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Thermal environment and inclination angle dependencies on the surface quality of selective laser melted 316L steel

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Abstract. Additive manufacturing processes offer the ability to manufacture highly complex geometries, but are limited in terms of the achievable surface quality. These limitations are based on physical restrictions, especially the need of support and the powder-bed environment, and economic decisions. In this study, the development of the morphology of surfaces with varying inclination angles was investigated on the example of 316L stainless steel. Surfaces with low inclination angles to the manufacturing plane suffered extensively from the process related staircase effect, whereas perpendicular side faces revealed high dependencies on the interaction with the powder-bed.

Introduction

The surface quality of components fabricated with powder-bed based additive manufacturing techniques is volatile to the thermal circumstances during the process, which are mainly governed by the selected irradiation parameters and the substrate plate temperature [1,2]. These circumstances are directly related to the melt pool characteristics and correspondingly the interactions of the melt with the surrounding powder-bed and the already solidified areas underneath [3]. Depending on the considered surface orientation, relative to the substrate plate, the predominant surface morphology changes due to varying environmental conditions, which was shown to have a more dominant influence on the surface quality than a slight change in the irradiation parameters [4,5]. The surface quality of perpendicular to the substrate orientated side faces is described by the bonding between subsequent layers, the applied contour irradiation parameters and the interaction of the corresponding heat influenced zone with the loose neighbouring powder particles [6,7]. Parallel to the substrate plate orientated faces are, in the case of upwards facing surfaces, governed by the irradiation strategy and pattern of the final layer, coupled with minor evident weld splashes [5]. In the case of downwards facing surfaces, their morphology is described by either the support structure underneath or the direct interaction of the loose powder-bed underneath with the melt pool on top, which causes drainage and penetration of the melt into the loose powder-bed [8]. Any surface orientation apart from the outlined ones represents a superimposition of the described phenomena, coupled with the staircase-effect [9]. Due to the layer thickness and the successive generation process, the contour of the component to be manufactured is approximated as sliced model,

whereby the achievable accuracy is dependent on the layer thickness, the slope angle and the powder particle size [6].

The often for specific applications insufficient surface quality is one of the big challenges yet to overcome. The crucial part hereby is to enhance the quality, while maintaining the geometrical flexibility of manufacturable parts, as it is possible when using a laser beam in a subsequent polishing procedure [10].

On a side note, the inclination angle during manufacture affects not only the surface quality, it has also an immense influence on the tensile strength and a measurable impact on the fracture toughness of the material [11-13].

Within this study, the changing surface morphology of side faces with progressing inclination angle is addressed, with the major focus on the process related dependencies and correlated challenges.

Methods

Manufacturing conditions, specimens and positioning.

Specimens were fabricated with a SLM 280HL machine (SLM Solutions AG, Lübeck, Germany), which utilized a 400 W Yb-fibre-laser. The available build space was 280 x 280 x 320 mm³. A perforated lattice structure with additional solid pins (D = 5 mm) was introduced as support structure (Figure 1). The applied manufacturing settings and parameters are given in Table 1. A total of five representative configurations, determined by the inclination angle of the specimen's longitudinal axis to the substrate plate, were manufactured in two charges (Table 2). Flat tensile specimens type E 5 x 10 x 40, according to the German standard DIN 50125:2009-07, were fabricated. The positioning in the build space is depicted in Figure 2. On a side note, no post-heat-treatments or surface postprocessing steps were carried out.

Figure 1: Customized support structure

Figure 2: Positioning of the specimens in the build space; (i) charge A, (ii) charge B

Table 1: Manufacturing setting

Parameter set	Scan speed [mm/s]	Laser power [W]	Hatch distance [mm]	Scan vector length [mm]	Rotation angle increment [°]	Energy density [J/mm ³]
Contour	400	100	0.09	-	-	55.6
Core	800	200	0.12	10	33	41.7
Final layer	400	300	0.1	-	-	150.0
Support	875	200	-	-	-	-
Layer thickness of 30 μm						
Mounting plate ¹ temperature of 200°C						
Nitrogen is employed as the inert gas						
Contour is irradiated first, followed by the core, utilizing the line scanning strategy						

Table 2: Positioning of the configurations in relation to the substrate plate

Configuration	α_{XY}	Charge	Runtime [h]
(a)	0°	A	39.5
(b)	15°	B	86.5
(c)	45°	B	86.5
(d)	75°	B	86.5
(e)	90°	A	39.5

Measurement approach.

