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Analysis of Fatigue Life and Surface Roughness in Laser Peened Al6082/SiC/7.5% Metal Matrix Composite

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Abstract

Objectives: To investigate the influence of laser shock peening (LSP) energy on fatigue life and surface roughness of stir-cast Al6082/SiC/7.5% metal matrix composites. **Methodology:** Al6082/SiC/7.5% composites were fabricated using stir casting and subjected to laser shock peening at energy levels of 1 J, 2 J, and 2.5 J using a Q-switched Nd:YAG laser. Rotating bending fatigue tests were conducted to determine fatigue life, while surface roughness was measured using a contact profilometer. **Findings:** Fatigue life increased by 29%, 34.77%, and 44.5% at 1 J, 2 J, and 2.5 J respectively compared to un-peened composites. Surface roughness decreased by 1.40% at 2 J and 6.50% at 2.5 J, indicating improved surface integrity at higher laser energies. **Novelty:** This study establishes a quantitative relationship between laser shock peening energy, fatigue enhancement, and surface roughness reduction in Al6082/SiC composites, identifying an optimal processing window that has not been clearly reported for particle-reinforced aluminum metal matrix composites.

Keywords: Al6082 MMC; SiC reinforcement; Laser peening; Fatigue life; Surface roughness

1 Introduction

Laser shock peening (LSP) has been widely recognized as a highly effective technique for improving the mechanical behaviour of aluminium alloys by generating deep compressive residual stresses that enhance durability, particularly in alloys such as 6061-T6 [1]. Research on 2024-T351 aluminium alloy has also demonstrated that LSP contributes to superior fatigue resistance by forming a beneficial compressive stress layer on the surface [2]. Beyond residual stress modification, LSP has been shown to produce significant grain refinement and increased surface hardness when aluminium alloys are subjected to high-pressure shock loading [3]. Comparative studies involving 6061 and 6082-T6 alloys further reveal that LSP consistently increases microhardness while stabilizing the microstructure, highlighting the technique's capability to strengthen a variety of aluminium systems [4]. Additional findings indicate that tailoring LSP parameters allows precise control over the depth and magnitude of residual stresses, enabling optimization of surface strengthening in aluminium substrates[5].

In the context of metal matrix composites (MMCs), investigations on SiCp/2009Al composites have established that LSP enhances fatigue behaviour by improving interfacial bonding and inducing favourable microstructural changes within the composite[6]. Studies examining fatigue cycling have reported that LSP-induced compressive stresses in SiC/Al composites remain sufficiently stable throughout loading, contributing to sustained fatigue resistance[7]. Numerical modelling efforts emphasize the importance of accurately predicting shockwave propagation to understand how LSP interacts with the heterogeneous microstructure of reinforced composites[8]. In addition, research on femtosecond-based LSP applied to SiCp/AlSi10Mg composites has demonstrated substantial improvements in wear resistance and overall tribological performance, reinforcing the versatility of LSP for composite systems[9].

Fatigue and crack-growth behaviour following LSP treatment has also been extensively documented. Experimental work shows that LSP significantly slows fatigue crack propagation in aluminium alloys by reducing crack-tip stress intensity and altering crack-growth mechanisms[10]. In additively manufactured (AM) AlSi10Mg alloys, LSP has been found to modify residual stress distributions in a way that enhances fatigue reliability under fluctuating loads[11]. Comparable improvements have been observed in AM Ti-6Al-4V components, where LSP contributes to fatigue resistance by refining the microstructure near the surface[12]. Computational studies further support these outcomes by illustrating how LSP counteracts tensile residual stresses commonly present in AM materials, thereby improving their fatigue performance[13]. Experimental validation on AM AlSi10Mg alloys confirms that LSP produces deep compressive stress layers that effectively delay crack initiation and extend fatigue life[14].

Surface integrity enhancement is another critical benefit associated with LSP. For instance, LSP substantially improves surface roughness and produces a deeper compressive stress layer in AA7050-T7451 alloy, making it a preferred treatment for components requiring superior fatigue resistance[15]. Research on Al–SiC composites also shows that although SiC particles enhance the composite's mechanical properties, they can introduce defects and localized stress concentrations that necessitate surface modification to improve long-term performance[16]. Multi-pass LSP studies demonstrate that repeated peening cycles promote further grain refinement and lead to progressive improvements in overall mechanical performance, especially in additively manufactured materials[17].

1.1 Research Gap Identified

From the reviewed literature, it is evident that while LSP is effective for monolithic aluminum alloys, its application to Al6082/SiC metal matrix composites remain insufficiently explored. Specifically, there is a lack of systematic, quantitative studies correlating laser shock peening energy with simultaneous improvements in fatigue life and surface roughness for particle-reinforced composites.

