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Testing of diffractive optical element as part of specific CO₂ laser equipment for metallic materials modification

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Abstract. Testing of a reflective diffractive optical element (DOE) as part of specific CO₂ laser equipment Oerlikon OPL 2000 for metallic materials modification was performed. The power density distribution in a plane located behind the DOE focal plane has been measured. It was found that DOEs make it possible to form a predetermined beam power density profile and to perform the transformation of laser energy, chosen by calculation previously. The use of these optical elements in the laser material treatment reveals new possibilities for controlling properties and operational characteristics of processed components. Additional redistribution of the beam power to edges of the laser spot is achieved by increasing the proportion of energy reflected by DOE peripheral zones, for example, by increasing the aperture of the focusable beam. It is proposed using a telescopic system of two lenses to change the aperture of the laser beam focusable by the DOE.

1. Introduction

Improvements in technical performance of mechanisms and machines are closely linked with the quality of main components, which is largely determined by complex physical and mechanical properties of structural materials used. Most often, basic materials used for manufacturing of construction elements are steel and other alloys, including materials with a high specific strength in a well specified range of operating temperatures. It is known that such important characteristics of metals and alloys, as tensile strength, fatigue strength and wear resistance are structurally-sensitive, i.e., can be controlled by proper changes in material structures. Laser beam machining is a progressive process for improving selected properties and performance characteristics of materials [1–3].

Numerous published experimental results show that most important factors, that influence resulting material properties and performance of products processed by laser irradiation, are the temperature and its change in the treatment zone [4–6]. It is known that the used thermal cycle leads to formation of a certain structure and modification of material properties. Thus, the temperature cycle in the treatment zone is the most significant factor influencing changes of physical and mechanical properties of materials. However, there are virtually no information and recommendations how to implement a control of the spatial energy distribution delivered to the processed material to implement a given



temperature cycle. A mismatch in the distribution of the heat flow on the surface of technological objects facilitates the development of various defects. As a consequence, efficiently processed materials are commonly used to prevent the development of such defects, instead of those that better fulfil required material properties after laser beam treatment.

At present, more and more applications of high-strength dual phase ferritic-martensitic steels with a controlled amount of martensite appear which have the most favourable combination of durability and plasticity compared to other low-alloy steels [7–9]. Dual phase ferritic-martensitic structures can be modified by using various combinations of heating and cooling parameters. Precise redistribution of the laser beam energy may be obtained by diffractive optical elements (DOEs) [10–12], where their application in technological processes open perspectives not only for the solution of the presented specific objective of laser modification of materials, but for others applications, too. Focusing with DOEs in a line is used for laser cutting [13, 14], welding [15], marking [16]; for marking also focusing in set points is used [17, 18]. At the same time there are some actual problems in laser material processing [19, 20, 21], the determination of which is necessary to generate the required - usually uniform - distribution of beam power density in a given flat area. The purpose of this study is functional testing, i.e. testing of functional suitability and interoperability DOE as part of specific CO₂ laser equipment allowing to perform a process of materials modification with a ferritic-martensitic structure by laser irradiation.

2. Optical systems for laser processing

The usage of lasers requires a careful choice of optical systems for positioning and transforming the laser beam [22]. Laser beam guiding systems are intended to deliver the beam from the beam source to the processing zone with as minimal degradation of beam power and quality as possible. Radiation of solid state and diode laser may be transmitted by optical fibres and formed by glass lenses, where in the case of high power densities guiding elements have to be cooled. Because of the wavelength of the radiation emitted by solid state and diode lasers, it is convenient to couple the output of a laser into an optical fiber in order to deliver the radiation to the place where it is needed. The beam, emitted by the fiber, behaves in conformity to the known beam propagation laws. However, the beam divergence is restricted by the numerical aperture of the optical fiber and depends notably on incoupling terms at the fiber input. Laser radiation passes through the fiber practically without losses. Higher power losses can occur at input and output fiber ends, especially if they are uncoated or if the coating is damaged. Mirrors are used as base elements of CO₂ lasers guiding systems. Very accurate and highly reflective mirrors surfaces in combination with precise mechanical guiding systems are basic requirements for constant beam quality during the whole treatment process.

