MACHINE SOLUTIONS WHITE PAPER

EXPLORING LASER WELDING IN CATHETER MANUFACTURING:
ANALYZING BEAM PROPERTIES, PROPAGATION, AND IMPLICATIONS

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Introduction

One of the most used procedures to bond catheters is laser welding for its precision and reliability. To do so, the base tubing and the catheter balloon are covered with a shrinking tube. The incoming laser beam provides a precisely controllable amount of energy to a specifically defined area. The shrinking tube provides the necessary welding force, whereas the laser provides the needed thermal energy to melt the polymer. This allows superior welding results in contrast to competing technologies, such as hot air bonding, which carry the danger to damage neighboring areas of the catheter. Understanding the most important welding parameters as well as the beam characteristics can help to develop successful processes and is addressed by this paper.

Established an understanding of:

- Understanding the correlation among the key welding parameters: power, time, and spot size.
- Exploring the fundamental attributes of the laser beam and the challenges in defining its diameter.
- Analyzing the propagation of the laser beam and its impact on spot size and energy density.

Power, Time and Energy

The main process parameters are the welding **power**, the welding **time** and the **spot size** of the laser. The product of the first two gives the amount of **energy** brought into the product:

$$E = P \cdot t \qquad (1)$$

Whereas E is the energy in [J], P the power in [W] and t the welding time in [s].

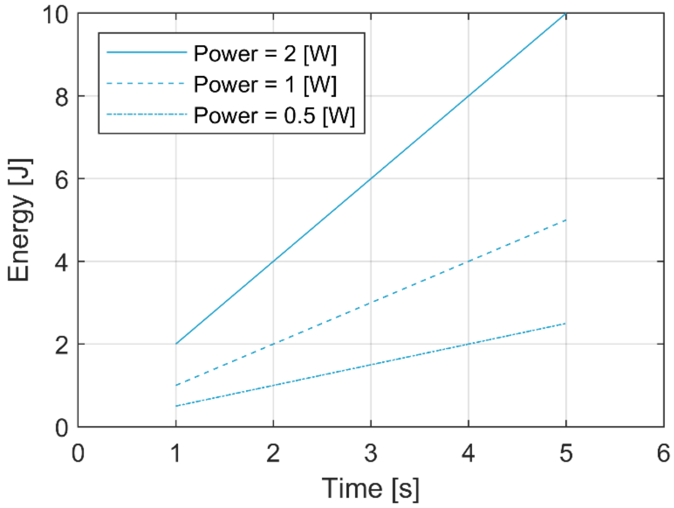

Figure 1: The correlation between energy and time using different powers.

The desired amount of energy input into the product can be reached by different power and time combinations as can be seen in Figure 1.This freedom can be used to design robust and reliable welds adapting to the product needs.

The energy is further distributed around the circumference by rotating the product, which is not necessary on the most sophisticated machines on the market. Furthermore, the product can be moved in longitudinal direction during the welding and the focal point can be changed to allow complex welding strategies.

The energy is an integral unit and describes therefore the total amount imparted on the product. With that energy, the product is heated up according to:

$$E = m \cdot c_p \cdot \Delta T \ (2)$$

With E the energy in [J], m the mass in [kg], c_p the specific heat capacity in [J/ kg K] and ΔT the difference in temperature in [K].

The amount of mass heated is defined by the spot size of the laser beam. If the spot size is big, much more mass is heated with the same energy than if a smaller spot size is used. And therefore, the resulting temperature is lower. The melting point of the polymer might not be reached. Whereas with the same amount of energy and a smaller spot size, the melting point can be reached. The spot size is therefore an important parameter for the welding success.

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Spot Size and Focus Distance

The common laser welding machines use a focused laser beam. A collimated beam is focused by a lens to concentrate the laser in a certain distance from the lens. The spot size decrease until the focal length is reached. Afterwards, the beam is expanding again.

