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Non-destructive evaluation of AlSi10Mg prismatic samples generated by Selective Laser Melting: Influence of manufacturing conditions

Zerstörungsfreie Untersuchungen an mittels Selective Laser Melting hergestellten prismatischen Proben: Auswirkungen und Einflüsse der Prozessführung

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Keywords: Powder-bed based Additive Manufacturing, Flushing Process, Irradiation Strategy, Positioning and Inclination, Surface Quality

Abstract

Before utilising selective laser melting in real applications, the process as well as the outcome component and its characteristics need to be fully understood. Based on the layer-wise fabrication, with its distinctive orientations in translations and thermal influences within this additive manufacturing process, the obtained material properties and the microstructure are anticipated to be anisotropic. The selective laser melting process involves: the laser movement pattern in plane and rotation between single layers; recoater movement; substrate plate heating and movement; laser irradiation from the top; and inert gas flow. In order to gain insight into the process and its related characteristics, different sets of prismatic specimens in terms

of orientation and inclination were produced and evaluated. The evaluation contained surface quality investigations with two independent measurement approaches, i.e. tactile and optical, density measurements based on the Archimedes principle and micro-section evaluation. Furthermore, ultrasonic analyses were conducted to study the feasibility of determining the mechanical properties, i.e. Young's modulus and Poisson's ratio, in accordance with the recorded longitudinal and transversal sonic velocities.

The chosen raw material for these investigations was AlSi10Mg and the fabricated parts exhibited a high relative density of at least 99.5%. Remarkable deviations were evident in the obtained surface quality and clear trends could be determined based on the inclination and orientation condition of the sample during manufacturing. In regards to the ultrasonic investigation, it was found that the reported inherent anisotropy of selective laser melted samples could not be detected with the non-destructive ultrasonic investigation, and destructive procedures, to date, represent the only reliable method to accurately reveal the material characteristics.

Schlüsselwörter: Pulverbettbasierende generative Fertigung, Inertgasstrom, Belichtungsstrategie, Positionierung und Neigungswinkel, Oberflächenqualität

Im Rahmen der erfolgreichen Implementierung des selektiven Laserstrahlschmelzens in industriellen Anwendungen sind die Kenntnis und das Verständnis der charakteristischen und verfahrensbezogenen Eigenschaften der generierten Komponenten unabdingbar. Dieses Verfahren beinhaltet im Fertigungsprozess zahlreiche richtungsbezogene Einflussfaktoren, wie beispielsweise das angewandte Belichtungsmuster pro individueller Schicht, sowie das sukzessive Rotationsinkrement aufeinanderfolgender Belichtungsmuster, das gerichtete Aufbringen der Pulverschicht mit der verfahrensbedingten Ebnung und Komprimierung der darunterliegenden Schicht(en), der thermische Einfluss der vorgeheizten Substratplatte und deren gerichtete inkrementelle Absenkung im Laufe des Prozesses mit der damit einhergehenden Veränderung der vorliegenden thermischen Umgebung, der positionierungsbedingte Wärmeeintrag über die Lasereinstrahlung von oben, sowie der gerichteten Inertgasströmung, weshalb von einem anisotropen Werkstoffverhalten und positionierungsbedingten Abweichungen der gefertigten Komponenten ausgegangen werden kann.

Im Zuge dieser Untersuchung wurden diese Charakteristika anhand prismatischer AlSi10Mg Proben mit unterschiedlichen Herstellungsbedingungen (Winkellage und Positionierung) ermittelt und die vorhandenen prozessbedingten Einflüsse, wie die Belichtungsabfolge mit resultierender Rauchentwicklung und Schweißspritzerbildung und deren Verteilung über den vorliegenden Inertgasstrom, hinsichtlich der lokalen Auswirkungen auf die Gleichmäßigkeit der belichteten Schicht, ermittelt. Die weiteren Analysen beinhalteten die Auswertung der Oberflächengüte von verschieden orientierten Flächen, mittels taktilen und optischem Messverfahren, sowie die Bestimmung der Restporosität mittels zweier Verfahren, der Archimedes Methode und anhand einer Schliffbildauswertung. Weiterhin wurde die Anwendbarkeit der zerstörungsfreien Ultraschallprüfung für die Ermittlung der anisotropen Materialparameter, im Detail richtungsabhängiger Elastizitätsmodul und Poissonzahl, anhand gemessener Schallgeschwindigkeiten ausgewertet.

Die untersuchten AlSi10Mg Proben wiesen eine sehr hohe relative Dichte von mindestens 99,5% auf und anhand der ausgewerteten Oberflächen ließen sich charakteristische Merkmale ableiten, welche direkt den vorliegenden Herstellbedingungen zugewiesen werden konnten. Weiterhin ergab die Studie, dass zum derzeitigen Stand die verlässliche Bestimmung richtungsabhängiger Materialeigenschaften mit der zerstörenden Werkstoffprüfung zu erfolgen hat und die Ermittlung über gemessene Longitudinal- und Transversalschallgeschwindigkeiten die vorhandene Anisotropie nicht adäquat erfasst.

1 Introduction

The selective laser melting (SLM) process belongs to the layer-wise additive manufacturing (AM) technologies and is similar to the older selective laser sintering (SLS) process regarding machines and equipment. The major distinction between these two techniques is the higher energy density applied in the SLM process, leading to full melting of the utilised raw powder, whereas in SLS only a weak connection between the powder particles is achieved, requiring further treatment to increase the overall density [1,2]. One common approach to gain the necessary geometrical information for AM production is to convert the CAD-data of the part to be manufactured into a sliced model with equally thick sections. Hereby, the thickness of the slices is directly related to the powder layer thickness during the

