STUDIES REGARDING THE PRECISION AT LASER CUTTING PROCESS OF MILD STEELS

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ABSTRACT: The paper presents the optimization of cutting speed for a Laser Cutting System Mazak Super Turbo-X 48 MkII. The study was performed using 3mm, 6mm and 10mm mild Steel S355JR. The optimization was conducted in an operational manufacturing environment using the OFAT methods and Curve Expert software. The main laser parameters were maintained constant and the perpendicularity tolerance U_{max} was measured according to DIN EN ISO 9013 versus the speed rate v as variable parameter. A complex model to show the perpendicularity tolerance U_{max} variation according to the cutting speed variation was obtained. The goal of experiment is to simulate the process and to calculate and define the maximum speed rate which assures that U_{max} is situated in certain classes of the quality. The experiments were conducted at $\alpha = 0{,}05$ confidence.

KEY WORDS: laser cutting process, OFAT method, optimization of cutting speed

1. INTRODUCTION

Laser cutting is a fairly new technology that allows metals to be cut with extreme precision. The laser beam is typically 0.2 mm in diameter with a power of 1-10 kW. Depending on the application of the laser cutter a selection of different gases are used in conjunction with the cutting.

When cutting with oxygen, material is burned and vaporized when heated by the laser beam to ignition temperature. The reaction between the oxygen and the metal creates additional energy in the form of heat, supporting the cutting process.

These exothermic reactions explain why oxygen can penetrate thick and reflective material; however, they need to be controlled, since violent reactions can occur and not only reduce cut quality but affect workplace safety.

Laser cutting for shaping and separating work pieces into parts of desired geometry is one of the most widespread tasks of laser material processing. For certain well defined applications, e.g. cutting metal sheet using CO_2-lasers, suppliers of laser cutting machines provide a comprehensive database for process parameters.

However, in general new customized cutting processes have to be individually optimized with respect to the targeted geometry and the material to be cut while taking into account the equipment to be used.

Since laser cutting processes are often governed by a multitude of parameters, some of which interacting with each other, the optimization of a process is determined by a high degree of complexity. As a consequence, the optimization of an industrial laser process might be a time consuming and cost intensive task, particularly in case simplified methods such as the one-factor at a time approach are applied.

The purpose of the paper is to find a model using Curve Expert software based also on the influence of the feed rate to the output parameter U_{max}. This study was realized on a laser system Mazak Super Turbo-X 48, Mk2, 1800W, CO_2, to cut mild steel with thickness 3 [mm], 6[mm] and 10[mm] using O_2 as assisting gas.

To investigate the influence of feed rate a model has been created for dependence upon the cutting parameters. Attempts to measure perpendicularity tolerance were performed on samples of mild steel. The measured parameter was perpendicularity tolerance, was U_{max} in mm and was measured with a profilometer.

2. DETERMINING THE QUALITY OF CUT

Laser cutting surface quality is governed by the norm EN ISO 9013: 2002. Quantitative parameters that quantify the state of laser cut surfaces are:

- deviation from perpendicularity and inclination;
- the surface roughness (Rz);
- inclination of the tread (n);

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- rounded of the cutting edge(R);
- the existence and size of craters;
- deviation from the shape and position.

The first two parameters determine the quality class of the cut surface and the following are used for visual assessment of the quality of the cut.

This International Standard applies to materials suitable for oxyfuel flame cutting, plasma cutting and laser cutting. It is applicable to flame cuts from 3 [mm] to 300 [mm], plasma cuts from 1 mm to 150[mm] and to laser cuts from 0,5 [mm] to 40 [mm].

This International Standard includes geometrical product specifications and quality tolerances. Perpendicularity or angularity tolerance levels are defined by EN ISO 9013: 2002 and are defined five quality classes (table 1 and fig.1).

Laser cutting is placed in the first two quality classes because if the cutting regime is optimum, laser cut surface quality is very good and the surface deviation having minimum values.

Table 1. Quality classes

Bereich	Rechtwinkligkeits- oder Neigungstoleranz, *u* mm
1	0,05 + 0,003*a*
2	0,15 + 0,007*a*
3	0,4 + 0,01*a*
4	0,8 + 0,02*a*
5	1,2 + 0,035*a*

Perpendicularity or angularity tolerance U is defined as the distance between two parallel straight lines (tangents) between which the cut surface profile is inscribed, and within the set angle (e.g. 90° in the case of vertical cuts), figure 1.

