Key Engineering Materials *Submitted: 2026-01-20*
ISSN: 1662-9795, Vol. 1047, pp 325-331 *Accepted: 2026-02-11*

Online: 2026-04-13

Anisotropy and Stress-State-Dependent Fracture in Additively Manufactured Metals

Ehsan Amini[1,a], Guijia Li[1,b], Sven Bossuyt[1,c] and Junhe Lian[1,2,d*]

[1]Department of Energy and Mechanical Engineering, Aalto University, Puumiehenkuja 3, 02150 Espoo, Finland

[2]Institute of Metal Forming (IBF), RWTH Aachen University, Intzestraße 10, 52072 Aachen, Germany

[a]ehsan.amini@aalto.fi, [b]guijia.li@aalto.fi, [c]Sven.bossuyt@aalto.fi, [d*]junhe.lian@ibf.rwth-aachen.de

*corresponding author: junhe.lian@ibf.rwth-aachen.de

Keywords: additive manufacturing, LPBF, anisotropy, ductile fracture, stress triaxiality.

Abstract. Despite remarkable advances in additive manufacturing (AM), the uncertainty in direction-dependent strength and fracture behavior of metallic components still poses major challenges for their reliable structural application. The layered nature of laser powder bed fusion (LPBF) produces highly anisotropic textures and microstructure architectures that influence both plastic flow and fracture. While numerous studies have characterized tensile anisotropy, the coupling between build-induced anisotropy and stress-state-dependent fracture remains largely unresolved, yet it governs the structural integrity of AM parts under multi-axial loading. In particular, the extent to which anisotropy alters the ductile-to-brittle transition or fracture locus is still unknown. This study addresses this gap by combining experiments and advanced constitutive fracture modelling for two typical AM metals, austenitic 316L stainless steel and AlSi10Mg aluminum alloy. The goal is to formulate a unified, physically based description of anisotropic plasticity and fracture that is applicable across various material classes. LPBF samples of 316L stainless steel and AlSi10Mg were built at multiple orientations between 0° and 90° relative to the build direction. Uniaxial tensile tests were carried out with digital image correlation to capture full-field strain evolution and to determine r-values as a measure of plastic anisotropy. Complementary fracture tests under different stress states ranging from simple shear to plane strain tension were designed to evaluate the fracture dependence on stress states and anisotropy. It can be concluded that both alloys exhibit orientation-dependent flow and r-value during plastic deformation. The fracture strain decreases with rising triaxiality, yet its rate of decrease depends strongly on orientation, demonstrating a clear coupling between anisotropy and stress state.

Introduction

Additive manufacturing (AM), and in particular laser powder bed fusion (LPBF), has emerged as a promising route to fabricate complex metal components with high design flexibility and short lead times. However, parts produced via LPBF often exhibit anisotropic mechanical behavior, meaning that their properties differ depending on the build orientation. This anisotropy is of great concern for design and qualification in structural applications.

A common trend observed in LPBF-processed alloys is that the specimens constructed horizontally (0°, parallel to the build plate) usually possess greater stiffness and strength than those constructed vertically (90°, along the build direction). For instance, in a systematic research on LPBF 316L stainless steel, vertically constructed specimens had a mean Young’s modulus of about 158.7 GPa, while horizontal builds reached nearly 198 GPa; the vertically constructed samples also had lower yield strength and elongation [1]. A review by Weaver et al. summarizes that the primary sources of anisotropic tensile behavior in LPBF metals include crystallographic texture, anisotropic grain/phase morphologies, lack-of-fusion defects, and melt-pool macrostructure. Among the alloys processed by LPBF, austenitic stainless steel 316L (SS316L) is widely used owing to its good corrosion resistance, weldability, and mechanical ductility in conventional processing. In LPBF form, SS316L has been shown to display distinct directional dependencies in tensile performance. In one investigation, horizontal build orientations resulted in significantly greater elastic modulus and strength compared to vertical builds [1]. To understand the cause of such anisotropy, numerical simulations of the build process combined with tensile tests revealed that residual stresses induced during layer-by-layer deposition can affect the apparent stiffness of vertically built specimens, reducing the measured modulus in standard tests.