1.2 Justification of Present Work

The present study addresses these gaps by experimentally investigating the effect of varying LSP energy levels on fatigue behaviour and surface roughness of stir-cast Al6082/SiC/7.5% composites. By establishing an optimized energy–performance relationship, this work advances existing knowledge and demonstrates the superiority of laser shock peening as a surface strengthening technique for aluminum metal matrix composites.

2 Methodology

Al6082/SiC/7.5% metal matrix composites were fabricated using the stir casting technique. Al6082 alloy was melted at 800 °C, and preheated silicon carbide particles were added along with 1% magnesium to improve wettability. The molten mixture was mechanically stirred for 5 minutes and cast into a steel mould. Standard specimens for fatigue and surface roughness testing were machined from the cast material.

Laser shock peening was performed using a flash-lamp-pumped, Q-switched Nd:YAG laser (Figure 1). Laser energy was varied at 1 J, 2 J, and 2.5 J, while pulse duration (6–7 ns), repetition rate (2 Hz), and spot diameter (1.5 mm) were kept constant. Rotating bending fatigue tests were conducted to determine fatigue life, and surface roughness measurements were obtained using a contact profilometer. Un-peened specimens served as reference samples for comparison

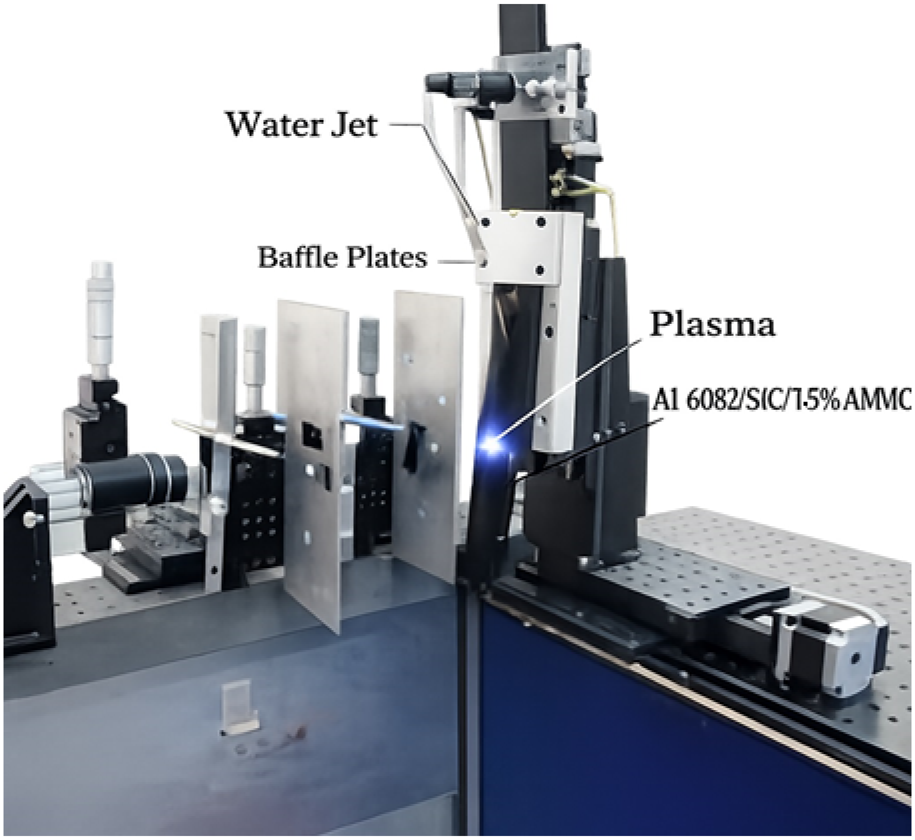

Fig 1. Flash-lamp-pumped, electro-optically (E–O) Q-switched Nd:YAG laser peening system

3 Results and Discussion

After laser peening treatment, on the specimens prepared for fatigue testing (Figure 2) and surface roughness evaluation (Figure 3) were experimentally examined, and the results are summarized in Table 1. The corresponding variations in fatigue life and surface roughness are illustrated in Figures 4 and 5, respectively.