manufacturing process, and following this, the cross-sections of the slices are obtained and applied as the description of the area to be consolidated by the moving laser beam. During the manufacturing process, the part is produced in a stepwise manner by exposing successive powder layers selectively with a laser beam as a driving force for local solidification of the powder layer. After finishing the exposure of one single layer, the substrate plate is lowered and a new powder layer is added on top by an inbuilt recoater system. Performing these steps multiple times generates the entire part as a summation of the individual layers [3-5]. This layer-wise fabrication overcomes limitations present in other conventional manufacturing techniques, like the accessibility required for milling or the limitations given by the mould in terms of casting [6-8]. These enlarged opportunities, given by the layer-wise manufacturing methods, represent an impressive outlook for further improvements, especially in the health sector [9-11]. However, there are a large number of influencing factors in SLM and distinctive environmental conditions based on the actual position in the building space. These include: the change from a bulk material dominant thermal environment for low build height towards a powder-bed dominant thermal environment with increasing build height [12-14]; distinct energy input and density caused by the moving laser beam irradiating from the top of the chamber, with its clear directions in plane and subsequent irradiation order of individual components [15-17]; influence of the preconditioning effect of the heated substrate plate and its decreasing effect with increasing build height combined with the different dwell times of the previously solidified material in the heated manufacturing environment [18-20]; the influence of the metal cave surrounding of the building chamber on the outwards positioned component, which is not preheated upfront and rises in temperature throughout the process and gain of build height; the influence of the inert gas mass flow and its impact on cooling rate and the transport of weld smoke and splashes [21,22]; characteristic interactions dependent on orientation and inclination, like the staircase effect [23-25] for inclined surfaces in regards to the substrate plate, the interaction between the first welding track along a full powder-bed and the accumulation tendencies leading to a higher first welding track in comparison to all subsequent ones [1,26,27], often referred to as the edge effect in case the contour is irradiated first; the distinct surface appearance of side faces (90° angle to the substrate plate) caused by the interaction between the loose powder-bed and the hot neighbouring solid face [28]; and the drainage of the melt

pool into the loose powder-bed beneath if no support structure is present [15,29]. These inherent SLM factors and distinctive environmental conditions cause large deviations of the component related properties, which can be categorised as mechanical, chemical, microstructural and geometrical properties. As a consequence of the volatility of the SLM process to the inherent numerous influencing effects, it is necessary to study their individual impact in order to predict the process outcome and improve its reliability. Once the predictability of the component properties is given, which is one of the major causes, in addition to the relatively long production times, hindering the process to be widely used, the success of the SLM technique in a broad area of applications is anticipated. Therefore, many adjustments were undertaken to optimise the SLM process and the commonly utilised quality criteria for these optimisations was obtaining full dense parts [30-32]. In general it could be concluded that the relative density is widely accepted as the most reasonable quality indicator. The reasons are: first, this value can be easily extracted from microstructure investigations (micro-sections) or obtained with the Archimedes principle; second, the mechanical performance is directly related to the component density, as the lower the relative density, the higher the amount of imperfections and porosity. Both represent, in regard to mechanical loading, a possible crack initiation point, hence lowering the material strength [33] and in particular, defects on the surface act in terms of bending loads as a critical failure point. Thus, when mechanical properties in terms of SLM fabricated specimen are discussed, the relative density and surface condition need to be taken into account. Furthermore, the unique properties of each individual raw material may lead to further challenges in the process control. In particular, aluminium based raw materials are known to comprise the particular properties of quick creation of a protective oxide layer combined with a high reflectivity and heat conductivity [30,34,35].

Within this study, the described quality criteria, i.e. the relative density and surface quality, were investigated on prismatic shaped AlSi10Mg samples, covering an enlarged range of global positions and inclinations. Based on these different configurations, several occurring effects within the SLM process were revealed and their distinct effects on the surface morphology described. In addition, the combination of circumstances, i.e. the irradiation sequence coupled with the unidirectional inert gas flow, and their effects on the homogeneity of the layer

consolidated, were investigated. Furthermore, the feasibility of ultrasonic investigations for obtaining the mechanical material parameters was studied.

2 Methodology

According to the aforementioned criteria, the research scheme, given in *Table 1*, resulted. Within this study, a SLM 280HL machine (SLM Solutions GmbH, Lübeck, Germany) equipped with a 400 W Yb-fibre-laser and an available building space of 280 x 280 x 350 mm³ was utilised. Nitrogen was employed as the inert gas.

2.1 Manufacturing conditions

The raw AlSi10Mg powder was supplied by SLM Solutions and its properties in terms of particle size, shape and distribution, were analysed with scanning electron microscopy (SEM) (Sigma 300 VP, Carl Zeiss Microscopy GmbH, Jena, Germany) (see *Fig. 1*). It was found to be mainly spherically shaped with an average diameter of 37 µm. The overall distribution, with weighting according to occupied area and number of appearances, is depicted in *Fig. 2*. The chosen parameter sets in the SLM process are given in *Table 2* and the major difference is represented in the applied energy density, which almost doubled in the case of the contour scanning. These differentiations are related to the disparate governing requirements, i.e. the high relative density for the core and the good surface finish for the contour. In regard to the applied support structure, only the block type, i.e. a honeycomb scaffold with open pores and characteristic sawtooth-like connectors towards the substrate plate and specimens, was applied and the supported areas were reduced to a minimum, which enabled the study of almost all inherent faces. For the SLM process, a slicing size of 50 µm was chosen within the data preparation. However, this slice thickness is not equal to the applied powder layer thickness during the fabrication process, due to the fact that the consolidated layer has a higher relative density¹ than the loose powder layer² [36-38]. Therefore, the powder layer thickness within the SLM process is greater than the specified 50 µm slice thickness; hence powder particles slightly larger in diameter than the final layer thickness can be employed.

¹ The relative density of the consolidated layer is in the ideal case almost 100%.

² The powder-bed density depends on the actual raw powder and its properties as well as on the utilised recoating system. However, in general a relative density of the loose powder-bed of around 50-60% can be assumed [36].

Table 1: Research scheme; input parameters and evaluation criteria

Tabelle 1: Evaluierungsschema; Eingabeparameter und Auswertungskriterien

Input		Evaluation method
Category	Parameter	
Powder	Restricted to AlSi10Mg	Surface roughness and morphology
Positioning	Inclination to substrate plate and recoater path	Micro-section analysis
	Positioning on substrate plate	Density
		Ultrasonic investigation

Figure 1: SEM Images of AlSi10Mg raw powder; (a) 500x magnification, (b) 3000x magnification

Bild 1: SEM Aufnahmen des AlSi10Mg Pulvers im Ausgangszustand; (a) 500 fache Vergrößerung, (b) 3000 fache Vergrößerung

Figure 2: Distribution of AlSi10Mg powder particle size; weighted by (a) area and (b) number of appearances

Bild 2: Streuung der Korngröße des AlSi10Mg Pulvers; (a) flächengewichtet (b) anzahlengewichtet

Table 2: Parameter set utilised for the irradiation of AlSi10Mg in SLM**Tabelle 2:** Angewandte Belichtungsparameter für die Verarbeitung von AlSi10Mg in SLM

	Scan speed [mm/s]	Laser power [W]	Hatch distance [mm]	Scan vector length [mm]	Rotation angle increment [°]
Contour	600	350	-	-	-
Core	930	350	0.42	10	90
Final layer	850	350	0.42	10	-
Contour offset	600	350	-	-	-
Support	900	350	-	-	-

The fabricated specimens had a prismatic shape with a squared cross section ($10 \times 10 \times 50 \text{ mm}^3$) and were produced with an oversize of 0.4 mm. The oversize was applied on all sides, since these samples were considered for the ultrasonic investigation and the surfaces needed to be defect-free and parallel to guarantee a good connection with the ultrasonic transducer head [39]. For the micro-section analysis, one cubic sample (edge length of 10 mm) was placed in the centre of the substrate plate.