Lightweight aluminum alloys, notably AlSi10Mg, are also key candidates for LPBF manufacture, especially for applications where weight and manufacturing flexibility are critical. Nevertheless, similar to stainless steels, AlSi10Mg parts fabricated by LPBF show pronounced anisotropic tensile responses. In studies, where specimens were built at 0°, 45° (diagonal to the building plate), and 90° orientations and then tested in tension, the 90° orientation often exhibited reduced plasticity and altered tensile behavior compared to the 0° orientation . Moreover, research indicates that even with heat-treatment, the influence of build orientation in AlSi10Mg remains significant: samples built in the 0° orientation typically show higher strength and hardness than those built in the 90° orientation [2].

Despite the extensive body of literature on mechanical anisotropy in LPBF metals, gaps remain. Many investigations focus on a single alloy or build orientation, and while microstructural characterization is abundant, fewer studies have examined both the strength and fracture behavior across multiple build directions under a large range of stress states, which is a key concern for the structural integrity analysis of the AM materials and components in structural-related applications. The present study addresses this gap by focusing primarily on the effect of build orientation (printing direction) on the plasticity and fracture behavior of LPBF-processed SS316L and AlSi10Mg. The objectives are: (i) to perform tensile tests on dog-bone specimens produced in multiple orientations relative to the build direction and evaluate the stress and plastic deformation anisotropy, (ii) to investigate the fracture dependence on stress states and anisotropy via tests from simple shear to plane-strain tension stress states for both alloys. By comparing two distinct materials under the same experimental and numerical workflow, the study aims to highlight how printing direction influences anisotropy in both ductile steel and lightweight aluminum LPBF alloys.

Materials and Methods

This study was carried out in several sequential stages, covering sample design, LPBF manufacturing, mechanical testing, fractography, and failure strain analysis.

Sample design and manufacturing.

In the first stage, smooth dog-bone (SDB) and featured fracture tests with a specific design of geometries to cover the stress states from simple shear (SH) to uniaxial tension by central-hole (CH) specimens and to plane-strain tension by notched dog-bone (NDB) specimens developed from previous studies [3, 4] for sheet metals were employed in their study. For the SS316L stainless steel, three orientations (0°, 45°, and 90°) with respect to the building plate were built for SDB tests, and the rest of the tests concerning fracture behavior. For AlSi10Mg, two directions (0°, and 90°) were employeed.

To manufacture these specimens, rectangular sheets were produced by using the LPBF EOS M290 machine. After fabrication, these blocks were subsequently machined into the final SDB and other fracture samples with specific geometries using wire electrical discharge machining (EDM), ensuring high dimensional accuracy and consistent notch geometry.

Tensile testing and digital image correlation (DIC).

Tensile tests were performed using a universal tensile testing machine to determine the mechanical response of the additively manufactured samples. A digital image correlation (DIC) system, as shown in Figure 1, was used simultaneously to obtain full-field strain data and to track the evolution of strain localization throughout loading. This enabled accurate measurement of tensile strength, elongation, and deformation patterns for both smooth and notched samples.

Data analysis.

Load-displacement and DIC data were processed to obtain engineering and true stress-strain curves. Localized strain evolution and the differences in deformation between SDB and notched geometries were also extracted. Insight into elastic-plastic response, notch sensitivity, and anisotropic behavior of the material was provided through these analyses.

Fractography.

The examined fracture surfaces of the tested samples were inspected using a ZEISS Sigma VP scanning electron microscope (SEM). The observations were related to the tensile test results so as to aid the interpretation of failure modes.

