

Determination of Residual Stress Redistribution of 2024T351 Aluminum Alloy by Vickers Indentation Test

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Abstract:

This study investigated the evolution of microhardness, fracture toughness, and residual stress in a 2024-T351 aluminum alloy under cyclic loading after various shot peening treatments. A modified Vickers indentation instrument, coupled with three different indentation models, was used to measure these properties. The experiments were conducted using variable amplitude tests on samples subjected to three different shot peening intensities: 4-6A, 6-8A, and 8-10A. The samples were tested under cyclic loading at two applied stress levels, 170 MPa and 280 MPa, for 1, 2, 10, 1000, and 10,000 cycles. Experimental results show that microhardness was reduced by 34% for samples treated with an 8-10A shot peening intensity after 10,000 cycles under a -280 MPa load. The reduction in microhardness is attributed to the relaxation of residual stress, with the rate of reduction being influenced by the material's percentage of cold work.

Keywords: Microhardness, Residual Stress, Shot Peen, Fatigue, and Aluminum Alloy.

تحديد إعادة توزيع الإجهاد المتبقي لسبيكة الألومنيوم 2024 T351 بواسطة اختبار صلادة فيكرز

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المخلص

بحثت هذه الدراسة في تطور الصلادة الدقيقة، ومتانة الكسر، والإجهاد المتبقي في سبيكة ألومنيوم 2024-T351 تحت حمل دوري بعد معالجات مختلفة بالقصف بالكريات. استُخدم جهاز فيكرز مُعدل لقياس الشقوق، مُقترناً بثلاثة نماذج مختلفة، لقياس هذه الخصائص. أُجريت التجارب باستخدام اختبارات سعة متغيرة على عينات خضعت لثلاث قوى مختلفة من القصف بالكريات: كثافة 4-6، كثافة 6-8، وكثافة 8-10. اختُبرت العينات تحت تحميل دوري عند مستويين من الإجهاد المطبق، 170 ميغا باسكال و 280 ميغا باسكال، لحمل دوري 1، 2، 10، 1000، و 10,000 دورة. أظهرت النتائج التجريبية انخفاض الصلادة الدقيقة بنسبة 34% للعينات المعالجة بشدة القصف بالكريات 8-10 بعد 10,000 دورة تحت حمل 280 ميغا باسكال. ويرجع الانخفاض في صلابة المواد الدقيقة إلى استرخاء الإجهاد المتبقي، حيث يتأثر معدل الانخفاض على الصلادة السطحية والتشكيل على البارد للمادة.

الكلمات المفتاحية: الصلادة الدقيقة، الإجهاد المتبقي، القصف بالكريات، التعب، وسبائك الألومنيوم.

Introduction

Hardness testing is a widely used technique for characterizing the plastic deformation and mechanical resistance of materials, such as the 2024-T351 aluminum alloys. It is favored for its non-destructive (or semi-destructive) nature, as it leaves only a small indentation, and its efficiency, allowing for the rapid collection of mechanical data without the need to excise samples for separate testing. While not a fundamental physical property, hardness is a material characteristic determined by measuring the permanent depth of an indentation created by a specific force and indenter. For example, Vickers hardness tests utilize a pyramidal indenter, which produces

geometrically similar indentations [1]. In fully work-hardened materials, stress increases elastically to a maximum known as the flow stress, after which it remains constant despite increasing strain. Early studies on the hardness of metals often selected these materials to ensure that the flow stress was equivalent to the residual stress, allowing for stress calculations that consistently estimated the residual stress.

The relationship between surface residual compressive stress and fatigue life has been a significant area of research. For instance, Mattson and Coleman [2] investigated the correlation between these factors in shot peened leaf-spring specimens, finding that the fatigue life had a direct relationship with the induced surface residual compressive stress. Similarly, Zaroog et al. [3,5] studied the behavior of residual stress in the 2024-T351 aluminum alloy during fatigue cycles. Their work showed that residual stress relaxation occurs in distinct stages: an initial significant relaxation due to surface yielding in the first cycle, followed by a more gradual relaxation in subsequent cycles. This significant decrease in residual stress during fatigue cycling, compared to specimens with no fatigue, was also corroborated by the findings of Torres and Voorwald [6].