The perpendicularity or angularity tolerance includes not only the perpendicularity but also the flatness deviations.

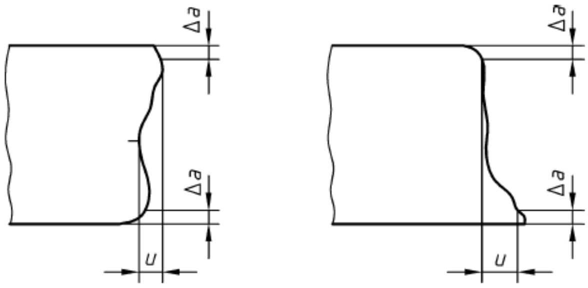


Figure 1 Perpendicularity or angularity tolerance

The measurements must be performed on purified; oxide-free and error-free outer ask sectional areas. A reference element applies the top and bottom of the thermally cut work piece. The work piece must be plane and be clean.

Number and location of measuring points must be agreed upon between manufacturers. If no requirements are established, are for U: 2 times 3 measurements with 20 mm distance from each other per meter section.

3. EXPERIMENTAL MODELING

On the laser cutting process, feed rate is the most important parameter terms of productivity operation (a higher feed rate means a higher economic efficiency). To accurately determine the levels of variation for the factorial experiment was performed an OFAT experiment were only the feed rate v[mm/min] was varied and perpendicularity tolerance U_{max} [mm] was measured.

The other parameters of the laser cutting machine were kept constant and their values were set according to recommendations of the machine programming book and laser operators.

Table 2. S355JR 3mm

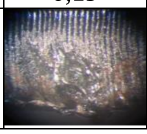
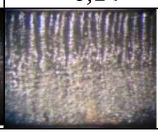
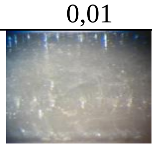
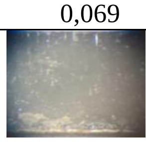
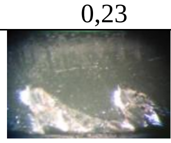
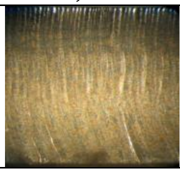
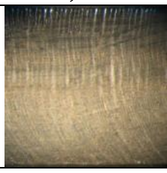
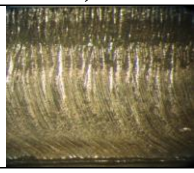
No.	64	63	62	65	66	67
v [mm/min]	800	1500	3000	3400	4000	4500
U_{max} [mm]	0,19	0,14	0,017	0,01	0,069	0,23
picture						

Table 3. S355JR 6mm

No.	36	35	32	31	30	33	34
v [mm/min]	1600	1800	2000	2100	2200	2350	2500
U_{max} [mm]	0,127	0,085	0,055	0,053	0,063	0,091	0,139

picture							

Table 4. S355JR 10mm

No.	10	1.3	9	11	8
v [mm/min]	1200	1330	1400	1500	1600
U_{max} [mm]	0,052	0,030	0,029	0,061	
picture					

For the parameters which remain constant the followings values were selected:

- ✓ nozzle size: 1,2 [mm];
- ✓ nozzle focus NF=-1 [mm];
- ✓ gap offset NW=1[mm];
- ✓ assist gas pressure p=0,6 [bar];
- ✓ laser power P=1400 [W];
- ✓ laser frequency F=600 [Hz];
- ✓ laser duty R=100[%].

In table 1 there is shown the roughness value by cutting mild steel, S355JR, with thickness 3 [mm] for different cutting speeds.

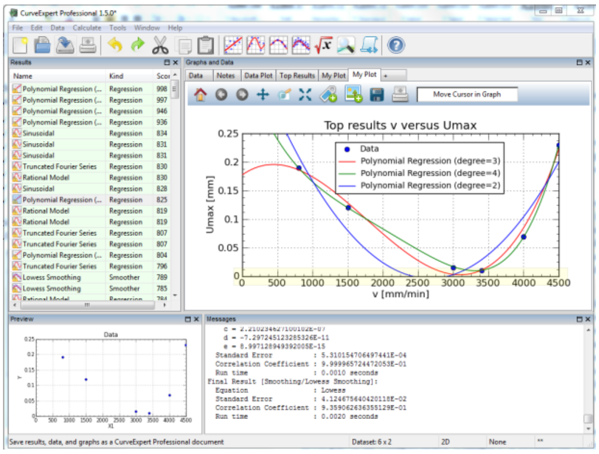


Figure 2 CurveExpert Professional Software

Using the CurveExpert Professional 1.5.0 software, figure 2 with input data from table 2 was find some regression functions which approximate the perpendicularity tolerance Umax[mm] variation by cutting speed v[mm/min].

