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Determination of Fiber Laser Cutting Parameters Taking Into Account the Distribution of the Laser Beam in the Material

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Abstract

The metal cutting speed determines the productivity of laser technological devices [1, 2, 3]. An essential characteristic of the metal cut quality evaluation is the value of the side wall roughness of the cut Rz [2, 3, 4, 9]. Also, the nature of the cut changes with depth. This means that the final roughness also changes. Laser cutting makes it possible to obtain finished parts without subsequent finishing, and the recommendations of technologies for industrial laser machines based on CO2 lasers contain the conditions of high-quality cutting for a wide range of materials [2,4,7,8]. This article covers setting up a fiber laser. It is assumed that effective channeling of the laser beam stops at a certain depth. The laser beam is scattered at large angles and absorbed by the material walls [5, 6]. Experiments have shown that scattering occurs at the depths comparable to the laser wavelength and inhomogeneities of the material being processed. Of course, it is worth considering the laser settings and the material being cut. It was assumed that at the appropriate depth, when the channeling of the laser beam is stopped, the material melts due to the incandescent gas jet and the thermal conductivity of the metal. The article also presents the calculation of fiber laser parameters to ensure the minimum divergence of roughness at the entire depth of metal cut. The results of the work were tested at the existing production.

Keywords: Laser, laser cutting of metal, CO2 laser, laser calculation

1. INTRODUCTION

Various factors have been considered in detail by the literature, that can affect the quality of gas-laser cutting and the depth of metal penetration during laser welding [1, 3, 9, 10]. These include: microinstabilities (thermocapillary, Rayleigh-Taylor, capillary-evaporation, capillary-wind), formation of a "step" at the front of penetration and cut, instability of the film boundary layer flow of the melt, etc. Let's note that many authors consider it is necessary to mention the great complexity processes within the laser cut and consequent difficulties during the attempts to interpret the experimental results unambiguously [5, 6, 7, 8, 9]. In this work, the goal was to identify the optimal modes of laser cutting for finished part obtaining.

2. METHODS

Choosing the right laser cutting speed and power is the main criterion for the production of sheet metal parts [10]. The formulas for calculation the optimal cutting speed are presented below [11, 12].

Figure 1 shows the side surface of mild steel cut with the thickness of 5 mm, made using an LS-3.5 fiber laser manufactured by NTO IRE-Polyus. The laser is equipped with a transport fiber the core diameter of which is 100 µm and is characterized by the quality parameter of the output beam M2 = 13.5. The cut was obtained using OPTOSKAND optical head. This head has a collimating lens with fc = 120 mm and a focusing lens with ff = 200 mm. The corresponding focal spot had the diameter d = 190 µm and the focus depth ZR = 2 mm. The laser power was 3.5 kW, air was the cutting gas. The cutting was carried out at the speed of 3 m/min.

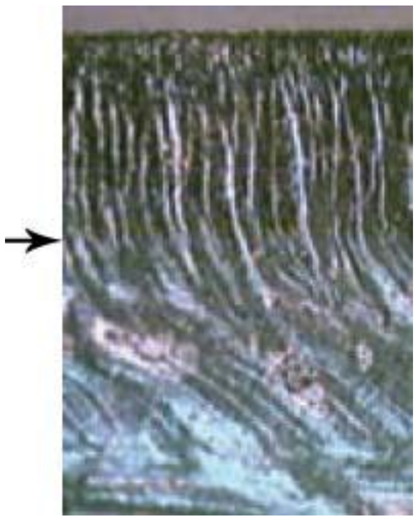

Fig. 1: Side cutting surface of low-carbon steel

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The arrow marks the depth below which the character of the cut changed significantly. Similar patterns of cuts are observed when they use CO2 lasers [14, 15].

It can be assumed that the effective channeling of the laser beam inside the cut stops at the corresponding depth, the beam is scattered at large angles and absorbed by the side walls. The material below the arrow heats up and melts not due to the direct action of laser radiation, but mainly due to the incandescent gas jet and the thermal conductivity of the metal. Scattering can occur at inhomogeneities comparable to the laser wavelength, which arise due to the above-mentioned microinstabilities, which have very large growth increments.

Since laser beams, including multimode ones, are always partially coherent, the start to the development of inhomogeneities can be given by the interference between the central part of the beam and its periphery, which is reflected from the cut walls. Interference causes spatial modulation of the radiation intensity within the cut and the corresponding non-uniformity of the radiation effect on the material.

