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DEVELOPMENT OF LASER CUTTING TECHNOLOGY WITH HIGH QUALITY OF THE CUT SURFACE

Key words: laser cutting, surface accuracy, cutting technology.

Abstract: This paper describes the development of thermal cutting technology aimed at the achievement of the best possible quality class in order to obtain smooth, aesthetic edges. The technology has been developed for two different types of materials: S235JR steel grade and AW-5754 aluminium alloy. The main objective of the developed technology is to eliminate the additional mechanical treatment of the surface following the laser cutting and to allow the classification of the obtained surfaces (without additional measurements) to the appropriate quality class defined by the ISO 9013 standard.

Opracowanie technologii cięcia laserowego o wysokiej jakości powierzchni

Słowa kluczowe: cięcie laserowe, dokładność powierzchni, technologia cięcia.

Streszczenie: W artykule przedstawiono technologię cięcia termicznego opracowaną pod kątem osiągnięcia możliwie najlepszej klasy dokładności w celu otrzymania gładkich, estetycznych krawędzi. Technologię cięcia opracowano dla dwóch różnych rodzajów materiałów: stali S235JR oraz stopu aluminium AW-5754. Przeprowadzono wstępne testy cięcia i dobrano wartości parametrów mocy cięcia, odległości ogniska wiązki (focus) oraz ciśnienia gazu jako stałe dla danych grubości i rodzajów materiału. Zmianie poddawano prędkość cięcia, gdyż ten parametr ma decydujący wpływ na dokładność cięcia.
Po przeprowadzonych badaniach zauważono, że wraz ze wzrostem prędkości, dla danej grubości blachy, generalnie obserwuje się zmniejszenie wartości chropowatości Rz5. Jednak z drugiej strony w większości przypadków wzrost prędkości cięcia powoduje wzrost wielkości tolerancji prostopadłości powierzchni „u".
Opracowano funkcje matematyczne, które umożliwiają dobór parametrów cięcia laserowego w zależności od rodzaju ciętego materiału, jak również od jego grubości. Zintegrowanie tych funkcji matematycznych z urządzeniem do cięcia laserowego może utworzyć zautomatyzowany system zapewniający wymierne korzyści prowadzące do otrzymania powtarzalnej technologii cięcia charakteryzującej się wysoką jakością powierzchni (odpowiadające ZAKRESOWI nr 1 zgodnie z normą ISO 9013) zarówno pod kątem prostopadłości powierzchni uzyskanej po cięciu „u", jak i chropowatości powierzchni wyrażonej wartością „Rz5".

Introduction

Laser technology was applied for the first time for cutting of steel sheets using a CO_2 laser. It took place in 1967 [1]. Thanks to advancements in the design of laser devices, laser cutting technology has become one of the basic technologies of cutting engineering materials [2]. CO_2 lasers have been used for a long time for laser cutting, but recently, fibre lasers have become more and more popular [3, 4].

Fibre optic lasers are characterized by a high quality laser beam. The BPP (Beam Parameter Product) value does not increase up to the cutting power value of 2 kW (i.e. the quality of the laser beam does not deteriorate). The BPP increases (the laser beam quality deteriorates) only when cutting with power greater than 2 kW [2].

Fibre-optic lasers emit waves of a relatively short length (e.g., their wavelength is tenth times shorter as compared to CO_2 lasers). Shorter wavelength improves the absorption coefficient of laser radiation. As a result, it is possible to cut materials such as copper, nickel and its alloys, as well as composite materials such as Kevlar coated sheet metal [2].

Studies available in the professional literature concerning tests on surfaces obtained using various types of lasers demonstrate that the quality of the cut surface depends mainly on the roughness. In the study [5] on the surface quality after cutting with a Nd-YAG laser, it was shown that the surface roughness increases with the increase of the cutting speed.

It also depends on the frequency of the pulse as well as on its length. In other studies [6], the authors observed that the surface roughness after cutting with Slab type CO_2 gas lasers was sometimes increasing and sometimes was falling with the increase of the cutting power. Other researchers [7] determined optimal cutting parameters without roughness measurement.

