

# Focus position dependence of radiation absorption on laser cutting fronts

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The influence of the focus position on the cw CO<sub>2</sub> monomode laser beam absorption within an idealized cutting front is numerically analysed. The existence of an optimum focal spot position in the depth of the workpiece providing a less sensitive integral absorption to inherent parameter deviations during the cutting process is inferred.

## 1. Introduction

Focused CO<sub>2</sub> laser beams can be used to cut complex shapes at high speeds with minimum set up costs. A high quality of cutting, *i.e.*, a narrow, perpendicular cutting kerf, a low roughness of the cutting edge which is free of burns and a small heat affected zone, is possible to obtain with high-quality beams of improved CO<sub>2</sub>-laser systems. The optimum parameters such as, for example, the focal length of the focusing lens, the focus position in the workpiece, the laser power and the cutting speed, are determined during very time-consuming experiments performed for each thickness of the used material.

In laser processing, a major physical phenomenon of interaction between high density laser radiation and matter is the absorption of the laser energy into the workpiece. A simple theoretical model has been developed in [1], in order to understand the influence of different parameters on the integral and homogeneity of the absorption distribution at the cutting front by taking into account an idealized cutting front geometry.

The purpose of this paper is to further analyse the influence of the focus position on the cw CO<sub>2</sub> laser beam absorption within an idealized cutting front.

## 2. Idealized laser beam and cutting front geometries

In laser cutting, the zone of interaction between the laser beam and the workpiece is the so-called cutting front. The geometry and the temporal behaviour of the cutting front are directly connected with the resulting cutting quality. Optimum parameters should provide a quasi-stationary cutting front development slightly inclined against the axis of the cutting beam and nearly straight across the entire cutting depth

with minimal striations and roughnesses on the cutting edges. Therefore, a convenient idealized cutting front geometry can be used in order to analyse the possibility of optimizing the integral and homogeneity of the absorption distribution by varying the focus position in relation to the surface of the workpiece.

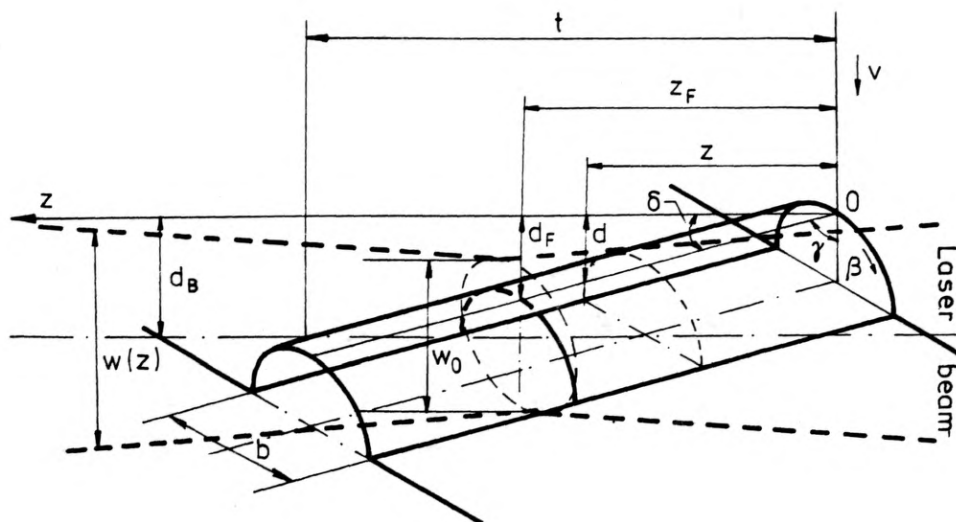


Fig. 1. Schematic drawing of the laser beam interaction with an idealized cutting front

The following simplifying assumptions [1], [2] are made (Fig. 1):

- Gaussian monomode laser beam normally incident on the workpiece surface and of focused waist diameter  $2w_0$  is considered.
- Cutting front is supposed to be stationary.
- Width  $b$  of the cutting front is identical with the diameter  $2w_0$  of the focused laser beam and it is constant for the entire cutting depth.
- Contour lines on the cutting front are semicircles of radius  $w_0$  running parallelly to the surface of the workpiece.
- Inclination  $\gamma$  of the cutting front in relation to the surface of the workpiece is constant on the entire cutting depth.

The beam waist at a distance  $z_1$  from the focus is given by the relation

$$w(z_1) = w_0 \{1 + [\lambda z_1 / (\pi w_0^2)]^2\}^{1/2} \quad (1)$$

where  $\lambda$  is the vacuum radiation wavelength.