In most technological processes, the laser beam has to be focused on the treated object surface to reach the desired power density. Beams of the available lasers, as a rule, do not provide the high power concentration and power density distribution which are required for the implementation of the corresponding effect. Various methods of beam focusing are used to create power densities in the range of 10^7 – 10^{12} W/m² on the surface being treated [6, 23]. Transmitting optical elements – lenses as well as reflecting optical elements (for example mirrors) could be used as focusing elements. Different types of lens systems (e.g., spherical, parabolic, and cylindrical) are widely used and provide the possibility of implementing the desired temperature action by changing the distance of the treated object from the focal plane, in some cases. Focusing lenses for CO₂ laser are mainly created from zinc selenide. These elements have a high transmittance in the infrared region of the spectrum and favourable heat dissipation characteristics. Beams of solid state and diode lasers are shaped by optical elements made from quartz, where appropriate anti-reflection coatings increase the beam transmittance. But refractive optical elements have low reliability and relatively short useful life due to the low laser damage threshold.

For the shaping high-power laser beams (more than about 1.5–3 kW), metal optics with high laser damage threshold and sufficient reliability are used. For example, coated copper substrates, which can be cooled with water easily, are mainly used as mirrors for CO₂ lasers. One of the features of used mirrors is a small scattering loss combined with a long life expectancy, if appropriately coated. Such mirrors are used in industrial systems at a power of up to 20 kW. However, the use of these systems and components for laser action is limited because in most cases it is impossible to obtain the required laser spot geometry

and spatial power density distribution in cross-section of a focused beam. Contour-beam and mask methods, including contact and projection varieties [24], are not often used to produce an optical image for laser treatment of various objects. The mask method of shaping a laser beam is deficient in that a large amount of laser energy is absorbed by non-transparent portions of the mask. This method cannot provide the desired distribution of laser power density throughout the treatment zone. The contour-beam method has the advantage of the efficient use of laser energy. But this method provides no optical means for creating a specific distribution of laser power density in the treatment zone.

An alike effect can be obtained by using of scanner systems or optical systems with mirror facets for laser beam homogenization. Scanner mirrors, preordained to work in dynamic regime, are constructed to be small and lightweight. Galvanometric moved rotated mirrors are used to deflect laser beam and change its position. The beam is afterwards focused with a system of optimized lenses. Focusing lens can be placed in front of the scanner head, if required. Limiting factor is also that the diameter of the focal spot. It is a function of the focal distance and depends on the laser beam properties. The focal distance of the optical system determines the size of processing field. Techniques such as rotating polygon mirrors or prisms, as well as high-frequency oscillations of mirrors, have been used for beam scanning [25, 26]. Mechanical beam scanning systems that produce a heating pattern on the treated surface by means of one- or two-axis movement of their components have significant weaknesses. These systems give a non-uniform spatial laser power distribution on the surface of the heat affected zone due to the variable speed of the beam movement and have low reliability due to the presence of mechanical parts, which are moving with high speeds. Deformable segmented mirrors and bimorph focusing mirrors [27, 28] are not often found in application of laser material processing due to their structural complexity and decreasing reliability with increasing number of control and correction channels.

The present analysis shows that various optical systems are developed for laser beam shaping. But the combination of a required distribution of laser power density with desired shape, with a laser beam power concentration in irradiated area and a high reliability are not reported. These functional capabilities of highly reliable optical systems are largely defined by the efficiency of treatment processes. The successful realisation of laser action is only possible on condition of the formation of the desired spatial power density profile in the desired area on the surface of the component. DOEs provide an opportunity to produce a laser spot as a pattern or an area with a specific distribution of laser power density [29-31]. Reflecting DOE are able to ensure the turn of the laser beam, its spatial phase modulation, and the redistribution of its power density [32-35]. DOEs provide an opportunity to achieve the required distribution of the laser beam power density [36-38]. As a consequence, it seems appropriate to use such new approaches which can take into account the specifics of creating a predetermined specific heat flow through the surface of an object.

