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EXPERIMENTAL STUDY ON SHRINKAGE OF NARROW PARTS PRODUCED BY LASER CUTTING PROCESS

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ABSTRACT:
THE EFFECTS OF DIMENSIONS OF NARROW PARTS ON LENGTH SHRINKAGE WERE INVESTIGATED. BASED ON TAGUCHI APPROACH TO DESIGN OF EXPERIMENTS (DOE), AN EMPIRICAL MODEL WAS BUILD TO CALCUALTE THE SHRINKAGE OF X5CrNi18-10 STAINLESS STEEL CUT BY CO_2 LASER USING N_2 AS AN ASSIST GAS. THE EXPERIMENTAL DESIGN WAS PERFORMED ACCORDING TO TAGUCHI L16 ORTHOGONAL ARRAY WITH A MIXED LEVEL DESIGN FOR SHEET THICKNESS, NOMINAL SAMPLE LENGTH AND NOMINAL SAMPLE WIDTH. WITHIN THE LIMITS OF ANALISED VALUES, SHEET THICKNESS HAS NO SIGNIFICANT EFFECT ON SHRINKAGE AND THE HIGHEST EFFECT HAS THE NOMINAL SAMPLE LENGTH. THE RESULTS ARE INLINE WITH THE HYPOTHESIS THAT THE SHRIKAGE OCCURS DUE TO THE RESIDUAL STRESSES INDUCED IN RESOLIDIFIED LAYER. DERIVED EQUATIONS CAN BE USED TO PREDICT THE SHRINKAGE AND CONSEQUENTLY TO MODIFY THE CUTTING HEAD TRAJECTORY THAT LENGTH OF THE PART AGREES WITH THE NOMINAL VALUE.

KEY WORDS: SHEET METAL, LASER CUTTING PROCESS, SHRINKAGE, DOE, TAGUCHI METHOD

INTRODUCTION

Austenitic stainless steels and nickel based super-alloys as well as titanium and its alloys are the most popular difficult to cut sheet materials used in the manufacturing industries due to their exceptional mechanical and physical properties. Cutting these materials by using conventional processes are difficult with plenty of disadvantages. Therefore, advanced processes

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like plasma beam cutting, abrasive water jet cutting and laser beam cutting are mostly used to machine such materials[5].

Laser cutting is one of the leading industry technology for cutting a wide variety of materials. Compared to other advanced cutting technologies, laser cutting process offers significant advantages and possibilities such as the ability to cut complex geometries, achieving tight tolerances, high cutting speeds, localized head affected zone, ease of automation, computer control, integration into assembly lines, etc.[6,7]. Mastering the influence of process parameters to cutting performances is a key not only to improve the quality of cut and cutting efficiency, but also to lower the production costs[6]. A lot of researches to master the technological process parameters have been conducted using Design of experiments (DOE) techniques. The Taguchi method is one of them. It is a well-known technique for improving the quality of products and processes. It represents a simple and efficient method of planning the experiment, it is not limited to specific problems and is most often used for experimental analysis and optimization of products and processes[6].

A large number of recent scientific studies dealing with the problem of the laser cutting process mainly describe the variation of the laser process parameters for different types of materials and their impact on the measured variables. However, there are almost no studies indicating the influence of geometric features and dimensions on processing errors and the discrepancy between the finished product dimensions and the nominal dimensions defined by the cutting head trajectory. Additionally, it was practically observed that narrow and long parts are shorter than nominal length defined by the cutting head geometry. The shrinkage in the direction of part length is most probably caused by the residual stresses induced by the formation of resolidified layer on the surface of the cut, which is formed due to the thermal material removal mechanism. The shrinkage could be calculated by mastering the formation of resolidified layer (especially its depth) and connect it with the expected shrinkage.

In this paper, the effects of the sample thickness, sample nominal width and sample nominal length on length shrinkage are determined using Taguchi method. The results are analysed from the point of view of residual stresses. The sample thickness is defined by the sheet thickness whereas nominal sample width and nominal sample length are defined by the laser cutting head trajectory.

