BİNGÖL ÜNİVERSİTESİ TEKNİK BİLİMLER DERGİSİ

Bingöl Üniversitesi Teknik Bilimler Dergisi
Bingöl University Journal of Technical Science
e-ISSN: 2757-6884

2026 Sayı-1, Sayfa: 1-10
Derleme Makalesi

2026 Number-1, Page: 1-10
Review Article

Doi: 10.5281/zenodo.18269012

Production Processes, Microstructural Properties, Heat Treatment Strategies, Mechanical and Fatigue Behavior of AlSi10Mg Alloys Produced by Additive Manufacturing Method

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(Alınış/Arrival: 08.01.2026, Kabul/Acceptance: 13.01.2026, Yayınlanma/Published: 15.06.2026)

Abstract
AlSi10Mg aluminum alloys are widely used in additive manufacturing (AM) due to their low density, high specific gravity/strength, good castability, and favorable heat properties. Laser-based powder bed fusion (LPBF) and directed energy deposition (DED) techniques are considered among the most suitable methods for producing parts with complex geometries, near-net shape, and requiring adjustable microstructure properties. This study presents a comprehensive review of high-performance AlSi10Mg alloys produced by additive manufacturing methods. The chapter covers production processes, microstructural properties, heat treatment strategies, mechanical and fatigue behavior, current challenges, and future research trends.

Keywords: AlSi10Mg, Laser powder bed melting (LPBM), Additive manufacturing (AM), Heat treatment, Microstructure and Mechanical properties,

Eklemeli Üretim Yöntemiyle Üretilen AlSi10Mg Alaşımlarının Üretim Süreçleri, Mikroyapısal Özellikleri, Isıl İşlem Stratejileri, Mekanik ve Yorulma Davranışları

Özet
AlSi10Mg alüminyum alaşımları, düşük yoğunlukları, yüksek özgül ağırlıkları/mukavemetleri, iyi dökülebilirlikleri ve elverişli ısı özellikleri nedeniyle eklemeli imalatta (AM) yaygın olarak kullanılmaktadır. Lazer tabanlı toz yataklı füzyon (LPBF) ve yönlendirilmiş enerji biriktirme (DED) teknikleri, karmaşık geometrilere, neredeyse nihai şekle sahip ve ayarlanabilir mikroyapı özelliklerine ihtiyaç duyan parçaların üretimi için en uygun yöntemler arasında kabul edilmektedir. Bu çalışma, eklemeli imalat yöntemleriyle üretilen yüksek performanslı AlSi10Mg alaşımlarının kapsamlı bir incelemesini sunmaktadır. Bölüm, üretim süreçlerini, mikroyapı özelliklerini, ısıl işlem stratejilerini, mekanik ve yorulma davranışını, mevcut zorlukları ve gelecekteki araştırma eğilimlerini kapsamaktadır.

Anahtar Kelimeler: AlSi10Mg, Lazer toz yataklı eritme (LPBM), Katmanlı imalat (AM), Isıl işlem, Mikro yapı ve Mekanik özellikler

1. INTRODUCTION

Al-Si cast alloys are widely used in the aerospace and automotive industries due to their superior strength-to-weight ratio, good castability, and good thermal and mechanical properties [1-4, 34]. Additive manufacturing has transformed the production of metallic components by enabling layer-by-layer fabrication directly from digital models. Compared to conventional casting or wrought processing, AM offers significant advantages such as design freedom, material efficiency, and the ability to manufacture lightweight structures with complex internal geometries. Among aluminum alloys, AlSi10Mg has gained particular attention because of its good weldability, low cracking susceptibility, and suitability for rapid solidification conditions inherent to AM processes [5-6]. Using a high-energy laser beam, LPBF (Laser Powder Bed Fusion) selectively melts and fuses powder particles on a bed. It is among the best methods for creating intricate components with few flaws, which are frequently found in conventional casting procedures [7–11]. Because of its superior flow properties and low susceptibility to solidification cracking, AlSi10Mg is especially well suited for LPBF [12]. The distinctive microstructures created by AM's high cooling speeds are very different from those made using conventional manufacturing techniques. AlSi10Mg alloys can reach excellent strength-to-weight ratios thanks to their microstructural characteristics and post-processing techniques, which makes them appealing for use in energy, automotive, and aerospace applications [13-24, 33]. Particularly when utilized as engine cylinders, AlSi10Mg alloys are susceptible to low-cycle stress and fatigue from millions of combustion cycles. Therefore, before utilizing AlSi10Mg alloy in end-use applications, it is imperative to improve its fatigue behavior [25]. As illustrated in Figure Table 2 [29], aluminum alloys can also be classified as heat-treatable or non-heat-treatable based on whether the alloy reacts to heat treatment via precipitation hardening.