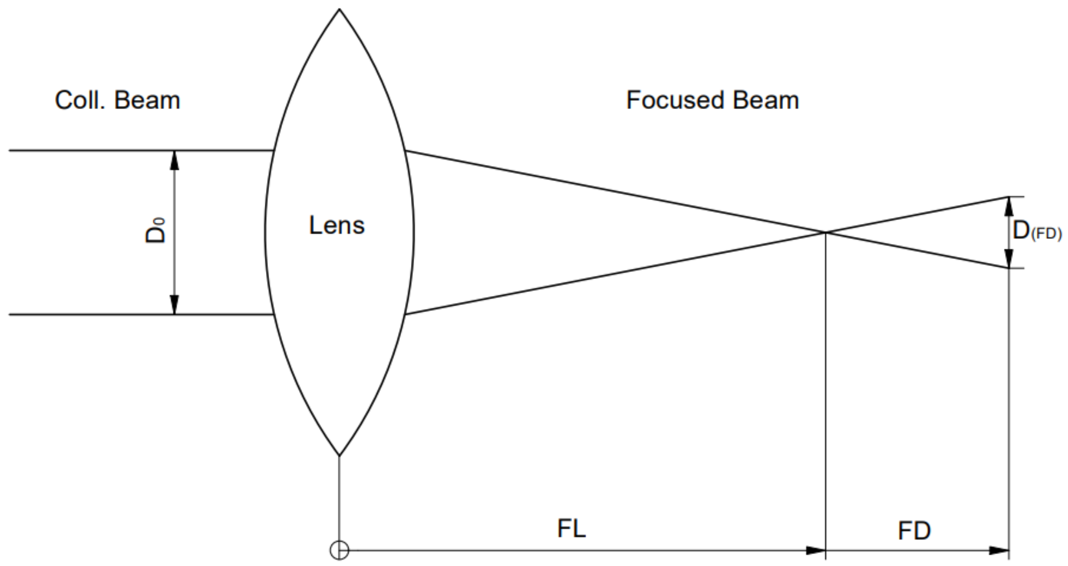

Figure 2: Collimated beam with an initial diameter D_0 is focused by a lens with a focal length FL resulting in a Diameter D dependent on the focal distance FD.

Geometrical optical considerations can be used to obtain the relationship for the spot size characterized by its diameter as:

$$D(FD) = \frac{D_0}{FL} \cdot FD \qquad (3)$$

Whereas D [mm] is the diameter of the spot at the focus distance FD [mm], in respect to the focal length FL [mm] and D_0 [mm] as initial beam diameter.

Figure 3: Spot diameter in respect to the distance from the focal length of 63.5 mm and 13.8 mm as initial spot size.

Within the typical working distance of 5 to 20 mm focus distance, this relationship holds true. Closer to the focal point, the gaussian beam model as to be considered (1).