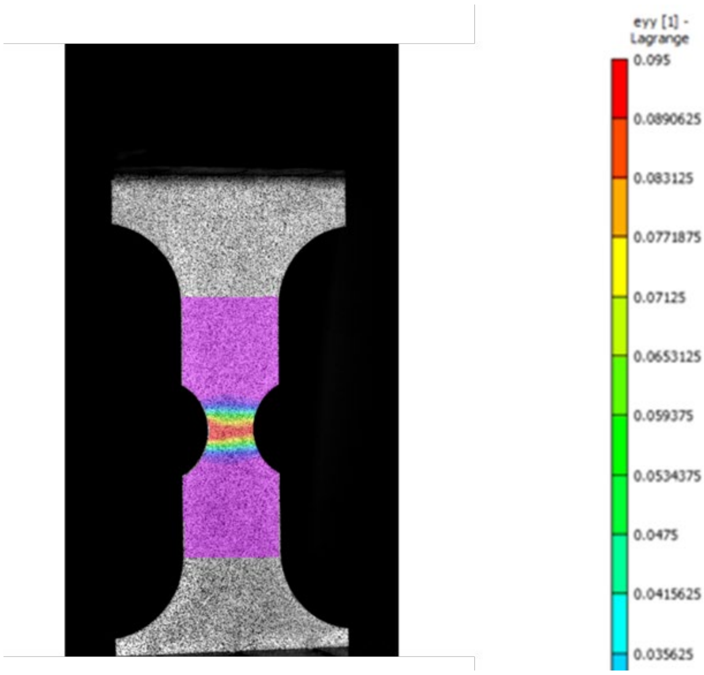


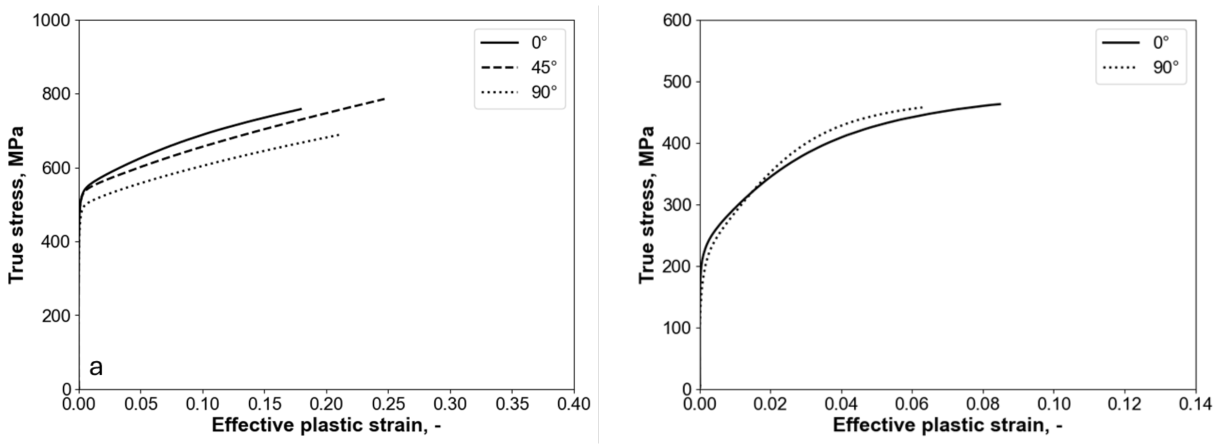
Fig. 1. DIC used for the tensile test of NDB specimens with a notch radius of 2 mm (NDBR2).

Results and Discussions

Tensile properties.

The true stress-strain curves measured from SDB specimens of both 316L stainless steel and AlSi10Mg along different loading directions are shown in Figure 2. The 316L shows a significant level of anisotropy in terms of both yield strength and ultimate tensile strength, with a maximum difference of about 100 MPa. Similar to Ref. [1], horizontally built specimens (0°) and intermediate orientations (45°) sustain higher flow stresses, while the vertically built specimens (90°) show the lowest flow stresses. Interestingly, the 45° orientation with relatively high strength reaches the largest uniform strain, indicating a high strain hardening rate.

In contrast, AlSi10Mg exhibits an opposite orientation trend in the SDB tensile curves: the 0° orientation shows higher ductility but lower ultimate strength, whereas 90° shows the inverse tendency. The overall anisotropy level between the two directions is less dramatic than that of 316L steel. However, the relative difference in uniform strain is about 25% for AlSi10Mg, which is much higher than that of 316 steel. These strongly anisotropic tensile features indicate that the anisotropic behavior is a profound feature to capture for AM metals, and the trend of anisotropy is strongly microstructure dependent. For 316 stainless steel, the anisotropy is governed strongly by residual stresses and texture, while the strength and strain hardening behavior is influenced largely by the Al-Si eutectic network structure for AlSi10Mg [5].

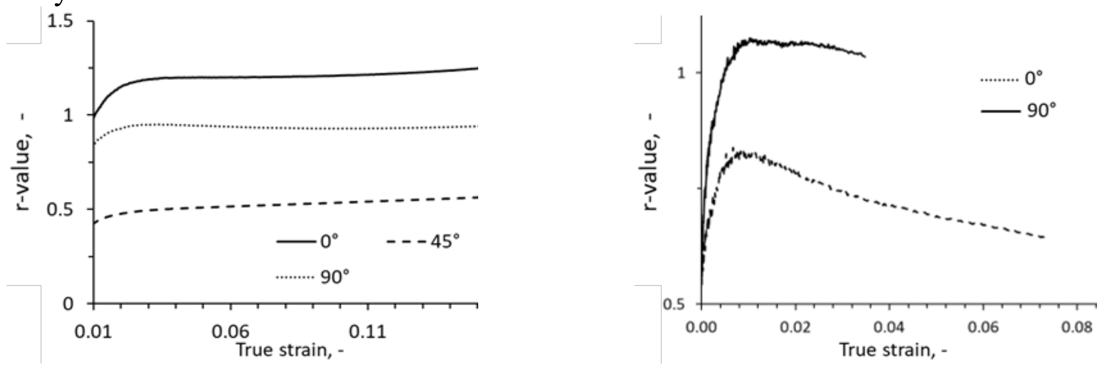


(a) (b)