Table 1. Mechanical Properties of AlSi10Mg Alloys Produced by Additive Manufacturing (Literature Review)

Manufacturing Condition	Yield Strength (MPa)	Tensile Strength (MPa)	Elongation (%)	Hardness (HV)	References
As-built (LPBF)	230–280	380–460	3–6	110–130	[17, 18, 22]
Stress relieved	200–250	340–420	6–10	95–115	[19, 21]
T6-like heat treatment	240–300	360–430	8–12	100–120	[18, 23]
HIP+ Heat treatment	220–280	350–420	10–14	95–115	[19]

Table 2. Processed aluminum alloys are colored green if they are not heat-treatable, and red if they are heat-treatable.

Al	Fe	Al-Fe-Si
	Cu	Al-Cu (Si, Mn)
		Al-Cu-Mg
		Al-Cu-Li
	Si	Al-Si
	Mg	Al-Mg
		Al-Mg-Mn
		Al-Mg-Mn
	Mn	Al-Mn
	Zn	Al-Zn
		Al-Zn-Mg
		Al-Zn-Mg-Cu

2. ADDITIVE MANUFACTURING METHODS FOR ALSI10MG

2.1. Laser Powder Bed Fusion (LPBF)

The most popular AM method for processing AlSi10Mg is LPBF. In this procedure, a high-energy laser selectively melts thin layers of metallic powder in accordance with a predetermined scanning technique. Strong metallurgical bonding between layers and fine cellular and dendritic microstructures are the results of rapid melting and solidification. Laser power, scanning speed, hatch spacing, layer thickness, and build orientation are important process variables that affect part quality. To reduce flaws such porosity, lack of fusion, and residual stress, these parameters must be optimized [27-28].

2.2. Directed Energy Deposition (DED)

DED processes utilize a focused energy source (see in Figure 2), typically a laser, to melt powder or wire feedstock as it is deposited onto a substrate. Compared to LPBF, DED allows higher deposition rates and is suitable for large-scale components and repair applications. However, the resulting microstructures are generally coarser due to lower cooling rates. Directed energy deposition is a popular 3D printing technique for producing gradient-structured metals and alloys. This technique uses a laser or electric arc to melt metals into wires or granules [31]. This allows for the precise manipulation of the structure of metallic materials, including the formation of gradient structures. For large-scale printing with high deposition rates, directed energy deposition is a cost-effective production method.

