Notch Sensitivity of AlSi10Mg Aluminum Alloy Produced by Laser Powder Bed Fusion Process

Avinesh Ojha, Wei-Jen Lai, Carlos Engler-Pinto Jr., and Xuming Su

Abstract Stress gradient influence factors and fatigue notch factors were measured for the AlSi10Mg aluminum alloy produced by laser powder bed fusion (L-PBF) processing with respect to different stress gradients (notch geometries). Modeling the stress gradient is critical for accurate fatigue life estimations for parts containing notches or fillets. Uniaxial fatigue tests were performed to obtain the fatigue strengths at R = −1 for notched and unotched specimens. The fatigue results were then used to calibrate the stress gradient influence factor model for fatigue life estimation. Due to the small grain size produced by the L-PBF process, the stress gradient influence factor is much lower compared to the cast A319-T7 alloy (at 120 °C) at the same stress gradient.

Keywords Notch effect · Fatigue · AlSi10Mg · Laser powder bed fusion

Introduction

Materials produced by the laser powder bed fusion (L-PBF) process are known for its distinct microstructure. The small grain size produced by this process gives rise to superior mechanical properties but can also change the notch sensitivity [1–3]. Potential high notch sensitivity was observed in fatigue test samples where failures tend to occur at the end of the straight gauge section. Slight stress concentration (approximately 3%) is commonly seen at the end of the straight gauge section, where the cross-sectional area starts to increase. However, it is usually not an issue when conventionally manufactured materials are tested, i.e. failure usually occurs within the gauge. A higher number of fatigue failure observed at the stress concentration location for the alloys produced by L-PBF suggests potential high notch sensitivity induced by this process. The study is to confirm this hypothesis and obtain notch sensitivity data for fatigue strength estimation of L-PBF AlSi10Mg parts.

A. Ojha · W.-J. Lai (✉) · C. Engler-Pinto Jr. · X. Su
Ford Motor Company, Detroit, MI, USA
e-mail: william721225@hotmail.com

TMS 2021 150th Annual Meeting & Exhibition Supplemental Proceedings,
The Minerals, Metals & Materials Series,
https://doi.org/10.1007/978-3-030-65261-6_9

Experimental Procedure

Sample Preparation

The AlSi10Mg aluminum alloy is selected for this study. The composition of the alloy is shown in Table 1. The fatigue samples were manufactured using the SLM-125 machine, by SLM Solutions Group AG. All the samples were built in the form of cylindrical rods with the tensile axis in the vertical direction. The dimension of the rod stock is 12.7 mm in diameter and 100 mm in length. The laser process parameters are summarized in Table 2. A three-step inside-out scan strategy was adopted: The laser hatches the center portion first, followed by a contour scan and lastly a border scan on the outer diameter.

The rod stock was stress relieved at 300 °C for two hours to remove residual stresses. Four types of samples were machined from the rod stock, as shown in Fig. 1.

The hourglass sample, shown in Fig. 1a, was used to obtain the fatigue strength without stress gradient. Figures 1b–d shows the notched fatigue samples with different notch geometries: 1.5-mm U-notched, 0.47-mm U-notched, and 0.25-mm V-notched samples, respectively. The notch geometries were designed to provide different stress gradients at the notch roots. The hourglass samples were mechanically polished in the longitudinal direction to remove the surface roughness due to machining. The notched fatigue samples were not polished. The reason for using an hourglass sample (instead of a straight gauge sample) is to maintain a similar volume of material under loading.

Fatigue Test

Uniaxial fatigue tests were performed at stress ratio R = −1 according to the ASTM E466 standard [4]. Tests were conducted at room temperature at frequencies ranging from 60 to 70 Hz. Samples were tested until full separation or until 10^7 cycles (runouts).