From the proposed functions it was selected the regression function with the bigger score (976 points) and witch approximate better the perpendicularity tolerance Umax[mm] variation by cutting speed v[mm/min]. The chosen model was the polynomial model, eq 1.

Regression function definition for 3 mm thickness with a confidence interval of 95%, it is shown below:

$$y = a + b*x + c*x^2 + d*x^3 \qquad (1)$$

where:

- ✓ a = 0.165134
- ✓ b = 0.000111566
- ✓ c = -1.21195e-07
- ✓ d= $2.20937e^{-11}$

The obtained function can be used to calculate the perpendicularity tolerance value for a specified speed rate or calculate the required speed rate to achieve a certain the perpendicularity tolerance.

The laser system manufacturer gives no indication about surface quality achieved and also gives no indication how the cutting parameters should be modified to achieve the perpendicularity tolerance imposed by the design or by standard classes.

At low speed rate (ex. 1000 mm/min) appear melted craters on the cutting surface, in the lower work piece (table 2, sample 64) because there is an excess of energy. At feed rates between 1500[mm/min] and 4000[mm/min] surface defects disappear and the perpendicularity tolerance decreases as speed rates increases until 3105[mm/min] and when the cutting speed increases above this value than the perpendicularity tolerance increases with increasing feed rates.

According to the standard ISO 9013 the work piece with thickness 3 [mm] is in the first quality class when the *Umax*<=0,059 [mm]. From our analysis results that for having a part situated in the first quality class the cutting speed must be v <=3849,5[mm/min]. The cutting speeds below 3105[mm/min] will be not used because below this value the perpendicularity tolerance increases and also the manufacturing costs will increase with reducing cutting speed.

The experiment shows that at the maximum feed rate suggested from laser system manufacturer v=3000[mm/min] the perpendicularity tolerance is U_{max}=0,0056 [mm] and the part is situated in the first quality class. At a feed rate v=3849,5[mm/min], which is with 28,31% higher than the maximum speed suggested from laser system manufacturer, the perpendicularity tolerance has the value U_{max}=0,059 [mm]. We can see that at this speed rate higher than indicated by the tool manufacturer (table 1, sample 66) cut quality is very good and the perpendicularity tolerance remain in the first quality class.

According to the standard ISO 9013 the work piece with thickness 3mm is in the second quality class when the U_{max} is between 0,059[mm] and 0,171 [mm]. From our analysis result that to have work pieces situated in the second quality class the cutting speed must be between 3849,5 [mm/min] and 4334 [mm/min].

The maximum cutting speed 4334 [mm/min] will be used to cut pieces for second quality class because the manufacturing costs will decrease with increasing cutting speed.

The experiment shows that at the maximum feed rate suggested from laser system manufacturer v=3000[mm/min] the perpendicularity tolerance is U_{max}=0,056 [mm], and at a feed rate v=4334[mm/min], which is with 44,46% higher than the maximum speed suggested from laser system manufacturer, the perpendicularity tolerance has the value U_{max}= 0,171 [mm] (table 1, sample 66) and the cut quality is situated in the second quality class.

At feed rates higher that 4334[mm/min] craters appear on the lower part of the work piece (table 2, sample 67), because the laser beam is fluctuating. Beam inconsistency is due to oxides occurring in the cutting area. These oxides are reflective and redirect photons randomly. Some of them will be directed outside the cutting area and will have no effect on the cut. The other will be in cutting area were creates more energy, which create melting material on the bottom edge and instantaneous oxidation with formation of oxides bags.

For cutting mild steel S355JR with thickness 6 mm, the parameters which remain constant were chosen as follows:

- ✓ nozzle size: 1,5 [mm];
- ✓ nozzle focus NF=-1 [mm];
- ✓ gap offset NW=1,5[mm];
- ✓ assist gas pressure p=0,6 [bar];
- ✓ laser power P=1800 [W];
- ✓ laser frequency F=600 [Hz];
- ✓ Laser duty R=100[%].