In similar study applied by [7,8] indicated the relaxation of residual stress in the 2024-T351 aluminum alloy during the initial cycles of fatigue. Their experimental findings indicated a significant relaxation of stress during the first few cycles, followed by a much smaller relaxation in subsequent cycles. This cyclic relaxation is primarily influenced by several factors: the initial magnitude and gradient of the residual stress field, the degree of prior cold working, the fatigue stress amplitude, the mean stress ratio, the number of cycles, and the material's cyclic stress-strain response, including its degree of cyclic work hardening/softening [9,10]. For Vickers indentation, Tabor [11] applied the wedge indenter model, originally developed by Hill et al. [12], to approximate a flat punch model would be a good approximation to Vickers hardness testing. This approach allowed him to derive a constraint factor of 3. The Vickers hardness test is specifically designed to produce a constant characteristic strain under the indenter, which Tabor [11] reported to be 8% and Johnson [13] later specified as 7%.

Literature Review

Residual stresses play a critical role in determining the mechanical performance and fatigue life of metallic materials, particularly aluminum alloys used in aerospace and automotive industries. The **2024-T351 aluminum alloy**, known for its high strength and excellent fatigue resistance, has been the subject of extensive studies focusing on residual stress formation, redistribution, and relaxation under cyclic loading.

Residual Stress and Its Measurement

Residual stress can significantly affect the structural integrity of engineering components. According to Peitl and Serbena [1], internal residual stresses in materials can be effectively evaluated using the **Vickers indentation technique**, which provides valuable insights into the relationship between indentation hardness and internal stress distribution. The indentation method offers a semi-destructive alternative to complex techniques like X-ray diffraction, making it suitable for comparative mechanical studies.

Theoretical foundations of indentation-based stress measurement were developed by Meyer [11], Hill et al. [12], and Tabor [11], who correlated indentation load with plastic deformation behavior and introduced the concept of a constraint factor in hardness testing. Johnson [13] later refined this understanding through his contact mechanics analysis, which related hardness to the local stress-strain response beneath the indenter. These fundamental models established the basis for modern approaches linking hardness variation to residual stress evolution.

Shot Peening and Fatigue Behavior

Shot peening is a mechanical surface treatment widely used to induce beneficial compressive residual stresses, thereby enhancing fatigue life. Mattson and Coleman [2] demonstrated as early as 1954 that the **fatigue life of leaf-spring specimens** increases proportionally with the magnitude of induced compressive residual stress. Their work emphasized the importance of controlling peening variables such as shot size, intensity, and coverage.

Torres and Voorwald [6] expanded on this concept by examining the combined influence of shot peening, stress relaxation, and fatigue on **AISI 4340 steel**, confirming that compressive residual stresses delay crack initiation and propagation. Similarly, Reddy et al. [10] showed that the microstructural refinement and surface work-hardening caused by shot peening significantly improve residual stress behavior and hardness in aluminum alloys. The behavior of residual stress in **2024-T351 aluminum alloys** under cyclic loading has been extensively studied by Zaroog et al. [3,7]. Their investigations revealed a two-stage relaxation mechanism: an initial sharp decrease in compressive stress during the first few fatigue cycles due to surface yielding, followed by gradual stabilization in subsequent cycles. These findings were further validated by Torres and Voorwald [6], who confirmed similar relaxation trends in steel components.

