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Fracture toughness of selective laser melted AlSi10Mg

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Abstract

Additive manufacturing represents a unique opportunity for the generation of highly complex components. Given the inherent anisotropic material behaviour, reasoned in the layer-wise generation process and the resulting span of mechanical properties with the lack of available data, the implementation of this manufacturing technique in industrial applications is challenging and requests expensive and time consuming material testing. This work focuses on the fracture toughness of selective laser melted precipitation-hardenable AlSi10Mg specimens, including positioning and inclination effects. Samples in accordance to the ASTM E 399-08 standard were fabricated in six different orientations and were subject to mode I fracture toughness testing. The notches were implemented in a subsequent milling procedure and the evaluation was undertaken as outlined in the ASTM E 1820-09 standard. Minor directional dependencies were found and the selective laser melted samples revealed similar fracture toughness results as conventional bulk material, namely K_{IC} -values in the range from 40 to 60 MPa $\sqrt{m}$.

1 Introduction

Selective laser melting (SLM) belongs to the layer-wise, powder-bed based additive manufacturing technologies and produces components by exposing successive powder layers selectively with a laser beam as the driving force for local solidification ¹. Due to the complete melting of the powder in SLM, this process is capable of manufacturing almost full dense parts within one manufacturing step, proven for AlSi10Mg in ². Given the fact that the layer-wise generation approach overcomes limitations present in conventional manufacturing techniques, like the accessibility required for milling or the limitations reasoned by the mould in terms of casting, a broad application in industry can be anticipated. However, due to the pronounced volatility of fabricated components in relation to their surface characteristics ³ and mechanical properties ⁴, coupled with the correlated uncertainty and the lack of substantial data, this promising manufacturing technique remains mostly unused. Thus, its peculiarities need to be investigated and documented based on destructive material tests, leading to a proper foundation for future optimizations and enabling the necessary linkage between the fabrication environment and finite element analyses.

Most studies in the area of fracture toughness of selective laser melted samples were dedicated to titanium based raw materials, especially Ti6Al4V, which is of special interest for aerospace and medical applications. The fatigue crack growth in the as-built and several heat treated states was investigated in ⁵ and the influence of varying build directions was added in ⁶. A combined study covering both the tensile strength and fracture toughness for various orientations was undertaken in ⁷.

Within this study, the fracture toughness behaviour of AlSi10Mg was investigated for various orientations based on notched tensile testing specimens. This particular alloy is widely utilized in the automotive industry, e.g. for undercarriages, gearbox housings and engine blocks, and can be fabricated with various casting technologies ^{8,9}. To the best of the authors' knowledge, this is the first work addressing the fracture toughness of aluminium based raw material fabricated with SLM. For this initial study no post-heat treatments like solution annealing or age hardening were considered.

2 Methodology

2.1 Manufacturing Conditions

The specimens were fabricated with a SLM 280HL machine (SLM Solutions AG, Lübeck, Germany) equipped with a 400 W Yb-fibre-laser and an available build space of 280 x 280 x 320 mm³. Nitrogen was employed as the inert gas and the temperature of the mounting plate^a was kept constant at 200°C throughout the entire manufacturing process. A detailed listing of the utilized irradiation parameter sets is given in the appendix (Table 4). In regard to the necessary support structure, only the block type, i.e. a honeycomb scaffold with open pores and characteristic saw-tooth-like connectors towards the substrate plate and specimens, was applied and the supported areas were reduced to a minimum. The raw AlSi10Mg powder was supplied by SLM Solutions and its properties, as well as the achieved relative density (~99.5%) of the fabricated samples, were reported in a previous study³. In addition, an extensive preliminary evaluation of the tensile strength in dependency to the positioning in the building chamber has been carried out⁴. The present paper is an extension of this previous study and utilizes those results as input (Table 5 in the appendix). Figure 1 and Table 1 summarize the considered orientations and inclinations covered in this work.

Figure 1: Schematic depiction of the chosen configurations in the build space, adopted from ³ and ^{4b}

^a The substrate plate is fixated on the mounting plate, which includes the thermal regulation. Due to this, the exact temperature of the substrate plate remains unknown. However, the powder-bed temperature at 10 mm above the substrate plate was determined being 130°C⁴.

^b Please note that the configuration (f) samples considered in the present investigation had a 45° angle to the recoater path.