The most common element focusing the laser beam is a plano-convex lens. This lens shape with the convex side towards the light source provides a reasonable minimal value of spherical aberration [3]. For evaluating the focal spot diameter and the focal depth  $s$ , the following formulas [4] can be used for the circular monomode beam

$$2w_0 = 2.44 \lambda f / D, \quad (2)$$

$$s = 2\pi w_0^2/\lambda \quad (3)$$

where  $D$  is the lens aperture diameter, and  $f$  — the focal length. The spot size of higher modes is obtained by using Eq. (2) and multiplying the result by  $\sqrt{\alpha}$ , where  $\alpha$  denotes the order of the oscillating mode [5].

### 3. Influence of the laser beam polarization

In the laser cutting, the radiation beam is incident on the cutting front at a large angle of incidence and so, the beam polarization has a considerable effect.

The polarization state of the incident beam can be resolved into two orthogonal  $s$  and  $p$  components of planes of incidence and polarization being mutually perpendicular and parallel, respectively. Depending on the angle of incidence  $\theta$ , the Fresnel formulas [6] yield the reflection coefficients  $r_s$  and  $r_p$ . The absorptivity which determines the proportion of absorbed beam intensity is then

$$A(\hat{n}, \theta) = 1 - |r|^2. \quad (4)$$

It depends on the complex refractive index  $\hat{n} = n - jk$  of the workpiece and the angle of incidence  $\theta$ , and is different for the two  $s$  and  $p$  components.

For given focal shape, intensity distribution and polarization of the focused laser beam, the absorption distribution on the cutting front can be evaluated. The local intensity and the angle of incidence of the beam have to be calculated for each point on the cutting front. Therefore, the absorption distribution has the form

$$A(z, \beta) = \cos\theta A(\hat{n}, \theta) I(z, \beta) \quad (5)$$

where  $z$  is the cutting depth,  $\beta$  — the circular angle, and  $I(z, \beta)$  — the local intensity. The integral absorption on the cutting front is determined up to a proportional constant by integration

$$A = \int_0^t \int_{-\pi/2}^{\pi/2} A(z, \beta) d\beta dz \quad (6)$$

where  $t$  is the workpiece thickness.

The influence of polarization on the absorption distribution  $A(z, \beta)$  is illustrated in Fig. 2 for linearly polarized laser radiation, with the plane of polarization parallel ( $\parallel$ ) and perpendicular ( $\perp$ ) to the cutting direction, and for circularly (c) polarized laser radiation at three inclinations of the cutting front,  $\gamma = 81^\circ$ ,  $85^\circ$  and  $89^\circ$ . A cw  $\text{CO}_2$  laser beam of 20 mm in diameter focused by a lens of  $f = 20$  cm on the surface of a 3 mm thick steel ( $\hat{n} = 23 - j24$ ) sheet has been considered. In the case of a fixed cutting direction, the linearly polarized radiation with the plane of polarization parallel ( $\parallel$ ) to the cutting direction provides the greatest radiation absorption and thereby the most efficient cutting. When the plane of polarization is perpendicular to ( $\perp$ ) to the cutting direction the absorption distribution has a minimum in the central region at  $\beta = 0$  and the totally absorbed radiation is considerably smaller providing a much lower cutting efficiency. Many applications require cutting in multiple

