Laser Micro-Machining of Aluminium Alloy 8090: A Review on High Precision and Sustainable Manufacturing

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Abstract: The need of aluminium-lithium alloys has increasing consistently in aerospace, defence and transportation industries due to its light weight, high corrosion resistance and high strength. Aluminium Alloy 8090 grade has a suitable candidate for a structural material due to its low density, high specific stiffness, excellent fatigue resistance and superior fracture toughness. However, traditional machining of AA8090 results in excessive wear, burr formation, poor dimensional accuracy and surface defects. A well-studied non-contact high precision fabrication method such as Laser micro-machining for fabricating complex micro-features with low mechanical stresses addresses the challenges faced by the traditional machining. This review explores the laser micromachining characteristics of AA8090, effect of its parameters on machining quality and sustainability aspects associated with laser-based manufacturing. The study includes present challenges and future research directions for high precision and environmentally sustainable laser micro-machining of AA8090.

Keywords: Aluminium Alloy 8090; Laser Micro-Machining, AL-Li Alloy; Sustainable Manufacturing; Surface Integrity; Precision Engineering.

Introduction

Generally, the fuel economy can be increased by light weight materials without compromising structural integrity in the transportation and aerospace industries. Because of their better fatigue resistance, low density, high specific strength, and outstanding corrosion performance, aluminum-lithium (Al-Li) alloys have become attractive options [1,2]. Among them, Aluminium Alloy 8090 (AA8090) has garnered a lot of interest for usage in space applications, wing panels, and aircraft fuselage structures [3]. However, issues such quick tool wear, burr development, poor surface quality, dimensional errors, and residual stress generation are frequently encountered during conventional machining of AA8090. These difficulties intensify when producing micro-scale features needed for contemporary electrical, biomedical and aerospace applications [4, 5]. Because of its non-contact nature, great flexibility, and capacity to create micro-features with micron-level accuracy, laser micro-machining has become a competitive option. By using laser-induced melting, vaporisation, and ablation to remove material, cutting forces and tool wear are eliminated [6]. However, the high thermal conductivity and reflectivity of aluminium alloys frequently result in micro-cracking, recast layers, heat-affected zone (HAZ) development, and decreased laser absorption. As a result, maintaining sustainable production while attaining high precision continues to be a crucial task. New possibilities for overcoming these constraints have been made possible by recent developments in ultrafast laser systems, process optimisation methods, and intelligent manufacturing strategies [7-9]. Recent advancements in laser micro-machining of AA8090 are examined in this paper, with a focus on process parameters, machining quality, sustainability issues, and potential directions for future research.

2. Related work

The main objectives of recent studies on aluminum alloys laser processing have been to improve sustainability, reduce thermal damage, and improve machining quality. Chen et al.[1] explored the overview of ultrafast laser micromachining of metallic surfaces, where the authors found that femtosecond lasers may create highly controlled micro and nano-scale structures with no thermal effects. Yang et al. [2] proved that ultrafast laser processing greatly reduces recast layer development and heat-affected zones while enabling the creation of intricate three-dimensional microstructures. These studies show that ultrafast laser systems are promising mechanisms for aerospace material precision cutting applications. Based on studies on aluminium laser processing [5], high reflectivity and heat conductivity continue to be significant obstacles. Energy absorption, porosity, thermal cracking, and residual stresses continue to have an impact on process stability and product quality, based on thorough analysis of laser additive manufacturing of aluminium alloys [6, 10]. Similar findings were noted in evaluations with a sustainability focus, which highlighted the necessity of optimising laser parameters to increase material utilisation and energy efficiency. Aluminium laser machining experiments have demonstrated that material removal rate, kerf geometry, and surface roughness are strongly influenced by laser power, pulse frequency, pulse duration, and scanning speed. In his investigation on fibre laser engraving of AA2024 alloy, Kasman found that machining depth and surface quality are significantly impacted by scanning speed and pulse parameters [6]. Further evidence that pulse fluence directly affects ablation depth and feature dimensions came from numerical and experimental investigations of ultrafast laser ablation of aluminium [7]. Likewise, Wang et al. [11] reported that laser-induced thermal cycles can alter microstructural evolution and consequently affect mechanical performance. Table 1 depicts the comparison of recent studies on laser micro-machining of aluminium alloys.

Table 1. Comparison of Recent Studies on Laser Micro-Machining of Aluminium Alloys

Authors	Laser Type	Major Process Parameters	Performance Measures	Major Findings	Research Gap
[1] Chen et al. (2022)	Femtosecond Laser	Pulse energy, scanning speed, repetition rate	Surface morphology, HAZ	Produced micro/nano structures with negligible thermal damage	Limited optimization for aluminium alloys
[2] Yang et al. (2022)	Ultrafast Laser	Pulse energy, beam shaping, overlap	Dimensional accuracy, surface quality	Improved precision and complex 3D microstructures	Sustainability not addressed
[6] Kasman et al. (2023)	Fiber Laser	Laser power, engraving speed	Surface roughness, engraving depth	Laser power significantly influenced machining	Only AA2024 investigated

				depth and quality	
[7] Omeñaca et al. (2024)	Femtosecond Laser	Pulse fluence, pulse duration	Ablation depth, HAZ	Numerical results agreed well with experiments	Limited industrial-scale validation
[8] Fan et al. (2024)	Laser Additive Manufacturing	Laser energy density	Microstructure, mechanical properties	Better microstructure and strength achieved through optimized energy density	Focused on additive manufacturing rather than micromachining
[14] Niranjana et al. (2026)	Low-power Laser	Laser power, scanning strategy	Energy consumption, machining quality	Demonstrated economical and sustainable micromachining	More validation on aerospace alloys needed

There is a lot of research on aluminium alloys like AA2024, AA6061, and AA7075, but there aren't many focused studies on AA8090. Instead of laser micro-machining, the majority of studies employing AA8090 concentrate on welding, joining, and mechanical characterisation. As a result, there are still a lot of research opportunities in the areas of process optimisation, sustainability evaluation, and laser-material interaction mechanisms for AA8090.