In order to gain knowledge about the orientation and inclination influence, four different representative orientations were considered. This range covers the influence of the inclination to the substrate plate, which is specified as the xy-plane and the corresponding angle is named as α_{xy} , as well as the alignment to the recoater. The translation direction of the recoater is hereby represented by the x-axis; hence the inclination to the recoater movement is consequently defined as α_x . As the representative counterpart to the global coordinate system, the longitudinal axis of the specimen is used to describe the direction in space and the considered configurations are given in *Table 3*.

Table 3: Orientation in dependency to the longitudinal axis of the specimen; definition of angles see Fig. 5**Tabelle 3:** Platzierung in Abhängigkeit zu der Probenlängsachse; die Definition der Winkel ist in Bild 5 dargestellt

Configuration	α_{xy}	α_x	Prismatic specimens	Cubic sample
(a)	0°	5°	X	-
(b)	45°	0°	X	-
(c)	90°	5°	X	-
(d)	45°	45°	X	-
(e)	0°	0°	-	X

The influence of the coupled distinctive environmental conditions (i.e. the subsequent irradiation order of individual cross-sections, with local generation of smoke and welding splashes, and the unidirectional inert gas stream above the powder-bed) was studied on a series of flat quadratic samples, placed in the direction of the inert gas stream. The chosen setup, including the irradiation sequence and direction of inert gas stream, is depicted in *Fig. 3* and hereby, are the characteristic directions in regard to the y-axis in reversed order. The inert gas stream follows the positive y-direction, whereas the irradiation pattern in plane follows the negative y- and positive x-direction. The investigation comprised a set of six small samples with a quadratic cross-section (20 mm edge length and 3 mm in height), split up into two series. In addition to these, on one series an additional quadratic frame (outer edge length of 50 mm, inner edge length of 25 mm and height of 3 mm) was considered (see *Fig. 3*).

Figure 3: Combination of circumstances; subsequent irradiation order and direction of inert gas stream; numbers from 1 to 9 indicate the subsequent irradiations

Bild 3: Kombinierte Betrachtung der Belichtungsreihenfolge und des gerichteten Flutungsprozesses mit einem Inertgas; Nummerierung 1 bis 9 entspricht der Belichtungsreihenfolge

2.2 Surface Morphology and Topology

The surface quality evaluation was conducted on a set of two samples per configuration and determined with two independent approaches. First, with tactile surface roughness measurement equipment (Mitutoyo SJ-301, Mitutoyo Corp., Kanagawa, Japan), using the following settings: measurement procedure in accordance to the ISO 1997 norm, with two different cut-off wavelengths, i.e. 800 and 2500 μm . Second, with an optical white light interferometer (Zygo Zemetrics ZeGage, Zygo Corp., Middlefield, Connecticut, USA), using a threshold of 0.5% and a saturation threshold of 5%. Hereby, each determined area increment had a quadratic shape with an edge length of 830 μm . For the tactile approach, two measurement paths, namely length-wise and cross-wise, were considered. However, it needs to be mentioned that the tactile measurement evaluates the topology of the surface represented by a received line and therefore, the consideration of the perpendicular path is needed in order to gain additional information about the surface condition. Considering an upwards orientated surface parallel to the substrate, in which the morphology is mainly driven by the upmost scan pattern or a side face with evident layers, the tactile surface measurement path might represent a track in between two scan tracks or layers. This result does not accurately represent the whole surface morphology considered, and thus, at least the perpendicular orientation, needs to be evaluated as well. Conversely, the optical approach considers a small area element and therefore, already covers by itself both directions. However, both approaches have in common that their area under consideration is limited in its size and hence, both approaches require a series of measurements in order to cover the location dependencies as well. A sketch, comparing the two different approaches and the belonging evaluated tracks or area, is given in *Fig. 4*. Based on the four configurations considered (Table 3), six distinctive face orientations could be determined (see *Fig. 5*) and this nomenclature was employed to describe the orientation dependent results obtained.

For the evaluation of the weld splashes on the flat quadratic samples, an optical light microscope (VR-3100 Keyence Corporation, Osaka, Japan) was employed to evaluate the surface topography. The measurements undertaken differed from the approaches considered for the prismatic samples. This time, the whole surface of the sample under consideration was recorded, which was necessary to gain insight into

the overall distribution and inherent deviations of the present welding splashes. In order to represent those inhomogeneous surface morphologies encountered as a single value per sample, the characteristic area roughness value S_a was chosen instead of using a series of R_a or R_z values (European Norm DIN EN ISO 25178-2:2012).

Figure 4: Surface roughness measurements; left: tactile, right: optical
Bild 4: Oberflächenrauheitsmessungen; links: taktil, rechts: optisch

Figure 5: Applied nomenclature for description of surface orientations
Bild 5: Angewandte Nomenklatur für Oberflächenorientierungen

2.3 Chemical composition

Given the fact that within the SLM process different parameter sets are applied for the core and the contour (Table 2) and the local energy input is coupled with material loss effects like melting loss or evaporation of material, the composition of the fabricated component might differ depending on the considered location. Therefore, the resulting material composition was determined with optical emission spectrometry (Q4 TASMAN, Bruker Corp., Billerica, Massachusetts, USA) on both the as-built and machined surfaces.

2.4 Density and volume porosity based on Archimedes principle

With the determined chemical composition of the component, the maximal theoretical density was calculated and a set of eight samples (machined condition)

was weighed in air and under water (Archimedes principle [40]). It should be noted that the water contained a small amount of additives in order to reduce the surface tension of the fluid, enhancing the reliability of the measurements.

2.5 Micro-section analysis

The cubic sample was embedded in a hot mounting resin, followed by a stepwise preparation procedure, i.e. a pre-grinding process to remove the contour area and a subsequent three-phase polishing procedure. After each machining step, the sample was cleaned in an ultrasonic bath, followed by manual cleaning with water and ethanol. The micrograph was then recorded with an optical light microscope (Axio Imager z2m, Carl Zeiss Microscopy GmbH, Jena, Germany).