However, the standard [8] clearly states that the mean height of the profile Rz5 and the value of the perpendicularity tolerance of the surface after cutting "u" are used to qualify the cutting quality. Authors of the paper [9] compared the quality of cutting with a CO_2 laser and a fibre laser based, among others, on the standard [8]. It was demonstrated that greater dimensional quality, better roughness, higher drag (n) quality, and perpendicularity or angularity tolerance (u) were obtained for cutting using a fibre laser.

This paper describes the development of thermal cutting technology aimed at the achievement of the best possible quality class in order to obtain smooth, aesthetic edges. The technology has been developed for two different types of materials: S235JR steel grade and AW-5754 aluminium alloy. The main objective of the developed technology is to eliminate the additional mechanical treatment of the surface following the laser cutting and to allow the classification of the obtained surfaces (without additional measurements) to the appropriate quality class defined by the ISO 9013 standard.

1. Research object

High quality cutting technology has been developed for two different types of materials: S235JR steel grade and AW-5754 aluminium alloy. Initial cutting tests were carried out and the cutting power values, the laser beam focus, and gas pressure were selected. The main tests were carried out using these parameters as constant ones for a given thickness and type of material. The cutting speed was subject to change because this is the parameter [7] that is decisive as regards the cutting quality.

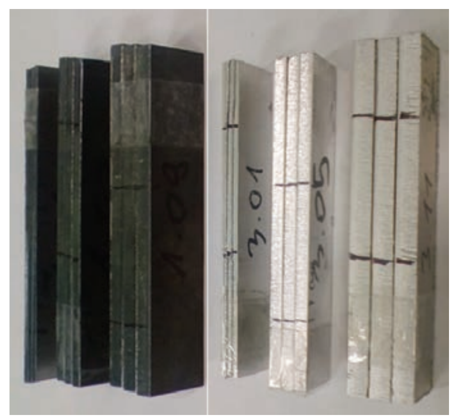

Fig. 1. A photograph of sets of samples prepared for testing

Eighteen samples of 100x20 mm and various thicknesses (2, 4 and 6 mm) were prepared for the main tests. Figure 1 shows photographs of sample packages. Cutting parameters for individual samples are summarized in Table 1.

Table 1. Specimen cutting parameters for the development of high quality cutting technology

	Sample number	Cutting speed mm/min	Sample number	Cutting speed mm/min	Sample number	Cutting speed mm/min
	Thickness 2 mm		Thickness 4 mm		Thickness 6 mm	
S235JR	Laser power = 1.2 kW		Laser power = 2 kW		Laser power = 2 kW	
	Focus = 0.2 mm		Focus = -1.6 mm		Focus = -1.6 mm	
	Pressure = 6.0 bar		Pressure = 0.65 bar		Pressure = 0.6 bar	
	1.01	$v_1 = 5000$	1.05	$v_1 = 3000$	1.09	$v_1 = 1800$
	1.02	$v_2 = 6000$	1.06	$v_2 = 3200$	1.10	$v_2 = 2200$
	1.03	$v_3 = 7000$	1.07	$v_3 = 3400$	1.11	$v_3 = 2600$
AW 5754	Laser power = 2 kW		Laser power = 2 kW		Laser power = 2 kW	
	Focus = -1.5 mm		Focus = 3.0 mm		Focus = 5.5 mm	
	Pressure = 10.0 bar		Pressure = 15.0 bar		Pressure = 15.0 bar	
	3.01	$v_1 = 6000$	3.05	$v_1 = 2000$	3.09	$v_1 = 840$
	3.02	$v_2 = 7000$	3.06	$v_2 = 2500$	3.10	$v_2 = 980$
	3.03	$v_3 = 7500$	3.07	$v_3 = 3000$	3.11	$v_3 = 1120$

2. Measurement of surface quality after cutting operation

According to the [8] standard, the quality of surfaces after thermal cutting should be mainly defined by characteristic values, such as perpendicularity or angularity tolerance “u” and the mean height of the profile “Rz_5”. Those parameters were tested using a Mahr MarSurf GD 120 testing machine. A sample photograph of the conducted measurements is shown in Figure 2.