In table 2 it is shown the perpendicularity tolerance value by cutting 6 [mm] mild steel, *S355JR*, with thickness 3 [mm] for different cutting speeds. Using the same procedure, the proposed function selected as the regression function for 6 mm thickness with the bigger score (978points) is a polynomial one, figure 3. Regression function definition for a confidence interval of 95%, in this case it is shown below:

y = a + b*x + c*x^2 + d*x^3 (2)

where:

- ✓ a = 0.324439
- ✓ b = 0.000441762
- ✓ c = -6.13603e-07
- ✓ d = 1.62961e-10

The obtained function can be used to calculate the perpendicularity tolerance value for a specified feed rate or calculate the required feed rate to achieve a certain perpendicularity tolerance.

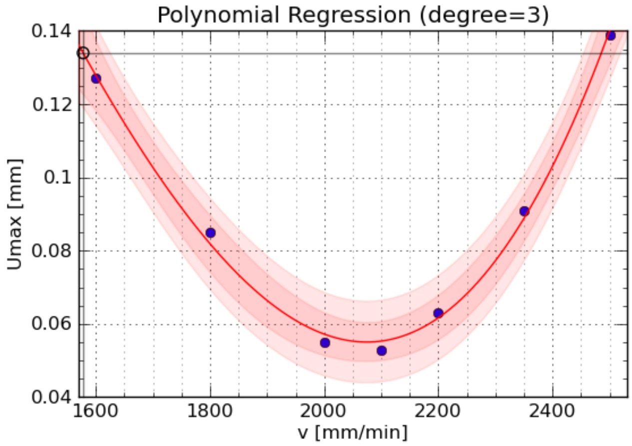


Figure 3 Regression function for 6 mm thickness

According to the standard ISO 9013 the work piece with thickness 6 [mm] is in the first quality class when the *Umax*<=0,068 [mm]. From our analysis results that to have work pieces situated in the first quality class the cutting speed must be *v* <=2248,3[mm/min].

The cutting speeds below 2075[mm/min] will be not used because below this value the perpendicularity tolerance increases and also the manufacturing costs will increase with reducing cutting speed.

The experiment shows that at the maximum feed rate suggested from laser system manufacturer v=2000[mm/min] the perpendicularity tolerance is U_{max}=0,057 [mm] and the work piece is situated in the first quality class. At a speed rate v=2248,3[mm/min], which is with 12,41% higher than the maximum speed suggested from laser system manufacturer, the perpendicularity tolerance has the value U_{max}=0,068 [mm]. We can see that at this feed rate higher than that indicated by the tool manufacturer (table 2, sample 32) cut quality is very good and the perpendicularity tolerance remain in the first quality class.

According to the standard ISO 9013 the work piece with thickness 6 [mm] is in the second quality class when the U_{max} is between 0,068[mm] and 0,192 [mm]. From our analysis result that to have work pieces situated in the second quality class the cutting speed must be between 2248,3 [mm/min] and 2604,9 [mm/min].

The maximum cutting speed 2500 [mm/min] will be used to cut pieces for second quality class because the manufacturing costs will decrease with increasing cutting speed.

The experiment shows that at a feed rate v=2500[mm/min], which is with 25% higher than the maximum speed suggested from laser system manufacturer, the perpendicularity tolerance has the value U_{max}=0,171 [mm]. We can see that at this feed rate higher than that indicated by the tool manufacturer (table 3, sample 34) cut quality is situated in the second quality class.

At feed rates higher that 2500[mm/min] the work piece can't be removed anymore from the metal sheet because it remain welded. For cutting mild steel S355JR 10 [mm], the parameters witch remain constant were set at the following values:

- ✓ nozzle size: 2 [mm];
- ✓ nozzle focus NF=-3 [mm];
- ✓ gap offset NW=2[mm];
- ✓ assist gas pressure p=0,6 [bar];
- ✓ laser power P=1800 [W];
- ✓ laser frequency F=600 [Hz];
- ✓ laser duty R=100[%].

In table 3 there is shown the perpendicularity tolerance value by cutting mild steel, *S355JR*, with thickness 10 [mm] for different cutting speeds. Using the same procedure, as in the above cases the proposed function selected as the regression function with the bigger score (979 points). The chosen model was also the *polynomial model*, fig.4.

