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# IMPACT OF LOCAL PLASTIC DEFORMATION ON FATIGUE LIFE AND STRENGTH OF 2024-T3 ALUMINUM ALLOY NOTCHED SPECIMENS

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***Abstract:*** This study investigates the impact of local plastic deformation on the fatigue life and strength of 2024-T3 aluminum notched specimens. Fatigue tests were performed under constant amplitude loading on both undeformed and plastically deformed specimens. The results indicated that significant plastic deformation induces numerous microcracks, reducing crack initiation time and shortening fatigue life, particularly near the fatigue limit. Fractographic analysis revealed a higher density of microcracks in pre-stretched specimens. Finite element analysis showed that residual compressive stresses delay crack initiation under high applied stresses. Additionally, fatigue tests on cold-expanded holes demonstrated improvements in fatigue resistance, with elliptical mandrels outperforming circular ones. The longitudinal orientation exhibited higher fatigue resistance than the transverse orientation for untreated holes. The beneficial effects of cold expansion were consistent regardless of the loading direction. These findings illustrate the influence of plastic deformation on fatigue life by altering crack initiation and propagation mechanisms, providing insights into discrepancies observed with different surface preparation methods.

***Key words:*** fractographic analysis, finite element analysis, microcracks, crack initiation, residual stress, fatigue life, fatigue strength.

## 1. INTRODUCTION

Engineering experience has shown that load-bearing components and structures can fail under cyclic loads, even when stresses remain below the material's yield or ultimate tensile strength—a phenomenon known as fatigue. Research on fatigue began nearly 200 years ago and gained prominence during the 19th-century Industrial Revolution, when failures of locomotives and boilers highlighted its impact. Key advancements in understanding fatigue included the introduction of concepts like the stress-number of cycles (S-N) diagram, the role of microscopic cracks, and fracture mechanics, shaping modern approaches to predicting and mitigating fatigue failures.

The critical importance of fatigue analysis was underscored during and after World War II, following several high-profile failures. Notably, Liberty Ships suffered cracking in the cold waters of the Atlantic due to brittle welds, and Comet Jet Airliners experienced in-flight fractures caused by cyclic aerodynamic loads. These events emphasized the necessity of robust fatigue analysis to prevent engineering failures [1-4].

The microstructure of materials plays a crucial role in FCG behavior. Jambor examined 304L stainless steel in two microstructural states and found that the coarser microstructure (solution-annealed state) resulted in higher levels of plasticity and roughness-induced crack closure, thereby increasing resistance to crack growth. These findings were corroborated by experiments conducted at varying load ratios [5]. Crack path branching also affects FCG rates.

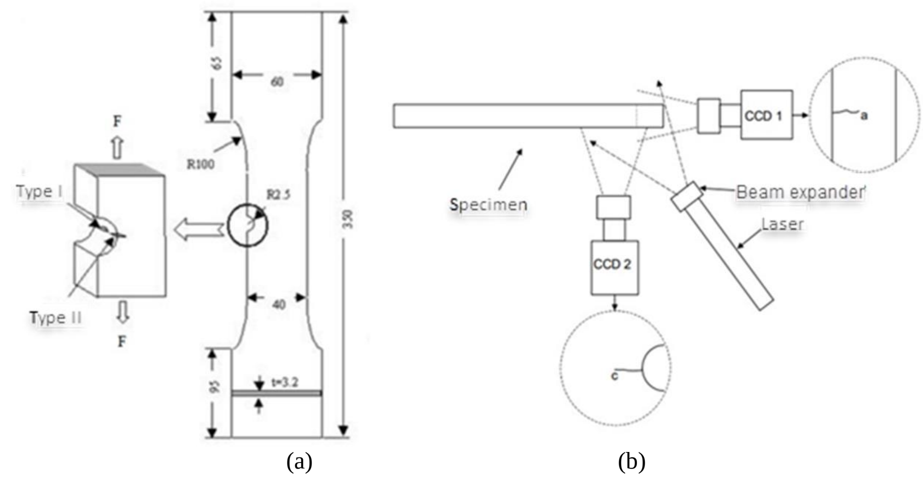
The following studies highlight the multifaceted nature of fatigue crack growth, influenced by factors such as crack closure, material microstructure, crack path branching, in-plane constraints, thermal fatigue, welding defects, crack initiation mechanisms, plastic deformation around holes and local plastic stretch on total fatigue life evaluation. Toribio showed that bifurcated cracks slow down the growth rate compared to straight cracks, with the retardation effect depending on the branch length and angle [6]. In-plane constraints, measured by T-stress, influence FCG behavior. Galkiewicz used a 2D-modified boundary layer model to demonstrate that higher levels of constraint increase FCG rates by limiting the development of plastic zones, which absorb less energy for new surface creation, [7]. Thermal fatigue, particularly in industrial applications like steel rolls, leads to the spalling of large particles. Bombac investigated this in high-Cr steel, revealing that thermal cycles and cooling significantly affect crack formation and propagation, [8].