Residual Stress Relaxation Under Cyclic Loading

The phenomenon of residual stress relaxation is primarily attributed to cyclic plastic deformation and microstructural rearrangements. Zaroog et al. [3] developed models describing residual stress decay in aluminum alloys during fatigue, linking relaxation behavior to applied cyclic stress amplitude and initial stress gradients. Their subsequent work [7] confirmed that relaxation progresses through distinct stages corresponding to surface and subsurface plastic deformation zones.

Zhuang and Halford [9] provided additional experimental evidence that the **rate of residual stress relaxation** is strongly influenced by the magnitude of applied cyclic stress, the degree of cold work, and the material's cyclic hardening or softening response. Their results established that materials with higher initial compressive stress exhibit greater stability under fatigue conditions.

Fareg and Abdoulhdi [5] investigated the relaxation of residual stress induced by shot peening parameters and its effects on fatigue performance of **2024-T351 aluminum alloy**. They concluded that higher peening intensities generate deeper compressive layers and better resistance to relaxation, leading to improved fatigue strength. Likewise, Fareg and Suliman [8] conducted both experimental and numerical analyses that confirmed the rapid reduction of surface compressive stress during early fatigue cycles, followed by a slower decay at higher cycle counts.

Microhardness and Correlation with Residual Stress

Microhardness is a reliable indirect indicator of residual stress and plastic deformation. Early studies by Meyer [11] and Hill et al. [12] established the correlation between indentation geometry and material flow stress. The micro-Vickers hardness test (ASTM E384-99) [18] provides precise localized measurements, making it suitable for detecting changes in residual stress fields caused by surface treatments or cyclic loading.

The relationship between microhardness and residual stress has been examined by Fareg et al. [4], who used both **X-ray diffraction and finite element analysis** to evaluate the residual stresses induced by shot peening in **2024-T351 aluminum alloy**. Their findings indicated that microhardness variation could accurately reflect the redistribution of residual stress during fatigue. The observed decrease in hardness values during cyclic loading was attributed to residual stress relaxation and surface micro-plasticity.

Influence of Alloy Composition and Microstructure

The microstructural characteristics and chemical composition of 2024-T351 alloy significantly affect its mechanical response. According to Kuyucak and Sahoo [15], the presence of copper and magnesium improves the alloy's age-hardening behavior, while manganese contributes to grain refinement and stability. The alloy's machinability and fatigue resistance were also highlighted in studies by Story et al. [14] and ASTM standards [16,17], which provided guidelines for specimen preparation and fatigue testing.

Summary of Findings

The reviewed literature consistently demonstrates that:

1. Shot peening effectively enhances surface hardness and induces beneficial compressive residual stresses [2,6,10].
2. Residual stress relaxation occurs predominantly in the early fatigue cycles and stabilizes thereafter [3,7,9].
3. Microhardness testing serves as a reliable, semi-destructive method to monitor stress redistribution [1,4,11,18].
4. The magnitude of relaxation depends on cyclic stress amplitude, cold work level, and initial residual stress gradient [5,8,9].

However, despite these contributions, there remains a need for **quantitative correlation between residual stress relaxation and microhardness reduction** under varying cyclic loads and peening intensities. The current study addresses this gap by employing a modified **Vickers indentation method** to evaluate residual stress redistribution in **2024-T351 aluminum alloy** subjected to cyclic loading and different shot peening intensities.

Experimental Procedure

Material Preparation

The study was conducted on 2024-T351 aluminum alloy, a material widely used for manufacturing the lower wing panels of large commercial aircraft. This selection is due to its reputation as one of the best-known high-strength aluminum alloys. Its combination of high strength and excellent fatigue resistance makes it ideal for structural applications where a favorable strength-to-weight ratio is crucial. Additionally, it is easily machined to a high-quality finish and can be readily formed in its annealed state before being heat treated [15]. The 2024-T351 alloy is a copper-magnesium-based, age-hardenable alloy. The presence of copper allows the material to be strengthened through the age-hardening process, while magnesium helps mitigate the embrittling effects of iron impurities [15]. This alloy is a solution of heat-treated; control stretched, and naturally aged material. The raw material, a plate measuring 1m x 1m with a thickness of 6.5 mm, was supplied by Alcoa China. The tested material had a tensile strength of 484 MPa, a yield strength of 348 MPa, and an elongation of 15%. The chemical composition is detailed in Table 1, and the raw plate is shown in Figure 3.2. Fatigue specimens were scaled according to the Airbus standard [16].

