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Influence of Laser Power Fluctuations on the Quality of Additive Manufactured Workpieces

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Abstract

There is a great potential in selective laser sintering (SLS) processes caused by increasing application areas in the field of additive manufacturing (AM). The related requirements to the quality of additive manufactured workpieces can be attributed to its process parameters. In this context, the examination of laser power fluctuations is interesting because of its direct influence on the workpiece quality. If the planar energy input into the powder bed is not constant, local areas can melt inhomogeneously beside the expected gauss-distributed intensity profile of the laser spot. For quality assessment a testing workpiece and its manufacturing strategy have been developed to measure the interactions between laser power and dimensional accuracy. Initially the appearing losses of the laser power in the beam path have been observed to optimize the energy input. In addition to the warm-up behaviour of the CO_2-laser, appearing energy peaks during short-term sequences also show an influence on the workpiece quality. Finally in post-process quality assessment, the correlations of laser power with the dimensional accuracy and surface roughness are analysed by optical fringe projection and focus variation technique.

Keywords: CO_2-Laser, selective laser sintering (SLS), energy input, laser power fluctuation, dimensional deviation

1. Introduction

With the continuous trend of additive manufacturing applications comes an industrial change from prototype fabrication to pilot production which leads to serial manufacturing. In this context the requirements for the quality assessment of workpieces, manufactured by additive manufacturing technologies like selective laser sintering, rise evidently [1]. Thus, each process parameter with a significant influence on the workpiece quality, from the powder consistency and temperature profile to the recoating speed, should be analysed and adjusted accurately. One of the major influencing factors is the energy input by the CO_2-laser to melt the preheated polymer powder.

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Thereby the characteristic variable E_A describes the inserted energy density of the CO_2-laser, which is according to *(eq. 1)* mainly influenced by the laser power P_L, the velocity v_s and the hatching distance h_s [2].

$$E_A = \frac{P_L}{v_s \cdot h_s} \qquad \text{(eq. 1)}$$

Empirically, the standard energy input for PA12 powders is 0.04 J/mm² to get high quality workpieces [3]. For the following analysis of the energy density, which is essential for the forming of melting area, especially the laser power fluctuations will be observed. Thus, the direct relation between the laser power and geometrical deviations can be examined within this research.

2. Measurement of laser power

For fundamental studies of the laser power several measurements are performed in the preliminary stages to gather the main influences of the energy input. In the field of laser sintering processes a CO_2-laser is established, because of its aligned wavelength of 10.6 µm, to ensure a high energy absorption rate to the PA12 polymer powder [4]. Initially, the losses of the used 50 W Synrad 48 series M-laser in the beam path are examined. Afterwards, different adjusted laser powers are recorded to detect the stability of the laser in dependency of its energy output. An analysis of temporal laser power effects is given at the end of the in-line measurements. Each optical path of selective laser sintering machines is similarly constructed. According to figure 1 a CO_2-laser (1) emits a laser beam, which is reflected almost ideally through gold coated mirrors (2) and is widened by a beam expander (3). After the beam is conducted to a galvano-scanning unit (6), the beam deflection is controlled appropriate to the shape which has to be melted. The deflected beam passes an f-theta lens (7) which focuses the laser light to the power bed. Considering the incoming laser power, the process parameter of interest is the absorbed energy input according to (eq. 1). But there is another important influence which is not detected standardly - the fluctuating laser power. For this reason a power measuring device (5) is implemented in the beam path, which gathers 2.1 % of the reflected beam by a beam splitter (4).