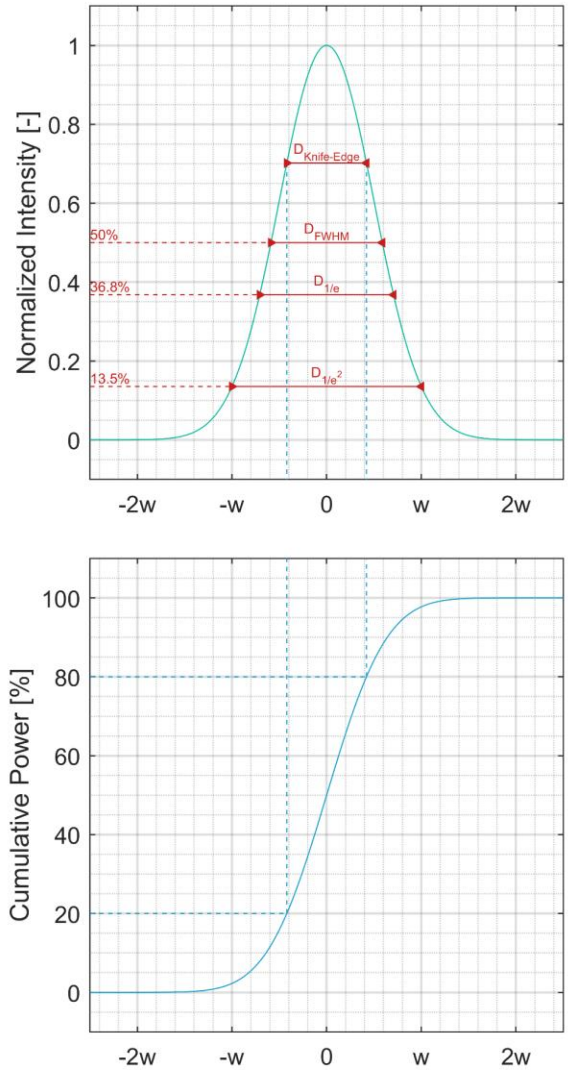

Figure 4: (t) normalized intensity and (b) cumulative power versus the beam radius, different definitions of the beam diameter.

Defining a diameter of a laser beam, however, is not straight forward. Several definitions are common:

- **FWHM:** Full width of half maximum; the diameter is defined as the distance between the opposite sides in the intensity distribution, where the beam intensity is half of the maximum.
- **D4σ**: Distance between the opposite sides in the intensity distribution, where four times the standard deviation of the intensity distribution is contained. This is used as the ISO definition of beam width.
- **1/e²:** Distance between the opposite sides in the intensity distribution, where the optical intensity drops to $1/e^2$ (≈13.5%). For single-mode gaussian beams, this definition gives the same result as the D4σ. For multi-mode beams, these definition gives no meaningful value.

- **1/e:** Distance between the opposite sides in the intensity distribution, where the optical intensity drops to 1/e (≈36.8%). This is used by the American National Standard.
- **Knife-edge width:** based on the knife-edge measuring method, the distance in the cumulative power distribution from 20% to 80%, alternatively 10 to 90%.
- **D86:** diameter of a circle centered at the beam power maximum containing 86% of the total power. Which is again equal to the $1/e^2$ definition for a gaussian single mode beam.

The commonly used CO_2 laser sources emit a gaussian beam profile in the TM00 mode. For this type of beam, the $1/e^2$ definition seems to be the most common one and will therefore be further used. With increasing diameter, the diameter is getting harder to be precisely measured due to the flat slope of the gaussian profile. Diameter measurements are therefore prone to unprecise measurements. This is reflected in the high measurement error of ±5% of commercially available sensors (2). If the diameter is estimated on a laser paper, the error can also be significant due to different sensitivities of different laser paper products and aging.

The inconclusive definition of the beam diameter and the difficulty to measure it precisely, lead to the common practice to define the recipe on a laser welding machine in terms of focus distance rather than beam diameter, even though for the sake of simplicity, this could be easily converted using equation (3) or Figure 3 to a rather theoretical value of the diameter.

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Power Density

As seen in Figure 4, the power of a gaussian beam with TM00 mode is not evenly distributed across the spot size. There is a peak in the center with decreasing intensity to the edges. The intensity profile is described by (1) and can be written by the equation:

$$I(r,z) = I_P(z) \cdot \exp\left(-2 \frac{r^2}{w(z)^2}\right) \quad (4)$$

Whereas I [W/cm²] is the beam intensity, I_P ·[W/cm²] the peak intensity in the maximum, w [mm] the beam radius at position z away from the focus point and r [mm] the radial coordinate of the evaluation point.

The peak intensity is given by:

$$I_P(z) = \frac{2\,P}{\pi\, w(z)^2} \cdot 10^2 \qquad (5)$$

P ·[W] is the total power and the factor accounts for the unit change from mm^2 to cm^2.

