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Improvement of selective laser melting by beam shaping and minimized thermally induced effects in optical systems

Dietrich Faidel[a,*], Alexander Laskin[b], Wilfried Behr[a], Ghaleb Natour[a]

[a] *Forschungszentrum Jülich GmbH/ZEA-1, 52425 Juelich, Germany*
[b] *AdlOptica GmbH, Rudower Chaussee 29, 12489 Berlin, Germany*

Abstract

Development and manufacturing of components with high tightness and complex geometry are important in researches of ultra-high vacuum applications in Central Institute of Engineering, Electronics and Analytics at Forschungszentrum Jülich. Modern Selective Laser Melting technology meets essential demands of experimental setups. Instabilities of SLM process caused by thermally induced effects in optics (focus shift, aberrations) and material overheating in middle of melting pool due to Gaussian intensity distribution of laser spot can cause melting defects leading to leakage of the parts. For stable and reproducible operation it is suggested to apply beam shaping optics providing optimum Flat-top or Doughnut profiles of focused laser spot and to implement optical components from athermalized material with negligible or minimized thermally induced negative effects. This approach is realized in working equipment, features of applied the optical system are described. Measurements of process parameters and analysis of properties of the manufactured parts are presented as well.

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1. Introduction

Optical effects induced by gradient heating of laser optics are well-known and described in literature, for example in Reitemeyer et.al. (2009), Feuerhahn et.al.(2015), de Lange et.al.(2005). The main issue is thermal focus shift, however in technologies of selective laser melting (SLM) or remote welding the thermally induced aberrations are of great importance as well. It is also important to distinguish typical for cutting and welding *static* thermal effects, where a beam location and its diameter on optics are constant, and important in SLM *dynamic* effects due to variable beam location on components of scanning optics. Thermal effects result in variable spot size and intensity distribution during processing session which are important factors of the process instability. Reliable operation of SLM can be realized only when dynamic thermal effects are negligible, especially when using beam shapers, which operation principle is based on careful manipulation of a beam wavefront to control intensity distribution in focus.

2. Theoretical considerations

Appearing of thermally induced optical power due to temperature gradient in optics is illustrated in Fig. 1 on example a protective window: Gaussian intensity distribution (a) of a laser beam causes a Gaussian temperature distribution (b), the temperature difference ΔT leads to gradient of refractive index (c) and bulges on the window surfaces (d). Thus, there are two main issues of additional optical power:

- change of *geometrical* shape of initially flat surfaces, thus the window becomes a positive lens, the induced optical power is proportional to coefficient of thermal expansion (*CTE*),

* Corresponding author. Tel.: +49-2461-61-6726; fax: +49-2461-61-6816 .
E-mail address: d.faidel@fz-juelich.de

- transformation of homogeneous glass into a gradient medium, the optical power induced due to this *refractive* effect is proportional to *dn/dT* - derivative of the refractive index *n* of the temperature *T* .

The higher is ΔT and window thickness, the stronger are thermal effects, Klein (1990). With TEM00 laser the temperature gradient is "sharper", therefore compensa-tion of thermal effects is of great importance in SLM where applying of TEM00 lasers is strongly recommended to achieve high resolution of the recorded images. As shown in Reitemeyer et.al. (2009) the ΔT increases drastically when the optic components are contaminated, - this is inevitable for protective windows of which the main function is protection of collimating or focusing optics from dust, smoke and spatter. Therefore, it is of great importance to develop windows with minimal or close to zero sensitivity to different temperature gradients and demonstrating zero or negligible thermally induced unwished effects.

SLM is based on material heating, its performance is improved when uniform temperature profile in focused spot where melting pool appears, Haglund et.al. (2013) and Okunkova et.al. (2014).

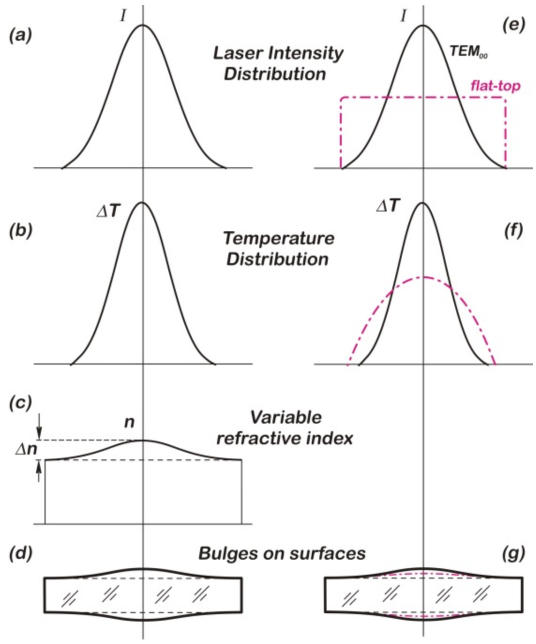

Fig. 1 Effects by gradient heating of a protective window.

In order to provide uniform temperature on a workpiece (powder layer) the optimum laser spot intensity distribution has to be described rather by doughnut or "inverse-Gauss" profile, particular distributions can be calculated by analysis of material properties and laser specifications. Most often just TEM_{00} lasers are used in SLM, and a working spot is about 100 µm size. To optimize intensity profile it is suggested to use beam shapers for focused beams transforming Gaussian intensity distribution to so called Airy disk, and focusing of such a beam by any diffraction limited lens, for example F-theta lens, results in flat-top or doughnut or "inverse-Gauss" profile of the spot in focal plane of the scanning optics.

3. Athermalized windows

Properties of widely used for protective windows fused silica and glass BK7 (Schott) are presented in Table 1.

