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Role of the Features of Focused Laser Beam at Pulsed Laser Cutting

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Abstract

In this article investigation of the roles of two important factors of focused laser beam, the focal spot diameter and the Rayleigh length as determining variables of the beam quality were made. The equations of these two factors are based on those most commonly used in the literature. The exchange between three different beam quality numbers were shown. It is proven on the basis of the scientific literature, that the beam quality degrades compared to the original data given by the factory of laser. The causes of the beam quality degradation are lens aberrations in the optical path of the given laser, and the shifting of the beam propagation ratio (M^2) to higher values. A new equation for estimation of the new, lowest value for M^2 factor is presented, based on the comparison of the laser cut material thickness to the depth of focus, which is two times the Rayleigh length.

Keywords: *laser cutting, laser beam, beam diameter, beam quality, beam propagation ratio (M^2), Rayleigh length.*

1. Introduction

In laser beam processing a special importance is given to the machining laser and within that to the cross section characteristics of the focused beam, the focal spot diameter, because the focused beam is that contactless tool which through energy transfer does the processing. Why is it important to know how large is the focal spot diameter? Because in laser cutting with a smaller focal spot diameter we get a smaller kerf, therefore there is less dross and a higher quality cutting requiring less post-production. Because of the narrower laser beam the heat affected zone is also smaller. The formulas for the focal point diameter are the same in much of the specialist literature, except that in order to reach a common format sometimes one has to double the radius to get the diameter and the data regarding the beam quality has to be calculated accordingly: by writing into the formula the M^2 beam quality factor which is the reciprocal of the K beam propagation factor (see no. 2.) **[1]**, **[2]**, **[3]**, **[4]**:

$$d_{f0} = \frac{4\lambda f M^2}{\pi d_b} \tag{1}$$

Here lambda λ is the wavelength of the laser, f is the focal distance of the lens that focuses the laser on the workpiece, M^2 is the beam quality factor which tells us which multiple of the ideal Gauss beam is the focal point diameter of the analysed beam, d_b is the diameter of the laser beam collimated close to the focusing lens. If we expand the laser beam collimated close to the focusing lens, the d_b beam diameter seen below will be multiplied with the beam expander factor, which is a number without measurement unit (B_e), it tells us how many times the beam diameter has increased compared to the unexpanded beam **[1]**:

$$d_{f0} = \frac{4\lambda f M^2}{\pi d_b B_e} \tag{2}$$

The Rayleigh length is a length, measured in the beam's own traveling direction, at which the surface of the laser spot doubles, its radius is multiplied by the square root of two, so the amount of energy that goes to a unit of surface is half of that which is calculated in the focal point. Generally speaking a beam is considered to be focused within the double of the Rayleigh length, this is what we call depth of focus, so when we're cutting with laser, this is approximately the thickness of the material that the laser can cut. Its formula is very similar to that of the laser spot diameter, only here the focal distance of the focusing lens and the beam diameter before the lens are squared [1], [4]:

$$z_r = \pm \frac{4\lambda M^2 f^2}{\pi d_b^2 B_e^2} \tag{3}$$

The mentioned variables of the focused laser beam are represented in **Figure 1.** where the z coordinate is in the spreading direction of the laser beam, Θ the opening angle of the focused beam. **Figure 1.** was based on the unified characteristics of the figures in references [1] and[5] The following articles also discuss the beam quality: [6], [7], [8], [9].

2. Quantities of the beam quality

The beam quality appears in the definitions of the two most important characteristics of the beam cross section: the focal spot diameter and the Rayleigh length. It is important to know the different ways of defining the beam quality and also, how can we switch between them.

The beam parameter product (BPP) is an expression of the focusability of the laser beam which is given most often as the product of the beam waist radius within the resonator and the far field divergence angle, Θ_σ divided by four. Here Θ_σ: the opening angle of the asymptote cone that covers the expanding beam [10]:

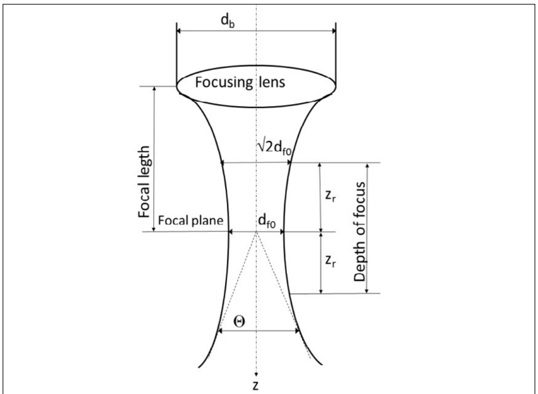

Figure 1. *Representation of variables of the focused laser beam*

$$BPP = \frac{d_{\sigma 0}\Theta_\sigma}{4} \tag{4}$$

Another definition is the beam quality factor, a measure that shows us how much the beam parameter product approaches the diffraction limit of an ideal Gauss-beam [10]:

$$M^2 = \frac{\pi}{\lambda}\frac{d_{\sigma 0}\Theta_\sigma}{4} \tag{5}$$

Yet another method is the K beam propagation factor which is the reciprocal of M^2: [10].