Micro-hardness measurements were performed on samples after each fatigue cycle under both stress loads. The samples were prepared using a Mitsubishi RA9 CNC EDM wire cutting machine with a wire diameter of 0.25 mm and a feed rate of 1.1 m/min. This method was specifically chosen to minimize the heat generated during the cutting process. To further control temperature, extensive cooling was employed to maintain the cutting temperature between 25 °C and 30 °C (room temperature). A thermometer was used to continuously monitor and

ensure the temperature remained within this range. Following cutting, specimens were prepared according to ASTM E3 standards to ensure the surface was free of any defects [17] that could affect the hardness indentations or subsequent measurements of the diagonals.

Shot peening was chosen as the surface treatment due to its widespread use, simplicity, global acceptance, and well-understood process. All specimens were shot peened at GT Industrial PTE LTD in Singapore. The surface flatness of the specimens was verified to be within close tolerances, as shown in Figure 1. The parameters of the shot peening process—such as the size, velocity, shape, angle, and flow rate of the shot—were carefully controlled to achieve the desired treatment. The specific shot material used for calibration was SAE 1070 cold-rolled steel. The relative work applied to the surface is known as peening intensity. To measure this intensity, a standard Almen strip was used. These strips are made from carefully controlled spring steel and are available in three standard thicknesses. For this research, the thickest strip was 2.38 ± 0.02 mm, and the thinnest was 1.30 ± 0.02 mm. The curvature of a peened strip is measured using a dial gauge while the strip is held magnetically against two pairs of ball contacts at a fixed distance. The gauge is zeroed with the unpeened side facing the dial, and the Almen height is read directly in thousandths of an inch or millimeters. An intensity range was selected using S110 cast steel shots to achieve Almen intensities of 4-6A, 6-8A, and 8-10A.

Table 1: Specific chemical composition of 2024-T351 Al Alloy (wt. %)

Component	wt. %	Component	wt. %	Component	wt. %
Si	0.50	Al	93.50	Fe	0.50
Ti	0.15	Cr	0.10	Mg	1.20-1.8
Zn	0.25	Cu	3.80-4.90	Mn	0.030-0.9
Zr	0.20	Ni	0.05	Pb	0.05



Figure 1: Image of test specimens after shot peened

Micro-hardness tests were conducted in full accordance with the ASTM E 384 standard test method for micro indentation hardness of materials [18]. The tests were performed using a 401 MVD micro-Vickers hardness tester, as shown in Figure 2. During the tests, a maximum force of 100 gf was applied smoothly at a constant rate of 0.1 N s^{-1} with a dwell time of 15 seconds. To ensure accuracy and account for potential errors, five measurements were taken at each depth and then averaged. The resulting data scattering did not exceed 10%.

