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Thermal focus shift avoidance strategies in high power laser cutting

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Abstract

Laser powers above 20 kW are getting more important to significantly increase productivity in laser cutting, especially of sheet thicknesses beyond 10 mm. Furthermore, laser powers of >40 kW exhibit potential to compete with plasma cutting, providing better edge quality, less material consumption due to smaller cutting kerfs at higher energy efficiency, thus also lowering CO2 emissions. This market demand is challenged by the intrinsic thermal focus shift of each optical element within the cutting system. Today, optical coatings for up to 20 kW of laser power are often optimized to balance performance and economic aspects. Minimizing focus shift can be done by, first, reducing energy deposition within AR-coatings, second, pre-correcting actual shifts by means of approximation, and third, measuring the shift and correcting it in a closed loop control. A detailed analysis of the in-situ thermal focus shift in real applications will be presented, providing an optimal combination of listed measures.

Keywords: high-power laser cutting; thermal focus shift; focus correction

1. Introduction

Recent market trends in 2D Laser Cutting applications reveal a strong influence of Chinese-driven power regimes up to 60 kW in the upcoming years with reasonable optical parameters like approximately 0.13 to 0.15 of numerical apertures on the output coupling of the laser light cable and thus M² values in the range of 12 to 16. These power levels are mainly achieved by significantly increasing the single emitter bars up to 5-8

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kW of power, so established beam combiners and geometrical arrangements are still applicable and do not need to be changed fundamentally. Known issues like stimulated Raman scattering within the laser light cable are significantly damped down to realize cable lengths of more than 20 meters. These improvements are challenging "down the optical train" for current state-of-the-art laser cutting heads, responsible for a reliable process focus by introducing a significant portion of so called "thermal lensing" causing the focus to shift uncontrolled in the vertical axis.

1.1. Process impact of thermally induced focus shift

Currently, well established laser sheet metal cutting is characterized by the following main process parameters (next to many other factors relevant for throughput and quality):

- Laser power
- Cutting speed
- Focal position
- Gas pressure and gas mixture / type

Within these four parameters laser power and focal position are strongly connected via the physical properties of the optics for focusing the optical power with magnifications between 1.5 to 4.0, for example.

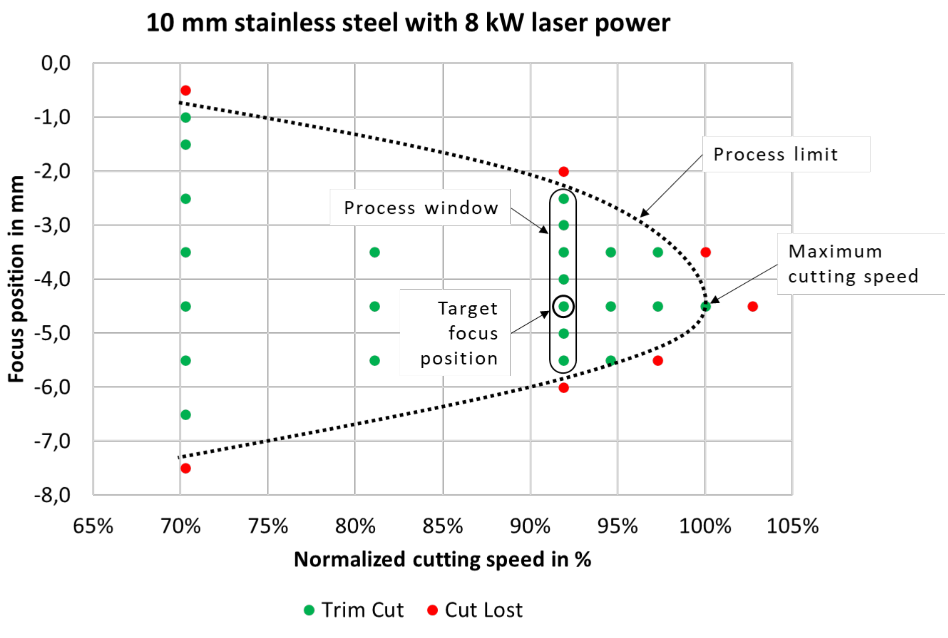

Fig. 1. Process window of a standard laser cutting application; The focal position is directly influencing the achievable cutting speed, thus productivity.