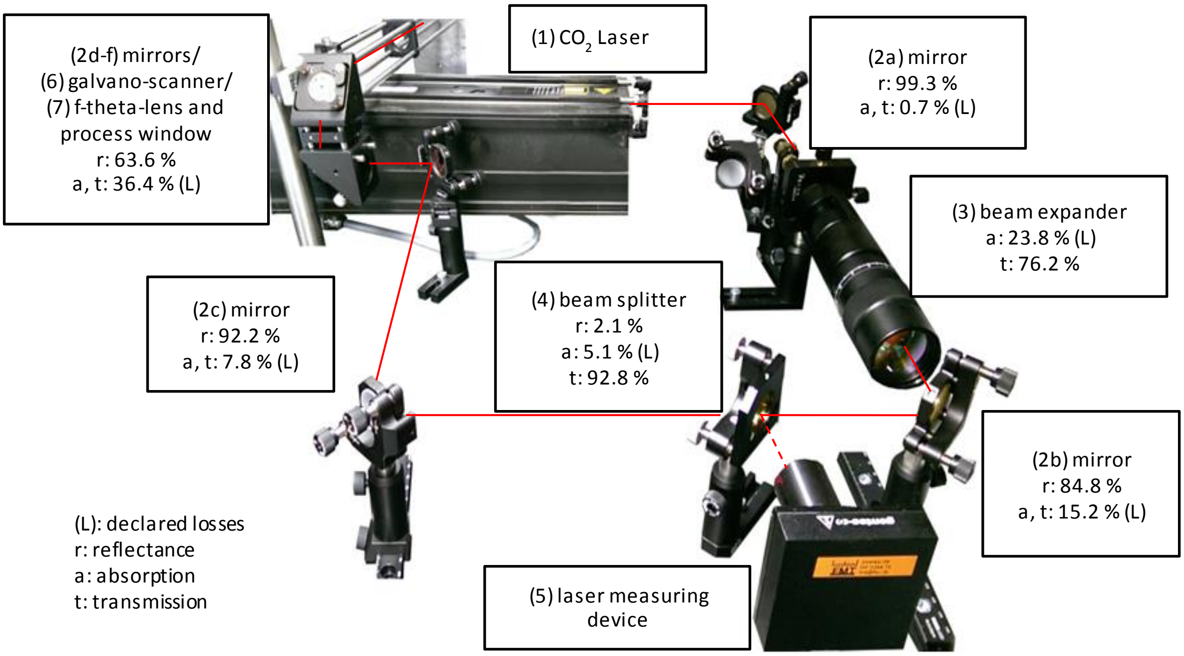

Fig. 1. Optical beam path and losses of laser power

2.1 Losses of laser power in the beam path

A first study show, that the losses in the beam path can be detected and optimized by an in-line measurement of the laser power. Therefore two laser measuring devices are used – a gentec XLP12-3S-H2 sensor with a continuous in-line recording and a LM 200HTD QuadSensor for punctual measurements, mainly at the powder bed surface.

Table 1. Data of power measuring devices

Sensor	Max. power in W	Resolution in W	Measuring accuracy	Spectral Range in µm
LM 200HTD	200	0.01	± 5 %	0.25-10.60
XLP12-3S-H2	3	0.01	± 5 %	0.19-20.00

Ideally there are only a few optical components in the beam path. But in some cases as considered, there is not enough space to align the CO_2-laser directly to the powder bed. Thus gold coated mirrors and other optical components of transparent ZnSe are necessary to guide the laser beam with its specific wavelength. If the incoming spot is focused and centered coaxially to the mirror, the reflectance ratio is very high (> 99 %) as seen at mirror (2a). But with the widened laser spot of the beam expander (3), which is necessary to focus the light to a small spot afterwards, the beam is not centered that ideal to the mirror and consequently the losses of the following mirror (2b) increase significantly up to 15.2 % of the power. Little scratches and dust at the mirrors surface intensify these appearing losses. Beside, each ZnSe component like the process window (7), the beam splitter (4) and especially the beam expander (3) exhibit a high material induced absorption rate. If all light output ratios are multiplied, only 35 % of the emitted laser power reaches the powder surface in the process chamber. Consequently it is relevant to analyse the ratio of the absorbed laser power to ensure the required energy input. In this context the laser power has to be controlled to reach a surface energy density of 0.04 J/mm².