The fatigue strength was calculated using the random fatigue limit (RFL) model [5], which fits the S-N curve using the equation below.

$$S_a - S_L = C\left(2N_f\right)^b \tag{1}$$

where S_a is the stress amplitude, S_L is the infinite-life fatigue limit of the material (a random variable), N_f is the number of cycles to failure, and C and b are empirical constants. In this study, the fatigue S-N curves were fitted using an RFL model with the aid of the maximum likelihood method, as described by Engler-Pinto [6], to

Table 1 Chemical composition of AlSi10Mg aluminum alloy

	Si (%)	Fe (%)	Cu (%)	Mg (%)	Cr (%)	Ni (%)	Ti (%)	Ca (%)	Ga (%)	Sr (ppm)	V (%)	Al (%)
AlSi10Mg	10.48	0.125	0.0057	0.291	0.012	0.0108	0.129	0.0059	0.0123	142	0.0146	88.8

Table 2 Summary of laser parameters of AlSi10Mg samples

Region	Power (W)	Speed (mm/s)	Hatch Spacing (mm)	Layer Thickness (mm)
Border & Contour	200	730	0.2	0.03
Hatch	350	1,650	0.13	

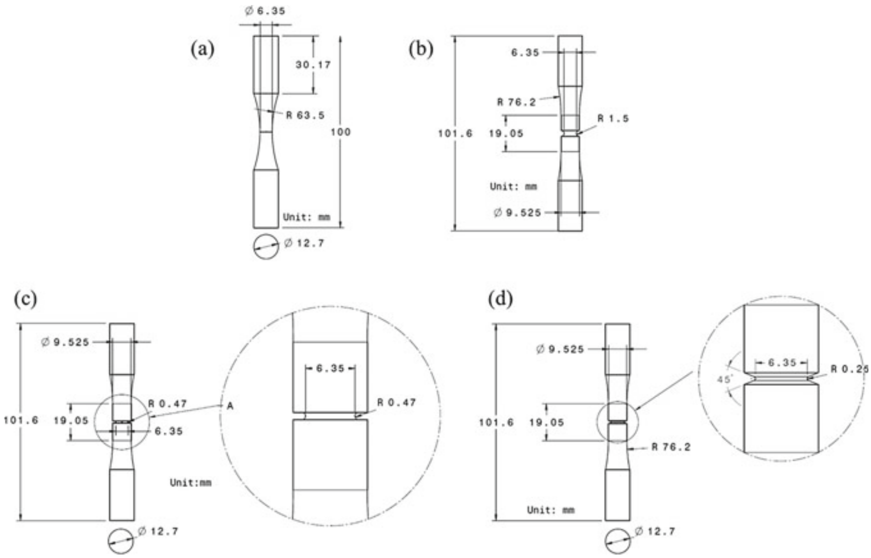

Fig. 1 Dimesions of **a** hourglass, **b** 1.5-mm U-notched, **c** 0.47-mm U-notched, and **d** 0.25-mm V-notched samples

account for the runout data points. The fatigue strength distribution is then estimated at 10^7 cycles.

Finite Element Stress Analysis

The finite element methodology (FEM) was used to obtain the maximum stress and the relative stress gradient at the notch. Quadratic axial symmetrical elements CAX8R were used in ABAQUS [7]. Elastic and elastoplastic analyses were performed. The elastoplastic analysis uses the experimental tensile stress–strain curve as input, as shown in Fig. 2. Note that, for this exercise, the nominal stress applied at the smallest cross section in the elastoplastic model is the fatigue strength of each specimen geometry ($\sigma_{f,-1}$), as listed in Table 3. Relative stress gradients were calculated based on the stresses at the notch root node and the node next to it,

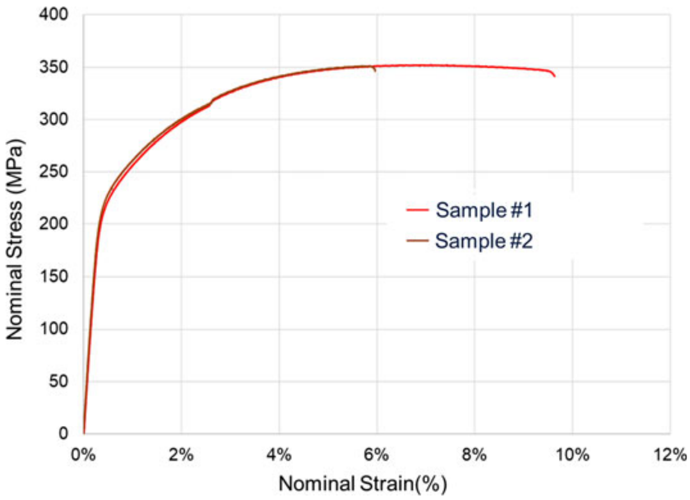

Fig. 2 Nominal tensile stress–strain curve of L-PBF AlSi10Mg stress relieved at 300 °C for 2 h. (Color figure online)

