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Effect of the laser beam polarization state on the laser cut surface quality

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Abstract

It is well-known that laser cut characteristics highly depend on the polarization state of laser beam. The works on laser cutting deal mainly with the effect of the polarization on the cutting speed, whereas the effect on the cut surface quality was almost neglected. This paper presents the experimental investigation of the effect of the laser beam polarization state on the laser cut surface roughness. The CO_2 laser was used to cut steel sheets of 3, 5, 8 and 10 mm. The cut surface roughness and maximal cutting speed were measured in the cases of the circular polarization of the laser beam, and plane polarization at various angles between the polarization plane and cutting speed direction. For all thicknesses, the roughness is minimal when the cutting speed direction is perpendicular to the polarization plane. The cutting speed and cut surface quality of the samples, cut by the CO_2 laser at various polarization states, were compared with the respective parameters of the samples cut by the fiber laser.

Keywords: laser cutting, CO_2 laser, fiber laser, polarization, surface roughness;

1. Introduction

During the laser cutting, cut characteristics highly depend on the state of laser beam polarization, which is well known [1]. The radiation incidence angle is grazing, the cutting front is a 3D surface. The laser beam propagates in the narrow channel with potential multiple reflections. The absorption coefficient value and spatial distribution depend on the polarization type, channel geometry, spatial properties, and laser beam focusing conditions. Even early tests of metal cutting with the CO_2 laser with the plane polarization enabled

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to state that the maximal cutting speed and cut channel shape depended on the mutual orientation of the polarization plane and cutting direction. The highest cutting speed is reached when the electric field vector direction coincides with the cutting direction [2]. This speed exceeds the maximal cutting speed at the circular polarization. In the practice, however, the beam has the circular polarization in the CO_2 laser case, to provide similar characteristics of the cut in different directions, and the chaotic polarization in the fiber laser case.

Experimental and theoretical investigations of the polarization effects in the laser cutting of metals are devoted in most cases to the effect of the polarization on the cutting speed. Zaitsev et al [3] present the numerical investigation of the Gaussian beam absorption in the cut channel at the flat, circular, and elliptical polarization. It is found that the maximum fusion depth is reached at the elliptical polarization, when the bigger axis is oriented along the cut direction, at a certain axes ratio. Niziev and Nesterov [4] present the numerical simulation of the laser cutting and shows that the radial polarization of the beam provides higher cutting efficiency than the plane or circular one. High cutting speed at the radial polarization against the circular polarization is demonstrated experimentally in [5], but the difference value is lower than the theoretical result [4]. The cutting with the plane polarization is studied in [6]; experimental data on the cut geometry (kerf width, wall inclination angle) and maximal cutting speed are gathered at different orientations of the polarization plane about the cutting direction.

The present work deals with the analysis of the effect of the polarization state on the cutting quality during the oxygen-assist laser cutting of low-carbon steel. The cut roughness and no dross are assumed as the quality indicator. The roughness value, maximal cutting speed and the speed correlating with the minimal roughness are measured at various orientations of the beam polarization plane to the cutting direction.

2. Experimental technique

The ytterbium laser IPG/IRE-Polus was used; its power was 2 kW, the collimator was IPG, model D5-WC/AC. The beam parameter product (BPP, the product of the beam radius in the near zone by the angular beam radius in the far zone) was equal to 3.8 mm·mrad. The beam diameter in the focusing lens after the collimator was 17 mm, the lens focal distance was 200 mm. Low-carbon steel sheets of 3, 5, 8 and 10 mm were cut at the radiation power from 0.5 to 2 kW. The continuous CO_2 laser was also used; its BPP was 4.7 mm·mrad [7]. The cutting was done by the circular-polarization beam by the conventional scheme. The radiation was focused by the ZnSe lens with the focal distance of 190 mm. The beam diameter on the lens was equal to 25 mm. The diameter of the focused beam in its waist was evaluated as a sum of the diffraction diameter and diameter of the dissipation spot resulting from the spherical aberration. The calculated total diameter is 180 µm for the fiber laser and 200 µm for the CO_2 laser.

The value of surface roughness (characteristic height of nonuniformities) measured with a laser confocal scanning microscope Olympus LEXT in two cross sections (near the upper and near the lower sheet surfaces) was adopted as a quality criterion. For this sample, the biggest from two values was taken to be characteristic one.

3. Results

The cut surface roughness is the major index of the laser cut quality for most applications. In the tests, the sheets of low-carbon steel were cut by the CO_2 laser with the plane polarization. The cut surface roughness was measured at different angles α between the polarization plane and cutting speed direction. Fig. 1 shows the photos of the cut surface, the sheet thickness 5 mm, at different α. The laser beam power was 1 kW, assisted gas pressure was 0.5 MPa, the speed of 1 m/min, the focused beam waist position was the same for all cuts. During the cuttings, the position of the beam polarization was constant, the cutting direction and polarization plane made the angle from 0 to 180 degrees.

