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Letters to the Editor

Simplified model to explain the lateral focus displacement during high-power laser material processing

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In almost all high-power laser material processings, a gas jet is added. The warm gaseous sheet on the workpiece surface in the zone of laser beam action can be assimilated to an anisotropic uniaxial medium. This model of anisotropic uniaxial gaseous sheet can be useful to explain some almost periodic lateral focus jumps revealed during high-power laser processings.

1. Introduction

Focused laser beams of high power density are used in material processings, such as cutting, welding, and heat treatment.

In almost all processings, a gas jet is added [1]. For example, in fusion cutting a sufficiently strong gas jet is used to blow the molten material out of the cut kerf. If the gas is capable or reacting exothermically with the workpiece, then the gas jet is not only dragging the melt away, but is also reacting with the melt. Usually, the reactive gas is oxygen or some mixture containing oxygen.

In laser welding, when the laser power density is sufficiently high to generate what is known as a "keyhole", the material vapour is partially absorbing becoming hotter and forming a plasma. A side gas jet is then added to blow the plasma away. The plasma vapour emerging from the keyhole may ionize the shroud gas and propagate towards the incident laser beam. A substantial shielding of the workpiece surface can be produced depending on the properties of the shroud gas jet. The plasma shielding effect is less for those gases having a high ionization potential. Thus helium is the best shroud gas in laser welding.

The gas jet can influence the position and the size of the focused beam spot on the surface of the workpiece. The focused beam spot is an important parameter for laser processing. It acts in two ways. Firstly, a decrease in spot size will increase the power density influencing the processing efficiency, and, secondly, it will decrease the heat affected zone increasing the processing quality.

In this note, we present a simple model showing how the warm gaseous sheet may influence the focused beam spot position and size on the surface of the workpiece during high-power laser processing. Using this model, an explanation can be provided for some almost periodic lateral jumps of the focused beam spot which have been revealed experimentally in [2]–[6].

2. Model of anisotropic gaseous sheet

Let us assimilate the warm gaseous sheet in the zone of laser beam action to an anisotropic medium with various refractive indices in different directions. There are several causes leading to this anisotropy. The most important of them can be the nonuniform heating during the workpiece translation; a higher temperature is attained in the moving direction compared to the perpendicular direction. A higher temperature is attained also in the laser beam direction compared to other directions.

For simplicity, let us assimilate the gaseous sheet in the processing zone to a homogeneous uniaxial medium.

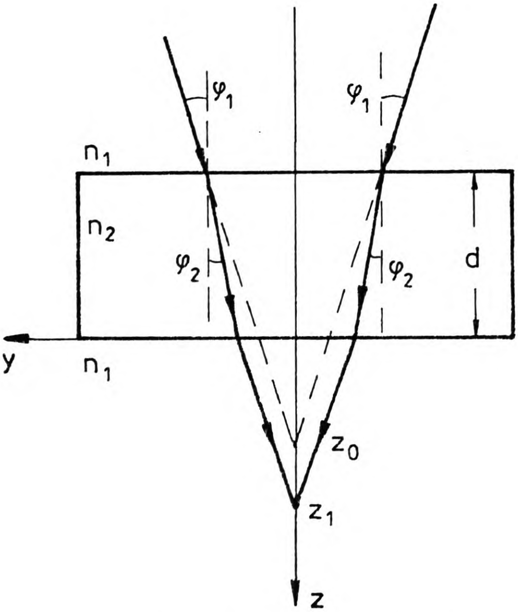

Fig. 1. Ray tracing through an isotropic plane-parallel plate

It is well known that, when a convergent beam falls normally on a plane-parallel plate of an isotropic material of index n_2 and width d (Fig. 1), the convergent point is displaced by [7]

$$\Delta z = z_1 - z_0 = d(1 - n_1/n_2) \tag{1}$$

where n_1 is the refractive index of the ambient medium, z_0 is the convergence point when the plate is removed, and z_1 is the convergence point of the beam through the plate.