Table 1: Positioning details for all considered configurations given in dependency to the substrate plate (xy-plane) and the recoater movement path (x-axis), adopted from⁴

Configuration	α_{xy}	α_x	Total runtime
(a)	0°	5°	20.0 h
(b)	0°	5°	20.5 h
(c)	0°	85°	38.0 h
(d)	45°	0°	
(e)	45°	5°	
(f)	90°	45°	33.0 h

2.2 Sample geometry

In this fracture toughness investigation the standardized tensile sample geometry, in accordance with the German standard DIN 50125:2009-07 - E 5 x 10 x 40, was employed. These flat specimens were produced with an oversize of 0.4 mm in width and thickness and were milled to obtain the final shape and the required surface quality. In order to utilize this type of sample for a fracture toughness investigation, an additional one-sided straight through notch was implemented in the centre of the samples (Figure 2). The geometry of the notch is defined in the international ASTM E 399-08 standard and the following parameters were chosen (see nomenclature in Table 2): $a = 0.5 \times W$; $N = 1$. The pre-cycling for crack initiation was neglected and the notch was directly implemented with a disc milling cutter with a thickness of 1 mm and a 45° top angle to its final initial length. It should be mentioned that additional fixation points for measurement equipment were introduced at the end of the notches. For the distortion free clamping of the specimens a drill-hole with a diameter of 7.5 mm was added on the clamping areas on both ends of the specimens. The fixation was then realized with bolts connecting the sample with the clamping jaws of the machine, ensuring the allowance of the necessary rotation movement during the crack opening. It should be mentioned that the distance in width direction between the force initiation points and the crack tip is zero^c in this setup.

^c In the ASTM 399-08 standard the distance between the fixation points and the crack tip is equal to the pre crack length a .

Figure 2: a) Test setup, including the crack mouth opening gauge; b) geometry of the notch (1 x 5 mm² with a 45° tip angle)

Table 2: Nomenclature in accordance to ASTM E 399-08 and DIN EN ISO 6892-1:2009-12

Parameter	Abbrev.	Explanation	Unit
Pre crack length	a	depth of the initial notch, per definition $0.45 \times W < a < 0.55 \times W$	[mm]
Notch width ratio	N	per definition $N < W/10$	[mm]
Thickness	B	thickness of the specimen	[mm]
Width	W	width of the specimen	[mm]
Young's modulus	E	material parameter in the elastic range	[MPa]
Poisson's ratio	ν	contraction of the material in the elastic range	[-]
Energy release rate	G_{IC}	verified deformation energy in relation to the crack front length	$\frac{N}{m}$
J-integral	J_{IC}	deformation energy in relation to the crack front length	$\frac{N}{m}$
Stress intensity factor	K_I	stress intensity factor (mode I)	MPa $\sqrt{m}$
Fracture toughness	K_{IC}	critical stress intensity factor (mode I)	MPa $\sqrt{m}$
Yield stress	$R_{p0.2}$	stress at 0.2% plastic deformation, also known as σ_F	[MPa]
Ultimate tensile strength (UTS)	R_m	material parameter, maximum stress	[MPa]
Elongation at failure	A_t	total elongation (elastic and plastic) at failure	[%]
Crack front length	r	crack propagation perpendicular to load	[mm]
Deformation energy	U	required energy for crack propagation	[Nm]
Principal axial stress	σ_{yy}	normal stress perpendicular to the plane of the crack	[MPa]
Crack mouth opening	x	expansion displacement measured at the notch	[mm]
Force	F	applied load, measured by the load cell	[N]

2.3 Testing procedure

For the destructive material tests, a tensile test machine (Zwick/Roell, Ulm, Germany) with a maximum load of 100 kN, equipped with a corresponding load cell, was utilized. The tensile test was carried out in accordance to the German standard DIN EN ISO 6892-1:2009-12 with a crosshead speed of 5 mm/min. The crack-mouth opening displacement was measured with a self-made double cantilever clip-in displacement gauge, based on the ASTM 399-08 standard, which fixated itself in the 90° notches (Figure 2) due to a preliminary tension. Hereby the displacement was determined by inbuilt strain gauges which are connected via a Wheatstone bridge with the tensile testing setup.