EXPERIMENTAL SETUP AND PROCEDURE

The experimental studies were performed by using a 5 kW continuous wave mode CO_2 Power Laser Platino (Prima Power, Italy) as shown in Figure 1. The samples of various dimensions were cut out of three plates of various thickness. All cuts were performed by the fixed laser machining parameters given in Table 1, thus eliminating the variance of the laser cutting parameters (cutting speed, gas pressure, laser power, focal point position, etc.) as influential parameters to shrinkage**.** Assuming that the mutual relations of the selected sizes and

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experimentally measured sizes are complex and nonlinear, four values (levels) of thickness and lengths were defined as well as two sample widths. The samples of high alloyed steel X5CrNi18-10 were measured on a flat table using Digital height and marking gauge (Vogel, Germany) with maximal total accuracy of 0.03 mm. Each dimension was measured at least two times, and the mean values were taken into consideration.

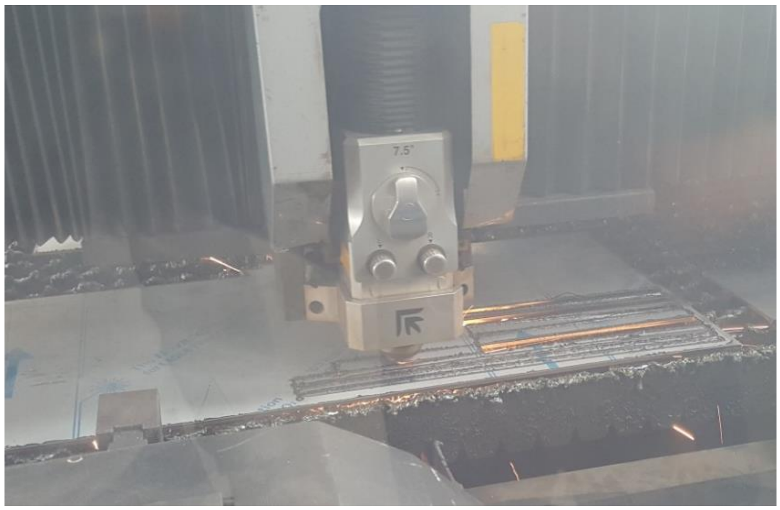
Figure 1. Cutting of samples

As shown in Table 2, nominal sample width has two values and nominal sample height and sample thickness have four values. In order to perform full factorial analysis, 4·4·2 = 32 experiments are required without counting the repetitions. By using the Taguchi method based on the L_{16} ($4^2 \times 2^1$) orthogonal array, the number of experiments is reduced to half (Table 2). Each experiment was repeated three times, therefore the total number of experiments is 48. The summary of experimental conditions are listed in Table 2. When applying any DOE method, the experimental parameters, in this case sample dimensions, are denoted as *control factors* or shortly just *factors*.

Table 1. Laser process parameters

Process parameter	**Symbol**	**Unit**	**Value**
Cutting speed	***v***	**mm/min**	**1900**
Gas pressure	***p***	**bar**	**12.8**
Focus	***f***	**mm**	**-4.5**
Used gas	**-**	**-**	**N_2**

Table 2. Control factors and their levels

Symbol	Control factor	Notation	Unit	Level values			
				1	2	3	4
A	Sheet thickness	*t*	mm	2	3	4	5
B	Nominal sample length	*l*	mm	150	250	350	450
C	Nominal sample width	*w*	mm	10	20	-	-

RESULTS AND DISCUSSIONS

The experimental parameters (factor levels) and the experimental results are given in Table 3. The mean value of the shrinkage is calculated by Eq.1.

$$\bar{Y} = \frac{1}{N}\sum_{i=1}^{N} Y_i \quad (1)$$

Since all the measured values are either greater or smaller than the nominal values (in our case smaller) and the smallest value of means is the best result, the "smaller-is-better" type characteristic (Eq. 2) may be used to obtain S/N value for each experiment[8].

$$S/N = -10 \cdot \log\left(\frac{1}{N} \cdot \sum_{i=1}^{N} Y_i\right) \quad (2)$$

In both cases N is the number of repetitions, in this case 3.

Table 3. Taguchi orthogonal array L_{16} ($4^2 \times 2^1$) with experimental results