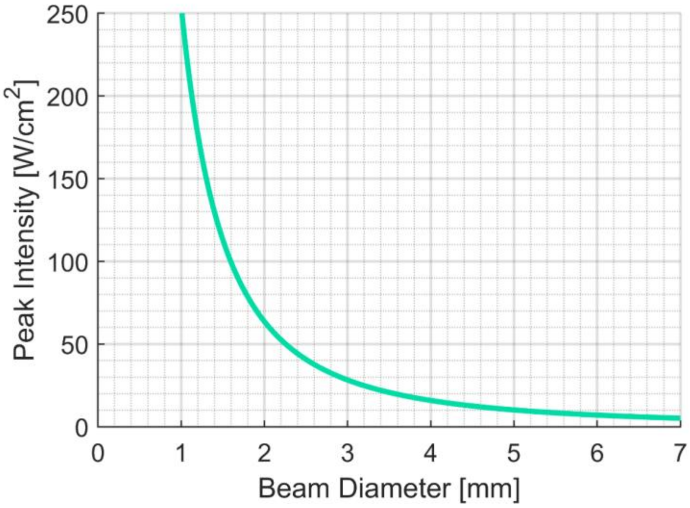

Figure 5: Peak intensity in dependence of the beam diameter.

Resulting from equation (5), the peak intensity is decreasing very quickly while increasing the beam diameter. Which implies, that changing the focus distance slightly, has a big impact on the welding characteristics. Furthermore, by decreasing the maximal intensity and increasing the diameter, the intensity distribution flattens out quickly:

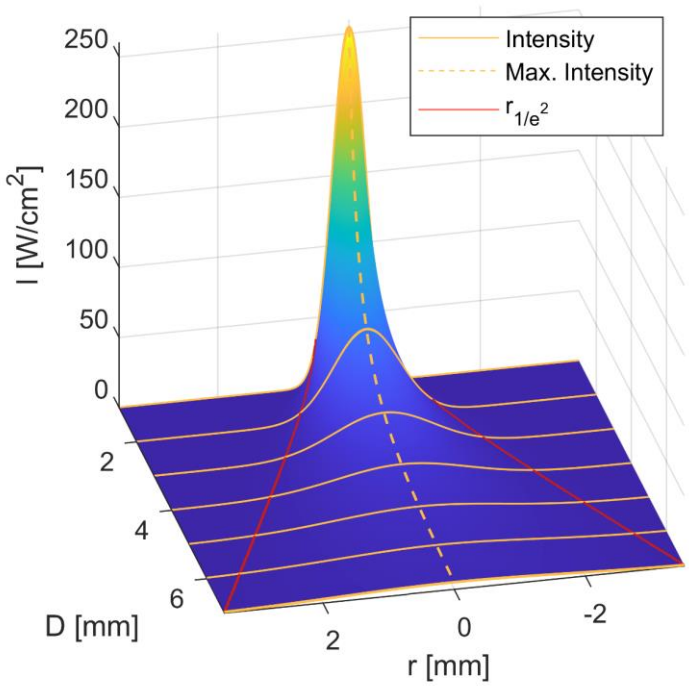

Figure 6: Intensity distribution over the radius r for different beam diameters D.

The changes in the intensity distribution become even more evident, when plotted for two individual, typical cases in 3D:

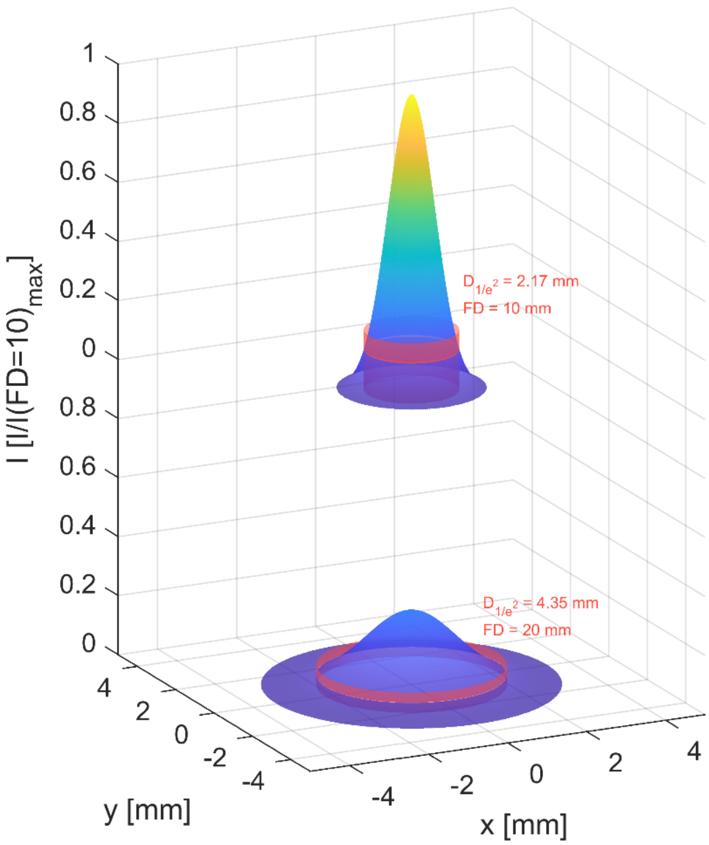

Figure 7: Intensity distribution in 3D and spot size for two typical cases.

The peak intensity drops massively by changing the focus distance, the intensity distribution flattens out. The power outside the diameter definition can still be significant for certain cases.

The beam diameter has therefore to be a tradeoff between the precision of having a small, well-defined spot to prevent damaging the surrounding product and a reasonable peak intensity to avoid local hotspots and overwelding.

Real Gaussian Beams

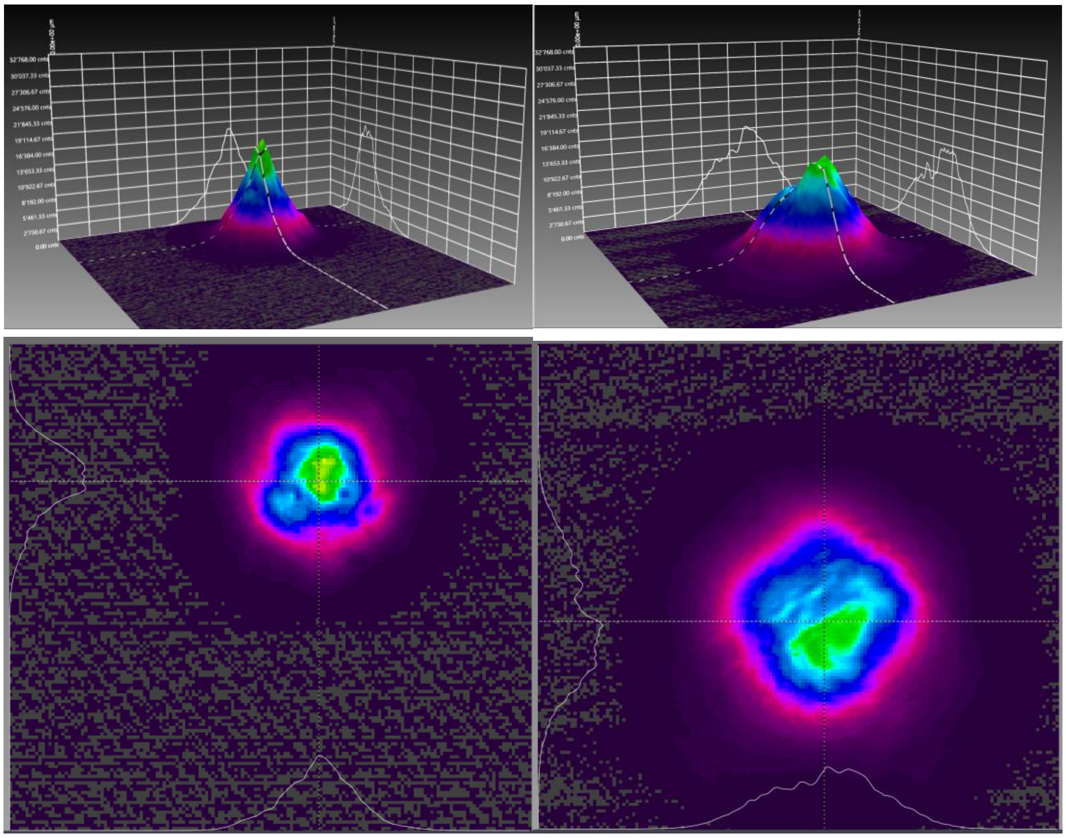

Figure 8: Beam profile measurements of a real gaussian beam with (l) FD=10mm, (r) FD=20mm with adapted power to maximize the sensitivity on the shape.