Figure 1 shows the dependency of the maximum cutting speed in respect to focal position for laser cutting of 10 mm stainless steel with 8 kW laser power and magnification of 1.5. Dashed line represents the process limit.

The optical path of a laser cutting head normally consists of several lenses and protective windows, which add up to a significant interaction path of laser light and the optics. Current anti-reflection coatings and substrates with focus shift values in the range of 8 - 10 % FS/z_R/kW are not optimized for the upcoming power regimes beyond 20 to 30 kW. Table 1 shows typical laser sources and its respective values of laser power, magnification and focus shift.

Table 1. Estimated increase of focus shift with raising laser power

Estimated increase of focus shift with respect to laser power	Laser power (kW)	Magnification (-)	Estimated absolute focus shift (mm)
Disc laser / low power fiber laser	8	1.5	0.6
Mid power fiber laser	20	2.0	4.0
High power fiber laser	40	2.5	10.0
Next generation high power fiber laser	60	3.0	18.0

2. Basic consideration of focus shift

2.1. Physical principle

Thermal lensing (thermally induced refractive power) was first observed in a laser optical cavity during the early stages of laser development and described by Leite et al., 1964. The effect describes the change in the optical properties of optical components due to an inhomogeneous temperature change because of localized heating. This results in a change in the propagation of light through such optical components, and leads to the so-called thermal focus shift, and a deterioration of the beam quality.

There are three main effects which contribute to the thermal lens as discussed by Koechner., 1970: the temperature dependent variation of the refractive index, the stress dependent variation of the refractive index, and the thermally induced deformations. The contribution of each effect depends on the material and geometry under consideration. The main material used in multi-kilowatt laser material processing applications is fused silica. As a result of its small coefficient of thermal expansion the thermal lens effect for refractive components made of fused silica is dominated by the temperature dependent variation of its refractive index. In other words, the absorbed laser power leads to an inhomogeneous temperature increase, which results in a thermally induced gradient index profile.

The influence of this gradient profile on the light transmission of a collimated beam through a plane parallel window is schematically depicted in Fig. 2. The light propagating through a medium with an inhomogeneous refractive index profile will refract according to Snell's law of refraction. Fig. 2. (b) shows a parabolic change in the refractive index n along the radial distance r, where the refractive index decreases as the radial distance increases. Light will bend towards the direction of increasing refracting index, leading to a focusing effect of the light like a conventional lens, Fig. 2. (d). Fig. 2 (e) is a calculated refractive index profile for a protective window in a cutting head. It has been calculated as described by Koechner., 1970, considering a 30 kW laser beam with 13 mm diameter, a wavelength of 1070 nm, a beam parameter product of 4 mm•mrad and considering a volume absorption of 15 ppm/cm through a window of 7 mm thickness.

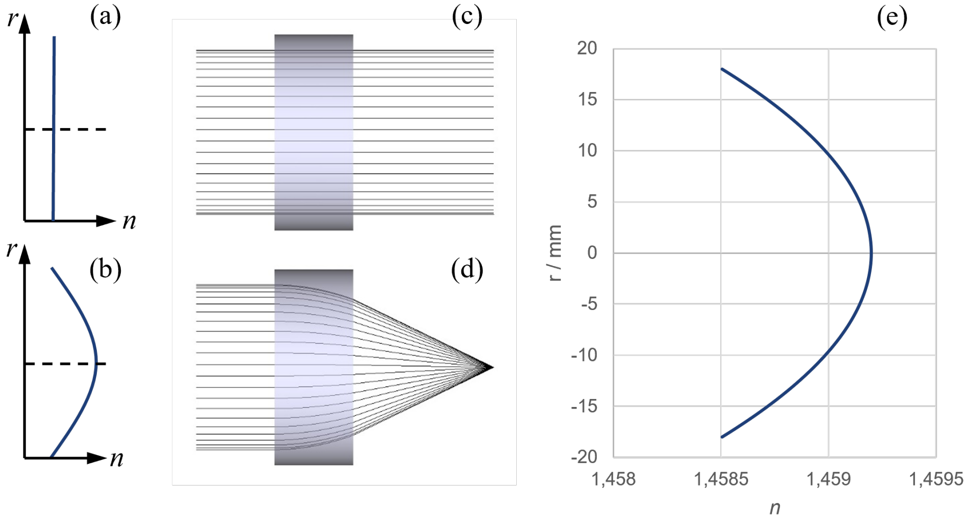

Fig. 2. Representation of a homogeneous (a) and inhomogeneous (b) refractive index profile and, respectively, their influence on the light transmission of a collimated beam through a parallel planar window (c), (d). Calculated refractive index profile for fused silica (e).