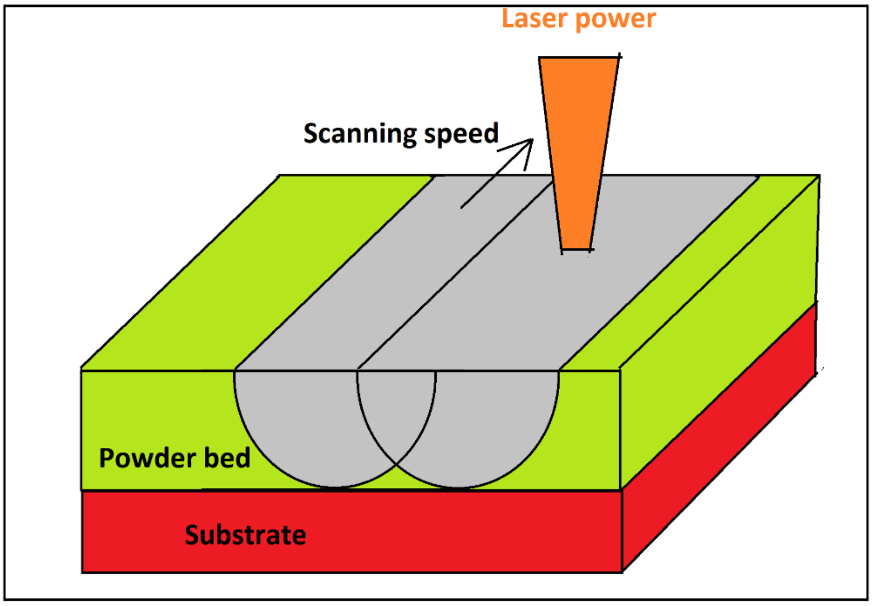

Figure 1. The process of laser powder bed fusion (LPBF) [26].

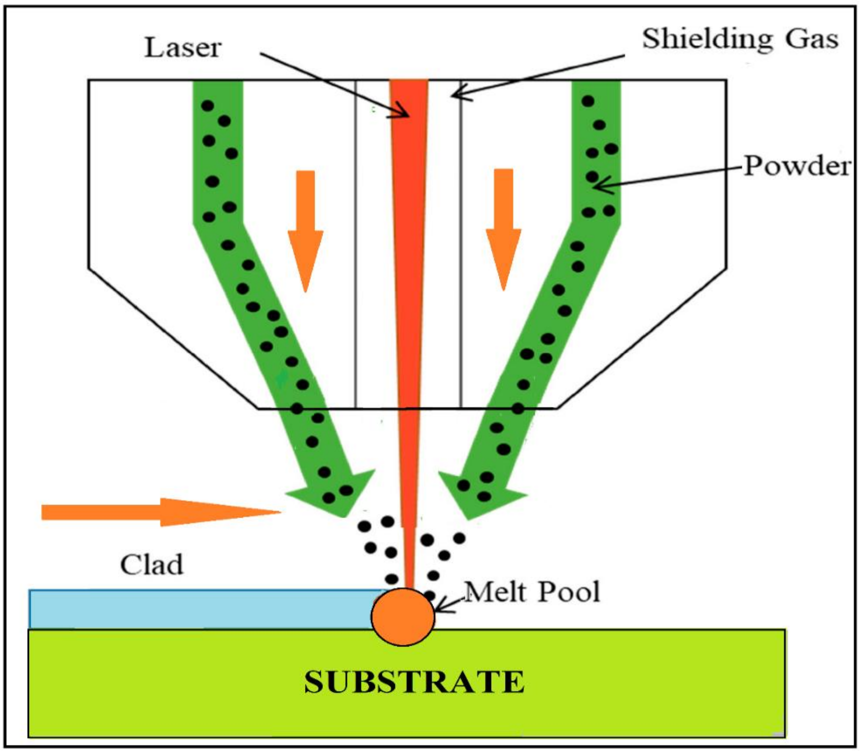

Figure 2. Schematic representation of Directed Energy Deposition [30].

2.3. AM-produced AlSi10Mg Comparison with Conventional Manufacturing

Unlike casting, where micro segregation and porosity are common issues, AM-produced AlSi10Mg can achieve refined microstructures and improved homogeneity. Compared to wrought alloys, AM parts exhibit anisotropy that must be carefully controlled through processing and heat treatment. In summary, Additively Manufactured (AM) AlSi10Mg has clear benefits over its conventionally manufactured counterparts, especially when it comes to mechanical, tribological, and microstructural characteristics [32-35].

3. MICROSTRUCTURAL CHARACTERISTICS

3.1. As-built Microstructure

The as-built microstructure of LPBF-fabricated AlSi10Mg typically consists of a fine cellular aluminum matrix surrounded by a silicon-rich network. This structure forms due to rapid solidification and solute trapping. Melt pool boundaries and epitaxial grain growth are commonly observed, leading to a characteristic layered morphology.

3.2. Defects and Porosity

Porosity in AM AlSi10Mg may originate from gas entrapment, keyhole instability, or insufficient melting. Mechanical and fatigue qualities are strongly influenced by the size, distribution, and shape of pores. Advanced parameter optimization and in-situ monitoring techniques are increasingly employed to reduce defect formation.