The fatigue behavior of welded joints is complex due to the presence of defects and residual stresses. Peng et al. studied MIG welding of 6005A-T6 aluminum alloy and found that impurities and oxide-induced crack closure influence fatigue crack propagation [9].
Fatigue crack initiation is a critical part of the fatigue life in components without initial defects. Fintová studied AZ91 magnesium alloy, noting that different initiation mechanisms in low and very high cycle fatigue regions influence fatigue limits [10]. Jesus examined Ti-6Al-4V specimens produced by selective laser melting, highlighting the significant impact of internal surface finish on fatigue performance, [1].
Makabe examined the effects of local plastic deformation on the fatigue life of holed specimens of aluminum alloy 2024-T3, indicating that plastic deformation around holes significantly influences fatigue performance, [12].
Wang studied the effect of local plastic stretch on total fatigue life evaluation, focusing on how plastic deformation impacts the overall fatigue life of materials used in aeronautical applications, [13].
This study investigates the impact of local plastic deformation on the fatigue life and strength of 2024-T3 aluminum notched specimens. Fatigue tests were performed under constant amplitude loading on both undeformed and plastically deformed specimens. Additionally, fractographic analysis and finite element analysis (FEA) were used to evaluate residual stresses and their impact on crack initiation and propagation. Microscopic and scanning electron microscope inspections were conducted to identify the mechanisms of crack initiation and growth in both undeformed and plastically deformed materials.
The results indicated that significant plastic deformation induces numerous microcracks, reducing crack initiation time and shortening fatigue life, particularly near the fatigue limit. Fatigue tests on cold-expanded holes demonstrated improvements in fatigue resistance, with elliptical mandrels outperforming circular ones. The longitudinal orientation exhibited higher fatigue resistance than the transverse orientation for untreated holes. These findings are applicable in aerospace and structural applications, where the durability of components under cyclic loading conditions is critical.
The study underscores the importance of considering local plastic deformation and residual stress in fatigue life predictions. It provides valuable insights for enhancing the durability of structural components through controlled plastic deformation techniques. Furthermore, the research demonstrates the beneficial effects of cold expansion of rivet holes, a common technique in aircraft, highlighting the superior performance of elliptical mandrels in improving fatigue resistance. These findings contribute to the understanding of how local plastic deformations influence crack initiation and propagation mechanisms, offering essential information for the design and maintenance of durable structures. However, these insights are often not taken into account by structural manufacturers.

## 2. MATERIALS AND METHODS

### 2.1. The impact of local plastic deformation on fatigue life

The geometry of the specimen is depicted in Figure 1(a). This specimen is specifically designed for fatigue testing of fastener joints, simulating various load transfer combinations and secondary bending conditions. The test specimen has a thickness of 3.2 mm. A single notch is cut on the side of the specimen to create a stress concentration point, which limits the location where fatigue cracks can initiate. The specimen is loaded along the transverse length, the orientation most resistant to fatigue. According to finite element analysis, the specimen exhibits a stress concentration factor of approximately 3.2 at the notch.




(a) (b)

Fig. 1. Fatigue test specimen and crack size measurement device

The test specimens were manufactured according to workshop standards, without any special treatments on the notch surfaces to smooth them or remove production-related damage and residual stresses. As shown in Figure 1(a), fatigue cracks can initiate either on the notch surface or at the notch corner if secondary bending occurs. The notch was cut using a cutting speed of 16 m/min and a feed rate of 2.5 mm/min, with a cutting tool diameter of 5 mm. For plastically stretched specimens, the notch was cut after applying a static load to achieve the plastic deformation.