3. Shaping of CO₂ laser beam using a DOE for processing a ferritic-martensitic steel

The beam of a CO₂ laser Oerlikon OPL 2000 was shaped by means of a reflective DOE. The OPL 2000 is a fast longitudinal flow laser with a stable resonator type and a folded resonator geometry which has a maximum output power of 1800 W and can be operated in pulsed mode between 0–5 kHz and CW. The K-number of a low order beam mode is 0.45, and a beam diameter is 14 mm. The CO₂ laser OPL-2000 shown in Figure 1 is used together with a 3-axis positioning system for laser treatment of metallic materials.



Figure 1. CO₂ laser Oerlikon OPL 2000.

A reflective DOE was used for beam shaping, the form of the reflective surface of which is described by the equation:

$$Z(U, V) = \text{mod}_{m\lambda/(2\cos\theta)} \left(\frac{1}{\cos\theta} \left(\frac{U^2 \cos^2\theta + V^2}{4f} - \frac{L \int_0^{U \cos\theta} dU \int_0^{\sqrt{R^2 - U^2}} \exp\left(-\frac{U^2 + V^2}{r^2}\right) dV}{\pi f (\mathcal{Q})^*} \right) \right) \quad (1)$$

where $Z(U, V)$ is the relief height at (U, V) point of the optical element; U, V are point coordinates on reflecting optical element in the system of axes where OU axis is directed oppositely the projection of focusable beam and begins in the center of reflecting surface placed at the area $G: U^2 \cos^2\theta + V^2 = R^2$; R is the maximum radius of the focusable beam; L is the laser spot length; f is the focal length of the optical element; θ is the angle between optical axis and central normal to the surface of the optical element; $\text{mod}(h)_{m\lambda/(2\cos\theta)}$ is a function equal to the smallest positive remainder of division h by $m\lambda/(2\cos\theta)$; λ is a wavelength; m is an integer; r is a parameter of the focusable beam with Gaussian power density distribution having the power density decreased in e times compared with the power density at the beam center at r distance from the center; $(\mathcal{Q})^*$ is a value of the double integral of the probability for the focusable beam with Gaussian power density distribution:

$$(\mathcal{Q})^* = \frac{4}{\pi} \iint_G \exp\left[-\frac{(U^2 + V^2)}{r^2}\right] dU dV \quad (2)$$

The form of the reflective surface of the optical element had following parameters: $f = 0.2241$ m; $L_0 = 5.6 \cdot 10^{-3}$ m; $R = 2.5 \cdot 10^{-2}$ m; $r = 0.7R$. Figure 2 shows a photo of DOE as part of specific CO₂ laser equipment for metallic materials modification. The use of water cooling allows increasing the radiation resistance of DOE – i.e. the maximum value of the threshold of stable functioning during laser irradiation – up to values of the power density of the focusable beam $[q] \geq 10^8$ W/m².



Figure 2. Photo of DOE as part of specific CO₂ laser equipment for metallic materials modification: 1 – CO₂ laser Oerlikon OPL 2000; 2 – DOE in the composition of the device, consisting of units for adjustment, fixation and cooling of the optical element; 3 – air supply hose; 4 – bedplate; 5 – means for measuring the power density distribution of laser beam.

To register the power density distribution of the laser continuous output beam using a technique based on the ability of certain materials and substances to evaporate (or sublime) under the action of laser radiation. The error of the method does not exceed 30 %. From the balance equation of the absorbed energy expended on the evaporation of the volume of the material during laser action, determine the power of the heat flow. The average power density of beam is defined as the ratio of the heat flow power to the area of the resulting imprint. The average integral depth of the imprint is equal to the ratio of the evaporated volume to the area of the imprint.

It is assumed that the depth of the imprint is proportional to the density of the incident flow. The coefficient of proportionality K , having the dimension $W/(cm^2 \cdot cm)$ and showing the scale of the imprint made during the laser action, is determined by the ratio of the density of the incident flow to the depth of the imprint. Measurements of the depth of the imprint make it possible to determine the power density and construct graphs of this distribution over the cross section of the laser beam. The task of processing measurement results is simplified when $K = 0.1$. In this case, the depth of the evaporated material [mm] will be numerically equal to the power density of the incident flow [W/cm^2].