As a result of this self-focusing effect, the focal position during laser cutting moves upwards, i.e., away from the metal sheet towards the optics. It should be noted that the transit behavior of the thermal focus shift has a strong impact during cutting. The time-dependent behavior of the focus shift is related to the propagation of heat through the optics, which takes time until a steady state is reached. The time scale is influenced by several factors like beam diameter, lens geometry, ratio of bulk to coating absorbance and material properties such as density, heat conduction and heat capacity.

3. Strategies for reducing and controlling the focus shift

To reduce the thermal focus shift, three strategies are possible. One possibility is to reduce the absorbed laser energy through optimized optical components. Another method is to use thermal compensation techniques. A noteworthy alternative is to actively compensate the focus shift by continuously adjusting the focal position.

3.1. Optimization of optical elements and coating

State-of-the-art coatings and substrates play a crucial role in minimizing thermal focal shift, a phenomenon that affects the overall performance of optical systems (Laskin, 2021). To address this challenge, advanced coatings with excellent thermal properties, such as low absorption, low thermal expansion coefficients and high thermal conductivity must be developed. In the infrared range, several metal oxides have demonstrated excellent properties for antireflection coatings aimed at reducing thermal focus shift. Silicon dioxide (SiO2) is a metal oxide that finds utility in the infrared range due to its low refractive index. Other metal oxides, such as tantalum pentoxide (Ta2O5), have relatively high refractive indexes and together with SiO2 can form thin film antireflective coatings with excellent thermal properties (Negres, 2022). The materials selected are characterized by low absorption for 1064 nm wavelength, hence the temperature increase is minimized. By combining these advanced coatings with optimized substrates (Laskin, 2021; Carpenter et al. 2012), the reduction of thermal focal shift is achieved, ensuring that optical systems maintain accurate focus even in high power regime. Low absorption coatings can be made by Ion Beam Sputtering technology, which allows to create very dense, high quality thin films, with high repeatability and precise control of process parameters (Ristau et al., 2005). Resulting absorption values are at the ppm level and thus limited characterization methods are available.

Absorption and heating of optical components can be characterized by performing Photothermal common path interferometry measurement and the thermovisor test. Photothermal common path interferometry (PCI) measurement provides researchers with a comprehensive tool to investigate and characterize thermal lensing, enabling the development of strategies to mitigate its impact on optical systems and enhance their overall performance (Alexandrovski et al., 2009). Unlike Laser Induced Deflection method (LID), PCI allows scanning and detection of bulk or substrate absorption which can greatly impact final measurement value; therefore, the sources of absorption can be identified more precisely. The thermovisor test enables to identify the presence and severity of thermal lensing, map its spatial distribution, and assess its impact on optical performance. This information is valuable for optimizing system design, identifying potential sources of degradation, and implementing corrective measures to mitigate thermal lensing effects.

Post deposition annealing is an ex-situ heat treatment process that can be used to reduce coating absorption in certain cases. Annealing promotes the reorganization of the coating's molecular or atomic structure, leading to a more uniform material (Bischoff et.al., 2014). Annealing involves subjecting the coating to high temperatures for a specified duration, which allows for the relaxation of internal stresses and defects within the material. As a result, the optical properties, including absorption, can be positively influenced, this is shown in Figure 3.

As previously mentioned, due to the excellent thermal and optical properties, Ta_2O_5 and SiO_2 dielectrics have been chosen for the antireflection coating in this work. The objective was to assess the impact of the annealing process on the absorption properties of the coating. For this purpose, individual layers of silica and tantala were deposited on single side of UVFS Corning 7980 0F substrates. The specific layer thicknesses were set at 300 nm for tantala and 540 nm for silica. Following the deposition, absorption measurements were carried out, both before and after annealing at 350°C in an air environment. The findings from the longitudinal scan measurement, which involves scanning through the substrate, are illustrated in Figure 3.

Both silica and tantala layers contribute the increased absorption of the surface prior to annealing, this is evident in the left-hand images. After the annealing, a significant decrease in absorption is observed, leading to coating-induced absorption values comparable to those of bare substrate surface, as imaged by the peaks at 4 mm and 5 mm distance. Ex-situ annealing procedure resulted in decreased coating absorption by the factor of 2 for tantala, and by the factor of 4 for silica layers.