2.4 Evaluation scheme

The evaluation of the fracture toughness was undertaken in accordance to the ASTM E 1820-09 and the procedure outlined in ¹⁰. Hereby, the determination of the deformation energy varies in relation to the present rupture behaviour (Figure 3). In our case the second type has been present, leading to the following equations to be used for the evaluation process. The J -integral is calculated by

$$J_{IC} = \frac{U}{B \times (W - a)} \times f\left(\frac{a}{W}\right) \quad (1)$$

with the function of the pre-crack length and specimen width being

$$f\left(\frac{a}{W}\right) = 2 \times \frac{1 + \alpha}{1 + \alpha^2}. \quad (2)$$

The following holds then for the determination of the parameter α ,

$$\alpha = \sqrt{\left(\left(\frac{2 \times a}{W - a}\right) + 1\right)^2 + 1} - \left(\frac{2 \times a}{W - a} + 1\right) \quad (3)$$

with the geometry dependent parameters being $a = 5$ mm and $W = 10$ mm. The deformation energy U is given by the area underneath the force-displacement curve, indicated in Figure 3. Once the J -integral is determined, the appropriateness of the chosen specimen geometry is verified by the relation

$$B > \frac{J_{IC}}{(R_{p0.2} + R_m) \times 0.5} \quad (4)$$

with the initial thickness $B = 5$ mm.

Given the fulfilled requirement, then

$$J_{IC} = G_{IC} \quad (5)$$

and finally the fracture toughness is calculated by

$$K_{IC} = \sqrt{\frac{G_{IC} \times E}{(1 - \nu^2)}}. \quad (6)$$

The material parameters E , ν , $R_{p0.2}$ and R_m are based on destructive tensile tests according to DIN EN ISO 6892-1:2009-12, documented in a previous study (Hitzler et al. (2017))⁴, with flat tensile sample geometries as outlined in DIN 50125:2009-07 (E 5 x 10 x 40), and can be found in Table 5 in the appendix. It should be mentioned that the samples for both examinations, i.e. tensile and fracture toughness testing, were manufactured as batches.

The K_{IC} factor is a measure for the stress tensor of a multi-axial stress field occurring on the tip of a crack or notch, caused by an external load ¹¹. Hence, a high K_{IC} value indicates a material with high fracture toughness. This relation is given with the stress intensity factor

$$K_I = \lim \left[\sigma_{yy} (2\pi r)^{\frac{1}{2}} \right], \quad (7)$$

which describes the significant stress concentration occurring at the distance r in front of the crack tip.

Figure 3: Determination of K_{IC} , differentiation between the type of rupture: type 1) linear elastic; type 2) elasto-plastic; adopted from ¹⁰

3 Results and discussion

A set of six samples per configuration has been tested, exemplified in Figure 4, and the valid force-displacement curves are depicted in Figure 5. It should be mentioned that some of the testing results revealed regressiveness in their displacement record and hence, were removed from the statistical evaluation. The final results with the according standard deviations are given in Table 3.

The resulting K_{IC} values were, independent from the orientation, remarkably high in comparison with the wrought alloy. Based on the simplifications made, the results given in this work are intended as guide-values to categorize the behaviour of selective laser melted AlSi10Mg. When it comes to stating a confidence value for the fracture toughness, numerous challenges are faced in the area of additive manufacturing, which all lead to a high spread of results. This can be shown based on the literature results of Ti6Al4V. In ¹² a K_{IC} value of $52 \pm 3.5 \text{ MPa}\sqrt{\text{m}}$ is given, whereas in ⁷ the K_{IC} values range from $16 \pm 1 \text{ MPa}\sqrt{\text{m}}$ to $28 \pm 2 \text{ MPa}\sqrt{\text{m}}$, dependent on the build orientation. Therefore, it can be concluded that the fracture toughness is extremely volatile to the manufacturing conditions, which include, amongst other things, the machinery, the raw powder, the scan parameters, the irradiation strategy, the layer thickness, as well as the thermal environment.

Hence, it is anticipated that the given results for AlSi10Mg represent the upper boundary for the fracture toughness values of AlSi10Mg under the given manufacturing conditions, and due to the simplifications made, the selection of an appropriate safety factor is recommended.

Given the dependency of the fracture toughness on the elastic material constants (Equation (6)) and their direct correlation to the orientation and inclination of the sample during manufacturing ⁴, it is of high importance to examine both the tensile and the fracture behaviour. Considering the direction dependencies of the K_{IC} results, it could be concluded that the configurations (a) to (e) revealed consistent results in the range of $50 \text{ MPa}\sqrt{\text{m}}$ to $60 \text{ MPa}\sqrt{\text{m}}$, whereas the in build direction orientated configuration (f) samples exhibited inferior results of around $40 \text{ MPa}\sqrt{\text{m}}$. In this case no clear tendencies based on the inclinations could be made and the K_{IC} value for configuration (b), which exhibited the best tensile strength and ductility, were in the upper range, but not even close to the maxima. In addition, there is also no clear correlation with the obtained Young's moduli. Comparing configurations (d) and (f), which both inhabited a low Young's modulus, the K_{IC} results showed high deviations between them.