Let us now consider a plane-parallel plate of an uniaxial material of indices n_o and n_e and thickness d with optic axis W in the incident plane $(y-x)$ at an angle θ with respect to the z axis (Fig. 2). The ordinary rays are refracted on the same

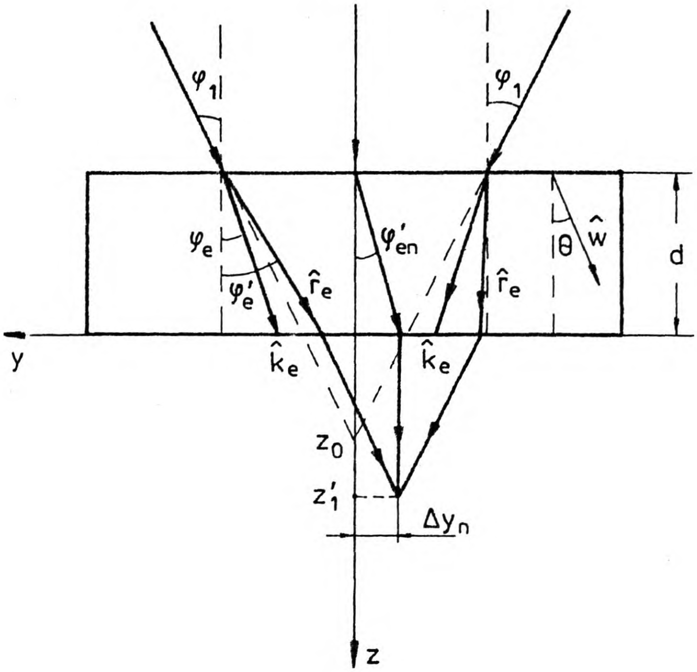

Fig. 2. Ray tracing through an anisotropic uniaxial plane-parallel plate with its optic axis W in the plane of incidence at an angle of θ to the normal of the plate surface

path as in an isotropic medium of refractive index n_o and the convergence point is determined by Eq. (1), setting $n_2 = n_o$.

The extraordinary wavefront direction is indicated by the versor $\hat{k}_e$. The angle φ_e between the versor $\hat{k}_e$ and the normal to the plate is determined by relation [8], [9]

$$\tan\varphi_e = \rho\varepsilon_{33}/[-\rho\varepsilon_{23} + n_o n_e(\varepsilon_{33} - \rho^2)^{1/2}] \tag{2}$$

where $\rho = n_1 \sin\varphi_1$, φ_1 is the angle between the incident ray and the normal to the plate, $\varepsilon_{23} = (n_e^2 - n_e^2)\sin\theta\cos\theta$, and $\varepsilon_{33} = n_o^2\sin^2\theta + n_e^2\cos^2\theta$. The extraordinary ray direction is indicated by the versor $\hat{r}_e$ which makes an angle φ'_e with the normal to the plate

$$\varphi'_e = \varphi_e + \delta \tag{3}$$

where δ is the dispersion angle of the extraordinary ray and is given by [10]

$$\tan\delta = (n_e^2 - n_o^2)\tan\gamma/[n_e^2 + n_0^2\tan^2\gamma], \tag{4}$$

γ is the angle between the optic axis and the wavefront directions $\hat{w}$ and $\hat{k}_e$, respectively, and is determined by relation

$$\cos\gamma = \sin\theta\sin\varphi_e + \cos\theta\cos\varphi_e = \cos(\theta - \varphi_e). \tag{5}$$

At normal incidence ($\varphi_1 = \varphi_e = 0$), there is a ray displacement at an angle