The power density distribution of the beam in a plane located behind the DOE focal plane at a distance of 355 mm away from the optical element plane has been measured. The maximum power density occurred near the center of the laser spot with dimensions of 6.5×2.4 mm and was equal to $q_{\max} = 3.5 \cdot 10^7$ W/m^2 . Figure 3 shows results of experimental studies of power density distribution along the axis Oy , as well as the contour of the laser spot. For the application of DOE for metallic materials modification, it is necessary to determine requirements for an adjustment of the optical element, as well as for the accuracy of setting parameters of the focusable beam. Deviations of the power density distribution and the temperature of technological objects, which in this case it is a most significant, should not exceed the permissible limits. The power density distribution along the laser spot shown in Fig. 3 corresponds to a displacement of the DOE of 3 mm in the vertical direction relative to the axis of the focusable beam. At this edge of the laser spot, to which the projection of the center of the beam is shifted, the laser power density increases; and at the other edge it decreases. As the focusable beam shifts in the direction of those layers of the DOE, which are designed to work in conditions of exponentially low laser power density, the power density q_{\max} in the laser spot is locally increased.

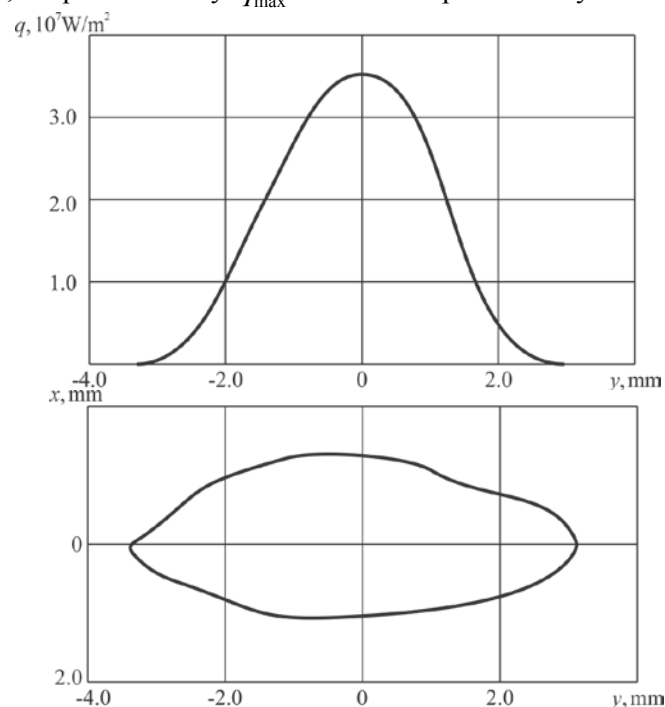


Figure 3. Results of experimental studies of power density distribution along the axis Oy , and the contour of the laser spot.

DOEs make it possible to form a predetermined beam power density profile and to perform the transformation of laser beam, which has been chosen by calculation previously. The use of DOE in the laser material treatment reveals new possibilities for controlling properties and operational characteristics of processed parts. An increase in the laser power density at edges of the laser spot compensates for increased heat dissipation from peripheral areas of the heat affected zone, and makes it possible to equalize maximum temperatures in the center and at the periphery during the action of moving heat sources on the material. Additional redistribution of the beam power to edges of the laser

spot is achieved by increasing the proportion of energy reflected by DOE peripheral zones, for example, by increasing the aperture of the focusable beam. To change the aperture of the laser beam focusable by the DOE, it is advisable to use a telescopic system of two lenses.

4. Conclusions

Laser beam shaping by a reflective DOE as part of specific CO₂ laser equipment Oerlikon OPL 2000 for metallic materials modification was performed. The power density distribution of the beam in a plane located behind the DOE focal plane at a distance of 355 mm away from the optical element plane has been measured. The maximum power density occurred near the center of the laser spot with dimensions of 6.5×2.4 mm and was equal to $q_{\max} = 3.5 \cdot 10^7 \text{ W/m}^2$.

It was found that DOEs make it possible to form a predetermined beam power density profile and to perform the transformation of laser beam, chosen by calculation previously. The use of DOE in the laser material treatment reveals new possibilities for controlling properties and operational characteristics of processed parts. Additional redistribution of the beam power to edges of the laser spot is achieved by increasing the proportion of energy reflected by DOE peripheral zones, for example, by increasing the aperture of the focusable beam. To change the aperture of the laser beam focusable by the DOE, it is advisable to use a telescopic system of two lenses.

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