$$K = \frac{1}{M^2} \tag{6}$$

For a non-ideal beam $M^2 > 1$, and $K < 1$. It follows from the above formulas that if one of the three variables that describe the beam quality is given, the others can be calculated, provided that we know the wavelength of the laser and we pay attention to the conversion of measurement units.

3. Effect of the possible changes in beam quality on the focal spot diameter and Rayleigh length

It should be clarified that the measuring of the beam quality is specified in standard ISO11146. For a correct measurement „the diameter of the laser beam *d(z)* has to be measured on at least ten different spots in the vicinity of the focus, along the ray axis. Half of these spots must be within the Rayleigh length, the other half outside the double of the Rayleigh length" [11]. In order to measure the beam cross section in the type of impulse lasers discussed in this paper, simpler methods such as knife edge scanning or slit scanning cannot be used because the laser is not continuously on. Therefore we need a matrix sensor and because of the high sensitivity of the detector we also need several instances of beam attenuation in a way that does not influence the measurement results and does not distort the original beam that is to be measured [11].

The following is intended to present the effect which possible changes of beam quality can have on focal spot diameter and on Rayleigh length. This is a simplified model of the reality described above, which nevertheless can yield useful results. This approach can be analysed also because the modus structure of the analysed lasers is near TEM 00 which is close to the ideal Gauss-beam according to the support service. As such it is easier to analyse and approximate the possible change of the focused beam cross section through these two variables. This analysis is also warranted by the fact that when we process something with a laser beam, we use the part of the beam that's close to the focal spot, so it is important to know where the focus is, what the size of the focal spot diameter is and that of the doubled Rayleigh length within which the laser can be used. Analysing the two variables described above has other advantages too. Based on these two variables the geometry of the focused laser beam can be described by equations: the beam diameter as a function of the z coordinate in the direction of the beam spreading, where z_0 is the z-coordinate of the focus plane [1]:

$$d_f(z) = d_{f0}\sqrt{1 + \left(\frac{z - z_0}{z_r}\right)} \quad (7)$$

Remembering the formulas for the focal spot diameter and the Rayleigh length, the question is: what gives the results in these formulas in each case? In both these formulas the same set of data appears (2 and 3). This analysis is linked to the cutting experiments described in our previous papers [12], [13], [14], [15], [16]:

- the wavelength: the changes in wavelength of the Nd:YAG laser used in our experiments are negligible.
- the focal distance of the focusing lens was constant: 50 mm.
- The diameter of the close collimated laser beam before the focusing lens is equal to the product of the unexpanded beam diameter d_b and the multiplier number of the beam expander (B_e): at a given beam expander state both are constant, the effect of the beam expander will be analysed later.
- The other parameters that appear in the formulas are constant.

Now let's analyse the cases of beam quality change that we found, these generally mean a degradation of the factory set beam quality, and as such an increase of the focal spot diameter and of the Rayleigh length:

There are five types of information that allow us to conclude that the beam quality is changing:

1. The LASAG KLS 246 FC's Nd:YAG laser developed for microprocessing is prone to thermal lensing: at a higher average power the middle of the crystal rod is warmer, it expands more than its outer surface, thus the two ends work as a lens with a curvature that changes as a function of the average power. A similar effect has been described in one of the reference papers: [5]. According to the support service up to an average power of 5 W it is M^2 = 3, at the maximum of 15 W it is M^2 = 5, between those two values it changes in a linear fashion.
2. The zoom 8-step beam expander as an optical system consists of at least 3 lenses, because 2 lenses would be necessary for a Galilei-telescope type fixed beam expander. These systems too have image failure, let's take a look at the one that has the strongest effect: the spherical aberration. The essence of this is that the farther the analysed rings are from the optical axis in a radial direction, the closer the focus will get to the lens. The LASAG support service told us that at beam expander position nr. 1 we should remove the beam expander, since in this situation it only lets the collimated beam through, this is yet another proof of the fact that the beam expander causes a decrease in focusability.
3. According to Kaplan [1]], with strong focusing and low F numbers the formulas for r_{f0} focus radius and z_r, are not true, corrective measures must be implemented (here: $F = f/d_b$):

$$r_{f0} = \frac{2\lambda F}{\pi K} + \frac{k_{sa} d_b}{2F^2} = \frac{2\lambda f}{\pi d_b K} + \frac{k_{sa} d_b^3}{2f^2} \quad (8)$$