Fig. 2. True stress-strain curves for (a) SS316L steel and (b) AlSi10Mg aluminum alloy.

The r-value evolution curves for both metals are shown in Figure 3. For 316L stainless steel, no obvious r-value evolution is observed over strains, but the difference between the three loading directions is substantial, over 0.7. The 0° specimens show the highest r-values over the strain range, while the 45° specimens show the lowest, and the 90° ones lie in between. This trend indicates that the 0° direction resists thickness reduction more effectively during plastic deformation, whereas the 45° specimens undergo the greatest thinning. To validate these observations, the thickness of the fractured gauge sections was measured using an optical microscope and compared with the corresponding r-value trends. The measured post-fracture thicknesses match the predicted behavior. Specimens with lower r-values, particularly those tested at 45°, show noticeably larger thickness reductions, while 0° samples retain a greater proportion of their original thickness.

AlSi10Mg shows the opposite tendency: the r-value for 90° is markedly higher (~1.0-1.2), while 0° is lower and decreases with strain (~0.6 trending down). It is also noticed that the trend of decreasing is significant for AlSi10Mg compared to 316L stainless steel. This shows that the 0° orientation (more ductile) does not correspond to a higher r-value (greater resistance to thinning). Therefore, for AlSi10Mg, it is already an indicator that fracture/ductility is not governed primarily by thickness-strain resistance, but by damage and fracture mechanisms related to microstructural connectivity.

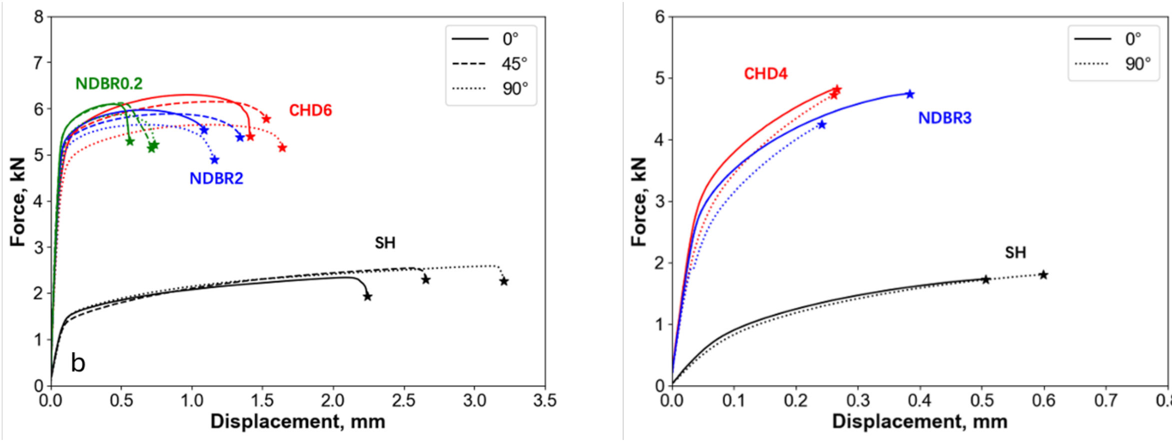


(a) (b)

Fig. 3. R-value evolution curves for (a) SS316L steel and (b) AlSi10Mg aluminum alloy.

Anisotropic fracture behavior across stress states.

The force-displacement curves across SH, CH, and NDB geometries show how stress states interact with build orientation. For 316L stainless steel, in general, the peak load is highest for 0° and decreases toward 90°, consistent with the SDB strength trend. Interestingly, a strong stress-state dependency is observed, and the trend is non-monotonic. When the stress triaxiality increases from NDBR2 to NDBR0.2, the anisotropic effects become much less in terms of both force and fracture displacement. However, when the stress triaxiality decreases from CH to SH, the force anisotropy also vanishes, but the fracture anisotropy is significantly amplified. In AlSi10Mg, the force-displacement response is generally less tolerant (shorter displacement to failure and more abrupt loss of load capacity), also indicating a more cleavage fracture mode [5].