Table 3 Summary of key values used for fatigue influence factor calculation

	1.5-mm U-notch	0.47-mm U-notch	0.25-mm V-notch
($\sigma_{e,i}$ (MPa), d_i (mm))	(36.94, 3.175)	(57.35, 3.175)	(74.66, 3.175)
($\sigma_{e,i-1}$ (MPa), d_{i-1} (mm))	(35.95, 3.160)	(49.54, 3.147)	(63.71, 3.159)
χ'	1.748	4.819	8.895
$\sigma_{f,-1}$ (MPa)	63.0	41.8	33.5
K_t (FEM)	1.811	2.859	3.746
K_t (Formula) [5]	1.83	2.81	3.49
$\sigma_{A,tsc}$ ($= \sigma_{f,-1} \cdot K_t$(MPa))	114.1	119.5	125.5
$f_{GR,af}$ (test)	1.329	1.391	1.462
K_f	1.36	2.05	2.56
q	0.433	0.580	0.626

The values are calculated based on the nominal stress of 22.5 MPa at the smallest cross section for specimens shown in Fig. 1

along the direction where the stress gradient is to be evaluated. The relative stress gradient (χ') is defined as

$$\chi' = \frac{\chi}{\sigma_e} \tag{2}$$

where σ_e is the Mises stress and χ is the stress gradient. The stress gradient (χ) is defined as

$$\chi = \frac{d\sigma_e}{dx} \tag{3}$$

In this study, the relative stress gradient is calculated at the surface node, as illustrated in Fig. 3.

The maximum stress from FEM was used to calculate the stress concentration factor (K_t) which is defined as

$$K_t = \frac{\sigma_{\max}}{\sigma_{\text{nominal}}} \tag{4}$$

where $\sigma_{\max}$ and σ_{nominal} are the maximum stress and the nominal stress at the notch root from the FEM analysis in the loading direction, respectively. The nominal stress (σ_{nominal}) is defined as the applied load (P) divided by the cross-sectional area at the notch root (A) (the smallest cross section).

Similarly, the fatigue notch factor K_f is defined as:

$$K_f = \frac{\sigma_{f,\text{smooth}}}{\sigma_{f,\text{notched}}} \tag{5}$$

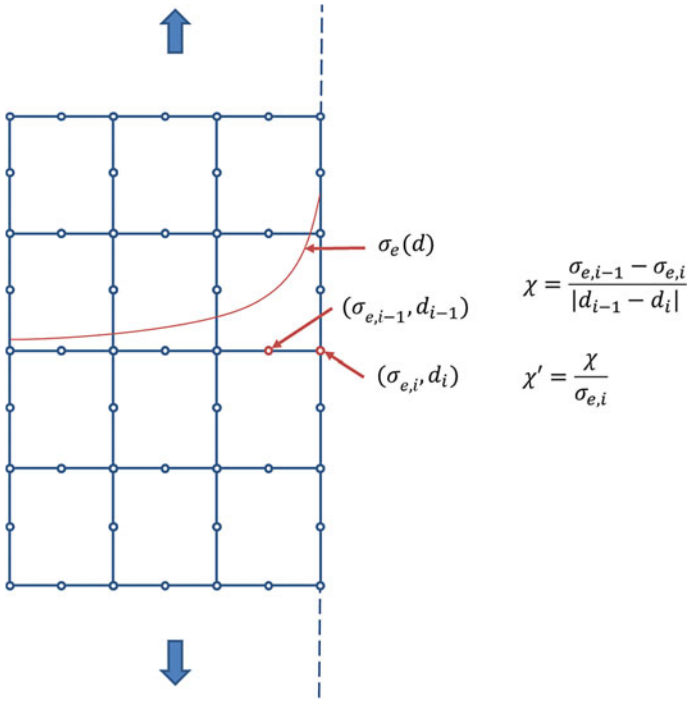

Fig. 3 A schematic showing how the relative stress gradient is calculated at the node in this study. (Color figure online)

where $\sigma_{f,\text{smooth}}$ and $\sigma_{f,\text{notched}}$ are the fatigue strengths at R = −1 of smooth and notched specimens, respectively. K_f is equal or larger than 1 and always less than or equal to K_t. Note that the fatigue strengths here are the nominal stress without considering stress concentration. The notch sensitivity parameter (q) can then be defined as:

$$q = \frac{K_f - 1}{K_t - 1} \tag{6}$$

The value of q typically ranges from 0 to 1. A value of 0 indicates that the material has no notch effect and a value of 1 indicates that the material has full theoretical notch effect.