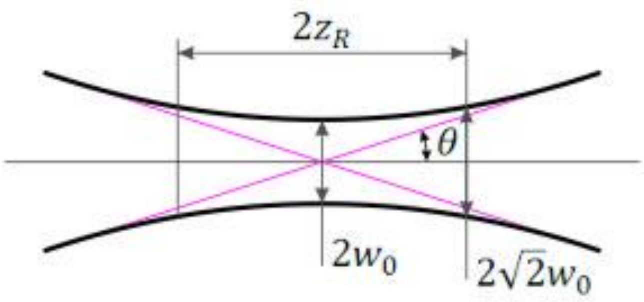

Fig. 2: Longitudinal section of an axisymmetric laser beam

Let's consider this interference in a simple model. Let's use the accepted generalized description of laser beams.

Fig. 2 shows a longitudinal section of an axisymmetric laser beam propagating along the z axis with the waist at the point z = 0. The boundary of the laser beam (at the intensity level 1/e2) is the hyperboloid of revolution, the angle θ determines the beam divergence in the far zone. The dependences of the laser beam radius w and the radius of curvature of its wavefront R on z are described by the following formulas [17, 18]:

$$\mathrm{w}(z) = w_0 \left[1 + \left(\frac{M^2 \lambda_z}{\pi w_0^2}\right)^2\right]^{1/2} \quad (1)$$

$$\mathrm{R}(z) = z \left[1 + \left(\frac{\pi w_0^2}{M^2 \lambda_z}\right)^2\right] \quad (2)$$

Here λ is the radiation wavelength, the dimensionless parameter M2 ≥ 1 characterizes the deviation of the laser beam from the ideal Gaussian (M2 = 1 for the latter) and determines the "focusing" of the laser beam, that is, the radius w0 in the waist (exact focus of the lens) according to the formula

$$w_0 \theta = \frac{M^2 \lambda}{\pi} \quad (3)$$

The focus depth or, as it is often called, the waist length, that is, the length at which the beam diameter changes √2 times, is characterized conveniently as the so-called Rayleigh length zR (see Fig. 2):

$$z_R = \frac{\pi w_0^2}{M^2 \lambda} \quad (4)$$

The waist length is twice the zR value. Figure 3 schematically shows the propagation of a laser beam inside the cut [21, 22, 24]. The maximum metal thickness for which a "clean" cut is possible is denoted as x0. The constriction of the cutting radiation is located on the surface of the material.

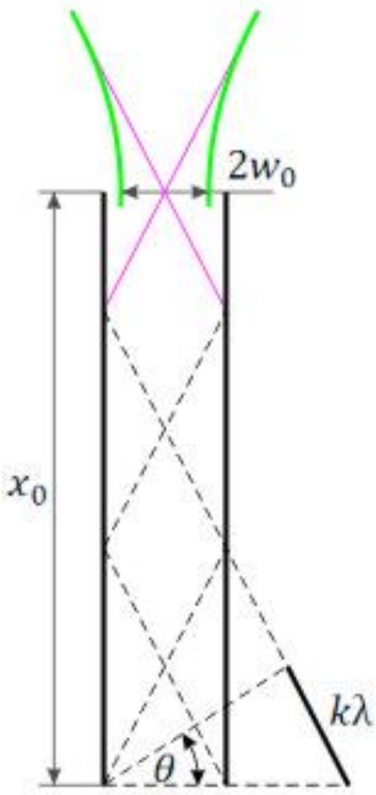

Fig. 3: Propagation of the laser beam inside the cut

kλ is the path difference between the peripheral and central part of the beam (achieved at the cut exit), at which the inhomogeneities arising from the interference do not lead to scattering at large angles and a "clean" cut of the material with the thickness x0 is possible.

Since kλ = x0Θ2, it is easy to obtain the following expression from the formulas (3), (4) [23]:

$$x_0 = \frac{k\pi(\pi w_0^2)}{M^2(M^2\lambda)} = \frac{k\pi}{M^2} z_R \quad (5)$$

Thus, under the assumption of the interference nature of the effects that lead to the limitation of radiation penetration depth into the cut, the limiting depth of the "clean" cut is proportional to the focus depth and is inversely proportional to the parameter M2, which determines the initial quality of the laser beam.

We will try to determine the dimensionless coefficient k included in the formula from the known experimental data.

From the album of technologies for the "Trumpf" complex based on CO2 laser (λ = 10.6 μm) with the power of 3.2 kW, and a beam at the output close to an ideal Gaussian beam (M2 = 1.1) with the 20 mm diameter at the focusing lens, with a focal length of the lens f = 180 mm, the maximum thickness of mild steel makes 15 mm, for which a clean oxygen cut with the same Rz over the entire lateral surface is possible. For these parameters, we have the following at the lens focus: Φ = 0.056 rad, w0 = 0.067 mm, zR = 1.2 mm. Then we obtain k ~ 4.4 from the expression (5).