3. Key contributions

Four significant contributions may be found in the literature. First, scientists have shown that laser micro-machining can effectively and more precisely create micro-scale features than traditional machining techniques [1, 2]. Second, improved surface integrity and dimensional accuracy are made possible by ultrafast laser technologies, which have greatly decreased heat degradation [6, 7]. Third, the best process conditions have been found by the successful application of optimisation techniques like Response Surface Methodology (RSM), Taguchi techniques, Grey Relational Analysis (GRA), and machine learning [13]. Fourth, studies on sustainability have emphasised how laser-based manufacturing improves material utilisation, requires fewer tools, and uses less coolant. Despite these developments, there are still few integrated studies that address AA8090's machining quality, productivity, sustainability, and cost-effectiveness [9, 14].

4. Methods Used in Laser Micro-Machining Research

The majority of research uses optimization-based, computational, and experimental methods. Fibre lasers, Nd lasers, picosecond lasers, or femtosecond lasers are commonly used in experimental research to manufacture aluminium specimens. To analyse their effect on machining characteristics, process variables such as laser power, pulse energy, pulse duration, repetition rate, scanning speed, hatch spacing, and focal location are systematically modified. Atomic force microscopy (AFM), optical microscopy, scanning electron microscopy (SEM), and surface profilometers are typically applied for surface characterisation. These methods yield data on microstructural changes, kerf breadth, recast layer thickness, and surface roughness. X-ray diffraction (XRD) and energy dispersive spectroscopy (EDS) are frequently used to evaluate compositional and phase changes brought on by laser irradiation. The simulation in numerical investigations for heat transmission, temperature distribution, and material removal mechanisms using two-temperature models and finite element modeling are frequently used in recent studies. Artificial intelligence and machine learning approaches have been used in recent studies to optimise process parameters and forecast machining outcomes. These methods increase process accuracy and efficiency while lowering experimentation costs. Table 2 represents the effect of important laser process parameters on machining performance.

Table 2. Effect of Important Laser Process Parameters on Machining Performance

Parameter	Positive Effect	Negative Effect
Laser Power	Higher Material Removal Rate (MRR)	Larger Heat Affected Zone (HAZ)
Scanning Speed	Better surface finish, lower HAZ	Reduced machining depth
Pulse Duration	Higher penetration	Increased thermal damage
Pulse Frequency	Faster machining	Heat accumulation
Spot Size	Better dimensional accuracy	Lower MRR
Pulse Energy	Increased ablation efficiency	Recast layer formation

5. Experimental findings

The most important factors influencing machining quality, according to experimental results, are laser power and scanning speed. Increased laser power can increase the rate of material removal and the depth of machining, but it can also increase surface roughness and the size of the heat-affected zone. Higher scanning rates, on the other hand, increase surface cleanliness and lessen thermal accumulation, but they may also impair machining efficiency. When compared to traditional nanosecond lasers, ultrafast laser systems have proven to perform better. Near-a-thermal ablation is made possible by femtosecond laser processing, which improves edge quality, minimises recast layer production, and reduces micro-cracking. Excellent agreement in forecasting ablation depth and feature shape has been demonstrated by numerical simulations and experimental validations, allowing for more efficient process design. Optimised pulse durations and fluence levels can greatly improve dimensional accuracy while reducing thermal flaws, according to studies on aluminium laser machining. From a sustainability standpoint, laser micro-machining eliminates tool wear and uses less cutting fluid. Because of localised material removal, material waste is significantly reduced when compared to traditional machining techniques. These qualities help to improve resource efficiency and lessen the impact on the environment [14, 15].

6. Discussion

Laser micro-machining is a potential production process for AA8090 components that require high dimensional precision and outstanding surface quality, according to the studied literature. Many of the drawbacks of traditional machining are eliminated when there is no tool-workpiece interaction. But thermal damage is always a big worry, especially when using high energy densities and longer pulse durations. By reducing heat diffusion and facilitating accurate material removal, ultrafast laser systems offer a practical alternative. The benefits of laser processing for sustainability are equally important. The objectives of green production are supported by lower coolant consumption, the removal of tool wear, and better material utilisation. However, because laser systems use a lot of electricity, energy optimisation is a crucial topic for further study. It is anticipated that the incorporation of digital twins, artificial intelligence, and real-time monitoring systems will enhance process sustainability and efficiency.

7. Conclusion

High-precision AA8090 components used in advanced engineering and aerospace applications have a lot of promise for production using laser micro-machining. Recent advancements in ultrafast laser technology have reduced thermal damage and significantly increased machining accuracy. According to recent studies, machining quality and sustainability performance are significantly impacted by process variables such laser power, pulse length, and scanning speed. Even though laser processing offers significant environmental advantages by requiring less coolant and equipment, further research is needed to maximise energy efficiency and create thorough frameworks for sustainability assessments. To fully realise the promise of AA8090 laser micro-machining, future research should concentrate on femtosecond laser processing, machine learning-based optimisation and intelligent production systems.

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