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The utmost thickness of the cut sheet for the qualitative oxygen-assisted laser cutting of low-carbon steel

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Abstract

The peculiarity of the laser cutting is its high speed combined with the high quality of the cut surface. The issues, how the cutting speed and cut roughness change with the sheet thickness, and what is the utmost thickness at which the quality is acceptable, are of practical importance. Theoretical models of the laser cutting developed today do not permit answering these questions. In the present work, the task is solved experimentally for the oxygen-assisted laser cutting of low-carbon steel. Under study was the dependence of the cut surface roughness on the cutting speed within the wide range of cut sheet thicknesses. The experiments were carried out with the CO_2 laser. The empirical dependencies of the optimal cutting speed (at which the cut surface roughness is minimal) on the sheet thickness are found. It is demonstrated that there is the utmost thickness of 40...50 mm, and above it the qualitative cutting is impossible. The obtained results are compared to the similar ones obtained for the fiber laser.

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Keywords: laser cutting; CO_2 laser; fiber laser; uncontrolled burning; utmost thickness

Nomenclature

V	cutting speed
t	sheet thickness
W	laser power
b	kerf width
γ	thermal diffusivity

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1. Introduction

In the recent decade, metal cutting is dominating in the world. Laser technologies in material processing provide high production rate and accuracy, save energy and materials, permits implementing new technological solutions and using hard-to-machine materials, plus guarantee environmental compliance. Today, the most common lasers used for the cutting are the gas-discharge CO_2 laser with the wavelength of 10.6 μm and fiber or disc lasers with the wavelength of about 1 micrometer (Steen 1991, Powell et al. 2012, Scintilla et al. 2013).

The quality of the processed part is one of the critical parameters of the laser cutting. For many applications, cut surface roughness and dross absence are the main quality indices (Orishich et al. 2014). At the minimal roughness, the other indices of the cut quality are also within tolerance. Thus, the laser cut of minimal roughness and no dross is of practical interest. It must be emphasized that the maximal cutting speed is not always optimal from the viewpoint of the cut quality (Mahrle et al. 2009, Orishich et al. 2015).

The present work deals with the investigations of the high-quality oxygen-assisted laser cutting of low-carbon steel by the fiber and CO_2 lasers in order to determine the utmost thickness of the cut sheet. The obtained results permit better understanding the scope for laser cutting.

Laser-oxygen cutting presents the forced burning of iron in oxygen. In this case, the laser power and exothermic reaction of oxidation make approximately equal contribution in the energy balance [Steen W. M., 1991]. During the laser-oxygen cutting, pure energy of the iron oxidation reaction is not enough to melt the material and propagate the cut front. Thus, the cut is “bound” to the laser beam, the cut channel width cannot essentially increase the diameter of the focused beam. The cut surface roughness is not too much in the steady mode, the maximal cut quality is reached at the velocity of V_{opt}.

The steady mode of the forced burning with the low roughness is reachable within a limited range of cutting speeds. The lower boundary of this range V_{bur} depends on the transition to the uncontrolled self-sustained burning. As the cutting speed decreases, the material temperature rises near the cut front, and, as the speed is below V_{bur}, iron burning and melting front propagation are possible without laser radiation support, just owning to the oxidation reaction energy. The cut channel width in this case may extend sideward within the limits of the oxygen jet which may have the diameter of 2 mm and more in the case of thick sheets. The oxygen jet at the laser-oxygen cutting is not optimized for the cut channel formation, the front of material rupture propagates irregularly, and the process becomes uncontrolled. Consequently, the cut channel has an uneven side surface and high roughness.

Having the speed V_{opt} of the high-quality cutting and its dependence on the sheet thickness, plus the critical speed V_{bur} of the transition into the uncontrolled mode, it is possible to find the utmost thickness from the condition $V_{opt}=V_{bur}$, above which the cut width and roughness rise dramatically, and the high-quality cutting is impossible.