Results and Discussion

The FEM models are shown in Fig. 4. The stress concentration factors and stress gradients are summarized in Table 3, together with the stresses at the surface nodes used for the calculation. The analytical solutions of stress concentration factors from Pilkey [8] are also listed for reference. One thing worth noting is that the elasto-plastic analysis results in all three models with notches show no plastic deformation anywhere in the models when the nominal stress at the smallest cross section equals the fatigue strength of each notched specimen. This means no plastic deformation occurs at the notch root when the specimen is tested at the stress level equal to the fatigue strength. Hence, the stresses are the same as the ones obtained from the elastic analyses. It is noted that the stress concentration factors for the 1.5-mm U-notch and 0.47-mm U-notch obtained from the FEM analyses are close to the analytical solutions, while the stress concentration factor for the 0.25-mm V-notch from the FEM analysis is higher than the analytical solution.

The fatigue S-N curves are shown in Fig. 5. The S-N curves were fitted using the RFL method described earlier. The fatigue strengths ($\sigma_{f,-1}$) were estimated at 10^7 cycles and summarized in Table 3. Note that the fatigue strength in Table 3 is the nominal fatigue strength. The true fatigue strength ($\sigma_{A,tsc}$) is the nominal fatigue strength multiplied by the stress concentration factor.

The stress gradient influence factor ($f_{\text{GR,af}}$) [9] used to characterize the effect of the stress gradient on the fatigue strength when the stress gradient is present is expressed as

$$f_{\text{GR,af}} = 1 + \frac{\frac{\sigma_{A,b}}{\sigma_{A,\text{tsc}}} - 1}{\left(\frac{2}{t}\right)^{\nu}} \cdot \chi'^{\nu} \tag{7}$$

where $\sigma_{A,b}$ is the fatigue strength for bending, $\sigma_{A,tsc}$ is the fatigue strength for tension–compression, t is the thickness or diameter of the bending fatigue sample,