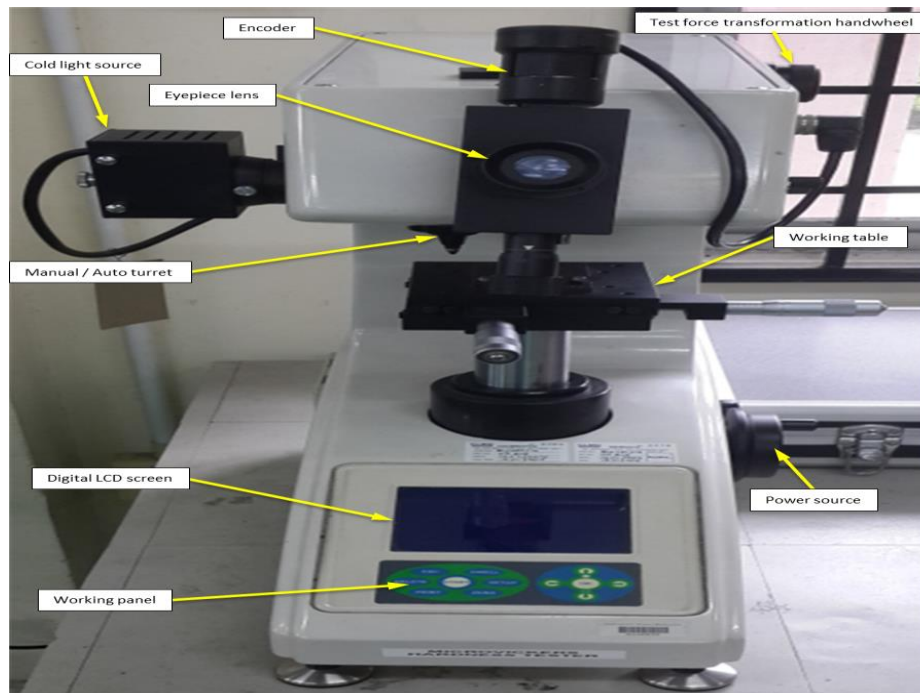


Figure 2: Microhardness test machine.

Results and Discussion

The initial micro-hardness of the unpeened 2024-T351 aluminum alloy was measured using a 401 MVD micro-Vickers hardness tester, yielding a baseline value of 131 HV. Following shot peening, a significant increase in micro-hardness was observed, directly correlating with the applied peening intensity. Specifically, the material's micro-hardness increased to 212 HV for the 4-6A intensity, 225 HV for the 6-8A intensity, and 234 HV for the 8-10A intensity. These results clearly demonstrate that shot peening effectively work-hardens the surface of the aluminum alloy, with a greater peening intensity leading to a more pronounced increase in hardness.

Figure 3 illustrates the reduction in microhardness of the shot-peened material after cyclic loading at an applied stress of 170 MPa. The data indicate that microhardness relaxation occurs rapidly in the initial cycles and continues at a slower rate as the number of cycle's increases. After the first cycle, microhardness for the 4-6A intensity was reduced by 20% to 169 HV. Similarly, the 6-8A and 8-10A intensities showed reductions of 17% (to 182 HV) and 14% (to 200 HV), respectively.