2.6 Ultrasonic investigation

A set of six machined specimens (prismatic samples) per configuration was taken into account. It should be mentioned that for this investigation solely machined samples must be employed, to ensure high quality surfaces in combination with a distinguished parallelism between opposing faces. In the investigation, the ultrasonic probe head was placed on one end of the prismatic sample in order to initiate the sonic waves (i.e. longitudinal and transversal) along the longitudinal direction of the prismatic sample, which was 50 mm in length. The ultrasonic investigation was conducted using two transducers, one for longitudinal (V129-RM 10 MHz, Olympus-IMS, Massachusetts, USA) and the other for transversal (V157-M 5 MHz, Olympus-IMS, Massachusetts, USA) measurements, combined with an ultrasonic gauge (Panametrics 25HP plus, Olympus-IMS, Massachusetts, USA). Based on the recorded ultrasonic velocities and the known relative density (taken from the results of the Archimedes approach) the corresponding material parameters, i.e. Young's modulus and Poisson's ratio, could be calculated [41].

3 Results and discussion

3.1 Surface quality

The fabricated samples exhibited huge deviations in their surface appearances (see *Figs. 6, 7*). The edge-effect, related to the distinct irradiation pattern applied, starting with irradiation of the contour, was clearly visible on the UOF of the configuration (a) samples. The mean roughness values are given in *Table 4* (tactile) and

Table 5 (optical). However, the conducted surface measurements revealed large deviations between the results obtained from the two approaches considered. Within the tactile approach similar deviations occurred depending upon the applied measurement settings. In particular, the chosen cut-off wavelength in the tactile approach was found to have had an impressive impact on the resulting surface roughness values (Table 4). This finding is related to the geometrical deviations inherent in the specimens under consideration, which can generally be split into primary deviations (i.e. deviations in shape, dimension and position) and secondary deviations (i.e. roughness and waviness). As the detected surface profile represents a superimposition of both types, a separation, which allows categorising the surface roughness apart from the profile information, needs to be undertaken to qualify the surface morphology. Hence, to obtain reasonable results, the range in surface roughness needs to be known upfront in order to select appropriate filter parameters (German Standard DIN 4288) for the separation process. Consequently, when the chosen measurement parameters do not match the surface characteristics under investigation, the results obtained will be inaccurate. Hence, based on this relation the deviations encountered within the tactile measurements can be explained.

Returning to the comparison of the two approaches considered, based on the mechanical detection involved in the tactile approach, with its sliding and scratching path in combination with the detection limitation related to the geometrical size of the probe tip, certain limitations in the accuracy were reasoned. The tiny welding splatters of the surface cannot withstand the mechanical force and are removed without detection. Furthermore, the small notches are not large enough to be detected (see *Fig. 8*).

Figure 6: Fabricated samples on substrate plate
Bild 6: Hergestellte Proben auf der Grundplatte

Figure 7: Major deviations in surface appearance

Bild 7: Erhebliche Unterschiede in der Oberflächenbeschaffenheit

Table 4: Average surface roughness determined via tactile approach, considering cut-off wavelength of 800 μm and 2500 μm ; definition of face orientations see Fig. 5

Tabelle 4: Gemittelte Oberflächenrauigkeit mittels taktilem Messverfahren, verwendete Grenzwellenlängen von 800 μm und 2500 μm ; Definition der Oberflächenausrichtung ist in Bild 5 beschrieben

Configuration			(a)	(b)	(c)	(d)
800 μm cut-off wavelength	left	Ra [μm]	5.62	6.10	6.72	7.70
		Rz [μm]	33.47	39.53	40.58	45.27
	right	Ra [μm]	8.42	6.08	4.68	8.66
		Rz [μm]	45.92	34.99	29.66	48.83
	UOF	Ra [μm]	3.17	5.61	-	7.49
		Rz [μm]	15.71	31.94	-	43.55
	DOF	Ra [μm]	-	14.37	-	20.25
		Rz [μm]	-	77.05	-	99.35
	door	Ra [μm]	-	-	7.36	-
		Rz [μm]	-	-	43.64	-
	back	Ra [μm]	-	-	5.36	-
		Rz [μm]	-	-	35.42	-
2500 μm cut-off wavelength	left	Ra [μm]	8.10	7.18	7.35	8.01
		Rz [μm]	52.10	46.93	49.67	51.88
	right	Ra [μm]	7.41	7.20	8.22	8.02
		Rz [μm]	48.72	49.83	56.53	54.73
	UOF	Ra [μm]	11.02	9.26	-	12.25
		Rz [μm]	57.05	58.42	-	74.10
	DOF	Ra [μm]	-	24.47	-	30.65
		Rz [μm]	-	142.25	-	171.50
	door	Ra [μm]	-	-	7.39	-
		Rz [μm]	-	-	49.73	-
	back	Ra [μm]	-	-	7.61	-
		Rz [μm]	-	-	55.26	-

Table 5: Surface roughness via white light interferometer: average values and standard deviations; definition of face orientations see Fig. 5

Tabelle 5: Oberflächenrauigkeit mittels Weißlichtinterferometer: Mittelwerte und Standardabweichungen; Definition der Oberflächenausrichtung ist in Bild 5 beschrieben

Configuration			(a)	(b)	(c)	(d)
Average roughness	left	Ra [μm]	6.88	8.38	6.15	7.43
		Rz [μm]	22.63	22.77	20.28	23.79
	right	Ra [μm]	7.34	5.75	8.38	7.15
		Rz [μm]	21.44	20.36	28.30	25.45
	UOF	Ra [μm]	7.67	6.80	-	7.14
		Rz [μm]	13.88	20.93	-	22.56
	DOF	Ra [μm]	-	27.02	-	23.58
		Rz [μm]	-	158.19	-	151.48
	door	Ra [μm]	-	-	6.94	-
		Rz [μm]	-	-	20.49	-
	back	Ra [μm]	-	-	6.71	-
		Rz [μm]	-	-	23.20	-
Standard deviation	left	Ra [μm]	1.517	2.216	1.687	2.170
		Rz [μm]	5.642	5.546	5.357	7.119
	right	Ra [μm]	2.431	1.843	2.500	2.789
		Rz [μm]	4.002	5.357	12.788	8.428
	UOF	Ra [μm]	3.904	3.032	-	2.109
		Rz [μm]	3.324	7.582	-	7.295
	DOF	Ra [μm]	-	15.397	-	7.862
		Rz [μm]	-	48.915	-	46.866
	door	Ra [μm]	-	-	2.571	-
		Rz [μm]	-	-	5.200	-
	back	Ra [μm]	-	-	1.983	-
		Rz [μm]	-	-	7.152	-

The optical approach was found to be more suitable for surface quality evaluations in regard to SLM fabricated as-built samples; hence, in the following comparative discussion solely the results obtained with the optical approach were taken into account. It was evident on the three representative images determined (see Fig. 8), that the appearance of the sample surface was highly volatile to its individual orientation during fabrication. However, the side faces revealed mainly similar images and were thus represented as one single group, whereas the UOF and DOF exhibited totally different appearances.