Measurements of the “u” parameter were performed three times in various places on the longer surface of the cut-out specimens. According to the [8] standard, the roughness was measured at a height of 1/3a as seen from the upper surface of the sheet metal. The measurements were performed three times at different spacings. Table 2 presents the results of the measurements carried out.

Fig. 2. A sample photograph of the roughness measurement

Table 2. Results of „u” and „rz_5” measurements

	Thickness	2 mm			4 mm			6 mm		
S235JR	**Sample number**	**1.01**	**1.02**	**1.03**	**1.05**	**1.06**	**1.07**	**1.09**	**1.10**	**1.11**
	u_1, µm	0.014	0.037	0.114	0.096	0.091	0.058	0.073	0.086	0.086
	u_2, µm	0.029	0.034	0.109	0.095	0.105	0.059	0.073	0.092	0.098
	u_3, µm	0.023	0.036	0.158	0.098	0.093	0.056	0.046	0.092	0.088
	$u_{śr}$, µm	**0.022**	**0.036**	**0.127**	**0.096**	**0.096**	**0.058**	**0.064**	**0.090**	**0.091**
	Rz_{5_1}	4.856	3.451	2.695	2.566	2.251	2.016	64.186	22.884	4.841
	Rz_{5_2}	4.543	2.026	1.689	2.670	2.256	1.693	60.458	18.168	6.584
	Rz_{5_3}	4.986	3.245	3.248	3.395	2.155	2.111	55.299	24.881	8.526
	$Rz_{śr}$	**4.795**	**2.907**	**2.544**	**2.877**	**2.221**	**1.940**	**59.981**	**21.977**	**6.650**
AW 5754	**Sample number**	**3.01**	**3.02**	**3.03**	**3.05**	**3.06**	**3.07**	**3.09**	**3.10**	**3.11**
	u_1, µm	0.014	0.037	0.114	0.096	0.091	0.058	0.073	0.086	0.086
	u_2, µm	0.039	0.034	0.109	0.095	0.105	0.059	0.073	0.093	0.098
	u_3, µm	0.033	0.036	0.158	0.098	0.093	0.056	0.046	0.093	0.088
	$u_{śr}$, µm	**0.029**	**0.036**	**0.127**	**0.096**	**0.096**	**0.058**	**0.064**	**0.091**	**0.091**
	Rz_{5_1}	4.856	3.451	3.695	3.566	3.351	3.016	64.186	33.884	4.841
	Rz_{5_2}	4.543	3.036	1.689	3.670	3.356	1.693	60.458	18.168	6.584
	Rz_{5_3}	4.986	3.345	3.348	3.395	3.155	3.111	55.399	34.881	8.536
	$Rz_{śr}$	**4.795**	**3.277**	**2.911**	**3.544**	**3.287**	**2.607**	**60.014**	**28.977**	**6.654**

3. Scopes of cutting quality classification according to ISO 9013

Table 3 summarizes the limit values of “u” and “Rz_5” specified for SCOPE 1 depending on the thickness of the material subject to cutting. When developing high quality cutting technology, both the “u” perpendicularity tolerance and the average height of the profile (Rz_5) as well as the efficiency of the cutting process will be taken into account.

Table 3. “u” and “rz5” tolerances for scope 1 determined in accordance with [8]

Scopes of perpendicularity or angularity tolerance „u”				Scopes of mean height of the profile „Rz_5”			
Thickness a, mm	2	4	6	Thickness a, mm	2	4	6
SCOPE 1, µm	0.056	0.062	0.068	SCOPE 1, µm	11.20	12.40	13.60

4. Selection of high quality surface cutting technology

While selecting the cutting technology, the data obtained during the tests presented in Table 2 were analysed. Great emphasis was also put on the relatively high efficiency of the cutting process, trying to select the highest cutting speed while maintaining high quality falling within SCOPE 1 (according to Table 3) for both "u" and "Rz_5". A graphic illustration of the results is shown in Figures 3 and 5 for S235JR steel grade and AW 5754 aluminium alloy, respectively. Vertical dashed lines in the presented graphs indicate the end of SCOPE 1 defined by the [8] standard. This scope, as shown in Table 3, depends on the thickness of the material being cut. The colours of the presented SCOPES marked by dotted vertical lines are consistent with the colours of the applied experimental points for a given material thickness.