(a) (b)

Fig. 4. Force displacement curves of SH, CH, and NDB specimens along different loading directions for (a) SS316L steel and (b) AlSi10Mg aluminum alloy.

Fracture strain is extracted using post-fracture thickness measurements for SH, CH6, NDBR0.2, and NDBR2 for 316L stainless steel for further analysis to confirm the observation from the force-displacement curves, as shown in Figure 5. The plotted results show a clear dependence on both stress state (geometry) and orientation. CH6 provides the highest fracture strain, and fracture strain decreases as constraint increases for the notched geometries and across geometries, 90° consistently exhibits the highest fracture strain, while 0° is the lowest. When the stress triaxiality is the largest (NDBR0.2), the fracture strain for three orientations is quite clustered with minor anisotropy, which is in line with the force-displacement analysis too. However, it shall be noted that because the fracture strain is derived from thickness reduction, it is a robust measure for tensile-dominated states (CH/NDB), but it can be misleading for shear-dominated tests, where large shear strains can accumulate with comparatively small thickness reduction. This is why the SH geometry appears to have the isotropic and lowest fracture strain. For this, finite element simulations shall be employed for fracture strain identification.

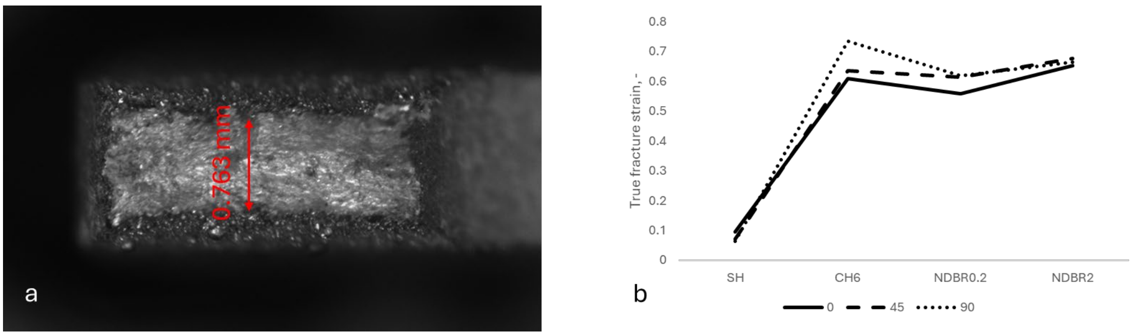


Fig. 5. (a) Fracture thickness measurement for the fracture strain calculation, (b) fracture strain for 316L stainless steel along three loading directions under different stress states.

Failure mechanism.

The SEM images of SDB fracture surfaces for 316L are shown in Figure 6 and show fully ductile fracture for all tested orientations, characterized by micro-void nucleation, growth, and coalescence [6-8]. The effects of anisotropy in uniform strain and r-value are not obvious from the SEM observations. For AlSi10Mg, as shown by Yang et al. [5], a brittle/cleavage fracture pattern is observed, which explains the contradiction between the uniform strain and the r-value.