No	Factor levels			Experimental results							
	A	B	C	Measured sample length, mm			Shrinkage Y, mm			Means $\bar{Y}$, mm	S/N ratio, dB
				I	II	III	I	II	III		
1	1	1	1	149.87	149.81	149.81	0.12	0.19	0.19	0.17	15.33
2	1	2	1	249.66	249.70	249.71	0.34	0.30	0.29	0.31	10.15
3	1	3	2	349.80	349.74	349.78	0.20	0.26	0.22	0.23	12.84
4	1	4	2	449.61	449.76	449.74	0.39	0.24	0.26	0.3	10.34
5	2	1	1	149.83	149.87	149.68	0.17	0.12	0.31	0.2	13.19
6	2	2	1	249.82	249.16	249.59	0.18	0.84	0.41	0.48	5.19
7	2	3	2	349.70	349.70	349.86	0.29	0.29	0.14	0.24	11.90
8	2	4	2	449.90	449.79	449.66	0.10	0.21	0.34	0.22	12.47
9	3	1	2	149.81	149.78	149.79	0.18	0.22	0.20	0.20	13.81
10	3	2	2	249.82	249.75	249.86	0.18	0.25	0.14	0.19	14.18
11	3	3	1	349.61	349.67	349.52	0.39	0.33	0.48	0.40	7.85
12	3	4	1	449.37	449.46	449.43	0.63	0.54	0.57	0.58	4.71
13	4	1	2	149.77	149.75	150.00	0.23	0.25	0.00	0.16	14.14
14	4	2	2	250.00	249.81	250.00	0.00	0.19	0.00	0.06	19.19
15	4	3	1	349.53	349.56	-	0.47	0.44	-	0.46	6.83
16	4	4	1	449.28	449.15	449.45	0.72	0.85	0.55	0.71	2.88

According to the Taguchi method, the response table for the means $\bar{Y}$ and S/N ratios were used to determine the factor effect on the difference between the nominal and measured sample length (Table 4). Each value given in the table is the average value of means $\bar{Y}$ or S/N ratios in which the observed factor was on the observed level[9]. Greater the difference between minimum and maximum value, greater the factor effect on the measured results. Therefore, nominal sample length has the greatest effect whereas the sheet thickness has the smallest effect in the range of the factor levels. These data may be presented as main effects plot for the factors. The plots are very helpful in visualizing the magnitudes of the investigated parameters on the response variable (Figure 2 and Figure 3).

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Table 4. Response table for S/N ratios and means

Means $\overline{Y}$, mm				*S/N* ratios, dB			
Level	A	B	C	Level	A	B	C
1	0.25	0.18	0.41	1	12.16	14.12	8.27
2	0.28	0.26	0.20	2	10.69	12.18	13.61
3	0.34	0.33	-	3	10.14	9.85	-
4	0.34	0.45	-	4	10.76	7.60	-
Delta	0.10	0.27	0.21	Delta	2.02	6.52	5.34
Rank	3	1	2	Rank	3	1	2