2.2 Laser power fluctuations

After the examination of the losses, another point of interest is the laser power fluctuation in dependency of the adjusted energy output of the CO_2-laser. The continuous power measurement in the beam path of figure 2

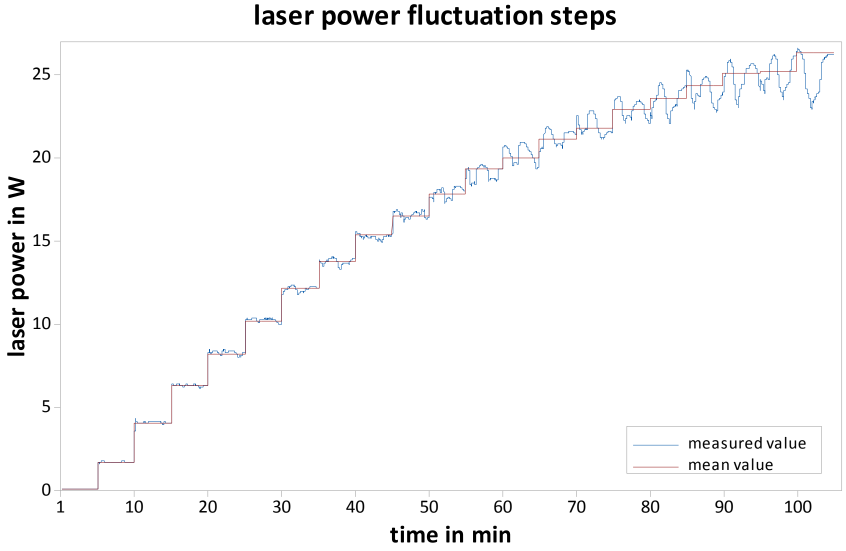

Fig. 2. Laser power for a stepwise (5 % steps) increased nominal output up to 100 %

permits a visualization of this appearing fluctuation by an increasing pulse-width modulation (PWM) each 5 minutes of 5 % up to 100 %. As it is shown, there is no ideal linear dependency of the emitted and absorbed laser power. A steady increase of the CO_2-laser power involves a higher fluctuation ratio up to a range of 3.6 W at 100 % of the measured power. This fact indicates that the laser is not stable at real process conditions. The assumption at this point is to check, whether this fluctuation has an influence to the workpiece quality. This research could be a first step to answer the question if there exist a more ideal laser power adjustment or if there are ageing phenomena of the emission rate of the eight year old CO_2- laser.

2.3 Temporal effects of laser power

Since the laser power fluctuations are detected with normal process conditions, it is obvious to consider the warm-up behaviour of the CO_2-laser. The long-term measurement offers information about the transient oscillation for a nominal laser power of 100 %. As already noticed, there is a high fluctuation of the power in the first section, also can be seen in figure 3, which approaches from~29 W to 24 W. A first result of this study suggests that the laser needs 20 minutes to reach this approximately stable plateau of the emitted laser power. Thus the warm-up duration of the laser has to be regarded at each additive manufacturing process.

Based on the fact, that the selective laser sintering is classified to rapid manufacturing processes [5], the short – time behaviour and its laser power peaks are of big relevance to the geometrical settings of additive manufactured workpieces. In real SLS process, the duration of the energy input is temporary, because of the high scanning speed of the scanner to melt local areas. In addition, this short energy input is amplified by the alternated switching of the CO_2-laser according to the scanned profile. Consequently the appearing laser power fluctuation gets the most important factor for the energy input. According to figure 4, three different laser powers are measured one minute for a nominal output of 100 %, 95 % and 90 %. Their detected short time fluctuations are rather small. In comparison to the measured laser power of figure 3 at 100 %, the same power of 29 W is observed. Thus not the warm-up behaviour of the laser is relevant for the melting process but the peak power with its higher value. Even if the laser has warmed up, the energy input in the additive manufacturing process is higher according to the detected peak level.