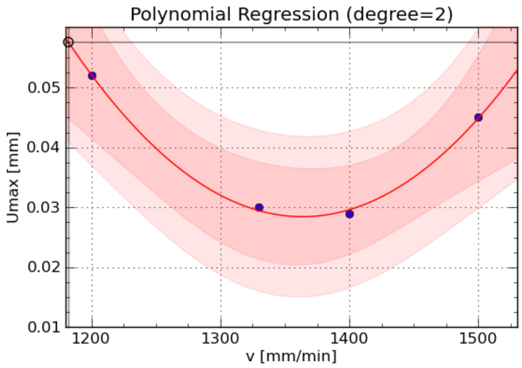


Figure 4 Regression function for 10 mm thickness

The obtained function can be used to calculate the perpendicularity tolerance value for a specified feed rate or calculate the required feed rate to achieve a certain the perpendicularity tolerance.

At speed rate v =1500[mm/min] appear melted edge on the bottom of the cutting surface (table 4, sample 11) because there is a lack of energy and will be used only cutting speeds below 1500[mm/min].

At cutting speed 1600[mm/min] the work piece can't be remove any more from the metal sheet and it remains welded (table 3, sample 8).

According to the standard ISO 9013 the work piece with thickness 10 [mm] is in the first quality class when the U_{max}<=0,08 [mm]. From our model results for having work parts situated in the first quality class the cutting speed must be <=1605,4[mm/min].

Cutting speeds below 1360[mm/min] will be not used because below this value the perpendicularity tolerance increases and also the manufacturing costs will increase with reducing cutting speed.

The experiment shows that at the maximum feed rate suggested from laser system manufacturer v=1200[mm/min] the perpendicularity tolerance is U_{max}=0,052 [mm] and the work piece is situated in the first quality class. At a speed rate v=1400[mm/min], which is with 16,66% higher than the maximum speed suggested from laser system manufacturer, the perpendicularity tolerance has the value U_{max}=0,029 [mm].

We can see that at this feed rate higher than that indicated by the tool manufacturer (table 3, sample 9) cut quality is very good and the perpendicularity tolerance remain in the first quality class.

4. CONCLUSIONS AND INTENTIONS

The main conclusions drawn from the paper are:

- The study performed in the present paper is a part of other researches made to determine other aspects of precision for the parts obtained by the laser cutting method;
- The importance of this parameter is done by the need that the part must have the same form on both faces with the corresponding quality class;
- In the previous papers we find the cutting speed as the main parameter of influence on perpendicularity tolerance and because it has also a major influence on the productivity of the process;
- The regression functions obtained gave us the possibility to find an optimum for the value of cutting speed suitable for the precision and also for improved productivity;

- The mathematical model derived from the experiment has a degree of confidence P=95% for the domain of variation of the input parameter;
- With this model we can find for the imposed value of U_{max} the corresponding limits of the speed rate.
- Perpendicularity or angularity tolerance is a very important factor output of the laser cutting process because its value is strictly defined by ISO 9013 and share quality laser cut parts in four quality classes.

- The experiment shows the possibility of a slightly increasing of the cutting speed limits in all the analyzed cases thus:
  - For the material with 6mm thickness cutting speed was increased by 12,41% obtaining parts located in 1st class quality and with 25% more than the value indicated by the machine obtaining parts located in second quality class.
  - For the material with 10mm thickness cutting speed was increased by 16,66% obtaining parts located in 1st class quality
- Was realized the simulation of the laser cutting process and parts classification in quality classes according to deviation from perpendicularity or angularity tolerance.
- In Figure 5 is plotted the variation of perpendicularity tolerance U_{max} with cutting speed and material thickness. It is noted that the perpendicularity tolerance increases with increasing of cutting speed and decreasing of the material thickness.

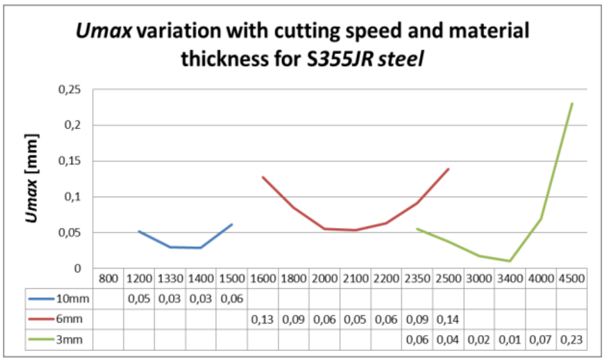


Figure 5. ***U_{max}* variation with feed rate and material thickness**

- Based on the graph from figure 8 we can affirm that perpendicularity or angularity tolerance increases in average with 96% at each decreasing with 3 [mm] of the material thickness.

5. REFERENCES

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