Figure 8: Characteristic surface topographies; representative images, obtained with white light interferometer, for all investigated configurations based on the orientation (a) side face [LOF, ROF, door, back], (b) UOF, (c) DOF

Bild 8: Charakteristische Oberflächenbeschaffenheiten; repräsentative Abbildungen, erzeugt mittels Weißlichtinterferometer, für alle betrachteten Konfigurationen und Orientierungen (a) seitliche Flächen [LOF, ROF, door, back], (b) UOF, (c) DOF

In order to get a deeper insight into these evident deviations, the orientation dependent results and their related spreading are shown as Gaussian normal distribution curves per configuration and corresponding faces in *Fig. 9*. It should be mentioned that for the following charts and discussion section, only the R_z values are considered, due to the fact that extrema/peaks show a greater influence on the obtained roughness values when the R_z weighting criteria is applied [42]. Of these, it could be concluded that the DOF exhibited an appreciable inferior surface quality and, in the case of functional surfaces, always required a surface finish in a subsequent machining procedure.

Figure 9: Surface roughness as Gaussian normal distribution per configuration (a to d) for all corresponding faces

Bild 9: Oberflächenqualität für alle betrachteten Konfigurationen (a bis d) und zugehörigen Flächen, dargestellt als Gaußsche Normalverteilung

However, all other face orientations revealed applicable surface qualities. Of course, this is just a subjective impression and always depends on the purpose of application. Nevertheless, there were also certain deviations and dependencies evident in between these faces. In order to investigate this low-roughness sector further, magnifications of this area are depicted in *Fig. 10*, to increase the resolution of the charts given in *Fig. 9*, where needed. For the configuration (a) samples it was evident that the parallel to the substrate plate orientated UOF confirmed the lowest roughness and spreading. However, this behaviour was anticipated as this face comprised just one single layer and was therefore driven by the final laser pattern and irradiation parameters applied. Whereas, the two side-faces, i.e. LOF and ROF, consisted of multiple layers and hence also depended on the entire process, including the connection between individual layers and the secondary effects occurring between the melt pool and the loose powder-bed. As soon as the specimen was inclined in regard to the substrate plane ($\alpha_{xy} \neq 0^\circ$), the UOF also comprised multiple layers and deviations in direct comparison to the side faces

alleviated. This effect was revealed for both inclined configurations, i.e. (b) and (d). Furthermore, for the UOF and DOF there was another characteristic effect evident. The inclination angle in combination with the given layer thickness and the resulting incremental generation led to a staircase-like surface finish. This manufacturing process related effect is commonly named as the staircase-effect and its emphasis on the resulting surface morphology is solely dependent on the inclination angle of the surface and the applied layer thickness. In terms of the DOFs, which were built without additional support structure, these two criteria (i.e. inclination angle and layer thickness), described the overhang of the layer to be consolidated in regard to the solid area beneath, or in other words the area of the new layer without a solid support underneath, which caused, besides the drainage of the melt pool into the loose powder-bed, a warping of the cantilevered area.

Some discrepancies were present for the configuration (c) samples, where only faces perpendicular to the substrate plane were present, i.e. LOF, ROF, door and back. Based on the previous mentioned circumstances, it could be concluded that for these samples no real deviations between the single faces should have been evident. However, major deviations for both the average surface roughness and the spreading were determined. Specifically, the ROF revealed a higher surface roughness and an immense inequality. Since these samples were positioned on the uttermost right-back edge (see Fig. 6), these tendencies were reasoned to the present deviations in the environmental conditions. That is, adjacent samples on the left-hand side with corresponding heat input and the solid wall of the building cave on the right-hand side, coupled with the influence of the laser beam irradiation angle in combination with the distinct subsequent irradiation order, leading to heat accumulation effects per single irradiated cross-section and in the whole consolidated layer. In addition, the influence of the inert gas stream, with its thermal influence and the transport characteristic of emerging smoke and splashes, also contributed to the present deviations in environmental condition.

Figure 10: Magnification to Fig. 9, depiction of the low roughness area; (b.1) config. (b), (c.1) config. (c), (d.1) config. (d)

Bild 10: Vergrößerte Darstellung der kleinen Rautiefen aus Bild 9 für (b.1) config. (b), (c.1) config. (c), (d.1) config. (d)

In order to analyse these present tendencies based on the specific face orientations in more detail, the evaluated faces were grouped according to their individual orientation. The corresponding charts are depicted in *Fig. 11*. In support of this, it was concluded that under the consideration of all involved configurations, the LOF and DOF exhibited consistent results throughout all investigated samples, although the locations on the substrate plate differed (see Fig. 6). Conversely, the ROF and UOF revealed major differences. As mentioned earlier, the deviations for the UOF were reflected in the change of the inclination angle which changed the characteristics of the surface from one single layer to multiple layers. Thus, this finding could be related to the inclination angle applied. In terms of the ROF, the significance of the configuration (d) samples should be emphasised. These samples included an additional influencing factor, which is the inclination angle to the recoater translation path ($\alpha_x = 45^\circ$). Hence, the deviation between configurations (b) and (d) could be apportioned to the influence of the inclination angle to the recoater. However, in order to clarify the encountered deviations in the configuration (c)

samples, the positioning effect coupled with the irradiation strategy and flushing procedure was investigated further.