2. Experimental technique

In the present experiments, cutting was performed by an IPG/IRE-Polus ytterbium fiber laser with a power W = 2kW, a beam parameter product (BPP), which is the product of the beam radius in the near field and the angular radius of the beam in the far field, BPP = 3.8mm·mrad, and an IPG collimator (D5-WC/AC model). The beam diameter on the focusing lens behind the collimator was 17 mm, and the focal length of the lens was 200mm. Fiber laser cutting was performed by laser beams with chaotic polarization. A CO_2 laser with BPP=4.7mm·mrad and a self-filtering cavity with a power up to 8 kW was also used. The beam diameter on the focusing lens was 25 mm at focal lengths of the ZnSe lens of 190 and 256 mm. CO_2 laser cutting was performed by laser beams with circular polarization. The distribution of radiation intensity in the focal spot was close to the Gaussian distribution. The focal spot diameter was estimated as the sum of the diffraction diameter of the beam and the diameter of the scattering region due to spherical aberration. The calculated total diameter was 180 μm for the fiber laser and 160 μm forthe CO_2 laser.

Low-carbon St. 3 steel sheets 3-25 mm thick were cut by using laser beams with a power W = 0.5–4.0 kW. The measure of roughness was taken to be the characteristic height of the roughness element R_z and the mean arithmetic deviation of the profile shape R_a. These parameters were measured by an Olympus LEXT laser confocal scanning microscope and a Rank Taylor Hobson profilometer of the FormTalysurf series.

In this work, the cutting was optimized by the criterion of minimal roughness and no dross for the search utmost thickness of the cut sheet. At the first stage, the optimal location of the focus lens was found in respect to the sheet for each sample thickness; this location influences the kerf width (Orishich et al. 2014). Then, the optimal cutting speed V_{opt} was found for the determined beam focus. To gain the minimal roughness necessary to increase the laser power proportionally to the thickness of the cut sheet, so as to satisfy the condition W/t=200±20 W·mm^{-1}.

3. Experimental results

Fig. 1 shows the surface roughness versus speed for the fiber laser at the sheet thickness of 5 mm. the minimal roughness is observed at the optimal speed of 13.3 mm/s. Similarly, the optimal speed was found for the other thicknesses at the fiber- and CO_2 laser cutting.

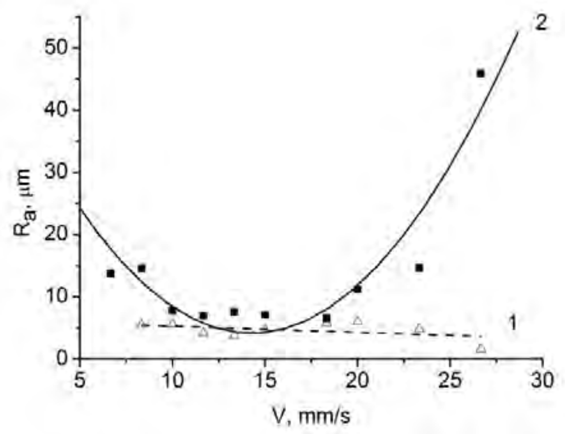

Fig. 1. Roughness versus the cutting speed in the case of laser-oxygen cutting of low-carbon steel sheets by the fiber laser with W=1 kW: roughness near the upper (1) and lower (2) surfaces of the sheet.

Optimized oxygen-assisted laser cutting for both laser types, plus the optimal cutting speed, give that the cut surface roughness rises linearly along with the cut sheet thickness (Fig. 2). Note that the roughness of the samples cut by the fiber laser is higher at any thickness as compared with the ones cut by the CO_2 laser.

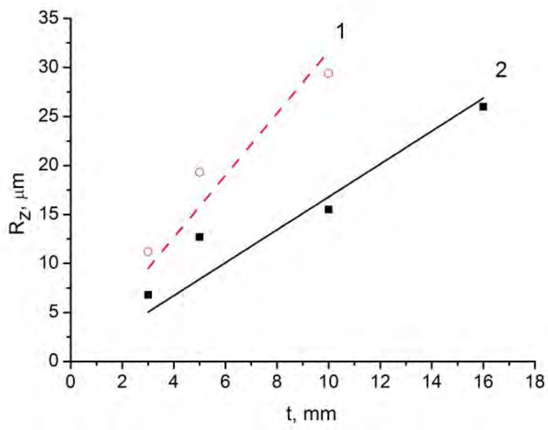

Fig. 2. Roughness value versus cut sheet thickness (1 – fiber laser, 2 – CO_2 laser).