Fatigue tests were conducted using hydraulically controlled fatigue testing machines, “Instron 8801 servohydraulic fatigue testing system (Instron, Norwood, USA)”, operating under constant amplitude loading with a stress ratio of R=0.1. Crack initiation and propagation were monitored using the measurement device shown in Figure 1(b). In this system, a laser illuminates the critical area of the specimen (notch surface and one side of the specimen). During fatigue tests, two CCD cameras track the crack initiation and propagation process and record images at predetermined fatigue cycles. The specimen is held stationary during image capture at a preset load.

After the specimen fractures, CCD images are analyzed to determine crack initiation and propagation by comparing correlations between image sequences. This measurement technique offers high precision in determining crack size. Subsequently, the fractured specimens are examined using both an optical microscope and a scanning electron microscope (SEM), “QUANTA 200 3D DUAL BEAM, (Thermo Fisher Scientific, Waltham, USA)”, to identify the micromechanisms of fatigue crack growth and to assess the effect of pre-stress on crack initiation and propagation. The specific microscopes used, along with their magnification and imaging parameters, should be detailed to ensure replicability of the study.

### 2.2. The impact of local plastic deformation on the fatigue strength of notched specimens made from 2024-T3 aluminum alloy

This study examined the impact of local plastic deformation on the fatigue strength of a 2024-T3 aluminum alloy specimen with a pre-drilled hole. The local deformation was applied by inserting a mandrel into the hole. Fatigue tests were performed under cycle asymmetry conditions (R=0 and R=-1), where R represents the cycle asymmetry coefficient. The results indicated that local plastic deformation significantly increased fatigue strength. To further understand this improvement, the hardness distribution around the hole was measured. The findings suggest that the increased fatigue strength is due to local plastic deformations and the compressive residual stress generated near the hole.

Rivet holes in aircraft structures are often subjected to cold expansion to enhance fatigue strength. This process introduces compressive residual stress around the hole's perimeter, delaying the onset of fatigue cracks. During cold expansion, an oversized mandrel is typically pulled through the hole, leading to non-uniform residual stresses across the specimen's thickness. Previous studies have shown that the effectiveness of cold expansion on fatigue crack initiation and propagation depends on the part's geometry, material, applied stresses, and the extent of cold expansion.

The objective of this study was to further understand the improvement in fatigue life achieved through cold deformation of specimens. The experimental procedure involved applying local plastic deformation around the hole by inserting a mandrel, which deformed the hole into a circular or elliptical shape. After the mandrel was removed, fatigue tests were conducted to examine the relationship between fatigue strength, residual stress due to local plastic deformation, and the shape of the hole. The findings demonstrated that cold-deformed holes significantly improved the fatigue life of the specimens, as evidenced by the experimental results.

The material used for the specimens was 2024-T351 aluminum alloy, rolled to a thickness of 3 mm. Circular and elliptical mandrels were inserted into the holes and removed before subjecting the specimens to fatigue testing. Two specimen orientations were tested: in one, the longitudinal direction was parallel to the rolling direction (LR), and in the other, it was perpendicular to the transverse direction (TR). The specimen configuration is shown in Figure 2, with a reduced section length of 33 mm and a width of 18 mm. A 5 mm diameter hole was drilled in the center of each specimen.

The hole expansion process involved inserting mandrels with tapered ends using a lubricant to facilitate insertion. The hole diameter remained consistent on both sides of the specimen. To prevent specimen bending and reduce material flow in the mandrel insertion direction, plates with slightly larger holes were used. The specimen and mandrel were aligned in a vise using a guide, ensuring the mandrel’s central axis, the specimen hole, and the plate holes were aligned. The mandrel was gradually inserted by operating the vise. Subsequently, a 4 mm diameter mandrel was used to push and remove the initially inserted mandrel. The circular mandrel (Type C) was 4% larger than the hole diameter, as was the major axis of the elliptical mandrel (Type E).

Hardness was measured at various distances from the hole. Fatigue testing was conducted at a frequency of 10 Hz with asymmetry coefficients of R=0 and R=-1.