Figure 11: Surface roughness as Gaussian normal distribution for different configurations, grouped per side orientation; (a) LOF, (b) ROF, (c) UOF, (d) DOF

Bild 11: Oberflächenqualitäten der einzelnen Konfigurationen gruppiert nach der Ausrichtung der Flächen, dargestellt als Gaußsche Normalverteilung; (a) LOF, (b) ROF, (c) UOF, (d) DOF

Based on the evaluated flat quadratic samples (see *Figs. 12, 13*), clear tendencies in the present surface quality were observed. The corresponding results are summarised in *Table 6*. Both considered series (the single and the framed quadratic samples) exhibited a decrease in their surface quality in direction from the left to the right side of the building area (negative y-direction, see *Fig. 3*). Hence, it could be reasoned that the emitted welding splashes could not be holistically wiped out by the constantly flowing inert gas stream and the few splashes which fell out led to a distinctive pattern in plane. Interestingly, there was no real emphasis on the areas of the frame present, which were in the travel direction of the emerging splashes of the centred neighbouring quadratic sample. This fact indicated that the emerged weld splashes were absorbed first in the inert gas stream and then randomly fell out after travelling a certain distance in the inert gas flow, leading to their random distribution

over the area. However, comparing the two single quadratic samples (Table 6), placed on the very left side in each individual series, it could be concluded that the increased amount and size of the solidified cross-sections, caused by the additional surrounding frames, also had an appreciable impact on the surface quality obtained. It needs to be mentioned that this effect was most emphasised on the left side of the building area (close to the inert gas outlet) and in terms of the samples on the right side (close to the inert gas inlet) almost no deviation was present.

Given this clear evidence of the resulting inhomogeneous surface appearance of the upmost layer and that this behaviour could be anticipated to occur constantly in every single layer consolidated and hence, affect the entire manufacturing process. It could be concluded that these constantly occurring inhomogeneities in the surface morphology caused a detrimental effect on the recoating process of the subsequent applied powder layer and influenced also its consolidation process. Thus, the irradiation strategy applied, coupled with the unidirectional inert gas flow, could be reasoned as one possible cause, contributing to the present deviations and spreading observed in the surface quality investigations of the prismatic samples, i.e. in particular the variation encountered in the surface quality between the LOF and ROF on the configuration (c) samples.

Figure 12: Surface topography of single quadratic samples; magnification factor 2; (a) left sample, irradiation number ③; (b) centred sample, irradiation number ⑥; (c) right sample, irradiation number ⑨; nomenclature in accordance to Fig. 3

Bild 12: Oberflächenbeschaffenheit der einzelnen quadratischen Mustern; Verstärkungsfaktor 2; (a) linke Probe, Belichtungsnummer ③; (b) mittlere Probe, Belichtungsnummer ⑥; (c) rechte Probe, Belichtungsnummer ⑨; Definition entsprechend Bild 3

Figure 13: Surface topography of framed quadratic samples; magnification factor 2; (a) left sample, irradiation numbers ① and ②; (b) centred sample, irradiation numbers ④ and ⑤; (c) right sample, irradiation numbers ⑦ and ⑧; nomenclature in accordance to Fig. 3

Bild 13: Oberflächenbeschaffenheit der umrahmten Mustern; Verstärkungsfaktor 2; (a) linke Probe, Belichtungsnummer ① und ②; (b) mittlere Probe, Belichtungsnummer ④ und ⑤; (c) rechte Probe, Belichtungsnummer ⑦ und ⑧; Definition entsprechend Bild 3

Table 6: Surface roughness results of flat quadratic samples; characteristic area roughness values (European Norm DIN EN ISO 25178-2:2012)

Tabelle 6: Ergebnisse der Oberflächenrauheitsmessungen an den flachen, quadratischen Proben; charakteristischer Flächenkennwert (DIN EN ISO 25178-2:2012)

Positioning	Area roughness Sa [μm]		
	Single quadratic sample (Fig. 12)	Single quadratic sample ³ (Fig. 13)	Framed quadratic sample ⁴ (Fig. 13)
left	18.73	33.00	49.09
centre	14.92	17.70	33.98
right	13.67	15.85	31.57

³ Solely the quadratic sample in the middle is considered.

⁴ The given value for the area roughness Sa comprises the whole combination, i.e. the quadratic sample and the surrounding frame.

3.2 Chemical analyses

The composition analysis was conducted on machined and as-built samples, thus representing both the chemical composition of the contour and core material. A set of three measurements for each were evaluated and the averaged results were determined (*Table 7*). However, small deviations were evident. The aluminium content in the contour composition was less than in the core and the contrary held for the corresponding silicium content.

Table 7: Averaged chemical composition in mass-percentage

Tabelle 7: Gemittelte chemische Zusammensetzung angegeben in Masseprozent

	Al ⁵	Si	Mg	Ca	Cr	Cu	Fe	Ga
machined	89.3280	10.0867	0.3073	0.0067	0.0024	0.0017	0.1627	0.0133
as-built	88.9463	10.4967	0.3043	0.0117	0.0041	0.0030	0.1700	0.0103
	Li	Mn	Na	Ni	P	Sb	Ti	V
machined	0.0005	0.0030	<0.0020	0.0074	0.0029	<0.0070	0.0727	0.0049
as-built	0.0007	0.0030	0.0170	0.0137	0.0026	0.0090	0.0077	<0.0020

Based on the determined compositions, the theoretical alloy densities were calculated in accordance to the mass-percentage and corresponding element densities [43]. In particular, the values 2.657 g/cm³ for the core and 2.654 g/cm³ for the contour composition were obtained. Given the fact that the contour represents only the outer shell and thus, has a rather negligible influence in relation to the entire component, the overall density is represented by the determined core density. Hence, for the subsequent density evaluations, the core value was considered as the representative theoretical, maximal achievable, density. At this point it should be mentioned that both compositions determined met the standardised composition specifications of the AlSi10Mg alloy [44].

3.3 Density based on Archimedes principle

For the density evaluation based on the Archimedes principle, the obtained masses in air and under water were transferred into averaged values for the density and volume porosity. The outcome is given in *Table 8*.

⁵ The aluminium percentage was slightly modified from the measured value, in order to obtain a total of 100%.

Table 8: Density and volume porosity based on Archimedes principle**Tabelle 8:** Dichte und Volumenporosität ermittelt mit der Archimedes Methode

Machined prismatic samples	Density ρ [g/cm ³]	Volume porosity [%]
Average	2.644	0.494
Standard deviation	0.00508	0.19427

In order to clarify the interpretation of the obtained results, the according spreading based on the Gaussian normal distribution [45] is depicted in *Fig. 14*. Out of this, it could be concluded that the produced samples exhibited a high quality in terms of their relative density.

Figure 14: Gaussian normal distribution: (a) relative density, (b) volume porosity**Bild 14:** Gaußsche Normalverteilung: (a) relative Dichte, (b) Volumenporosität

3.4 Microstructure and micro-section

Subsequently, to gain further insight into the distribution of the remaining porosity in the area, a micro-section analysis was conducted on the cubic sample and the following results were obtained (*Table 9*). It should be noted that for the evaluation of the area porosity only laid open pores larger than 5 μm have been considered.