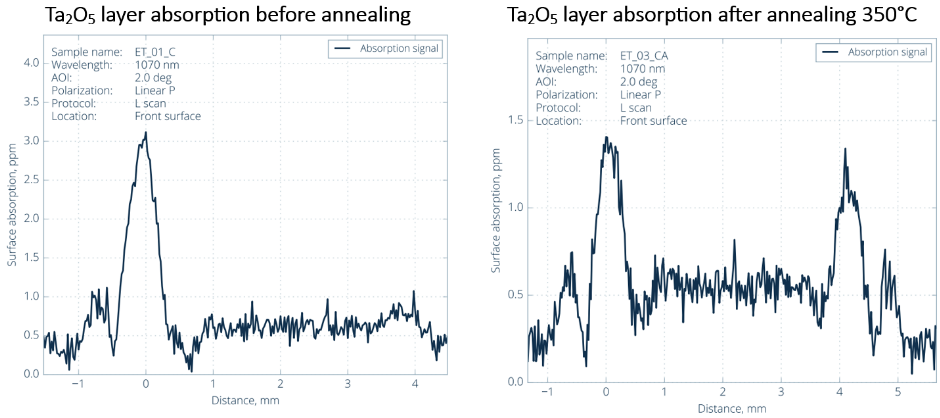

Fig. 3. PCI-Longitudinal scan absorption measurements before and after annealing procedure. (PCI metrology)

3.2. Passive compensation

A-thermal design of optical systems

Optical focus compensation through a-thermal design principles is a well-known technique employed in the development of advanced optical systems, yet not extensively used within the field of high-power laser cutting. In optical designs used for example in imaging and sensing, temperature fluctuations can significantly impact the performance of the systems, leading to defocus and loss of image quality. A-thermal design principles aim to mitigate these effects by incorporating elements that counterbalance the thermal expansion and contraction of materials. Materials with positive and negative thermal expansion coefficients are used in combination, counteracting each other, resulting in minimal changes in the overall length of the optical mounting.

Alternatively, and often in combination with mechanical measures, refractive index compensation is employed and uses optical elements with different thermal sensitivities of refractive index (e.g. Leviton, 2006). These optics are selected and combined to minimize variation in refractive index across temperature changes. By precisely adjusting the composition and arrangement of these materials, the optical system can maintain consistent optical performance over a wide range of temperatures. For example, materials with positive and negative thermo-optic coefficients exhibit different changes in refractive index with temperature, and when appropriately combined, their effects can cancel each other out, resulting in a system with reduced temperature-induced focal length shifts. Other solutions incorporate compensating lens groups or utilizing fluids with controlled thermal properties.

The so-called thermo-optical constant G is an approximate measure for both effects, expansion due to heating and change in refractive index with temperature and thus for the sensitivity of an optical material to radial gradients.

$$G = CTE \cdot (n-1) + \frac{dn}{dT} \qquad (1)$$

Where n is the refractive index, CTE the coefficient of thermal expansion, and dn/dT is the change in refractive index with respect to temperature dn/dT or thermo-optic coefficient. Table 2 shows the values of these material constants for fused silica and calcium fluoride (Corning®, 2015, Heraeus 2023, Thorlabs 2023). As can be seen both materials could be used to compensate each other.

Table 2. Optical material constants for room temperature

Material	dn/dT (ppm/K)	CTE (ppm/K)	n @$\lambda \cong 1\mu m$	G (ppm/K)
Fused Silica	9.6	0.5	1.450	10
Calcium fluoride	-10.6	18.9	1.428	-3

Due to mechanical and optical complexity, restricted choice of suitable materials, high costs and limited compensation lengths a-thermalization methods are less likely to be used in high power cutting applications.

3.3. Active compensation with focus shift approximation and given metrology

Active compensation is a well-proven method to reduce the effects of thermal lensing and its potential was demonstrated already in the late 1970s, by Stephens et al, 1978, with the help of a deformable mirror to correct misalignment errors in a laser resonator. An alternative to using deformable mirrors is to change the position of a lens to compensate for the thermal focus shift. The Precitec ProCutter cutting head uses a movable collimating lens to adjust the focal position, making an active compensation of the focus shift feasible. Two different approaches can be considered.