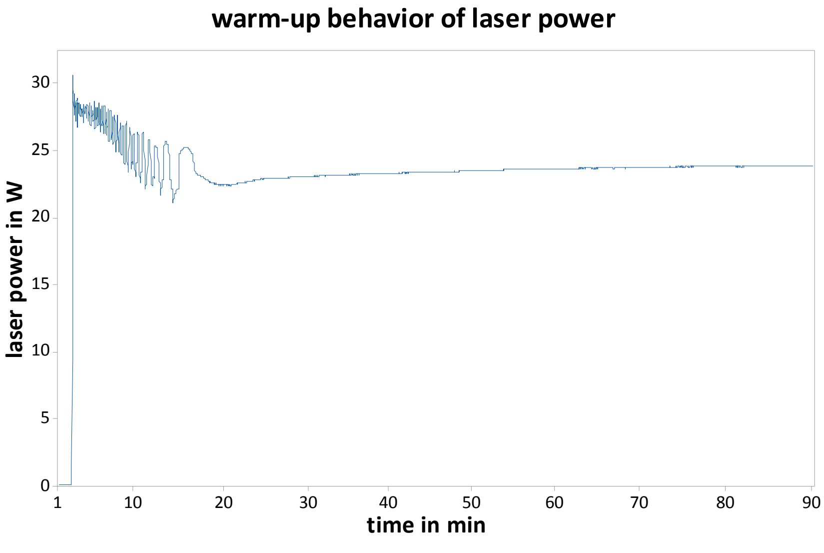

Fig. 3. Long-term measurement of laser power

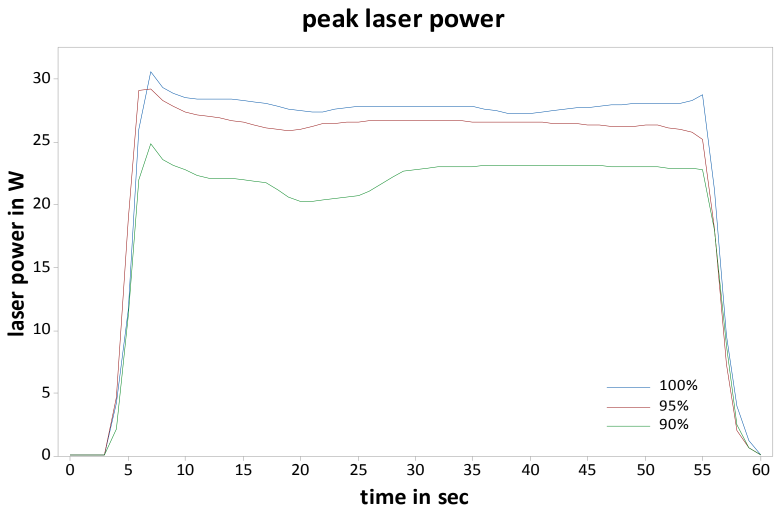

Fig. 4. Short-term measurement of laser power for different nominal outputs

3. Post process analysis of AM workpieces manufactured with different laser power

For the post process analysis a testing workpiece and its manufacturing strategy have been developed to measure the interactions between the laser power and the dimensional accuracy. According to the achieved results of the preliminary examinations a pin testing artefact has been manufactured with three different laser powers and constant velocities v_s = 2500 mm/s and hatching distances h_s = 0.25 mm. The nominal laser powers has been chosen as 100 %, 80 % and 60 % to produce three pins, which differentiate significantly in dependency on this parameter. All manufactured pins have the same reference geometry, shown in the technical drawing of figure 5 with 70.00 mm height, 27.40 mm length, 20.00 mm width, 6.00 mm inside radius, 13.70 mm hole diameter and 10.00 mm outside radius. It has to be mentioned that the pin geometry have been scaled with a standardized manufacturing factor of 103.2 % to compensate effects of shrinkage.

