amount of pitch between adjacent trajectories, near the main parameters of the processing mode, determines the curvature of the existing surface. In particular, using a pitch of 15 mm, the radius of curvature of the obtained surface was 95.5 mm, at a pitch of 10 mm; the radius of curvature was 44 mm. (Fig. 5).

A decrease in pitch between irradiated tracks leads to a decrease in the radius of curvature of the developed surface, while keeping all other factors stable.

Table 4. Formation results with10 mm pitch

№ of pass	Step, [mm]	Angle,		decimal	average	deviation from average, [%]
		[deg.]	[min]			
1	10	12	20	12.33333	12.6	2.116402116
2		12	0	12		4.761904762
3		12	38	12.63333		-0.264550265
4		12	50	12.83333		-1.851851852
5		12	40	12.66667		-0.529100529
6		12	44	12.73333		-1.058201058
7		13	40	13.66667		-8.465608466
8		12	26	12.43333		1.322751323
9		12	6	12.1		3.968253968

Fig. 6. Sample shape at irradiation with variable pitch of 20, 15, 10, 5 mm (in pairs starting from edge to middle)

Table 5. Results of formation with variable pitch of 20, 15, 10, 5 mm (in pairs startingfrom edge to middle)

№ of pass	Step, [mm]	Angle,		decimal	average	deviation from average, [%]
		[deg.]	[min]			
1	20	11	30	11.5	11.10952	-3.514787827
2	20	11	10	11.16667		-0.514359194
3	15	11	6	11.1		0.085726532
4	15	11	0	11		0.985855122
5	10	11	0	11		0.985855122
6	10	11	0	11		0.985855122
7	5	11	0	11		0.985855122

Therefore, at a step of 5 mm, the radius of curvature of the surface was 29 mm, and at a step of 2.5 mm - 13 mm. (Figure 7).

Fig. 7. Shape of the sample at irradiation with a pitch of 5 m. and 2.mm

If you do not use parallel tracks, but place them at a certain angle to each other, then you can obtain prismatic and conical forms of samples (Figure 8). At the same time, the nature of reproduction of the strain value will remain stable.

Fig. 8. Shape of the sample during irradiation with variation of parallel passages and oriented at an angle to each other

In general, by varying the direction of the irradiation trajectories, their pitch and the number of passes on each trajectory and a complex spatial configuration of the article can be obtained.

Conclusions

1. Laser shaping, with a combination of irradiation modes and mutual arrangement of irradiation trajectories, allows obtaining complex predicted surface configurations.
2. The position on the complex energy parameter of formation is experimentally confirmed. The deviation of the strain value obtained in alternative modes, compared to the base, and did not exceed 2.46% for a three-pass cycle and 5.8% - for a nine-pass cycle.
3. The repeatability of the formation results during laser shaping is quite high; the discrepancy in the strain value did not exceed 5%, and, preferably, was lower.
4. When installing the sample for treatment and during irradiation, it is necessary to monitor the preservation of focusing conditions.

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