Table 9: Results of micro-section evaluation on cubic sample**Tabelle 9:** Ergebnisse des Schliffbildes der würfelförmigen Probe

Evaluated area [mm ²]	Count of voids	Area porosity [%]
95.7	994	0.3

However, the area porosity appeared to be lower than the volume porosity (*Table 8*). This might be a side effect of neglecting the not fully laid open pores or may be caused by the mechanical preparation process of the micro-section, which could lead, under certain circumstances, to the closure of some pores. Nevertheless, the

micro-section enabled the insight into the pore distribution over the cross-section (see *Fig. 15*). Furthermore, the pore size distribution weighted in accordance to the occupied area is depicted. As a representative value for the pore size the determined maximal Feret diameter⁶ [46] was chosen. It could be concluded that in the core area, the pores were arbitrarily distributed and no clear tendency was present. However, towards the contour (side faces) the porosity density increased, whereas the area on top, which was irradiated using the parameter set for the final layer, resulted in a very low amount of inherent porosity. Based on these findings, it could be concluded that the varied irradiation parameters applied resulted in evident inhomogeneities in terms of the overall distribution of pores. In particular, the parameters applied for the contour scanning, coupled with the distinctive irradiation strategy (irradiation of the contour first), led to a high porosity in the adjoining area, i.e. the transition area where the shift from the contour irradiation to the core irradiation was performed. This critical accumulation of voids can be explained by the characteristic tendency in the size of adjoining subsequent laser tracks, i.e. the first laser track is larger in its size and leaves gaps in the neighboring area, leading to a smaller subsequent track with an increased likelihood of imperfection occurrence. At last, it should be noted that the evident porosity in the lower area was governed by the interaction between the highly porous support structure and the first couple of solidified layers.

⁶ The maximal Feret of a region is the maximum value of a series of 32 distance measurements with different angular positions.

Figure 15: Micro-section and area-weighted porosity distribution of cubic sample
Bild 15: Schliffbild und flächengewichtete Porositätsverteilung der würfelförmigen Probe

3.5 Ultrasonic evaluation of mechanical properties

The averaged results and the according standard deviations for Young's modulus and Poisson's ratio are given in *Table 10*. However, the determined mechanical parameters based on sonic velocities did not reflect the inclination dependent anisotropic material behaviour reported in destructive material testing [30,18,47,48]. The obtained results appeared constant throughout all configurations under consideration, combined with a very low spreading.

Table 10: Ultrasonic investigation; Young's modulus and Poisson's ratio based on longitudinal and transversal sonic velocities

Tabelle 10: Ultraschallmessung; ermittelte Materialkennwerte, E-Modul und Poissonzahl, basierend auf gemessenen Schallgeschwindigkeiten

Config.	Young's Modulus [MPa]		Poisson's Ratio [-]	
	Average	STDEV	Average	STDEV
(a)	74787	430.25	0.336	0.00130
(b)	75200	411.39	0.338	0.00162
(c)	75119	251.58	0.334	0.00070
(d)	74999	433.48	0.337	0.00147

Consequently, it can be reasoned that the anisotropy caused by the layer-wise AM method cannot be determined with non-destructive procedures, like the ultrasonic investigation, and therefore, the destructive material testing is indispensable. This relation was at least evident for tensile load cases, as proven in this work. However, in the case of compressive loads, there might be a better agreement as the inherent

voids do not affect the material behaviour in such a strong manner, as is the case for tensile loads. These effects will be studied further by employing the prismatic samples in compressive tests and the according results will be reported.

4 Conclusion

Based on the microstructural investigations undertaken, it could be concluded that the fabricated samples exhibited a good quality in terms of their relative density, on average above 99.5%, for both investigations considered (Archimedes principle and micro-section evaluation). In regards to the evaluated surface quality, several characteristic influencing factors, i.e. position of the sample in the building space, inclination angle of the surface, interaction with the loose powder-bed, transport of weld splashes with the inert gas stream, were determined, leading to the major distinctions observed. Out of these, the inclination angle of the surface was found to have the most emphasised effect on the resulting surface morphology, followed by the interaction between the melt pool and the loose powder particles. Furthermore, the impact of the occurring combination of circumstances, i.e. the order of subsequent irradiations and the inert gas flow in the building chamber, was examined and huge deviations in the homogeneity of the surface appearance of the last consolidated layer was observed. This inhomogeneity was determined to have an impact on the surface qualities of opposing side faces, mainly between left and right facing surfaces, and the evident tendencies encountered for the surface quality of the upmost layer, in relation to the overall positioning in plane. For the determination of the material parameters, i.e. Young's modulus and Poisson's ratio, the ultrasonic approach was found to be unsuitable, as the evident anisotropic behaviour could not be detected. However, as these anisotropies were justified by solely tensile loadings, the significance occurring in compressive load cases needs to be proven in further investigations.