3.3. Anisotropy and Texture

The layer-wise fabrication process introduces anisotropy in mechanical behavior. Columnar grains aligned with the build direction and crystallographic texture influence strength, ductility, and fatigue resistance. Understanding and controlling anisotropy is essential for reliable structural applications.

4. HEAT TREATMENT AND POST-PROCESSING

4.1. Stress Relief Treatments

Residual stress generated during AM can lead to distortion and reduced fatigue life. Stress relief heat treatments at relatively low temperatures are commonly applied to reduce internal stress while preserving the fine microstructure.

4.2. Solution Treatment and Aging

Conventional T6 heat treatment, widely used for cast AlSi10Mg, may not always be optimal for AM parts. Solution treatment dissolves the silicon network, while artificial aging promotes precipitation hardening. Modified heat treatment cycles have been developed to balance strength and ductility in AM-fabricated components.

4.3. Hot Isostatic Pressing (HIP)

HIP is an effective post-processing technique for reducing internal porosity and improving fatigue performance. By applying high temperature and isostatic pressure, HIP enhances densification and mechanical reliability, particularly for safety-critical components.

5. MECHANICAL PROPERTIES

5.1. Tensile Properties

According to reports in the literature, as-built AlSi10Mg alloys made using the LPBF technique have yield strengths of roughly 230–280 MPa and tensile strengths of 380–460 MPa [17,18,22]. The silicon network structure and tiny cellular microstructure are responsible for these high strength values [13]. However, ductility is often restricted to the range of 3–6% in the as-built condition [18]. According to reports, stress reduction or T6-like heat treatments can cause elongation values to reach 8–12% [19,23].

5.2. Hardness and Wear Behavior of ALSi10Mg alloy

The presence of a silicon-rich network contributes to relatively high hardness and good wear resistance. Post-processing treatments may alter hardness depending on microstructural evolution and precipitation behavior [18-21]. The sliding wear behavior of AlSi10Mg alloy made by gravity casting and LPBF in both its as produced and T6 heat-treated states was compared by Tonolini et al. While no abrasive wear was found, all examined materials displayed adhesive and tribo-oxidative wear mechanisms. Because of a considerable increase in porosity and a drop in hardness, the heat-treated sample had the weakest wear resistance, whereas the as-produced sample had the greatest [36].

5.3. Fatigue Behavior

Fatigue performance is a critical consideration for AM AlSi10Mg. Surface roughness, porosity, and residual stresses play dominant roles in fatigue crack initiation. Post-processing methods such as machining, surface polishing, and HIP significantly enhance fatigue life. Due to surface, internal, and residual stresses, LPBF AlSi10Mg's fatigue performance is quite poor in its as-fabricated state. By successfully resolving important problems such residual stresses, surface roughness, and porosity, post-processing treatments enhance fatigue performance. Heat treatment works best for items with complicated geometries because mechanical surface treatments are difficult. [1, 17-23,].

6. APPLICATIONS OF AM ALSI10MG ALLOYS

High-performance AlSi10Mg alloys produced by additive manufacturing are increasingly used in lightweight structural components, heat exchangers, aerospace brackets, automotive parts, and tooling inserts with conformal cooling channels. The ability to integrate complex geometries and functional features provides a significant competitive advantage over conventional manufacturing routes.

7. CHALLENGES AND FUTURE PERSPECTIVES

Despite significant progress, several challenges remain in the widespread adoption of AM AlSi10Mg alloys. These include process reproducibility, standardization, anisotropy control, and long-term performance under service conditions. Future research is expected to focus on advanced process monitoring, data-driven optimization, alloy modification, and hybrid manufacturing approaches.

8. CONCLUSIONS

This chapter has presented a comprehensive investigation of high-performance AlSi10Mg aluminum alloys produced by additive manufacturing methods. The unique microstructures generated by AM processes enable enhanced mechanical properties, while appropriate post-processing treatments further improve performance and reliability. Continued research and technological development will expand the application potential of AM AlSi10Mg alloys in high-performance engineering systems.

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