For the analysis of the obtained test results, it was assumed that the relationship of "u" and "Rz_5" as a function of the cutting speed for a given material thickness is similar to a straight line. In all the analysed cases, the R^2 determination coefficient was higher than or equal to 0.75.

3.1. For S235JR Grade Steel

In the case of S235JR grade steel, for the thickness of 2 mm, when cutting at speeds approaching 7 000 mm/min., the "u" value above SCOPE 1 defined by the standard shall be obtained (Fig. 3a). Regarding the "Rz_5" value, for the thickness of 2 mm, all tested parameters fall into SCOPE 1 (Fig. 3b). It was observed that the roughness value defined by the "Rz_5" parameter decreases as the speed increases. However, increased speed for a thickness of 2 and 6 mm can cause deteriorated perpendicularity of the cut.

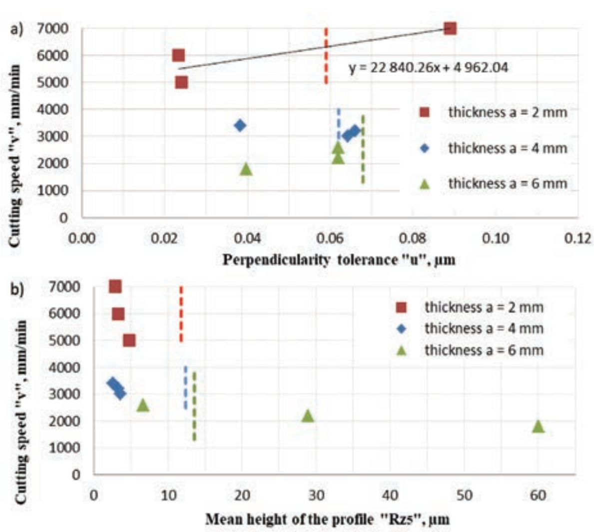

Fig. 3. Graphical representation of test results for S235JR steel grade

The parameters for the thickness of 2 and 6 mm were used to determine the function defining the parameters for the selection of the technology of cutting with high quality falling within SCOPE 1 of the [8] standard. For a thickness of 2 mm, the optimum cutting speed was chosen from the intersection of the regression line with the dotted line of SCOPE 1. This value amounted to 6310 mm/min. For cutting 6 mm thick sheet metal, the use of lower speeds (below 3500 mm/min) causes a significant deterioration of the surface roughness "Rz_5". However, a reduction of the cutting speed improves the perpendicularity of the surface obtained after cutting. The use of the highest of the tested speeds for cutting 6 mm thick sheet metal results in achievement of the quality of the surface that qualifies it to SCOPE 1.

Figure 4 shows mathematical functions defining the selection of parameters by means of which cutting quality at the level of SCOPE 1 can be obtained. The functions, depending on the thickness of the material to be cut, allow the selection of the optimum laser power (P), cutting speed (v), and focus location (F).

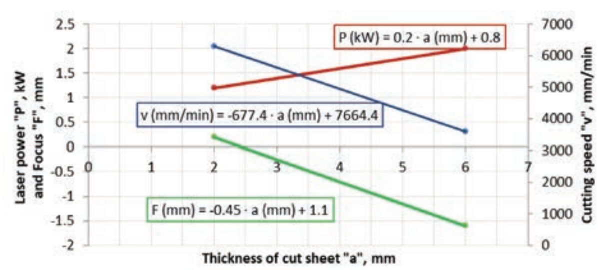

Fig. 4. Mathematical functions defining the selection of cutting parameters for S235JR steel grade

3.2. For AW 5754 aluminium alloy

Aluminium alloys are materials characterized by a relatively low laser beam energy absorption coefficient. This means that a relatively large portion of the laser beams are reflected from the surface of the aluminium sheet. Cutting of these materials requires higher laser power than in case of cutting, e.g., "black" sheet metal.