The typical values for lenses with n refracting index and k_{sa} factors that correct lens aberrations, depending on the lens material, are the following:

ZnSe	n = 2.40, k_{sa} = 0.0312
GaAs	n = 3.27, k_{sa} = 0.0139

One thing surely follows from this equation: the value of r_{f0}, and with it that of d_{f0} and z_r will increase, therefore the focusability of the lens will be worse. Here the K beam expanding factor and the correction appear separately, we would include these in the value of the M^2 factor because that seems to be more logical even if the author treats them separately. In the paper quoted in nr. 4 this correction is part of the M^2 factor. There are two reasons why we cannot count these two factors: the first one is that the author doesn't tell us where the limit of strong focusing is, obviously it means a large beam diameter before the lens and a lens with a small focal distance, we suspect that the maximal beam expander position and the 50 mm focusing lens is part of it. The second one is that we cannot identify the material of the lens, therefore we don't know which corrective factor to use.

4. In Harp's paper [4]:]: „A Practical method for determining the beam profile near the focal spot" which was published in a prestigious Springer magazine the author analysed the beam quality of the IPG Photonics made 300 W, CW, Ytterbium fiber laser by creating welding seams on the material inclined in front of the focused laser beam. The initial beam quality factor was M^2 = 1.04. The laser beam exited from a 9 µm diameter fibre, after collimation its diameter was of 4.5 mm. They used a fivefold beam expander to get a smaller focal spot, following that they tried three different focusing lenses, with a focal distance of 150 mm, 100 mm, and 60 mm. The M^2 value given by the factory was first corrected because of an unnamed optical failure in the lenses: here too the author divides with the square of the lens' focal distance in the correction, the „a" factor is given by the welding experiment:

$$M^2 = M_0^2 + \frac{a}{f^2} \tag{9}$$

According to the diagram that sums up the results in the paper for a 60 mm focus lens, using the above correction the initial 1.05 value of M^2 increases to 2.5, if one includes the spherical aberration, the value will be approximately 6.

5. In Zimmermann' paper [3] an IPG YLR-200-SM single modus fibre laser is analysed, the author gives the unfocused beam diameter for the collimated beam, the theoretical focal spot diameter calculated from this, the Rayleigh length and the power density. But in reality the optical failures of the lens, most importantly the spherical aberration will increase the theoretically achievable focal spot size. The focal spot diameter increases in proportion to the cubic diameter of the beam before the focusing lens. The variables of the focused beam were measured with the knife edge scanning method defined in standards ISO 11145 and 11146. During the experiments they analysed the focus shift which occurred in the direction of the spreading and which depended on the laser power; its value was around 110 µm, exceeding the 89 µm Rayleigh length. This focus shift was caused by the warming up of the laser guiding optical elements and their sockets. Data for calculations: wavelength: 1070 nm, $M^2 < 1.1$; focal distance of the focusing lens: 50 mm, initial beam diameter: 6.5 mm [4]. An interesting aspect of the experiment is that they used the beam expander first as an expander and thus the measured focal spot diameter was larger than the theoretical value (Table 1. row 3.), next they decreased the beam to half and so they got a focal spot diameter that was smaller than the theoretical value (Table 1. row 1.). The advantage of decreasing is that the Rayleigh length increased so a thicker material could be processed.
The degradation of the beam quality can be caused by the staining of the protective glass that's in front of the focusing lens that may be caused by the small droplets of material splashing from the workpiece, if we notice that, the protective glass must be changed.

Table 1. *Comparison between the calculated theoretical values according to the paper and the measured results* [3]

Beam diameter (mm)	3.25	6.5	13
Theoretical focused diameter (µm)	23	12	6
Theoretical Rayleigh-length (µm)	355	89	22
Measured focused diameter (µm)	20	14	9.4

4. Estimating the degradation of the M^2 factor in five previous experiments

Here we give a new method which allows for a lower approximation to the degradation of the M^2 factor based on the comparison between the processed material thickness and the Rayleigh length. During the five experiments we used a LASAG KLS 246 FC laser. According to the support service for this laser M^2 ($P_{average}$ =< 5W)=3 and M^2 ($P_{average}$ = 15W)=5 and between these two values it is linear. From this we can state the equation of the straight $y = 0{,}2x + 2$ if $5 < x < 15$, where y is the M^2 factor and x the $P_{average}$. In the table presenting the characteristics of the first three experimental processing (Table 2.) the M^2 factor can be calculated which gives values between 3.7 and 4.2. Thus the size of the focus spot and a first approximation of the Rayleigh length can be calculated. The double of the Rayleigh length was much less than the thickness of the cut material therefore we had to readjust the M^2 factor.