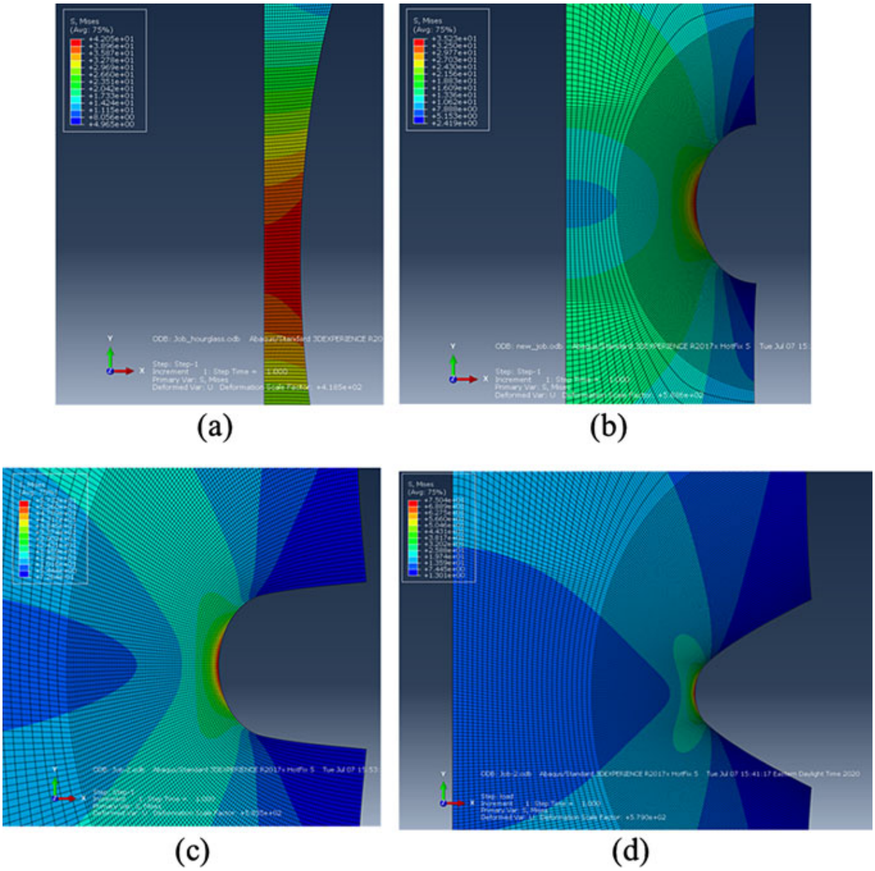

Fig. 4 FEM models of **a** hourglass, **b** 1.5-mm U-notched, **c** 0.47-mm U-notched, and **d** 0.25-mm V-notched samples. (Color figure online)

and ν is the material parameter. Thus, the fatigue strength with the stress gradient is expressed as

$$\sigma_{\mathrm{af},C} = \sigma_{A,\mathrm{tsc}} \cdot f_{\mathrm{GR,af}} \tag{8}$$

where $\sigma_{\mathrm{af},C}$ and $\sigma_{A,\mathrm{tsc}}$ are the fatigue strengths with and without stress gradient at R = −1, respectively. Note that $\sigma_{\mathrm{af},C}$ is the true stress at the notch instead of the nominal stress used for $\sigma_{f,\mathrm{notched}}$ in Eq. 5. In this study, the fatigue strength of the hourglass sample is used for $\sigma_{A,\mathrm{tsc}}$. Thus, the parameters needed to be fitted are $\sigma_{A,b}$, t, and ν in Eq. 7. The stress gradient influence factors of different samples are shown in Fig. 6. The values are also listed in Table 3. The parameters ($\sigma_{A,b}$, t, and ν) were fitted using Excel solver. The fitted parameters are listed in Table 4.

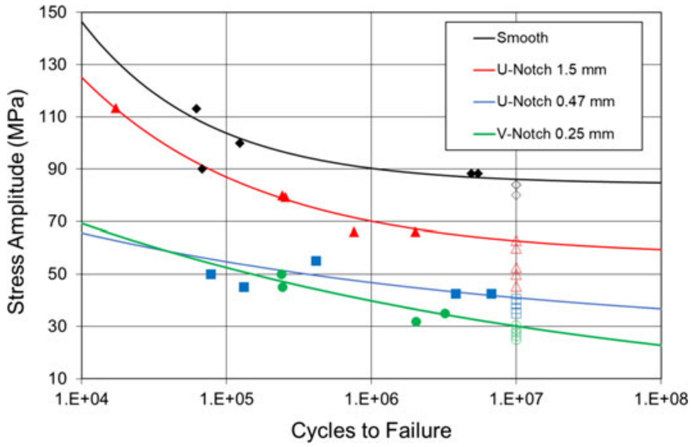

Fig. 5 S-N curves of hourglass, 1.5-mm U-notched, 0.47-mm U-notched, and 0.25-mm V-notched samples at R = −1. (Color figure online)