$\varphi'_{m} = -\delta_{n}$, where δ_n is determined by Eq. (4), setting $\gamma = \theta$. It means that the image is displaced laterally at the distance

$$\Delta y_n = d\tan\varphi'_{en} = -d\tan\delta_n. \tag{6}$$

When $\theta = 45°$, the lateral displacement is

$$\Delta y_n \Big|_{\theta = 45°} = -d(n_e^2 - n_o^2)/(n_e^2 + n_o^2). \tag{7}$$

It depends on the difference $\Delta n = n_e - n_o$ of the refractive indices. When $n_e \simeq \simeq n_o = n$, one obtains

$$\Delta y_n \Big|_{\theta = 45°} \simeq -d\Delta n/n \tag{8}$$

The longitudinal displacement of the convergence point is determined by [7]

$$\Delta z'_1 = z'_1 - z_0 = d - (d\tan\varphi'_e - \Delta y_n)/\tan\varphi_1. \tag{9}$$

When $\theta = 0$, there is only the longitudinal displacement of the convergence point.

3. Discussion

If the warm gaseous sheet on the surface of the workpiece is assimilated to an anisotropic uniaxial medium, then the lateral displacement of the focused beam spot during laser processing can be estimated using Eq. (6). This displacement depends on the orientation of the anisotropy with respect to the laser beam direction and the difference of refractive indices. An order of magnitude can be obtained from Eq. (8). For a difference of refractive indices Δn of 10^{-3}, at $n = n_e \simeq n_o = 1$, and $d = 10$ mm, one obtains a lateral displacement of the focused beam spot of 10 µm.

Generally, the workpiece is hardly absorbing, having a complex refractive index $\hat{n}_g = n_g - jk_g$. Then, the angle of refraction φ_g of the laser beam into the workpiece is small. It can be determined by relation [11]

$$\sin\varphi_g = \rho[\rho^2 + q^2(n_g\cos\alpha - k_g\sin\alpha)^2]^{-1/2} \tag{10}$$

where q and α are given by

$$\tan 2\alpha = 2n_g k_g \rho^2/[(n_g^2 + k_g^2)^2 - (n_g^2 - k_g^2)\rho^2], \tag{11}$$

$$q^2\sin 2\alpha = 2n_g k_g \rho^2 (n_g^2 + k_g^2)^{-2}. \tag{12}$$

For example, in the case of a steel workpiece of complex refractive index $\hat{n}_g = 23 - j24$ at 10.6 µm, the refraction angle corresponding to $\varphi_1 = 30°$ is $\varphi_g = 1.24°$, that is, the rays enter into the material almost in the normal direction, and the focal spot is approximately the same with the focused beam spot on the workpiece surface. Then, the focused beam spot size decreases as the material is vaporized and removed from the interaction zone. Practically, it is rather difficult to control the focus position during the laser processing. The focal shift and aberration generated at high temperature into the focusing lens should also be accounted for [12]–[14].

Experiments [2]–[6] revealed the existence of some almost periodic lateral jumps of the focused beam spot during laser processings. In laser cutting, the striations produced on the cut can be generated also by periodic lateral displacements of the focused beam spot. Thus, these striations can be seen as a "frozen" image on the cut of the lateral displacements of the focused beam spot position. The model of the uniaxial anisotropic gaseous sheet could explain qualitatively the lateral displacement of the focus during laser processing. The periodicity of the lateral focus jumps can be the result of a self-regulated balance of heating and diffusion during the workpiece translation, some of the processes involved having sudden variations at high local temperatures. Refractive index measurements of the gaseous sheet on the workpiece surface, performed using the method of the probelaser beam deviation, revealed the principal contribution of electrons [15], [16]. They are generated by the gas and metallic vapour photoionization. This process can go on in avalanche manner in the direction of the highest local temperature, leading to a sudden modification of the refractive index in the respective direction, and consequently to a lateral focus jump.

Experiments revealed the importance of the nozzle and the alignment of the nozzle with respect to the laser beam direction at certain distances to the workpiece surface [1], [17], [18]. These experimental observations could be seen to acknowledge the model of anisotropic uniaxial gaseous sheet. Although it resorts to gross simplifications, this model could be useful for the qualitative understanding of the lateral focus jumps during laser processing and for order of magnitude calculations.

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