Fig 2. Fatigue Test Specimens, a) Un-peened Al and AMMC, b) Laser Peened AMMCs

Laser shock peening resulted in a significant improvement in fatigue performance of the Al6082/SiC composite. Compared to the un-peened condition, fatigue life increased by 29%, 34.77%, and 44.5% at laser energies of 1 J, 2 J, and 2.5 J respectively. This

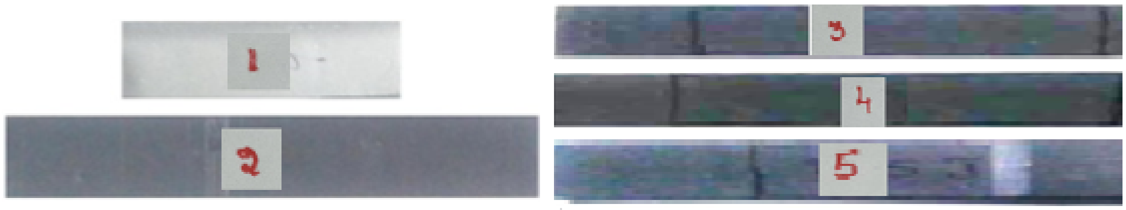

Fig 3. Surface roughness test specimens, a) Un-peened Al and AMMC b) Laser Peened AMMC

Table 1. Fatigue life and surface roughness test results

Sl No	Specimen	Peening Condition	Fatigue Life (cycles)	Surface Roughness (μm)
1	Al6082	Un-peened	901,348	1.04433
2	Al6082/SiC/7.5% AMMC	Un-peened	998,921	1.665
3	Al6082/SiC/7.5% AMMC	LSP 1 J	1,297,281	2.08467
4	Al6082/SiC/7.5% AMMC	LSP 2 J	1,346,311	1.64167
5	Al6082/SiC/7.5% AMMC	LSP 2.5 J	1,443,622	1.5567

enhancement is attributed to the introduction of deep compressive residual stresses and shock-induced plastic deformation, which effectively delay crack initiation and crack propagation.

Surface roughness exhibited an energy-dependent response. A slight increase in roughness was observed at 1 J due to localized plastic deformation. However, higher laser energies resulted in surface smoothing, with reductions of 1.40% at 2 J and 6.50% at 2.5 J. This improvement is associated with uniform plastic flow and redistribution of surface asperities under higher shock pressures.

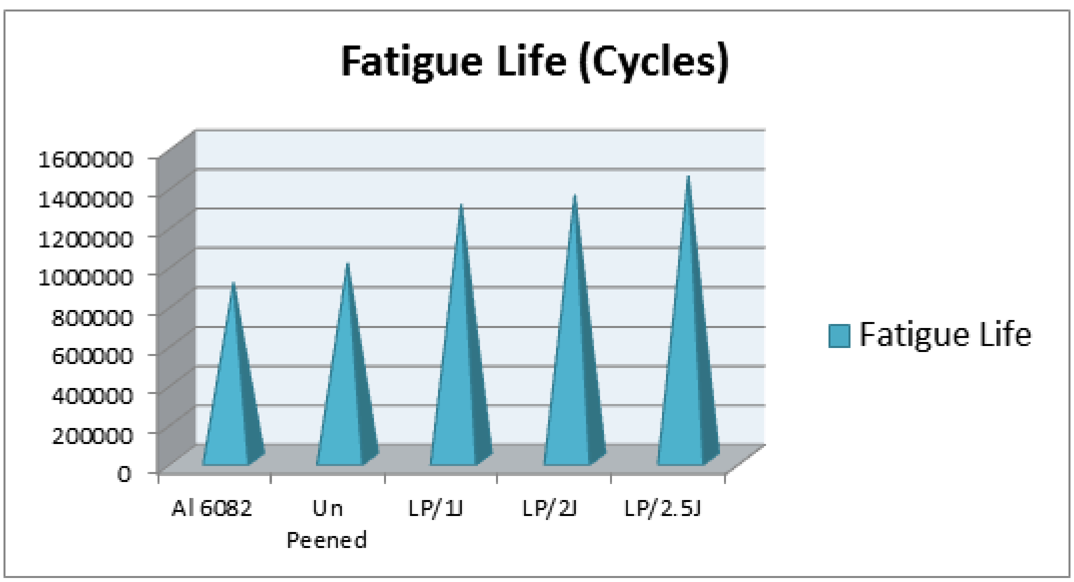

Fig 4. Variation of fatigue life with laser peening energy

3.1 Comparison with Existing Studies

The improvements observed in fatigue life—up to 44.5% at 2.5 J—are higher than the typical 20–40% enhancement reported for monolithic aluminium alloys treated with LSP[(1)],[(2)]. This indicates that the presence of SiC particles in the composite