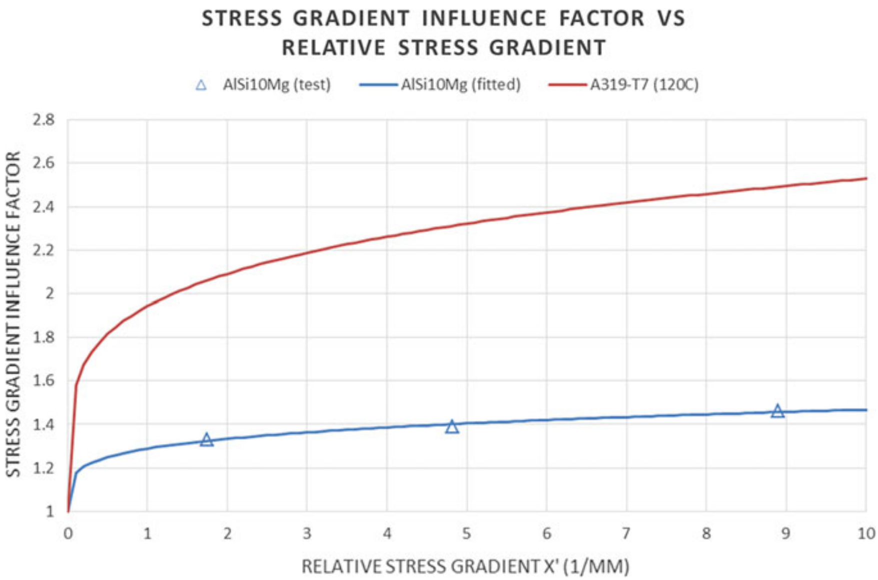

Fig. 6 Stress gradient influence factor versus relative stress gradient for L-PBF AlSi10Mg and A319-T7 (120°C). (Color figure online)

Table 4 Summary of parameters in Eq. 5 for L-PBF AlSi10Mg and A319-T7 (120 °C)

	$\sigma_{A,\text{tsc}}$ (MPa)	$\sigma_{A,b}$ (MPa)	t (mm)	ν
L-PBF AlSi10Mg (stress relieved)	85.88	**108.3**	**3.20**	**0.209**
Cast A319-T7 (120°C) [10]	45.5	72.2	**5.56**	**0.464**

Bold values are fitted parameters

The fitted curve is compared with the cast A319-T7 tested at 120 °C [10]. As seen in the figure, L-PBF AlSi10Mg shows much lower values than A319-T7. This is consistent with the experimental observation that the notch sensitivity increases with the decreasing grain size [1]. The high notch sensitivity of L-PBF AlSi10Mg is possibly the main reason which causes failures at the end of the straight gauge section of samples during fatigue testing.

Conclusion

Stress gradient influence factors were measured for L-PBF AlSi10Mg aluminum alloy with respect to different stress gradients using notched fatigue samples. L-PBF AlSi10Mg shows much lower stress gradient influence factors at the same relative stress gradients compared to cast aluminum A319-T7 (at 120 °C). Also, the high notch sensitivity factors (q) for L-PBF AlSi10Mg (shown in Table 3) suggest that the material is very notch sensitive, which could be resulted from the small grain size. The fitted stress influence factor curve should be used for fatigue strength estimation to obtain the most accurate prediction.

References

1. Karry RW, Dolan TJ (1953) Influence of grain size on fatigue notch-sensitivity. Am Soc Test Mater Proc 53:789–804
2. Kanemaru T, Kawagoishi N, Kondo E, Wang QY, Ohzono Y (2008) Influence of grain size on notch sensitivities in fatigue of carbon steel. Key Eng Mater 385–387:197–200. https://doi.org/10.4028/www.scientific.net/kem.385-387.197
3. Lorenzino P, Navarro A (2015) Grain size effects on notch sensitivity. Int J Fatigue 70:205–215. https://doi.org/10.1016/j.ijfatigue.2014.09.012
4. ASTM E466-07 Standard practice for conducting force controlled constant amplitude axial fatigue tests for metallic materials (ASTM International, West Conshohocken, 2007). https://doi.org/10.1520/e0466-07
5. Pascual FG, Meeker WQ (1999) Estimating fatigue curves with the random fatigue-limit model. Technometrics 41:277–290
6. Engler-Pinto C, Lasecki J, Frisch R, DeJack M, Allison J (2005) Statistical approaches applied to fatigue test data analysis. SAE Technical Paper 2005-01-0802. https://doi.org/10.4271/2005-01-0802
7. Abaqus Analysis User's Guide (2018)
8. Pilkey WD (1997) Peterson's stress concentration factors, 2nd edn. Wiley, New York
9. Eichlseder W (1989) Rechnerische Lebensdaueranalyse von Nutzfahrzeugkomponenten mit der FE-Methode, Dissertation, TU Graz
10. Shea A, DeJack M, Lasecki J, Su X, Allison J (2002) Applying fatigue and stress analysis of a notched W319 cast al alloy to the FEMFAT software program, Research Conference on Statistics in Industry and Technology, May, 20–22, Ann Arbor, MI