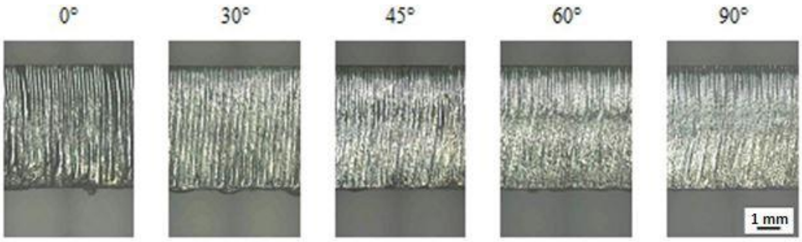

Fig. 1. Photos of the cut surface for different values of the angle α at sheet thickness of 5 mm.

As is seen from Fig. 1, the cut quality depends on the α angle, the lowest height and striation pitch are reached when the cutting speed direction is perpendicular to the laser beam polarization. Fig. 2 demonstrates the measured dependence of the cut surface roughness on the α angle. The roughness minimum at α = 90° is evident. Similar dependencies were obtained for the samples of 3, 8, and 10 mm. The roughness is minimal in every case when the angle between the cutting speed direction and polarization plane is 90° degrees.

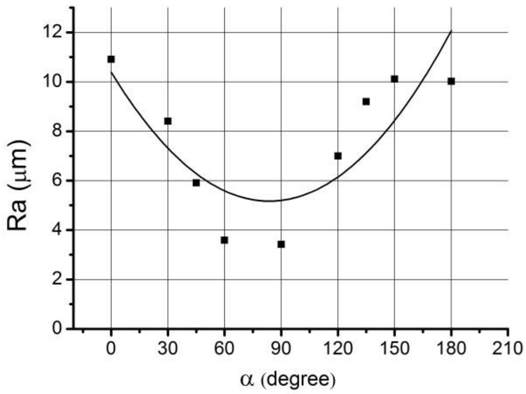

Fig. 2. Roughness value versus α, sheet thickness 5 mm.

Table 1 presents the data on the maximal cutting speed for the sheet of 5 mm and laser power of 1 kW. The maximal cutting speed, as well as the cut quality, highly depend on the α angle, but the relation is inverse: the highest cutting speed is reached at α = 0°, the lowest at α = 90°.

Table 1. Maximal cutting speeds for various modes.

α (degrees)	0	30	45	60	90
V_{max} (m/min)	2.6	2.3	2.2	1.8	1.8

Aside for the analysis of the laser cutting with the linear polarization, we worked with the CO_2 laser with the circular polarization, and ytterbium fiber laser with the chaotic polarization. The laser cutting of the same steel was optimized for these two laser types by the minimal roughness criterion. Table 2 presents the values of the surface roughness of the best quality.

Oxygen-assisted laser cutting of low-carbon steel by the CO_2 laser radiation with the circular polarization and fiber laser with the chaotic polarization was performed. The chosen cutting parameters provided the minimal surface roughness. The results are presented in Table 2, for more details see [8].

Table 2. Surface roughness R_a at CO_2 and fiber laser cutting.

Sheet thickness (mm)		3	5	10
R_a (μm)	CO_2 laser	1.6	2	2.8
	Fiber laser	2.7	3.9	6.1

As is seen from Table 2, the CO_2 laser cutting provided much lower roughness than the fiber laser does at any sheet thickness. Note that as the sheet thickness rises, the difference in the cut quality rises, too.

4. Discussion

Fig. 2 and Table 1 show that both the cutting speed V_{max} and cut surface roughness R_a considerably depend on the angle α between the polarization plane and cutting direction. Both dependencies have their minimum at α = 90°, i.e. the maximal cutting quality is reached at α = 90°, and the maximal cutting speed – at α = 0°. The latter result is well known [2]. Maximal cutting speed is reached at α = 0° because of the following. The laser beam is incident on the cut front in a grazing manner. In this case, the maximum of the absorption coefficient is reached at the p-polarization, which takes place at α = 0°. Thus, at this angle the absorbed power has its maximum which actually provides the maximal speed. The power absorbed on the side walls of the cut channel is minimal.

The reason why the minimal roughness of the cut surface is reached at α = 90° can be explained by the same manner. At this angle, the power absorbed on the side walls of the channel is maximal. Beam absorption on cut surface irregularities leads to their smoothing. At higher temperature, the melt on the walls has lower viscosity, lower surface tension coefficient, and is removed from the channel more effectively. The idea of cut quality comprehension by means of the laser power absorption on the side walls is proposed by K. Hirano in [9]. It is suggested that the beam with the radial polarization should be used for the metal cutting by the laser with the wavelength of 1 µm. Experimental results on the cutting of stainless steely by the beam of the CO_2 laser with the radial polarization were presented in [10]. Reduction of the cut surface roughness against the circulation polarization case is demonstrated. In [5] the authors report about the increase of the speed of the high quality CO_2 laser cut with the radial polarization as compared to the circular polarization. The results of [5] and [10] agree with the results of the present work.