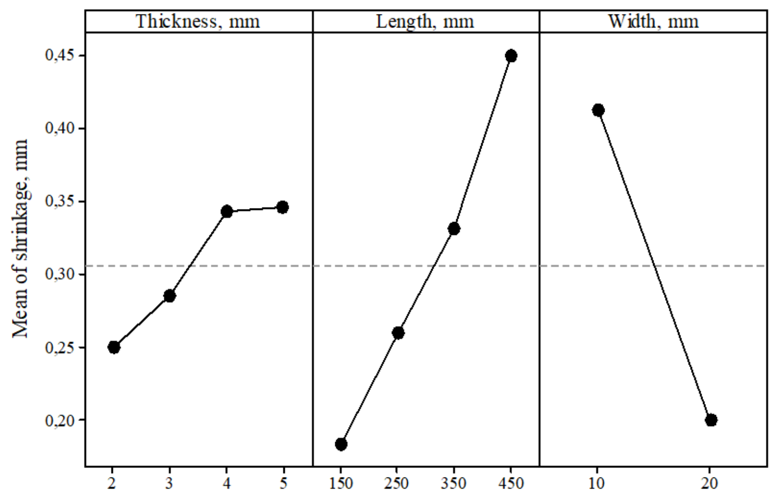

Figure 2. Main effects plot of means for shrinkage

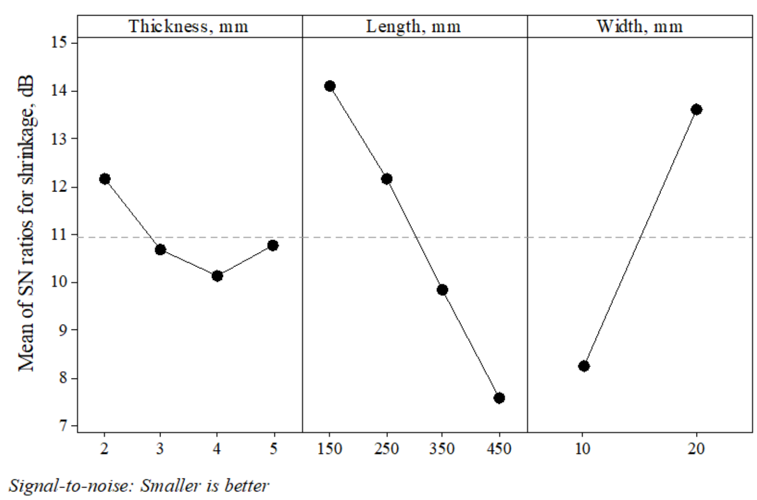

Figure 3. Main effects plot of S/N ratios for shrinkage

In order confirm the statistical significance of the factors, the analysis of variance (ANOVA) is used. The results of ANOVA are given in Table 6 and are showing that the sheet thickness t, that was varied in the range from 2 mm to 5 mm, has no statistical significance on the shrinkage, since the p-value exceeds the significance level of 5% (p>0,05). Thus, the model to predict the shrinkage encompass only sample nominal width and length (Eq. 3). The calculated shrinkage $\hat{Y}$ can be further used to modify the cutting head trajectory in order to produce parts that have the required length. The model is valid for the given laser process parameters (Table 1), stainless steel X5CrNi18-10 as the workpiece material and for the samples that have the thickness t in the range from 2 mm to 5 mm, nominal width w in the range from 10 mm to 20 mm and nominal length l in the range from 150 mm to 450 mm. According to the values $R^2 = 87.01\%$, $R^2_{adj} = 83.8\%$, $R^2_{predicted} = 78.5\%$, Figure 4 and Figure 5, the model is satisfactory accurate.

$$\hat{Y} = -0{,}119 + 0{,}00248 \cdot l + 0{,}01095 \cdot w - 0{,}000107 \cdot l \cdot w \quad (3)$$

Table 6. The effects of sample nominal dimensions on shrinkage determined by ANOVA.

Source	Degrees of freedom (DF)	Sum of Squares (SS)	Mean Square (MS)	F-test F	p-value p
Thickness (mm)	3	0.026	0.009	0.80	0.528
Length (mm)	3	0.154	0.051	4.7	0.036
Width (mm)	3	0.181	0.181	16.6	0.004
Error	8	0.087	0.011		
Total	15	0.448			

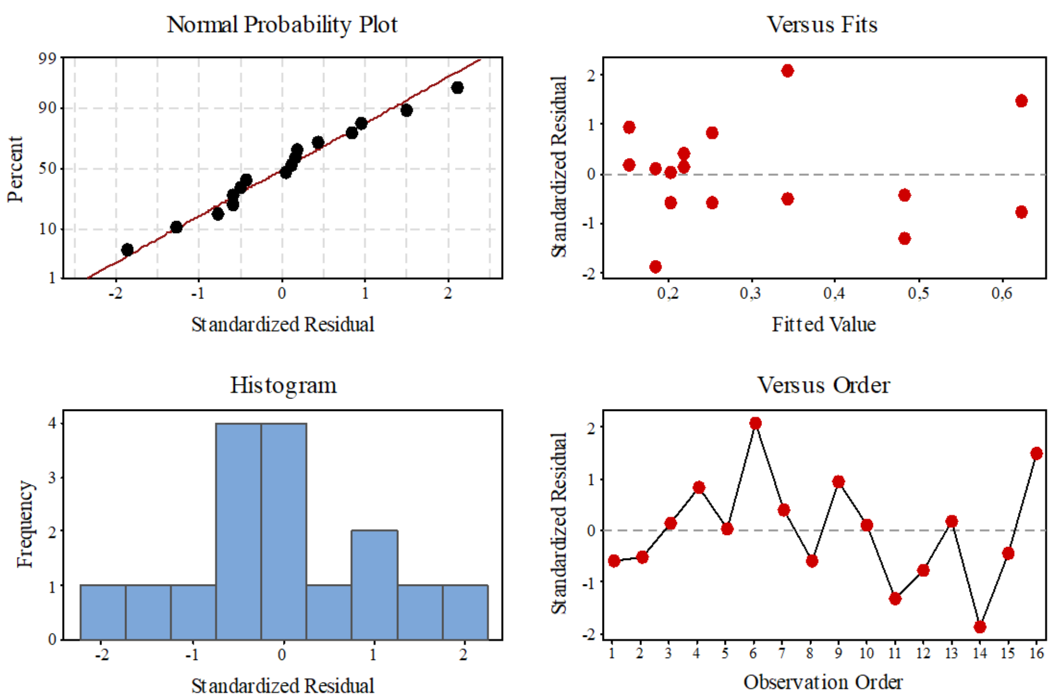

Figure 4. Residual plots of the linear model to predict shrinkage

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The shrinkage of parts calculated by the derived model are compared to the measured values and given on Figure 5. The biggest difference between the calculated and measured values is 0.135 mm, which is acceptable for most industrial applications.