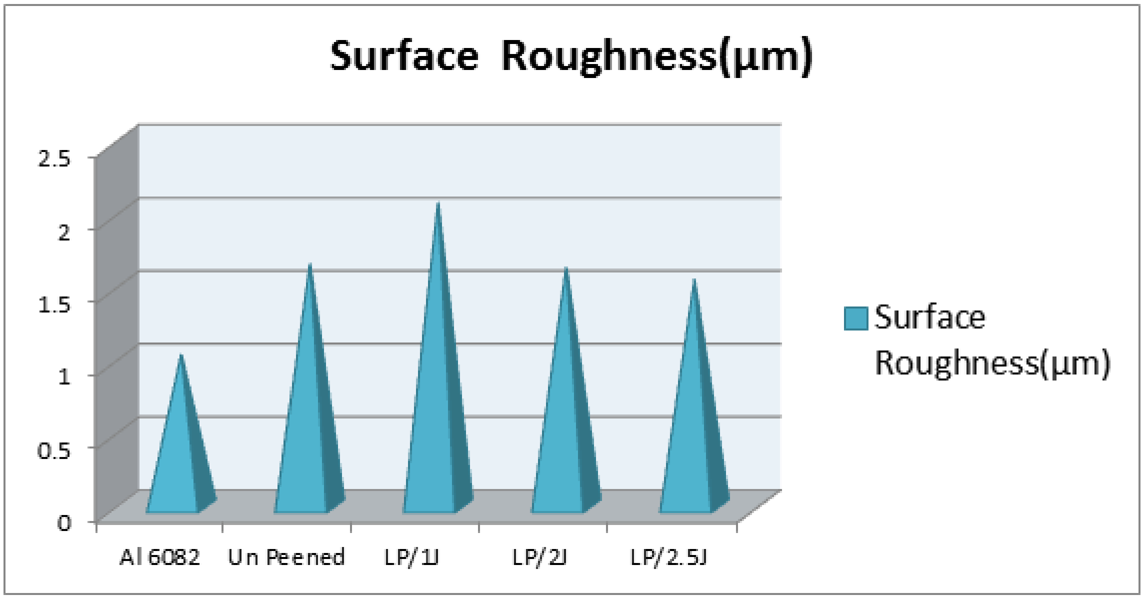

Fig 5. Variation of surface roughness with laser peening energy

may amplify the beneficial effects of LSP by stabilizing compressive residual stresses and impeding crack initiation. Similar trends were noted in SiCp/2009Al composites, where LSP improved fatigue behaviour through interfacial strengthening and microstructural refinement[6],[7]. However, those studies did not quantify the influence of varying laser energy. The present work fills this gap by establishing a clear, energy-dependent relationship between LSP intensity and fatigue performance specifically for Al6082/SiC MMCs, which has not been previously reported.

Surface roughness results also show favourable comparison with earlier literature. While prior work on aluminium alloys demonstrated roughness reduction following LSP due to improved plastic flow[15], studies on MMCs remain limited. The present energy-dependent reduction in roughness (up to 6.50%) aligns with findings from femtosecond-LSP studies on SiCp/AlSi10Mg composites[9] and demonstrates LSP's capability to mitigate casting-induced surface defects commonly associated with SiC reinforcements[16]. Overall, the results not only corroborate known LSP mechanisms but also demonstrate superior performance improvements relative to many existing systems, establishing LSP as an effective and optimized strengthening technique for Al6082/SiC metal matrix composites.

4 Conclusion

The present study confirms that laser shock peening is an effective surface modification technique for enhancing fatigue life and surface quality of Al6082/SiC/7.5% metal matrix composites. Fatigue life improved progressively with laser energy, reaching a maximum enhancement of 44.5% at 2.5 J. Surface roughness was reduced by up to 6.50% at the same energy level. While the study establishes an optimal peening condition, residual stress depth profiling and microstructural characterization were not addressed and remain as limitations. Future work will focus on residual stress measurements and corrosion behaviour of laser-peened AMMCs.

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6 Contributory Statement

Conceptualization of study problem: Banavath Haritha Bai, Sreenivasulu Reddy A Experimental Design: Banavath Haritha Bai, Sreenivasulu Reddy A Data generation: Banavath Haritha Bai Data analysis: Banavath Haritha Bai Research Guidance:

Sreenivasulu Reddy A, Venkataramaiah P. Original Drafting: Banavath Haritha Bai Editing & Reviewing: Sreenivasulu Reddy A, Venkataramaiah P.

7 Data Availability Statement

Any other experimental data generated during the present study are available from the corresponding author upon reasonable request.

8 Details of Ethical Clearance

This study does not involve human participants, animals, or clinical trials. Therefore, ethical clearance approval was not required.

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