One approach is to use a model to compensate for focus shift to an expected, approximate value. To a first approximation, the thermal focus shift increases linearly with the absorbed laser power and its time-dependent behavior is related to the heat propagation through the optics. Measurements of such properties can be stored in a look-up table, or some other similar approach can be used as a model to compensate the focal position with such an approximation.

Since the focus shift is strongly influenced by contamination during laser cutting, a better approach is to measure the focal position online and correct it in a closed loop. Wavefront detection and correction is a well-known adaptive optics technique used in the fields of microscopy and astronomy. Although these methods are very promising, they all require sensor devices with complex integration into a cutting head and make the compensation expensive.

4. Experimental results with and without active compensation

Precitec BeamTec is a model based active compensation technology and can be used to fundamentally control the thermal focus shift. This new technology uses the knowledge of applied laser power and of the time-dependent behavior of the focus shift of the built-in optics to reduce the drawbacks of the thermal lens. In addition to the default compensation settings, BeamTec gives the customer the possibility to adapt a set of compensation parameters to optimize them during cutting. BeamTec takes the history into account (for multiple short piercing and cutting operations / cutting of small contours)

Figure 4 shows the measured focal position with and without BeamTec for a varying laser power up to 8 kW for one hour. An Ophir BeamWatch was used to measure the focal position of a Precitec ProCutter with a magnification of 1.5. The measured focal position without BeamTec varies up to 0.8 mm while with BeamTec varies up to 0.2 mm, which means a reduction by a factor of four.

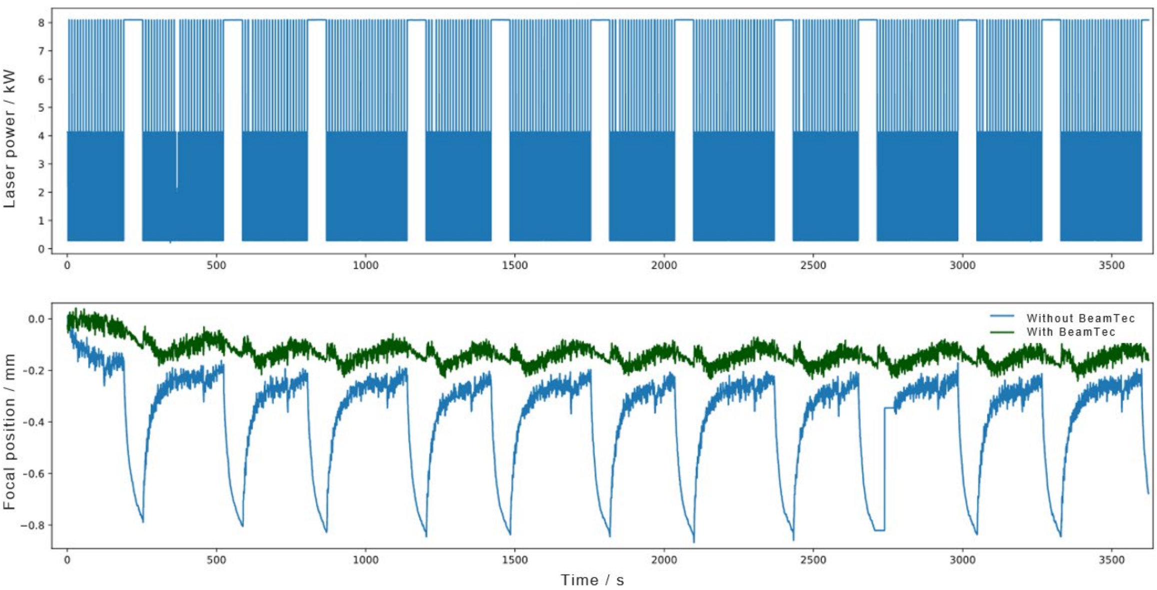

Fig. 4. Laser power (top) and measured focal position (bottom) with (green line) and without (blue line) BeamTec.

Cutting of stainless steel 1.4301 was performed using a fiber laser with a wavelength of 1.07 µm in combination with a Precitec ProCutter cutting head. The optical fiber had a core diameter of 150 µm and the magnification of the cutting head was 3.0. The laser power was 30 kW, the focus was positioned 6.7 mm below the sample's surface and nitrogen with a pressure of 8 bar was used as cutting gas. The cutting nozzle with an outlet diameter of 5 mm was positioned 0.3 mm above the 10 mm thick sample.