At the optimal oxygen-assisted laser cutting, both in the fiber and CO_2 laser cases, the evident roughness minimum is observed (Fig.1). For both laser types, as the cutting speed exceeds the optimal value, the cut surface roughness rises, which is followed by the kerf channel sealing. At low cutting speeds (considerably lower than the optimal cutting speed V_{opt}), there is the difference between the laser types. During the cutting with the CO_2 laser when the cutting speed reaches ~8.3 mm/s or below, the mode of uncontrolled burning of the material in oxygen begins (Fig. 3.a.). In the case of fiber laser cutting, this effect is not observed even at 0.83 mm/s. (Fig. 3.c.).

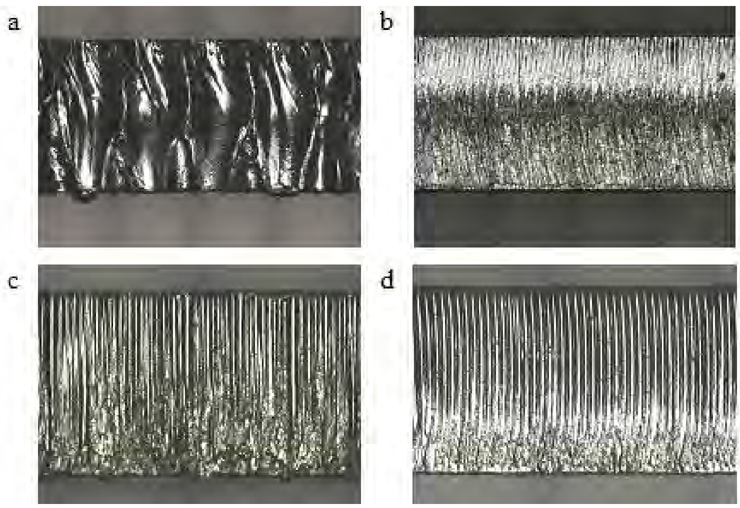

Fig. 3. Photos of the surfaces of samples (t=5 mm) cut by the CO_2 laser (a, b) and fiber laser (c, d) (a – $V=V_{bur}$=8.3 mm/s, b - $V=V_{opt}$=25 mm/s, c – $V=V_{bur}$=0.83 mm/s, d - $V=V_{opt}$=13.3 mm/s).

The cut surface roughness was measured at different focus positions about the sheet surface. It follows from experiments that there is the optimal position of the focus at which the cut surface roughness has its minimum. As the focus position changes, the cut width changes, too. The optimal cut width bopt was found, it corresponds to the minimal roughness. Both for the fiber and CO_2 laser, the optimal kerf width rises along with the cut sheet thickness.

Analysis of the gathered data shows that the minimal cut roughness is reached at $V_{opt} \cdot b_{opt}$ = const. This product does not depend on the sheet thickness and is 11 mm^2/s for the CO_2 laser and 7 mm^2/s for the fiber laser.

Obtained data also permit determining the dependence of b_{opt} on the sheet thickness (Fig. 4). Note that the dependence of the kerf width on thickness weakly relates with the chosen laser type.

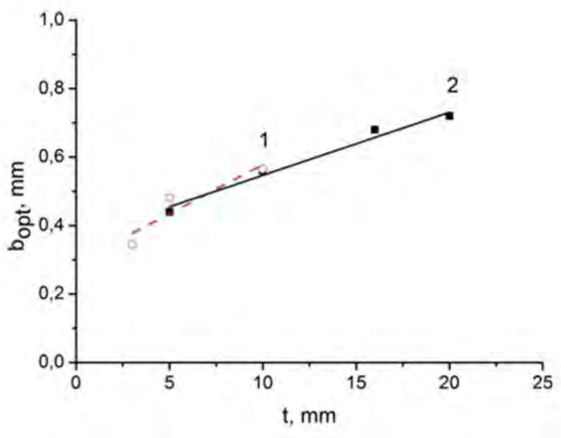

Fig. 4. Optimal kerf width versus the sheet thickness (1 – fiber laser, 2 – CO_2 laser).