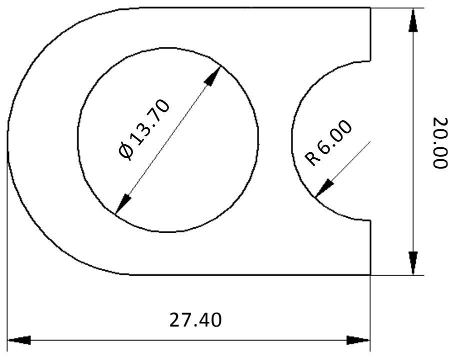

Fig. 5. Geometrie of the developed pin

3.1 Dimensional analysis by fringe projection

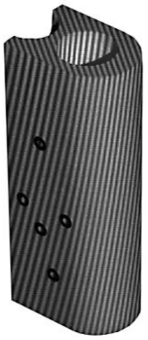

Fig. 6. Striped pattern on the pin

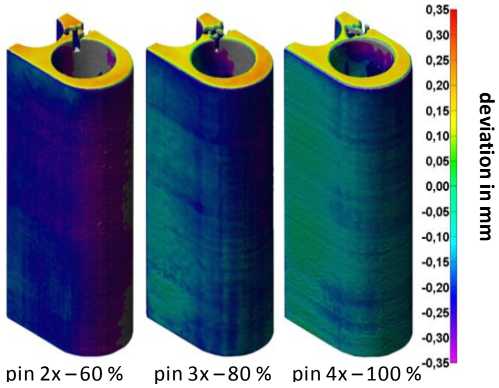

Fig. 7. Geometrical deviations of pins

The measurement of the pin geometry is implemented by the ATOS Compact Scan 2M fringe projection sensor. The fringe projection is based on the principle of triangulation and uses a projection of a periodical and equidistant structured light pattern on the component surface. At the same time the pin geometry and surface points are detected with two angled cameras and evaluated by triangulation. For each pin a series of measurements are done with different observation directions to get a holistic measurement result [6]. The orientation of the pins and its translational location in relation to the global coordinate system can be monitored by reference points and be used for the data fusion of the measurements (figure 6).

The evaluation of the distorted fringe pattern by PolyWorks in figure 7 admits calculations of the surface points. The comparison of the detected surfaces to the CAD-reference geometry reveal the appearing single-point-deviations. The following detailed analysis of the geometrical characteristics in figure 8 confirms the expected trend, that a high laser energy input causes low dimensional deviations. Except of the outside radius, which shows a reverse trend, for the laser power of 100 % the smallest deviations of < 0.25 mm occurs. In contrast a low energy input of 80 % up to 60 % impairs to the geometrical accuracy. The geometrical length and width are generally small and should be scaled more accurate, whereas the height and the radius features are in excess.

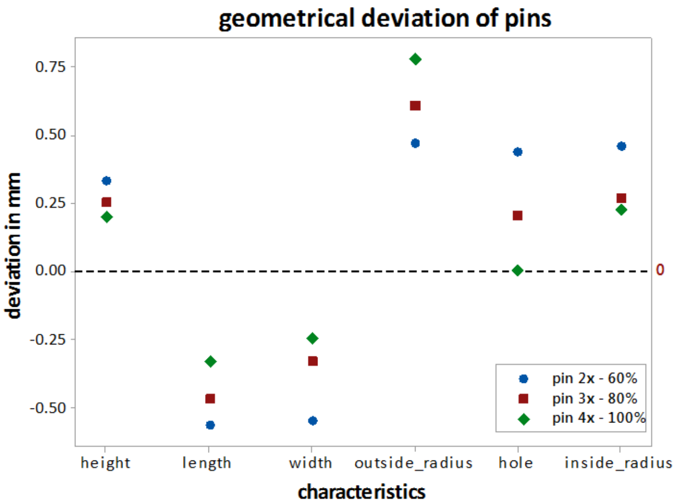

Fig. 8. Deviations of geometrical features of pins

3.2 Surface analysis by focus variation

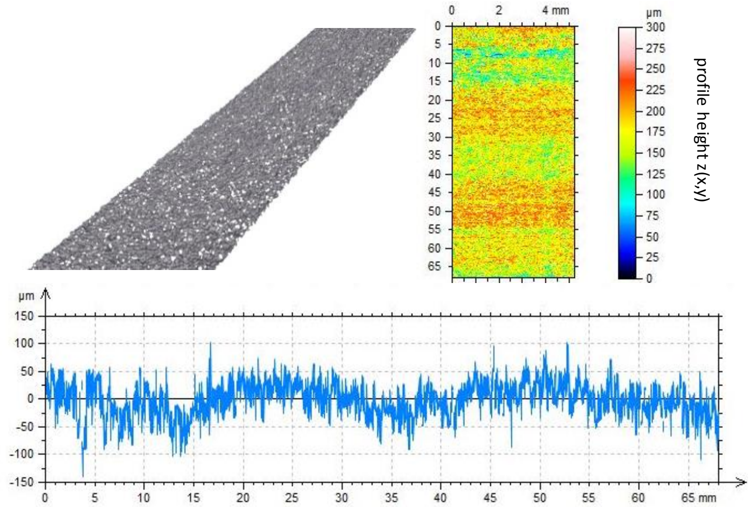

Fig. 9. Surface evaluation of the lateral pin walls

A further optical post process analysing method is the focus variation, which uses the focus depth to extract height information about the surface points of the pins [6]. This distance measurement is achieved by a variation of image sharpness depending on the topography relative to the displacement of optics. The pins are observed by Alicona Infinite Focus G4 measurement system. For each pixel of the camera, the contrast to the surrounding pixels are calculated and thus at an axial scan, the position of the contrast maximum is determined [7].