The parameters for the thicknesses of 2, 4, and 6 mm were used to determine the function defining the parameters for the selection of the technology of cutting with high quality falling within SCOPE 1 of the [8] standard. For a thickness of 2 mm, the optimum cutting speed was chosen from the intersection of the regression line with the dotted line of SCOPE 1 (Fig. 5a). This value amounted to about 6780 mm/min. For a thickness of 4 mm, the most optimum speed as regards to the surface quality after cutting was the highest tested speed of 3000 mm/min. In the case of cutting 6 mm thick aluminium alloy sheets, the use of the cutting speed up to about 870 mm/min will result in the qualification of perpendicular tolerance to SCOPE 1. However, at this speed, Rz_5 roughness will exceed SCOPE 1

(Fig. 5a). On the other hand, a cutting speed of above 1075 mm/min (Fig. 5b) will result in a cutting surface that can be qualified to SCOPE 1 in terms of the "Rz_5" roughness value. However, in that case, the perpendicularity tolerance "u" will be outside the SCOPE 1. Searching for a compromise in order to develop a high quality cutting technology, the mean value of those two specified speeds was used. However, cutting sheet metal plates made of the tested alloy with a thickness close to 6 mm may result in the non-qualification of the cutting surface in terms of "u" or "Rz_5" to SCOPE 1.

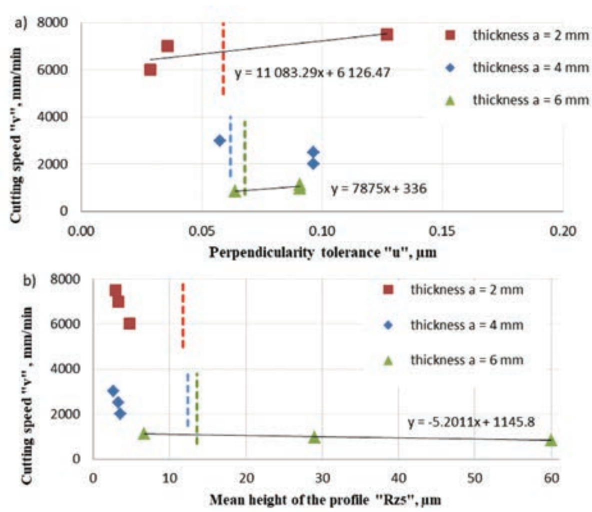

Fig. 5. Graphical representation of test results for AW 5754 aluminium alloy

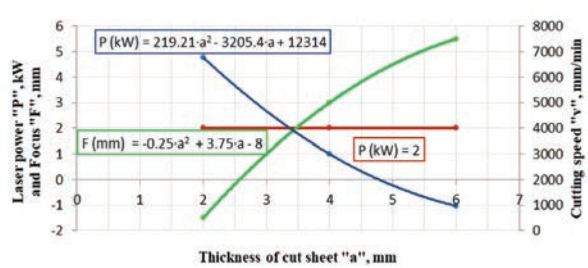

Fig. 6. Mathematical functions defining the selection of cutting parameters for AW 5754 aluminium alloy

Figure 6 shows mathematical functions which allow obtaining a high surface quality for a given material thickness and presents a graphical representation.

Summary

After the tests, it was noticed that, for a given sheet thickness, the "Rz_5" roughness value is generally reduced with the increase of the speed. On the other hand, in most cases, an increase in the cutting speed results in an increase in the "u" tolerance value. In order to select the technology ensuring a high quality surface, it is worth determining which parameter – "u" or "Rz_5" – is more important when it comes to the quality of the surface after the cutting process.

This paper provides a method of developing a cutting technology that allows one to obtain high quality of cutting surfaces for two types of materials: S235JR and AW 5754. Within the framework of this study, mathematical functions have been developed that enable the selection of laser cutting parameters depending on the type of material being cut as well as its thickness. By integrating these mathematical functions with a laser cutting equipment, an automated system can be created that provides tangible benefits leading to development of a reproducible cutting technology characterized by high surface quality (corresponding to SCOPE 1 according to the [8] standard) both in terms of the perpendicularity of the surface after cutting "u" and surface roughness expressed by "Rz_5."

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