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6 References

- [1.] V. E. Beal, P. Erasenthiran, N. Hopkinson, P. Dickens, C. H. Ahrens, *Int. J. Adv. Manuf. Technol.* **2006**, 30, 844.
- [2.] P. Rochus, J. Y. Plessier, M. Van Elsen, J. P. Kruth, R. Carrus, T. Dormal, *Acta Astronaut.* **2007**, 61, 352.
- [3.] I. Gibson, D. W. Rosen, B. Stucker, *Additive Manufacturing Technologies*, Springer US, **2010**.
- [4.] D. Manfredi, F. Calignano, M. Krishnan, R. Canali, E. Paola, S. Biamino, D. Ugues, M. Pavese, P. Fino, *Light Metal Alloys Applications: Additive Manufacturing of Al Alloys and Aluminium Matrix Composites (AMCs)*, InTech, **2014**.
- [5.] W. Meiners, Dissertation, RWTH Aachen, Germany, **1999**.
- [6.] P. Fastermann, *3D-Drucken*, Springer, **2014**.
- [7.] K. Kempen, PhD Thesis, KU Leuven, Belgium, **2015**.
- [8.] X. Su, Y. Yang, D. Wang, Y. Chen, *Rapid Prototyping J.* **2013**, 19, 166.
- [9.] F. Alifui-Segbaya, J. Evans, D. Eggbeer, R. George, *Progress in Additive Manufacturing* **2014**,
- [10.] M. Figliuzzi, F. Mangano, C. Mangano, *Int. J. Oral. Maxillofac. Surg.* **2012**, 41, 858.
- [11.] A. Gebhardt, F.-M. Schmidt, J.-S. Hötter, W. Sokalla, P. Sokalla, *Physics Procedia* **2010**, 5, 543.
- [12.] F. Verhaeghe, T. Craeghs, J. Heulens, L. Pandelaers, *Acta Mater.* **2009**, 57, 6006.
- [13.] A. Wegner, G. Witt, *Process Monitoring in Laser Sintering using Thermal Imaging*.
http://www.researchgate.net/publication/268061485_PROCESS_MONITORING_IN_LASER_SINTERING_USING_THERMAL_IMAGING. Accessed 12/05/2015.
- [14.] I. Yadroitsev, P. Bertrand, I. Smurov, *Appl. Surf. Sci.* **2007**, 253, 8064.
- [15.] J. P. Kruth, M. Badrossamay, E. Yasa, J. Deckers, L. Thijs, J. Van Humbeeck, Paper presented at 16th International Symposium on Electromachining (ISEM XVI), Shanghai, China, 19.-23. April, **2010**.
- [16.] C. Qiu, N. J. E. Adkins, M. M. Attallah, *Mater. Sci. Eng., A* **2013**, 578, 230.
- [17.] I. Yadroitsev, P. Krakhmalev, I. Yadroitsava, *Addit. Manuf.* **2015**, 7, 45.
- [18.] D. Buchbinder, W. Meiners, K. Wissenbach, R. Poprawe, *J. Laser Appl.* **2015**, 27, S29205.
- [19.] K. Kempen, B. Vrancken, S. Buls, L. Thijs, J. Van Humbeeck, J.-P. Kruth, *J. Manuf. Sci. Eng.* **2014**, 136, 061026.
- [20.] B. Zhang, L. Dembinski, C. Coddet, *Mater. Sci. Eng., A* **2013**, 584, 21.
- [21.] S. Dadbakhsh, L. Hao, N. Sewell, *Rapid Prototyping J.* **2012**, 18, 241.
- [22.] T. Grünberger, R. Domröse, *Laser Tech. J.* **2015**, 12, 45.
- [23.] J. Kranz, D. Herzog, C. Emmelmann, *J. Laser Appl.* **2015**, 27, S14001.
- [24.] G. Strano, L. Hao, R. M. Everson, K. E. Evans, *J. Mater. Process. Technol.* **2013**, 213, 589.
- [25.] B. Vandenbroucke, J. P. Kruth, *Rapid Prototyping J.* **2007**, 13, 196.
- [26.] J. P. Kruth, E. Yasa, J. Deckers, *Roughness Improvement in Selective Laser Melting* University of Leuven, Heverlee, Belgium, **2008**.
- [27.] I. Yadroitsev, I. Smurov, *Physics Procedia* **2011**, 12, 264.
- [28.] J. T. Sehr, Dissertation, University Duisburg-Essen, Germany, **2010**.
- [29.] R. Mertens, S. Clijsters, K. Kempen, J. P. Kruth, *J. Manuf. Sci. Eng.* **2014**, 136, 061012.
- [30.] D. Buchbinder, W. Meiners, E. Brandl, F. Palm, K. Müller-Lohmeier, M. Wolter, C. Over, W. Moll, J. Weber, N. Skrynecki, J. Grad, V. Neubert, *Abschlussbericht - Generative Fertigung von Aluminiumbauteilen für die Serienproduktion, 01RIO639A-D, BMBF, Fraunhofer ILT, Aachen, Germany*, **2010**.
- [31.] K. Kempen, L. Thijs, E. Yasa, M. Badrossamay, W. Verheercke, J. P. Kruth, *Solid Freeform Fabrication Symposium* **2011**,
- [32.] J. P. Kruth, L. Froyen, J. Van Vaerenbergh, P. Mercelis, M. Rombouts, B. Lauwers, *J. Mater. Process. Technol.* **2004**, 149, 616.
- [33.] A. Öchsner, *Continuum Damage and Fracture Mechanics*, Springer, Singapur **2016**.
- [34.] K. Kempen, L. Thijs, J. Van Humbeeck, J. P. Kruth, *Mater. Sci. Technol.* **2015**, 31, 917.

- [35.] E. Louvis, P. Fox, C. J. Sutcliffe, *J. Mater. Process. Technol.* **2011**, 211, 275.
- [36.] E. O. Olakanmi, *J. Mater. Process. Technol.* **2013**, 213, 1387.
- [37.] E. O. Olakanmi, K. W. Dalgarno, R. F. Cochrane, *Rapid Prototyping J.* **2012**, 18, 109.
- [38.] D. Q. Zhang, Q. Z. Cai, J. H. Liu, R. D. Li, *Adv. Mat. Res.* **2010**, 97-101, 3820.
- [39.] J. Krautkrämer, H. Krautkrämer, *Ultrasonic Testing of Materials*, Springer-Verlag Berlin Heidelberg, **1990**.
- [40.] Sartorius, Density Determination Kit.
http://www.dcu.ie/sites/default/files/mechanical_engineering/pdfs/manuals/Density%20Determination%20Kit%28a%29.pdf. Accessed 23/10/2015.
- [41.] P. Trubitz, B. Rehmer, G. Pusch, Die Ermittlung elastischer Konstanten von Gusseisenwerkstoffen
http://www.dgm.de/past/2004/werkstoffpruefung/download/687_8.pdf. Accessed 29/10/2015.
- [42.] G. Schuetz, Surface Texture From Ra to Rz. <http://www.mmsonline.com/columns/surface-texture-from-ra-to-rz>. Accessed 30/10/2015.
- [43.] LENNTECH, Chemische Elemente geordnet nach der Dichte. <http://www.lenntech.de/data-pse/dichte.htm>. Accessed 26/10/2015.
- [44.] C. Kammer, *Aluminium Taschenbuch Band 1 - Grundlagen und Werkstoffe*, Beuth Verlag, **2009**.
- [45.] K. Mosler, F. Schmid, *Wahrscheinlichkeitsrechnung und schließende Statistik*, Springer-Verlag Berlin Heidelberg, **2011**.
- [46.] National Instruments, Particle Measurements. http://zone.ni.com/reference/en-XX/help/372916L-01/nivisionconcepts/particle_measurements/. Accessed 31/10/2015.
- [47.] K. Kempen, L. Thijs, J. Van Humbeeck, J. P. Kruth, *Physics Procedia* **2012**, 39, 439.
- [48.] I. Yadroitsev, I. Smurov, *Physics Procedia* **2010**, 5, Part B, 551.