Table 1: Properties of fused silica and BK7 glass

Glass	*dn/dT* [1/K]	*CTE* [1/K]
Fused Silica	$8.8 \cdot 10^{-6}$	$0.5 \cdot 10^{-6}$
BK7	$1.5 \cdot 10^{-6}$	$7.1 \cdot 10^{-6}$

Analysis of the data allows some conclusions:

- BK7 has high *CTE*, therefore just geometrical change of surface shape is the dominant thermal effect,
- fused silica is characterized by high *dn/dT*, hence the refractive effect is a main issue,
- by contamination and gradient heating both materials demonstrate essential thermal focus shift and aberrations.

Evidently, the considered materials are not optimal for protective windows operating under industrial conditions with dust, smoke, spatter, metal powder or other contaminations. The basic requirements to protective windows for modern SLM laser technologies are

- zero or negligible focus shift and aberrations under gradient heating,
- independence of static or dynamic laser heating,

- independence of or low sensitivity to optics contamination,
- independence of intensity distribution of TEM_{00}, multimode lasers or flat-top beams,
- resistance to high laser power.

To fulfill these conditions it is suggested to use athermalized protective windows aThermoXX® with basic features:

- applying of optical materials with optimum matching of *CTE* and *dn/dT*,
- compensation of optical power from geometrical effect by optical power from refractive effect.

Since thermally induced effects of focus shift and aberrations have the same physical nature, Klein (1990) they are compensated or minimized simultaneously.

4. Experimental results

The technical approaches of beam shaping focused beam and using athermalized protective windows were realized in the SLM machine in Forschungszentrum Jülich with the optical system implying transformation of TEM_{00} fiber laser radiation (up to 500W) by the collimating Focal-πShaper into the Airy disk collimated beam, which is focused by the focusing optics locating ahead of the 2-mirror scanner, the protective window separates the scanner and process chamber. The beam shaper and focusing lens are made from fused silica, two protective windows from BK7 and athermalized glasses were tested, beam diameter on the windows about 5 mm diameter (power density ~3kW/cm² @ 500W), average Rayleigh length z_R of focused beam about 10 mm. There were carried out caustic measurements at 25 W and 250 W laser power, with and without contamination of windows by smoke, with time delay to stabilize heating of optics, only thermal effects from windows were considered. Measurement results for BK7 and athermalized glasses are presented in Fig. 2: laser beams propagate upwards and are marked by red arrows, left screenshots - low power 25 W (no thermal effects), right screenshots – 250W with thermal effects, values of the waist shifts are given on right side, constant thermal shift of Focal-πShaper and focusing optics is subtracted.

Tests with BK7 glass window: thermal waist shift -8.7… -11.7 mm ($-0.9z_R…-1.1z_R$), because of aberration the optimum for SLM doughnut intensity distribution is transformed to Gaussian-like one. These effects make SLM unstable, lead to dependence of melting process on features of recorded pattern, increase porosity.

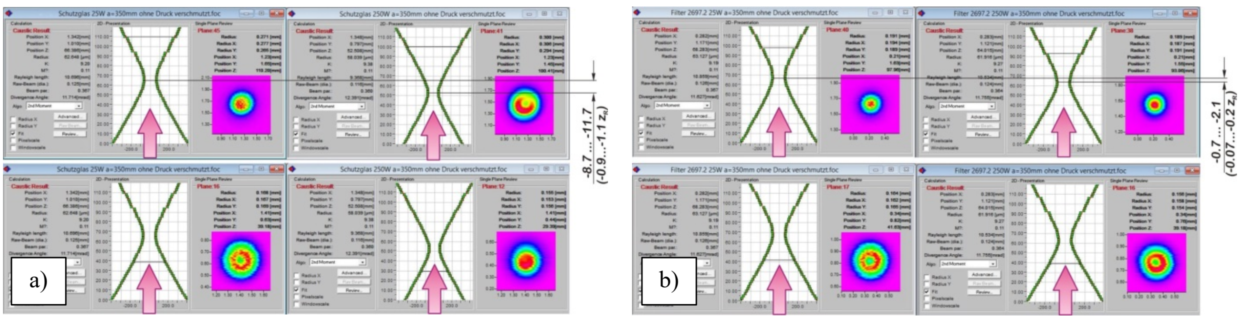

Fig. 2. Caustics measurements protective windows from: a) BK7 glass, b) athermalized glass.

Tests results with windows from athermalized glass demonstrate drastical reduction of negative thermal effects: thermal waist shift -0.7… -2.1 mm ($-0.07z_R…-0.2z_R$), intensity distributions and spot sizes are practically constant in all working planes, this guarantees stability of SLM process.

5. Conclusions

Dynamic laser heating of optics is a characteristic feature of SLM technology, and stability of the SLM process depends strongly on intensity distribution in laser spot and thermally induced effects of laser beam waist shift and wave aberrations resulting in variable spot size and intensity distribution in the working plane. Uniform temperature profile on powder layer is optimum for the process stability and productivity, it is provided by doughnut or inverse-Gauss intensity distribution in laser spot, which is realized using beam shaping optics for focused laser beams. Thermal properties of the protective window are of great importance because of their contamination and consequent increased gradient heating by laser radiation. Due to low absorption fused silica is right material for collimating and focusing optics, but like ordinary glasses it demonstrates strong thermal effects when applied in protective windows being under contamination. To athermalize protective windows it is suggested to apply optical materials with physical properties that provide inherent compensation of the optical power from geometrical change of surfaces shapes (bulges) by the optical power induced as a result of the gradient of refractive index. Experiments with these self-compensating windows from special glass confirm correctness of this approach: comparing to ordinary windows there were provided order of magnitude smaller thermal waist shift and diffraction limited focusing.

6. References

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