At the linear approximation, the dependencies are expressed as follows: $b_{opt}=0.35+0.02t$ for the CO_2 laser and $b_{opt}=0.32+0.027t$ for the ytterbium fiber laser. It permits excluding the kerf width from the condition $V_{opt}b_{opt}$=const, and, within the limits of experimental scattering of +/-15%, presenting the optimal cutting speed through the sheet thickness by the analytical dependence. The relations for the optimal cutting speed look as follows: $V_{opt}=11/(0.35+0.02t)$ for the CO_2 laser and $V_{opt}=7/(0.32+0.027t)$ for the fiber laser (Table 1).

Table 1. Optimal kerf width and optimal cutting speed versus the sheet thickness.

Laser	Kerf width	Cutting speed
CO_2 laser	$b_{opt}=0.35+0.02t$	$V_{opt}=11/(0.35+0.02t)$
Fiber laser	$b_{opt}=0.32+0.027t$	$V_{opt}=7/(0.32+0.027t)$

The criterion based on the limitation of the high-quality laser cutting due to the uncontrolled burning at $V_{opt} = V_{bur}$ is proposed in order to determine the utmost thickness of the cut sheet. It is found experimentally that at any thickness under study, the uncontrolled burning begins at V_{bur} = 6.7 – 8.3 mm/s in the CO_2 laser case. The critical speed V_{bur} was found as follows. Straight-line cuts of 70 mm is length were made. The cutting speed decreased with the pitch of 0.8 mm/s up to the occurrence of the uncontrolled mode when the roughness rises abruptly. The critical speed V_{bur} was found as the speed at which the uncontrolled mode occurs at least on the half of the cut length. The authors of (Steen W. M., 1991) give the value of the critical speed 10 mm/s, which is close to the result of the present work. The difference seems to result from engineering factors such as chemical composition of steel and sheet surface condition.

So, using the resulting expression for V_{opt} (Table 1), one can find the utmost cut thickness at the oxygen-assisted laser cutting of low-carbon steel by the CO_2 laser (Fig.5). Taking into account the error of +/-15% for V_{bur}, it follows from the condition $V_{opt} = V_{bur}$ that the maximal thickness of the sheet at which the high-quality laser-oxygen cutting of low-carbon steel is possible is 40…50 mm.

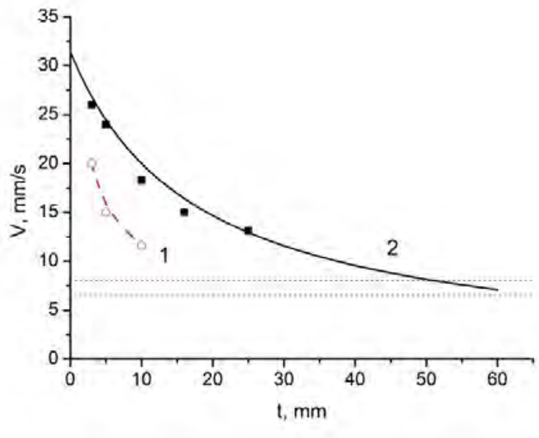

Fig. 5. Optimal cutting speed versus cut sheet thickness (1 – fiber laser, 2 – CO_2 laser).

Since, during the fiber laser cutting of thin sheets (3 – 10 mm) at low speeds, no transition to the uncontrolled burning is observed, we can assume that it will not occur during the cutting of thicker sheets. In this case, the method of determination of the utmost thickness of the cut sample used for the CO_2 laser cutting, cannot be applied to the fiber-laser cutting.

4. Conclusions

The oxygen-assisted laser cutting by the ytterbium fiber laser and CO_2 laser is studied. Empirical dependencies of the optimal cutting speed and optimal kerf width on the cut sheet thickness are found. The criterion to determine the maximal thickness of the cut sheet achievable by the laser cutting is found. It is demonstrated that, during the CO_2 laser cutting, there is the utmost thickness of 40...50 mm, above which the qualitative cutting is impossible. In turn, this criterion cannot be applied to the fiber laser case because the mode of uncontrolled metal burning at low speeds is absent.

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