From the equation that gives Rayleigh length = half of the material thickness (v_a) rearranging (3) formula and stating a new equation (10) we calculated the estimated value of the new M^2 which turned to be around 7.

$$\frac{\frac{v_a}{2}\pi d_b^2 B_e^2}{4\lambda f^2} = M_{új}^2 \tag{10}$$

Table 2. *Values of M^2 factor and d_{fo} and z_r both theoretical and readjusted based on the material thickness of the cut tube*

	First experiment [8]	Second experiment [9]	Third experiment [10]
Material thickness (mm)	0.117	0.12	0.12
Operation	cutting	cutting	cutting
Average power	8...11.2 W	10-12 W	8.7 W
Medium average power	9.6 W	11 W	8.7 W
M^2 on medium average power based on data from the support service	3.9	4.2	3.7
d_{f0} (μm)	13.3	14.2	12.7
$\pm z_r$ (μm)	±33.2	±35.6	±31.7
The z_{rnew} necessary because of the thickness of the cut wall (μm)	±58.5	±60	±60
The new M^2 factor calculated from this	6.9	7.1	7.1
The new focal spot diameter calculated from this (μm)	23.4	24	24

Based on the new M^2 factor the focal spot diameter was recalculated which was around 20 micrometers, the interesting part of that is the fact that with a beam expander in the 8th position, that was the approximate size of the kerf (**Table 2.**). The results are represented in **Figure 2.**: both the focal spot diameter and the Rayleigh length increased.

Applying this line of thought to the sheet cutting experiment done with a 0.4 mm, beam expander in the 4th position, the value of the M^2 factor calculated from the equation based on the data given by the support service turned out to be between 3.8–4.8. The double of the Rayleigh length calculated from this data was still less than the material thickness. If we made the Rayleigh length equal to half of the material thickness, M^2 turned out to be 5.9 which is 1 less than what we get with the beam expander in the 8th position. (**Table 3.**). This result matches those of the previously presented analysis, obviously if the diameter of the beam that passes through the lens system decreases, if we apply a beam expander multiplier in the 4th instead of the 8th position, the spherical error decreases and thus the beam quality improves.

Table 3. *Values of M^2 factor and d_{fo} and z_r both theoretical and readjusted based on the material thickness of the cut tube*

	Fourth experiment [11]	Fifth experiment [12]
Material thickness (mm)	0.4	0.4
Material geometry	sheet	sheet
Material quality	AISI 304L	AISI 304L
Operation	cutting	cutting
$P_{average}$	12.5....16.	9.2
Beam expander multiplier	4	4
Medium average power	14.25 W	9.2 W
M^2 on medium average power based on data from the support service	4.85	3.84
d_{f0} (μm)	32.87	26.02
$\pm z_r$ (μm)	±164.3	±130.12
The $z_{rúj}$ necessary because of the thickness of the cut wall (μm)	±200	±200
The new M^2 factor calculated from this	5.9	5.9
The new focal spot diameter calculated from this (μm)	40	40

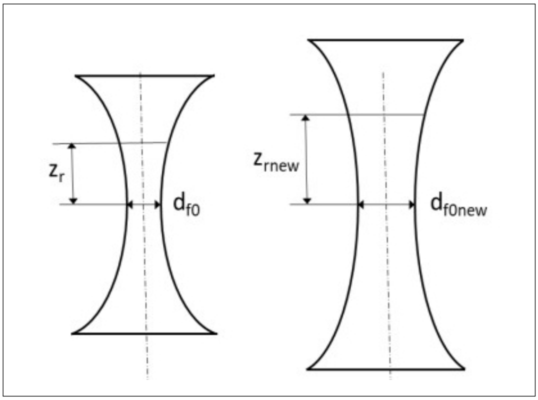

Figure 2. *A representation of the theoretical values of the focal spot diameter and the Rayleigh distance, along with those calculated on the basis of the estimated M^2 factor*

5. Conclusions

In this paper we analysed the effect of changes in the two important variables of a focused laser beam: the focal spot diameter and the Rayleigh length as variables that appear in the most widespread formulas in the reference bibliography. We present the way these variables that express beam quality and are present in both formulas can be converted into each other and based on reference bibliography we prove that in comparison with the factory given values of these lasers the beam quality will be degraded due to the flaws in the lenses that are in the optical path of the laser beam, thus the value of the M^2 factor will increase. To estimate the lower limit of this increased M^2 variable we presented a new correlation which is based upon a coordination between the thickness of the cut material and the double of the Rayleigh length as the depth of focus.

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