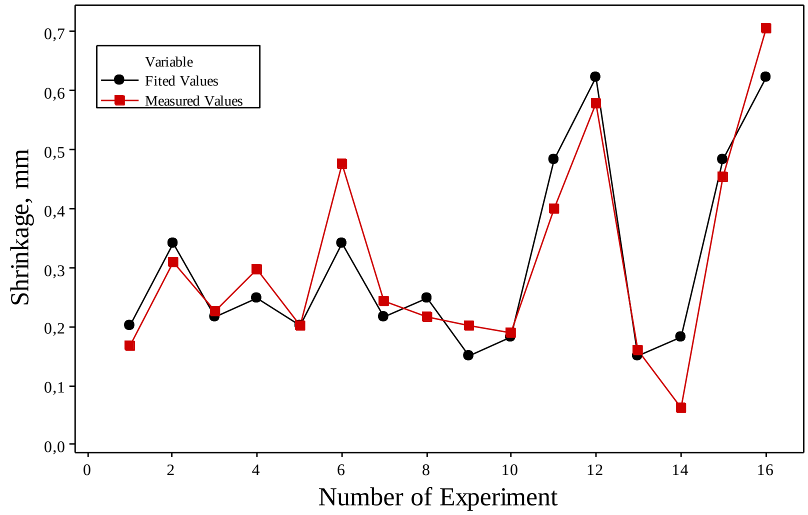

Figure 5. Experimentally measured and predicted shrinkage by the linear empirical model

The results are in agreement with hypothesis that residual stress in resolidified layer is causing the shrinkage. The tensile stresses in resolidified layer are causing the compressive stresses in the thermally unmodified material. Since the cutting parameters are constant for all experiments, the thickness of resolidified layer must be the same in all experiments. Thus, the surface area ratio of resolidified layer and the base material measured in the cross section perpendicular to the sample length depends only on the sample width. Sample thickness and sample length have no influence on the surface area ratio. Greater the sample width, smaller the volumetric ratio and thus smaller the shrinkage (Figure 2). The material thickness has no influence on the volumetric ratio therefore its effect on shrinkage is not significant (Table 6). Although the sample length has no influence on volumetric rate it affects the shrinkage, since the shrinkage of any material due to residual stresses depends on the nominal dimensions. The sample length has the strongest effect on the shrinkage (Figure 3).

CONCLUSION

In this study, the Taguchi technique was used in order to determine the shrinkage of narrow X5CrNi18-10 stainless steel parts machined by the laser cutting process. All experimental results were evaluated using the S/N quality characteristic and ANOVA. The following conclusions are valid for the given laser process parameters (Table 1), sample material stainless steel X5CrNi18-10 and for the samples that have the thickness t in the range from 2 mm to 5 mm, nominal width w in the range from 10 mm to 20 mm and nominal length l in the range from 150 mm to 450 mm.

(1) According to the response table for S/N ratios and data means it was found that the order of importance of the control factors (sample dimensions) to the measured output variable (shrinkage in length) is the following: sample length, sample width and sheet thickness.
(2) Based on the results of ANOVA, the sample length and the sample width have effect on the shrinkage, but not the sample thickness.
(3) The derived model is accurate enough. The highest discrepancy between the measured and calculated shrinkage is 0.15 mm, which is sufficiently accurate for practical use.
(4) Through the variation of the sample dimensions in the laser cutting process, despite the constant laser cutting process parameters, the heat input into the material influences the shrinkage due to variations of a volumetric ratio between resolidified layer and the base material. The obtained results are in agreement with hypothesis that residual stress in the resolidified layer is causing the shrinkage.

The model describes the phenomena of shrinkage well enough. In further work it will be tested for different machining parameters. The most significant parameters affecting the thickness of resolidified layer are cutting speed, laser beam power and assist gas flowrate. By adding these parameters into the model will make a model significantly more general, it will enable to better understand the phenomena of shrinkage and last but not least, it will be ready for practical use.

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