The detected profile (*R*) and areal (*S*) average roughness parameters of the 70 mm lateral pin walls indicate to another influence in dependency on the energy input. The surface analysis of table 2 points to the fact, that a high laser power up to 100 % causes low roughness values. In this case the polymer molecules are sintered more densely and as a result a smoother surface can be achieved.

Table 2. Surface roughness of pins

roughness parameters in µm (DIN EN ISO 4287) [8] (DIN EN ISO 25178-2) [9]		**testing workpiece (laser power)** pin 2x (60 %)	pin 3x (80 %)	pin 4x (100 %)
arithmetic average roughness	$R_a = \frac{1}{l_c}\int \lvert z(x)\rvert dx$	31.8 µm	22.5 µm	20.3 µm
	$S_a = \frac{1}{A}\iint \lvert z(x,y)\rvert dxdy$	34.6 µm	27.7 µm	26.5 µm
quadratic average roughness	$R_q = \sqrt{\frac{1}{l_c}\int z^2(x)dx}$	39.9 µm	28.1 µm	25.4 µm
	$S_q = \sqrt{\frac{1}{A}\iint z^2(x,y)dxdy}$	44.1 µm	34.9 µm	33.3 µm

l_c : measurement length A : measurement surface area $z(x,y)$: height

4. Summary

As the presented examinations have shown, an influence of laser power fluctuations on the quality of additive manufactured workpieces has been detected. There is a great potential to improve the laser power losses in the beam path and the associated energy input to the polymer powder bed. Laser power fluctuations appear depending on the adjusted laser beam pulse-width modulation. The energy input of 0.04 J/mm² at 100 % of the laser power oscillates very much, but in contrast the geometrical deviations and also the surface values show the best results. Even if the CO_2-laser has warmed-up and reaches a stable power plateau, the peaks of the short-time behaviour has to be considered with its high energy input level. This fact is important for the real process with a temporary and inhomogeneous energy input by the laser according to the melting contour. A perspective for further analysis of the laser power will be an optimization of the laser energy input. An acceptable compromise of the dimensional deviations with explicit reduced laser power fluctuations has to be found.

Acknowledgements

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References

[1] Schmid, M.: *Selektives Lasersintern (SLS) mit Kunststoffen - Technologie, Prozesse und Werkstoffe.* Carl Hanser Publisher, Munich, 2015. - ISBN 978-3-446-44562-8

[2] Nöken, S.: *Technologie des selektiven Lasersinterns von Thermoplasten.* Dissertation, Shaker Verlag, Aachen, 1997.

[3] Lanzl, L.; Greiner, S.; Wudy, K.; Drummer, D.: *Selective laser sintering of a polypropylene polyamide 12 blend: Bulk and component properties.* 6th International Conference on Additive Technologies – iCAT, p. 170-189, 2016.

[4] Klein R.: *Laser Welding of Plastics.* First Edition, Wiley–VCH Publisher GmbH, p. 3-69, 2011.

[5] Kruth, J.-P.; Vandenbroucke, B.; Van Vaerenbergh, J.; Mercelis, P.: *Benchmarking of different SLS/SLM processes as rapid manufacturing techniques.* International Conference of Polymers & Moulds Innovations (PMI), Gent, Belgium, 2005.

[6] DIN EN ISO 25178-6: 2010: *Geometrical product specification (GPS) – Surface texture: Areal – Part 6: Classification of methods for measuring surface texture parameters.* Beuth Verlag, 2010.

[7] Heinl, M.; Galovskyi, B.; Hausotte, T.: *Surface and dimensional measurements of additive manufacturing workpieces.* 6th International Conference on Additive Technologies iCAT, p. 267- 273, 2016.

[8] DIN EN ISO 4287: 2009-11: *Geometrical product specification (GPS) – Surface texture: Profile method – Terms, definitions and surface texture parameters.* Beuth Verlag, 2009.

[9] DIN EN ISO 25178-2: 2012: *Geometrical product specification (GPS) – Surface texture: Areal – Part 2: Terms, definitions and surface texture parameters.* Beuth Verlag, 2010.