It is known that the cutting of thick metal sheets (thickness above 4 mm) by a fiber or disk laser with the chaotic polarization of the beam gives the rougher surface than after the cutting by the CO_2 laser with the circulation polarization [9, 11 – 13]. The same result is obtained in [8] which dealt with the oxygen-assisted laser cutting. Various explanations of the cut quality difference are proposed [9, 11 – 13], though the final solution of the problem is still not found, so the physical reasons responsible for different cut quality are still under investigation. The result of this work, i.e. reduction of the cut surface roughness obtained at the electric field vector orientation in the laser beam perpendicularly to the cutting speed during the cutting with the flat polarization, when the absorption on the side walls is maximal, permit suggesting the same reason of the lower roughness by the CO_2 laser as compared to the fiber laser. In the case of the CO_2 laser, the cut surface has lower roughness also due to the higher absorbed power, but this higher absorption has another physical reasons. The first is that the Fresnel absorption at the grazing incidence on the wall is higher for the CO_2 laser with the wavelength of 10.6 µm than for the fiber laser with the wavelength of 1.07 µm, even at the same incidence angles [11]. The second reason is related with the higher angle of the geometrical beam divergence behind the lens focus in the CO_2 laser case, which also increases the absorption coefficient on the walls at the grazing angle of incidence.

5. Conclusion

The correlation between the cut quality and polarization state of the CO_2 laser beam during the oxygen-assisted laser cutting is studied experimentally. At the plane polarization, both the cut surface roughness and maximal cutting speed depend on the mutual orientation of the polarization plane and cutting direction. Both dependencies have their extremums: the minimal roughness is reached when the vector of the laser beam electric field is perpendicular to the cutting direction, whereas the maximal cutting speed is reached when the field vector coincides with the cutting direction. The minimal roughness at the plane beam polarization is approximately of the same value as at the circular polarization. The cut surface roughness during the oxygen-assisted laser cutting of low-carbon steel by the fiber laser is approximately two times higher. Obtained results have been qualitatively explained.

References

1. Olsen F. O., 1980. Cutting with Polarized Laser Beams. DVS-Berichte 63, p. 197.
2. Steen W., 1991. Laser Material Processing. Springer-Verlag, London, p. 87.
3. Zaitsev A. V., Kovalev O. B., Orishich A. M., Fomin V. M., 2005. Numerical analysis of the effect of the TEM00 radiation mode polarization on the cut shape in laser cutting of thick metal sheets. Quantum Electron 35, p. 200.
4. Niziev V. G., Nesterov A. V., 1999. Influence of beam polarization on laser cutting efficiency. Journal of Applied Physics 32, p. 1455.
5. Weber R., Michalowski A. , Abdou-Ahmed M., Onuseit V., Rominger V., Kraus M., Graf T., 2011. Effects of Radial and Tangential Polarization in Laser Material Processing. Physics Procedia 12, p. 21.
6. Ozaki H., Mima T., Kawakami H., Suzuki J., 2014. Effect of Laser Polarization on Cutting Properties in Assist Gas Free Laser Cutting. Advances in Materials Science and Applications 3, p. 53.
7. Afonin Yu.V., Golyshev A.P., Ivanchenko A.I., Malov A.N., Orishich A.M., Pechurin V.A., Filev V.F., Shulyat'ev V.B., 2004. High-quality beam generation in a 8-kW CO_2 laser. Quantaum Electron 34, p. 307.
8. Golyshev A.A., Malikov A.G., Orishich A.M., Shulyatyev V.B., 2014. Experimental study of laser-oxygen cutting of low-carbon steel using fibre and CO_2 lasers under conditions of minimal roughness. Quantum Electron 44, p. 970.
9. Hirano K., Fabbro R., 2012. Possible explanations for different surface quality in laser cutting with 1 and 10 µm beams. Journal Laser Applications 24, 012006.
10. Ahmed M.A., Vos A., Vogel M.M., Austerschulte A., Schulz J., Metsch V., Graf T.,2009. "Radially polarized high power lasers". XVII International Symposium on Gas Flow, Chemical Lasers, and High-Power Lasers, vol. 7131, p. 71311I-1.
11. Mahrle A., Beyer E., 2009. Theoretical aspects of fibre laser cutting. Journal of Applied Physics 42, 175507.
12. Scintilla L.D., Tricarico L., Mahrle A., Wetzig A., Himmer T., Beyer E., 2010. "A comparative study on fusion cutting with disk and CO_2 lasers". 29th International Congress on Applications of Lasers & Electro-Optics. Anaheim, USA, paper #704.
13. Petring D., Shneider F., Wolf N., 2012. "Some answers to frequently asked questions and open issues of laser beam cutting". 31th International Congress on Applications of Lasers & Electro-Optics, Anaheim, USA, paper #615.