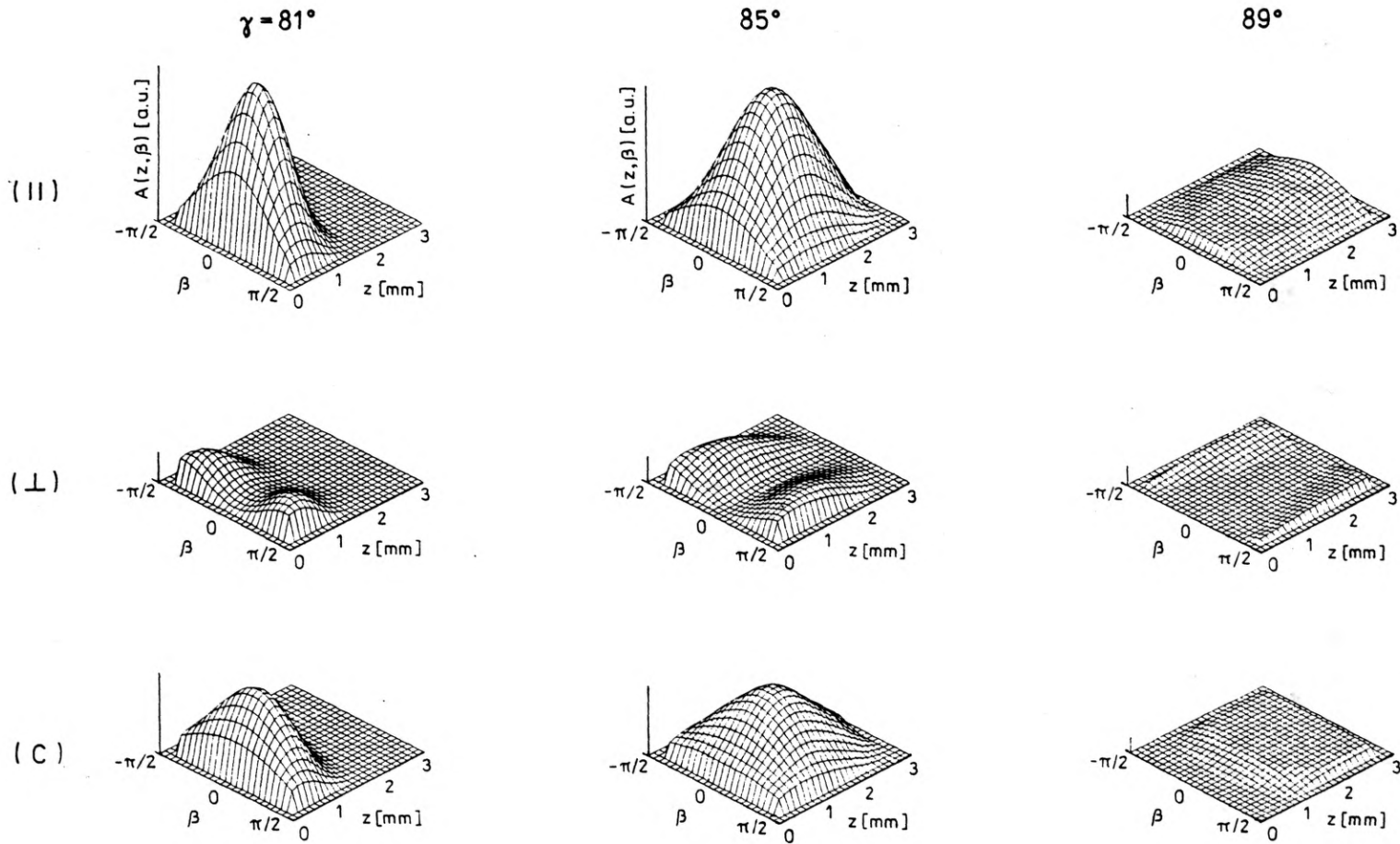


Fig. 2. Absorption distributions  $A(z, \beta)$  of a cw  $\text{CO}_2$  monomode laser beam of 20 mm in diameter focused by a lens of  $f = 20$  cm on the surface of a steel ( $\hat{n} = 23 - j24$ ) sheet of 3 mm in thickness at three inclinations of the cutting front  $\gamma = 81^\circ$ ,  $85^\circ$  and  $89^\circ$  for linearly polarized laser radiation with the plane of polarization parallel (||) and perpendicular ( $\perp$ ) to the cutting direction and for circular (c) polarization

directions. For these and other types of material processing applications, circular polarization is a convenient, controllable way to preserve the processing homogeneity.

#### 4. Focus position dependence of the laser beam absorption

The focus position and the beam divergence in the focal region which is mainly determined by the focal length of the lens and the mode and diameter of the laser beam have a great influence on the homogeneity and the maximum of the absorption distribution and thereby on the cutting result.

Let us denote the focus position by two coordinates,  $z_F$  and  $d_B$ , as shown in Fig. 1. When the distance  $d_B$  from the  $z$  axis to the beam centre is varied by the laser beam translation along the cutting direction at fixed  $z_F$ , the homogeneity and the integral of the absorption distribution on the cutting front are modified as one can see in Fig. 3 for circular polarized beam under the same conditions as those in Fig. 2 but for two values of the steel refractive index [7]. The cutting front inclination  $\gamma$  corresponding to the maximum integral absorption is smaller for a greater distance  $d_B$ . The optimum value of distance  $d_B$  at given  $z_F$  is  $d_B = w_0$ .