Real gaussian beams are not as perfect as the theory might anticipate. Figure 8 shows two beam profile measurements with a beam profiler at the same focus distances as Figure 7. The difference in spot size is well seen. The distribution of power is not as smooth as expected, but still hold true as a basic characteristic. The peak intensities cannot be compared due to the different power levels on which the images were taken.

Damping Effect of the Shrinking Tube

The effect of the high peak intensity and the not-perfect intensity distribution of a real gaussian beam is mitigated by the thermal damping effect of the shrinking tube. Welding catheters, the shrinking tube is heated first. The heat is therein distributed through conduction before hitting the product on a limited scale. This makes the process more robust. Note, that the behavior might differ significantly for different types of shrinking tube materials.

Spot Size vs. Product Size

Applying a laser beam to a product, the ratio between the spot size and the product size has to be considered as well. If the laser beam is bigger than the product, a significant part of the energy will pass the product, as can be seen in the following figure.

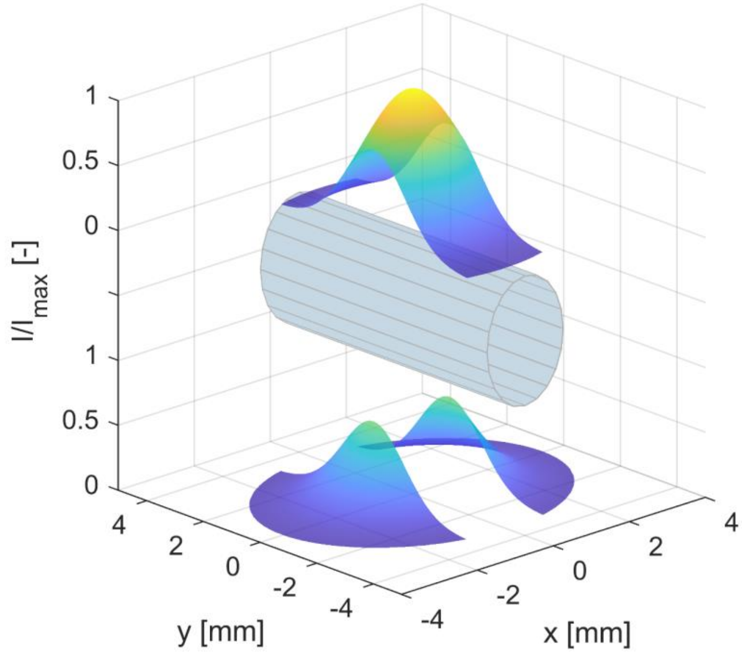

Figure 9: Laser beam of $D_{1/e2}$ =4.35 mm applied on a product of $D_{Product}$=2.0 mm

This might help to create a robust process, for it may compensate minor wobbling of a rotating product. Nevertheless, it should be done by purpose.

Conclusion

Laser welding is a powerful tool to join catheter components. Understanding the relationship between laser power, time and the intensity distribution, which is mainly defined by the spot size, gives a good starting point to develop and apply robust laser welding processes. By increasing the spot size, the laser intensity distribution flattens quickly. The peak intensity drops and the affected area increases. The shrinking tube helps to damp the effect of the peak intensity and the non-ideal gaussian distribution of a real gaussian beam. Combined with size considerations between the product and the beam size, excellent laser processes can be developed.

Bibliography

1. **Self, Sidney A.** *Focusing of spherical Gaussian beams.* s.l. : APPLIED OPTICS, Vol. 22, No. 5, 1983.

2. **MKS Ophir.** *Laser Power & Energy Measurement, Laser Beam Analysis 2023, p. 55.*