The surface quality was determined based on three measurements, area increments of 800 x 800 μm^2 , along the longitudinal axis per sample (Figure 3). Measurements were undertaken with a white light interferometer (Zemetrics Zegage, AMETEK Germany GmbH) in accordance to the ISO 25178 standard. The evaluated surface roughness profile lines were placed in the direction of the highest surface roughness, i.e. perpendicular to the scan vectors of the final layer, or perpendicular to the layers for side faces. Thus, the surface roughness values stated in this study represent the worst case scenario. Throughout the work, the surface orientation is described by its polar angle Φ , referring to the inclination between the considered surface and the substrate plate (xy-plane).

Figure 3: Exemplification of the evaluated areas, depicted for the $\Phi=0^\circ$ surface of a configuration (a) sample

¹ The substrate plate is placed on top of the mounting plate, which includes the thermal regulation.

Results and discussion

Surface quality.

Major changes in the surface morphology were evident based on the present thermal environment, governed by the surface inclination and the related factors, i.e. proximity of already solidified areas, interaction with the loose powder particles, as well as irradiation energy and pathway (Figure 4). According to Strano et al. [6], adjoined and partially molten powder particles appear more likely on the edges of layers, which coincides with the results in this study. The morphology of the inclined surfaces can be described as superimpositions of the governing effects of the final layer, perpendicular side face and the stair case effect and can be grouped as follows.

In the $0^\circ < \Phi < 30^\circ$ range, the surface morphology is mainly dependent on the stair case effect, thus, a significant surface roughness reduction can only be achieved by drastically reducing the layer thickness. This goes hand in hand with an increase in the fabrication time and the need of fine raw metal powder. Hence, in the comparison in Figure 5, the achieved surface roughness in the low inclination angle range is comparably poor due to the 33% lower layer thickness applied in the reference study.

In the $60^\circ < \Phi < 90^\circ$ range, the surface roughness is dominated by the adjoined and partially molten powder particles. The employed raw powder in this study had an averaged particle diameter of $35.5 \mu\text{m}$ [5] and the resulting surface roughness of R_a , equalling $17 \mu\text{m}$, coincided with halfway molten particles. Thus, in this range the surface roughness has a strong dependency on the powder particle size, coupled with the thermal influenced zone, described by the contour irradiation parameters. Correspondingly, a roughness reduction in this range can be achieved by lowering the powder particle size as well.

The intermediate range of $30^\circ < \Phi < 60^\circ$ represents the transition area, moving from a strong stair case influence to a high dependency on adjoined powder particles.

Relating back to the comparison in Figure 5, it could be concluded that the tendencies observed in this study represent a close match, considering the variation in the layer thickness ($20 \mu\text{m}$ vs. $30 \mu\text{m}$), which correspondingly results in the need of a finer powder. Given that fine powders have a very narrow tolerance regarding the powder particle diameter distribution, the powder particle dependent surface roughness becomes more homogenized due to the lack of peaks, described by the large particles. Thus, the spread of the surface roughness results was higher in this study, as it was the case in the reference.

Figure 4: Surface morphology dependency of upwards orientated surfaces on the polar angle Φ

Figure 5: Surface roughness in dependency to the polar angle Φ ; comparison with literature [6]

Material related challenges.

The fabrication of downwards orientated faces without support structure underneath was found to be more complex with 316L (1.4404), as it has been the case in previous studies with AlSi10Mg raw material [4,11]. In the first attempt, the configuration (c) samples were fabricated without support along the $\Phi = 135^\circ$ surface, which resulted in warping issues and led to the necessity of additional support. Due to the fact that, in this instance, the challenge at hand has been related to thermal induced stresses and corresponding distortions, a modification of either the geometry of the specimens and/or the irradiation parameters can be appropriate actions as well.