Lastly, the influence of the build height itself, apart from the orientation angle, appeared secondary, although the height had an immense influence on the tensile strength and especially the hardness results due to the age hardening state ⁴. This could be reasoned based on configurations (c) to (e), which were fabricated in one single build job. Hence, given the runtime of the considered job coupled with the absolute positions along the z-axis (Figure 1) along the samples where the notches were implemented, and the

corresponding aging state of that particular area due to the dwell time in the manufacturing environment at elevated temperatures, these results could be seen as fracture toughness tests with varying precipitation hardening states. Hereby, the span reached from 51 $\text{MPa}\sqrt{\text{m}}$ (configuration (d)) to 56 $\text{MPa}\sqrt{\text{m}}$ (configuration (e)) to 58 $\text{MPa}\sqrt{\text{m}}$ (configuration (c)). Configurations (c) and (d) represented a similar aging state, whereas configuration (c) had a prolonged aging cycle due to the samples being completely generated at an early point in time during the fabrication process. Interestingly, the deviations between related configurations like (d) and (e) or also (a) to (c) have been more pronounced than those seen between varying heights, leading to the conclusion that the build height and the corresponding height dependent state of precipitation hardening, at least to a certain extent, have only a minor impact on the fracture toughness of selective laser melted AlSi10Mg.

Figure 4: Exemplary depiction of fractured samples (configuration (d) shown)

Figure 5: Testing diagrams for configurations (a) to (f); force via load cell and displacement via double cantilever clip-in displacement gauge

Table 3: Fracture toughness of notched AlSi10Mg samples at room temperature, averaged results and standard deviations in relation to the considered orientations (Figure 1, Table 1)

Configuration	α_x	α_{xy}	Fracture toughness K_{Ic} [MPa $\sqrt{m}$]	Standard deviation [MPa $\sqrt{m}$]
(a)	0°	5°	59.06	1.430
(b)	0°	5°	51.60	1.794
(c)	0°	85°	58.03	1.321
(d)	45°	0°	55.79	3.614
(e)	45°	5°	50.76	1.917
(f)	90°	45°	40.63	1.247
Die-cast			18-29 ¹³ (AlSi7Mg)	
Wrought alloy			16-42 ¹⁴ (Al alloys in general)	

4 Conclusion

Notched tensile samples built in various orientations were subject to fracture toughness testing. Minor directional influences were found amongst the configurations with 0° and up to 45° inclination to the substrate plate. Only the in-built direction (90°) orientated samples revealed inferior fracture toughness. In addition, the build height and the corresponding age hardening state was found to have only a minor impact.

These findings raise the question to which extend the fracture toughness is in the stable plateau (50 MPa $\sqrt{m}$ to 60 MPa $\sqrt{m}$) and at which angle the drop down towards the inferior fracture toughness (40 MPa $\sqrt{m}$) occurs and what are the characteristics it follows. Thus, the future outlook is the thorough examination of the fracture toughness behaviour in the range from 45° to 90° inclination angle to the substrate plate and the examination of CT-specimens, including the pre-cycling for crack initiation.

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Conflict of interest

The authors declare that there is no conflict of interest.

Appendix

Table 4: Parameter sets utilized for irradiation in SLM for the processing of AlSi10Mg

	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 irradiation parameters listed in Table 4 were found to result in an averaged relative density of 99.5% based on the Archimedes method and an area porosity of 0.3% determined on a micro section (Hitzler et al. (2016))³.

Table 5: Averaged material properties per configuration, adopted from ⁴

Configuration	Young's modulus E [MPa]	Yield strength $R_{p0.2}$ [MPa]	Ultimate tensile strength R_m [MPa]	Elongation at failure A_t [%]	Poisson's ratio ν [-]
(a)	72322	206.74	366.43	6.12	0.2901
(b)	72888	241.15	399.10	6.47	0.3205
(c)	71715	222.83	360.27	5.33	0.3619
(d)	65640	188.15	330.11	4.47	0.3235
(e)	69515	179.71	314.32	3.97	0.3448
(f)	62560	198.13	344.73	3.20	0.3040

The material parameters listed in Table 5 were examined based on destructive tensile tests on flat tensile specimens (German standard DIN 50125:2009-07 - E 5 x 10 x 40) equipped with strain gauges (Hitzler et al. (2017))⁴. The tensile tests were carried out in accordance to the DIN EN ISO 6892-1:2009-12 standard with a crosshead speed of 5 mm/s at room temperature on non-heat-treated samples.

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