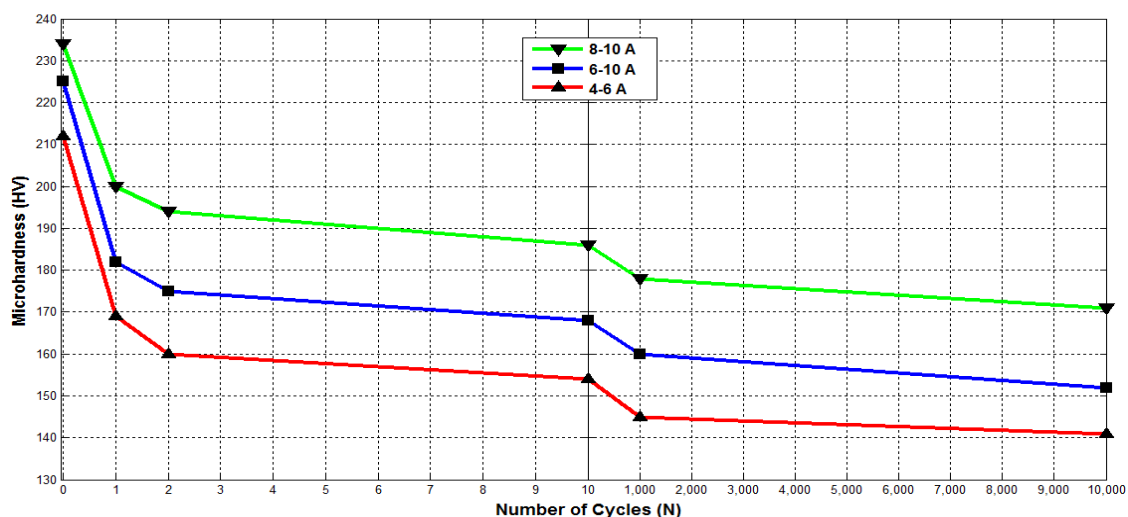


Figure 3: Microhardness reduction for the applied stress of 170 MPa of three different shot peening intensities (4-6A, 6-8A, and 8-10A) at certain number of cycles.

Following the second cycle, the reductions were 24% (160 HV) for 4-6A, 22% (175 HV) for 6-8A, and 20% (194 HV) for 8-10A. After 10 cycles, the values were 151 HV (28% reduction) for 4-6A, 168 HV (25% reduction) for 6-8A, and 186 HV (20% reduction) for 8-10A. At 1,000 cycles, the hardness values dropped to 145 HV (31%

reduction) for 4-6A, 160 HV (28% reduction) for 6-8A, and 178 HV (23% reduction) for 8-10A. Finally, at 10,000 cycles, the microhardness stabilized at 141 HV (33% reduction) for 4-6A, 152 HV (32% reduction) for 6-8A, and 171 HV (26% reduction) for 8-10A. These results demonstrate a clear trend: the higher the initial peening intensity, the more resistant the material is to hardness relaxation under cyclic loading. This suggests that the residual compressive stress from shot peening effectively mitigates the plastic deformation that leads to microhardness reduction.

Figure 4 illustrates the reduction of initial microhardness for different shot-peening intensities under a cyclic load of 280 MPa. The data shows a progressive decrease in microhardness with an increasing number of cycles. After the first cycle, the microhardness was reduced to 165 HV (a 22% reduction) for the 4-6A intensity. For the 6-8A and 8-10A intensities, the values were 179 HV (20% reduction) and 196 HV (16% reduction), respectively.

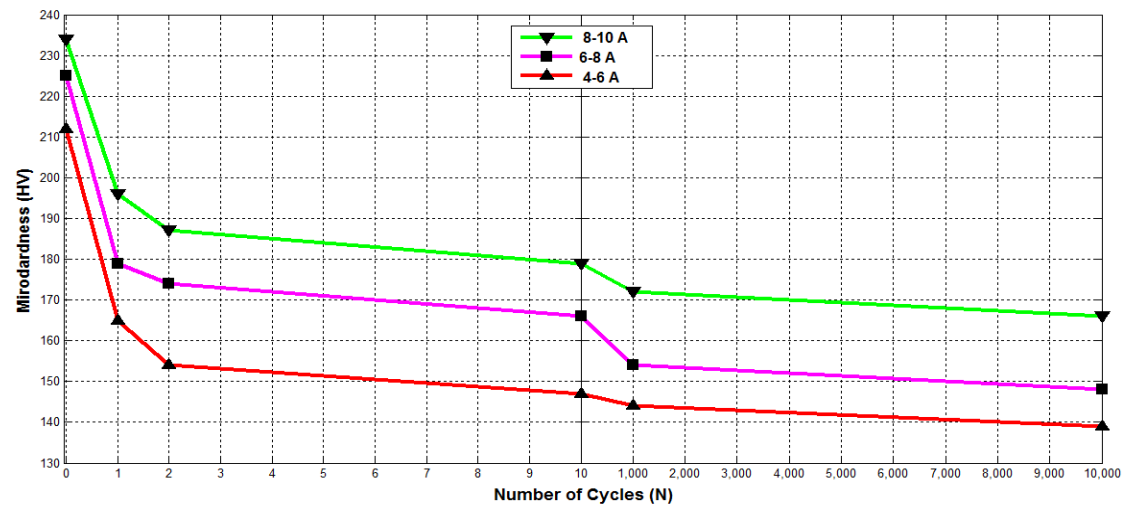


Figure 4: Microhardness reduction for the applied stress of 280 MPa of three different shot peening intensities (4-6A, 6-8A, and 8-10A) at certain number of cycles.