For the aforementioned fiber laser LS-3.5 with an optical head, collimator and objective focal lengths, respectively, fc = 120 mm and ff = 200 mm, at which the parameters in the focus are the following: Φ = 0.048 rad, w0 = 0.096 mm, zR = 2 mm, - the same Rz value along the entire height, corresponding to a "clean" cut, was obtained for mild steel with the thickness up to 3 mm. Substituting these values into (5), we obtain k ~ 6.5.

Although the formula (5) is of an approximate nature and does not take into account a number of effects associated with the formation of a gas jet and the position of the waist relative to the material surface, the values of the coefficient k obtained for different types of lasers and the thicknesses of the processed material differing 5 times turned out to be close (if we take the average value, the deviation is within ± 20%).

On the whole, the validity of the expression (5) was confirmed in the experiments known to us on operating devices with fiber lasers in Nizhny Novgorod (2 kW) and Dubna (1 kW), where the lasers with a transport fiber of 50 μm are used (the corresponding value is M2 = 6.5).

As can be seen from the relation (5), for a given width of cut, determined by the size of the beam in the waist 2w0, the depth of focus, and hence the depth of the "clean" cut, is inversely proportional to the radiation wavelength λ, that is, other things being equal, a laser with a shorter wavelength should provide a great depth of "clean" cut. But the depth of the "clean" cut depends on the optical quality of the beam M2 - with a fixed cut width even more strongly than on the wavelength, the dependence is inverse quadratic. This is related to the significantly lower value of the "clean" cut obtained by us during the experiments with a fiber laser in comparison with similar data for a single-mode CO2 laser of the same power. To increase the thickness of the processed materials, it is necessary to improve the quality of laser beams [28]. So, when they use a fiber laser with a transport fiber and a core diameter of 50 μm (M2 = 6.5) instead of 100 μm (M2 = 13.5) with the same waist diameter of about 0.2 mm, the maximum thickness of a "clean" cut will be 13 mm ... Single-mode fiber lasers are even more efficient in this respect [29, 30]. True, single-mode fiber lasers with an output power of less than 1 kW are currently commercially available.

We present an additional useful relationship for technologists using fiber lasers.

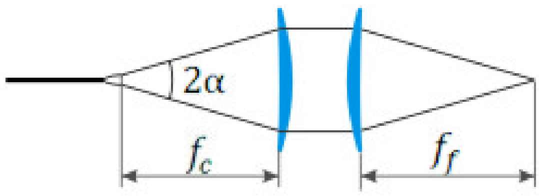

Fig. 4: Schematic representation of the fiber laser optical head

Fig. 4 is a schematic diagram of the fiber laser optical head. At the exit from the optical multimode transport fiber, the laser beam diverges with an aperture angle of 2α, which makes ~ 0.16 rad for ytterbium lasers and the fibers with the diameters of 50–300 μm. Then the beam is converted into a plane-parallel beam by a collimating lens unit with a focal length fc and is focused on the material by a lens with a focal ff. From the formulas (3) - (5), it is easy to obtain the following expression for the maximum depth of a clean cut:

$$x_0 = \frac{k\lambda}{\alpha^2}\left(\frac{f_f}{f_c}\right)^2 \quad (6)$$

That is, the depth of the clean cut is determined only by the square of the lens focal point ratio in the optical head and does not depend on the diameter of the used transport fiber. The dimension factor in front of the brackets is ~ 1 mm. Note that for a single-mode laser and single-mode transport fiber 2α = 0.1 rad and this coefficient is ~ 3 mm.

3. RESULTS AND DISCUSSION

Based on the results of our experiments, it is possible to draw a preliminary conclusion about the inverse proportionality of a high-quality cut speed to the material thickness, all other things being equal (for a given laser power, the transport fiber diameter, and the optical head characteristics).

On the other hand, the cutting speed is directly proportional to the radiation power density on the material, that is, with equal characteristics of the optical head, it is inversely proportional to the square of the transport fiber diameter.

4. SUMMARY

The results of the experiments showed that effective channeling of the laser beam stops at a certain depth. The laser beam is scattered at large angles and absorbed by the walls of the material. It is shown that at the corresponding depth, when the channeling of the laser beam is stopped, the material melts due to the incandescent gas jet and thermal conductivity of the metal. The experiments have shown that scattering occurs at the depths comparable to the laser wavelength and inhomogeneities of the material being processed. Of course, it is worth considering the laser settings and the material being cut. The article also presents the calculation of fiber laser parameters to ensure the minimum divergence of roughness at the entire depth of metal cut. The work performed provides the calculation basis for choosing the fiber laser type and parameters, based on the specific conditions of their use in technological systems. The results of the work were tested in the existing production.

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