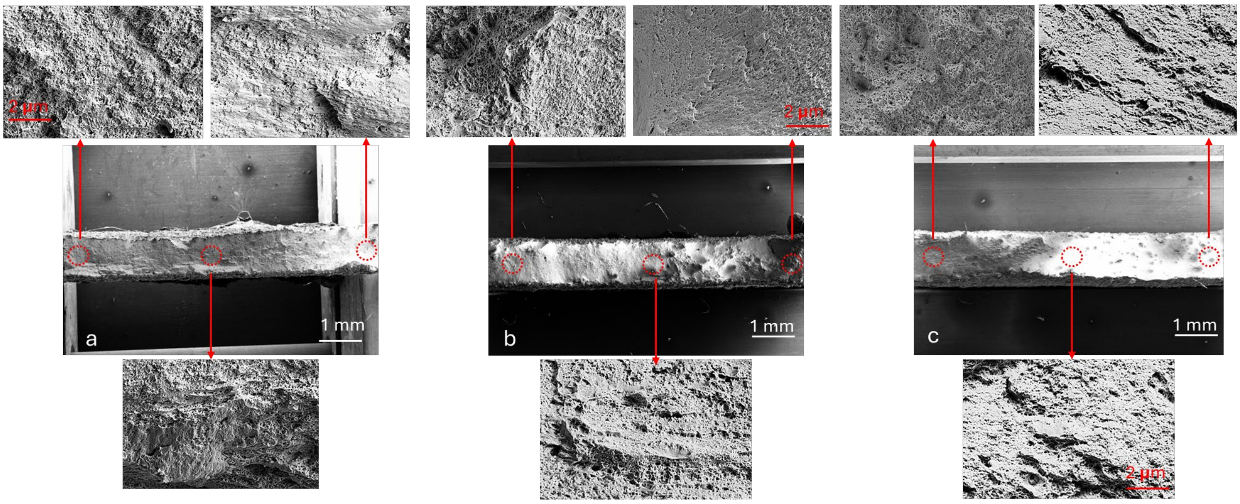


Fig. 6. SEM images of fracture surfaces of SDB samples for 316L (a) 0°, (b) 45°, and (c) 90°.

Conclusion

This work investigated how build-orientation-induced anisotropy couples with stress-state-dependent fracture in additively manufactured metals, 316L stainless steel, and AlSi10Mg aluminum alloys as two representative material classes. A consistent experimental workflow combining tensile characterization, r-value evaluation, fracture testing from shear to plane-strain tension, and fractography was applied across orientations. The main conclusions are:

- Both alloys exhibit pronounced orientation-dependent plastic flow and anisotropic deformation, as evidenced by direction-dependent true stress–strain responses and r-value trends.
- The orientation trends differ significantly between material systems. 316L shows higher strength for horizontal builds and higher fracture strain for diagonally built, whereas AlSi10Mg exhibits an inverse orientation tendency in strength-ductility and a markedly different r-value evolution, indicating different controlling microstructural features.
- Fracture resistance decreases with increasing stress triaxiality, but importantly, the rate of this decrease depends on build orientation, demonstrating a clear coupling between anisotropy and stress state.
- Fractography confirms ductile micro-void coalescence in SS316L across orientations, while AlSi10Mg exhibits more brittle/cleavage-like features, supporting the observed differences in macroscopic ductility and anisotropy signatures.

Overall, the results highlight that reliable design and qualification of additively manufactured components require orientation-aware characterization under relevant stress states, not tensile anisotropy alone. Future studies include stress-state quantification and fracture locus construction by finite element-assisted simulation, enabling an orientation-dependent fracture locus for both alloys.

References

[1] A. Fedorenko, B. Fedulov, Y. Kuzminova, S. Evlashin, O. Staroverov, M. Tretyakov, E. Lomakin, I. Akhatov, Anisotropy of Mechanical Properties and Residual Stress in Additively Manufactured 316L Specimens, Materials 14(23) (2021) 7176.

[2] A. Argyrou, L. Gargalis, L. Karavias, E.K. Karaxi, E.P. Koumoulos, Multi-Scale Mechanical Anisotropy and Heat Treatment Effects in Additively Manufactured AlSi10Mg, Metals 15(8) (2025) 890.

[3] Z. Li, F. Shen, Y. Liu, C. Hartmann, R. Norz, S. Münstermann, W. Volk, J. Min, J. Lian, Anisotropic fracture behavior of the 3rd generation advanced high-strength – Quenching and Partitioning steels: Experiments and simulation, J. Mater. Res. Technol. 30 (2024) 9395–9414.

[4] R. Juan, J. Lian, Failure mechanisms in quenching and partitioning (Q&P) steel under varying stress states, J. Mater. Sci. Technol. 263 (2026) 175–188.

[5] S. Yang, Y. Zhang, R. Juan, Z. Li, J. Wu, S.O. Akinwamide, J. Kuva, R.V. Björkstrand, J. Lian, Effect of building orientation, thickness, and contouring on the microstructure and mechanical properties of AlSi10Mg via laser powder bed fusion, Mater. Sci. Eng., A 923 (2025) 147685.

[6] A.E. Tekkaya, P.O. Bouchard, S. Bruschi, C.C. Tasan, Damage in metal forming, CIRP Ann. 69(2) (2020) 600–623.

[7] A. Pineau, A.A. Benzerga, T. Pardoen, Failure of metals I: Brittle and ductile fracture, Acta Mater. 107 (2016) 424–483.

[8] P.J. Noell, J.D. Carroll, B.L. Boyce, The mechanisms of ductile rupture, Acta Mater. 161 (2018) 83–98.