Figure 6: Occurred distortion due to arising thermal stresses

Conclusion

Inclined surfaces fabricated with SLM follow clear tendencies regarding their morphology and the development with changing polar angles. Improvements on the surface roughness can be achieved by lowering the layer thickness and utilizing fine raw metal powders with narrow tolerances in the particle size, as far as improvements within the fabrication process² are considered. Unfortunately, these optimization options reduce the economic feasibility of the process; decreasing the layer thickness drastically increases the fabrication time and choosing a finer powder increases the costs of the raw material.

² A change in the raw powder characteristic and/or the powder layer thickness requires adapting the irradiation parameters as well.

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References

- [1] L. Hitzler, A. Charles, A. Öchsner, The Influence of Post-Heat-Treatments on the Tensile Strength and Surface Hardness of Selective Laser Melted AlSi10Mg. *Defect and Diffusion Forum* 370 (2016) 171-176.
- [2] M.J. Matthews, G. Guss, S.A. Khairallah, A.M. Rubenchik, P.J. Depond, W.E. King, Denudation of metal powder layers in laser powder bed fusion processes. *Acta Mater* 114 (2016) 33-42.
- [3] M.R. Alkahari, T. Furumoto, T. Ueda, A. Hosokawa, Consolidation characteristics of ferrous-based metal powder in additive manufacturing. *Journal of Advanced Mechanical Design, Systems, and Manufacturing* 8 (2014) JAMDSM0009.
- [4] L. Hitzler, C. Janousch, J. Schanz, M. Merkel, F. Mack, A. Öchsner, Non-destructive evaluation of AlSi10Mg prismatic samples generated by Selective Laser Melting: Influence of manufacturing conditions. *Mat-wiss u Werkstofftech* 47 (2016) 564-581.
- [5] L. Hitzler, J. Hirsch, M. Merkel, W. Hall, A. Öchsner, Position dependent surface quality in Selective Laser Melting. *Mat-wiss u Werkstofftech* 48 (2017) 327-334.
- [6] G. Strano, L. Hao, R.M. Everson, K.E. Evans, Surface roughness analysis, modelling and prediction in selective laser melting. *J Mater Process Technol* 213 (2013) 589-597.
- [7] L. Löber, C. Flache, R. Petters, U. Kühn, J. Eckert, Comparison of different post processing technologies for SLM generated 316L steel parts. *Rapid Prototyping J* 19 (2013) 173-179.
- [8] J.P. Kruth, M. Badrossamay, E. Yasa, J. Deckers, L. Thijs, J. Van Humbeeck (2010) Part and material properties in selective laser melting of metals. Paper presented at the 16th International Symposium on Electromachining (ISEM XVI), Shanghai, China, 19.-23. April
- [9] B. Vandenbroucke, J.P. Kruth, Selective laser melting of biocompatible metals for rapid manufacturing of medical parts. *Rapid Prototyping J* 13 (2007) 196-203.
- [10] J. Schanz, M. Hofele, L. Hitzler, M. Merkel, H. Riegel Laser polishing of additive manufactured AlSi10Mg parts with an oscillating laser beam. In: *Machining, Joining and Modifications of Advanced Materials*. Springer, Singapore, 2016, pp 159-169.
- [11] L. Hitzler, C. Janousch, J. Schanz, M. Merkel, B. Heine, F. Mack, W. Hall, A. Öchsner, Direction and location dependency of selective laser melted AlSi10Mg specimens. *J Mater Process Technol* 242 (2017) 48-61.
- [12] L. Hitzler, J. Hirsch, J. Schanz, B. Heine, M. Merkel, W. Hall, A. Öchsner, Fracture toughness of selective laser melted AlSi10Mg. *P I Mech Eng L: J Mat IN PRESS* (2017).
- [13] A. Öchsner, *Continuum Damage and Fracture Mechanics*. Springer, Singapur, 2016.