Following two cycles, the microhardness for the 4-6A intensity dropped to 154 HV (27% reduction), while the 6-8A and 8-10A intensities showed values of 174 HV (22% reduction) and 187 HV (20% reduction), respectively. Further reductions were observed at higher cycle counts: 10 cycles: The microhardness for the 4-6A intensity was 147 HV (30% reduction), for the 6-8A intensity it was 166 HV (26% reduction), and for the 8-10A intensity it was 179 HV (23% reduction). 1,000 cycles: The hardness was 144 HV (32% reduction) for 4-6A, 154 HV (31% reduction) for 6-8A, and 172 HV (26% reduction) for 8-10A. 10,000 cycles: The final microhardness values were 139 HV (34% reduction) for 4-6A, 148 HV (34% reduction) for 6-8A, and 166 HV (29% reduction) for 8-10A. The results indicate that a higher applied load (280 MPa vs. the previous 170 MPa) leads to a more significant initial and overall reduction in microhardness. The trend of greater peening intensity providing more resistance to hardness relaxation remains consistent, although the magnitude of the reductions is higher across all intensities due to the increased stress.

Conclusion

The state of residual stress directly influences microhardness, with compressive residual stresses leading to an apparent increase in hardness values. The elevated microhardness observed in the shot-peened material is a direct consequence of changes in dislocation density and arrangement induced by the peening process. Consequently, the relaxation of residual stress under cyclic loading directly results in a proportional reduction of microhardness. Our findings indicate that the microhardness reduction rate is dependent on the applied cyclic load amplitude. Specifically, an applied load of -280 MPa resulted in a greater microhardness decrease compared to a load of -170 MPa. The most pronounced reduction was observed under the highest load: a 34% decrease in microhardness was recorded after 10,000 cycles at -280 MPa with an 8-10A shot-peening intensity. These results demonstrate that the percentage of cold work in the peened material plays a critical role in mitigating the rate of microhardness reduction.

Limitations

Despite the valuable insights obtained, this study has several limitations that should be acknowledged:

1. The investigation was limited to **one alloy type (2024-T351)** and **three shot-peening intensities**, which may restrict generalization to other aluminum alloys or treatment parameters.
2. Residual stress was evaluated **indirectly through microhardness testing**, without complementary validation using **X-ray diffraction** or other direct measurement techniques.

3. Fatigue testing was conducted only up to **10,000 cycles**, which may not fully represent long-term cyclic behavior.
4. **Statistical analysis and error estimation** were not included, limiting the quantitative confidence in the results.
5. Environmental effects such as **temperature, humidity, or corrosion** were not considered, though they could influence stress relaxation in practical applications.

These limitations provide opportunities for future studies to extend and refine the current findings.

Recommendations

This study highlights that the redistribution of residual stress in **2024-T351 aluminum alloy** is strongly affected by shot-peening intensity and cyclic loading. Based on the findings, the following points are recommended:

1. Use **higher peening intensities (8–10A)** to improve resistance against residual stress relaxation.
2. Combine **Vickers indentation** with **X-ray diffraction** for more accurate stress evaluation.
3. Extend fatigue testing beyond **10,000 cycles** to simulate real service conditions.
4. Apply **statistical analysis** (e.g., ANOVA) to verify data reliability.
5. Use **periodic microhardness testing** as a quick indicator of surface stress condition in industrial components.

These measures will enhance the **fatigue life** and **surface integrity** of aluminum parts in aerospace and automotive applications

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