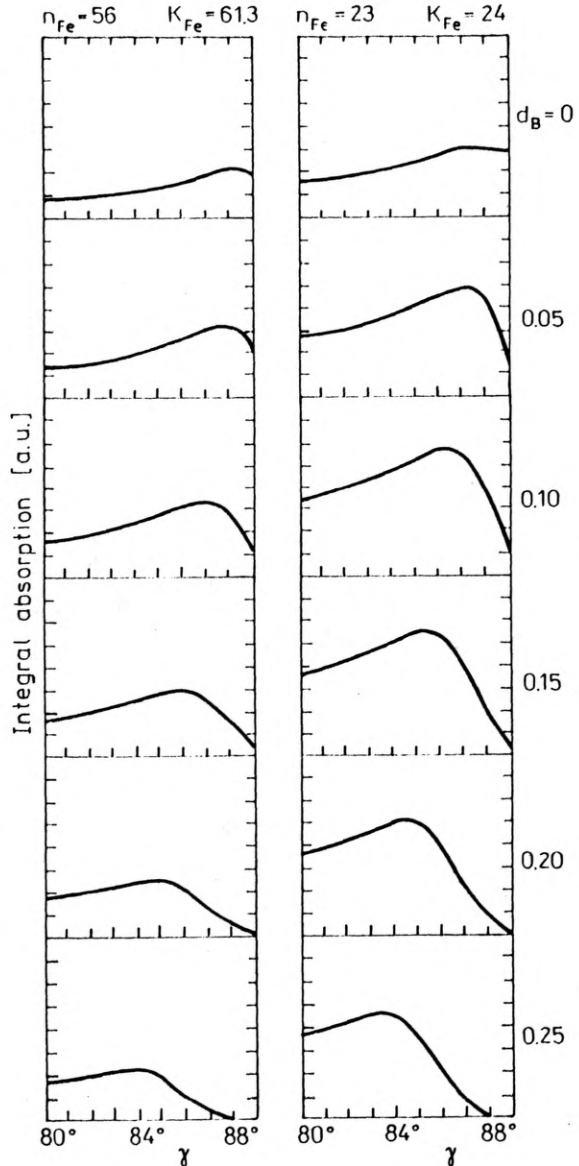


Fig. 3. Integral absorption of a circularly polarized  $\text{CO}_2$  laser beam focused on the surface of the steel sheet in the same conditions as in Fig. 2 against the cutting inclination for a variable distance  $d_B$  given in millimetres. Two values of the complex refractive index  $\hat{n}_{Fe} = n_{Fe} - jK_{Fe}$  of the steel sheet are considered

The variation of the integral absorption against the distance  $z_F$  of the focal spot measured from the surface of the workpiece in the depth of the sheet, for three different values of  $d_B$  is presented in Fig. 4 under the same conditions as those in Fig. 2 and for two values of the cutting front inclination,  $\gamma = 81^\circ$  and  $85^\circ$ . One can see from Fig. 4 that there is a range of  $z_F$  values which is greater at the smaller front inclination, providing a less sensitive integral absorption to different focus positions  $d_B$  along the cutting direction. At greater cutting front inclination which is of practical interest, the optimum value of  $z_F$  is  $z_F \approx 1$  mm, and it is smaller than focal depth  $s$ .

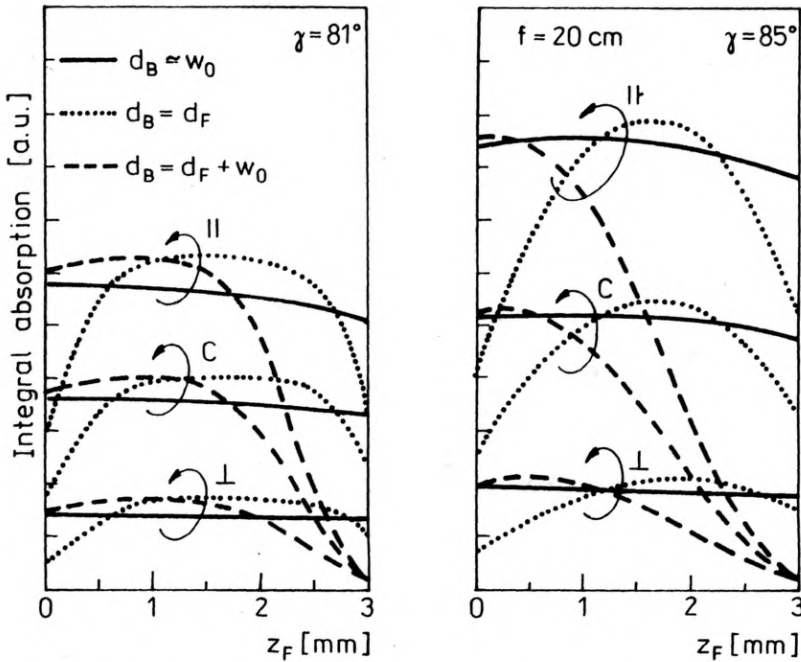


Fig. 4. Integral absorption against the distance  $z_F$  for three different values of  $d_B$  on the cutting direction at two cutting front inclinations,  $\gamma = 81^\circ$  and  $85^\circ$ . The same conditions as in Fig. 2 are considered

The variations of the focal position  $d_B$  could be produced in practical cases by small deviations of different parameters in the course of the cutting process; for example, by small deviations in the workpiece displacement velocity at fixed laser beam position. That is why it is important to place the laser beam focal spot at a certain optimum distance  $z_F$  in the depth of the sheet to get a lower sensitivity of the radiation absorption to inherent parameter deviations during the cutting process.

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