To obtain the maximum cutting speed for stable cutting conditions, cuts with a length of 120 mm were made while the cutting speed was increased until cut losses were observed. To obtain the process window, the focus was varied at 90% of the maximum cutting speed until cut losses were foundd. Subsequently, cuts of 1000 mm and 3000 mm lengths were made, reducing the cutting speed until stable cutting conditions were achieved. In each case, cuts were made with and without BeamTec to compare results.

Figure 5 shows the cut surfaces for cuts with a length of 3000 mm with (right) and without (left) BeamTec, for two different cutting speeds: 11.1 m/min (above) and 9 m/min (below). Without BeamTec, stable cut was possible at a maximum speed of 9 m/min. When cutting at 9 m/min with BeamTec, a reduction in dross adhesion was observed. In addition, stable cut at 11.1 m/min was observed with BeamTec. This corresponds to an increase in cutting speed of 23%.

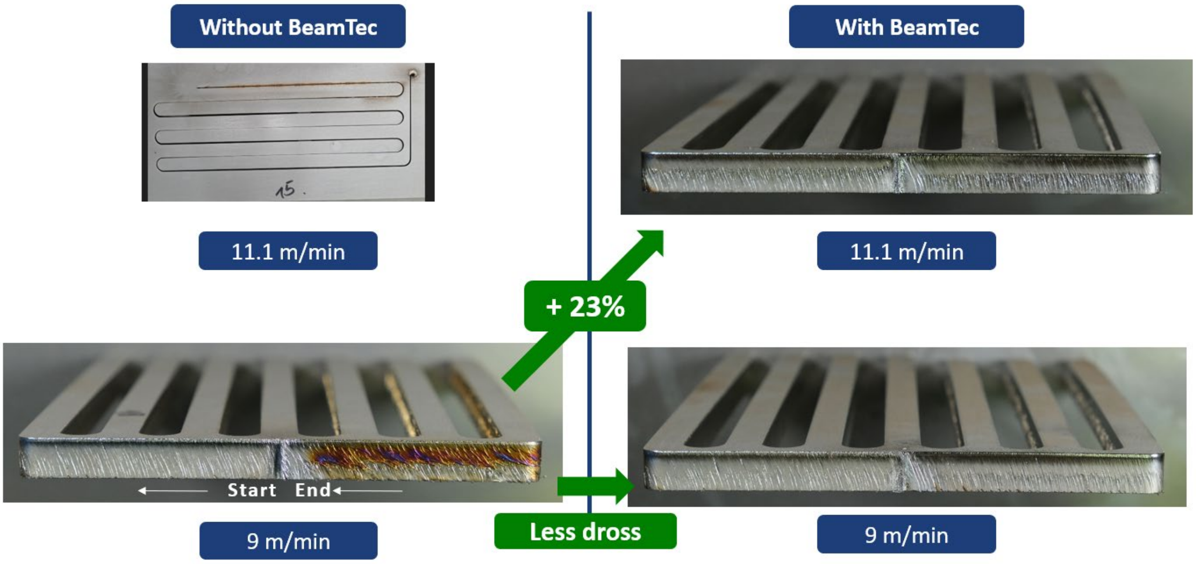

Fig. 5. Cut surfaces on 10 mm stainless steel plate (laser power of 30 kW, nitrogen assist gas pressure of 8 bar, cut length of 3000 mm) with and without BeamTec at two different cutting speeds of 11.1 m/min and 9 m/min. Read text for further details.

The experimental results shown in Figure 4 indicate that BeamTec leads to a more stable focal position. Two advantages had been shown in Figure 5 for high power laser cutting applications: a significant improvement in cutting quality (less dross) and in productivity (cutting speed).

5. Conclusion

Thermal focus shift can prevent full use of the cutting speed advantage in high power laser cutting applications. Different strategies have been considered.

Design optimization for low absorption of coatings and substrates is essential to effectively avoid and compensate for thermal losses. Passive strategies are very well suited for high-resolution imaging but are inappropriate for high-power laser cutting due to limited material choices and cost. Active compensation using measuring devices for focus measurement is possible, but complex and expensive.

Experimental results of active compensation by approximation show promising results in terms of accuracy and usability. This software-based capability also opens future possibilities for advanced features such as automated cutting and AI-based forward-looking predictions for increased quality and productivity.

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