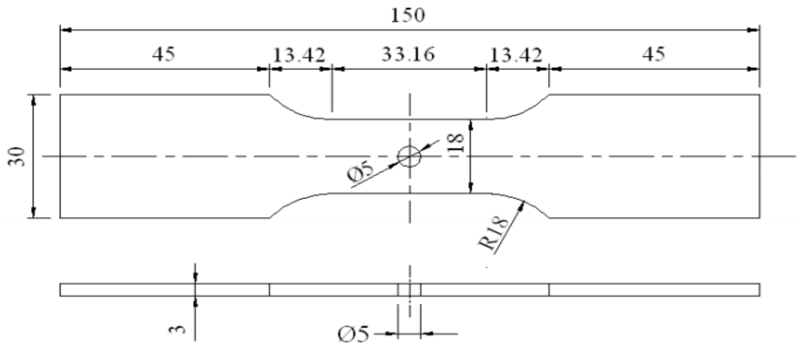



Fig. 2. The specimen used for testing

## 3. RESULTS AND DISCUSSION

### 3.1. The impact of local plastic deformation on fatigue life

Several static tests were conducted to determine the static mechanical parameters of the 2024-T3 aluminum alloy. These tests revealed that the material can undergo a plastic strain exceeding 18% before fracture when subjected to tensile loading. Consequently, a pre-stretch of 10% was applied to the specimens in the fatigue tests to evaluate the impact of plastic deformation on fatigue life. The reference fatigue test results closely matched those reported by the Advisory Group for Aerospace Research and Development (AGARD), though the fatigue lives observed in this study were slightly longer, as illustrated in Figure 3.

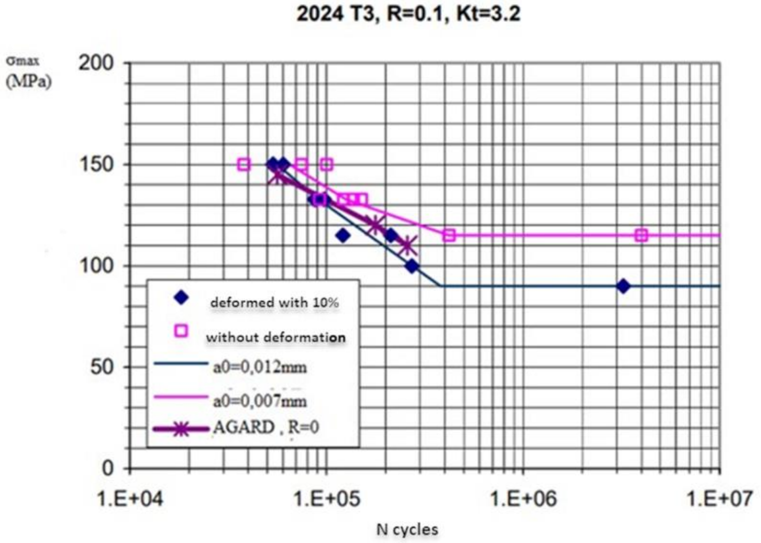



Fig. 3. Comparison of fatigue life between undeformed and pre-deformed specimens.

The fatigue tests indicate that plastic deformation affects the fatigue life of the material, depending on the specimen's loading level. As shown in Figure 3, a reduction of over 20% in fatigue strength was observed near the fatigue limit, while smaller or no reduction was noted at higher stress levels.

Fractographic inspections suggest that plastic deformation can reduce fatigue life by creating numerous microcracks in the material matrix Figures 4(c) and 4(d).

The presence of microcracks reduces the crack initiation time, resulting in a shorter fatigue life. Furthermore, microcracks caused by plastic deformation decrease the variability in fatigue life. Although plastic deformation may slightly influence the crack growth rate, experimental results indicate that this effect is negligible. Figure 5 illustrates the crack growth rate, da/dN, where a (mm) represents the crack length, for a specimen subjected to a 10% pre-stretch compared to a reference specimen under a stress of 115 MPa. The crack growth rates, derived from the experimental crack length (a) versus load cycle (N) curves, are consistent under both conditions. This consistency suggests that the influence of plastic deformation on the fatigue crack growth rate can be disregarded in engineering applications. The observed difference in total fatigue life is attributed mainly to the crack initiation phase.

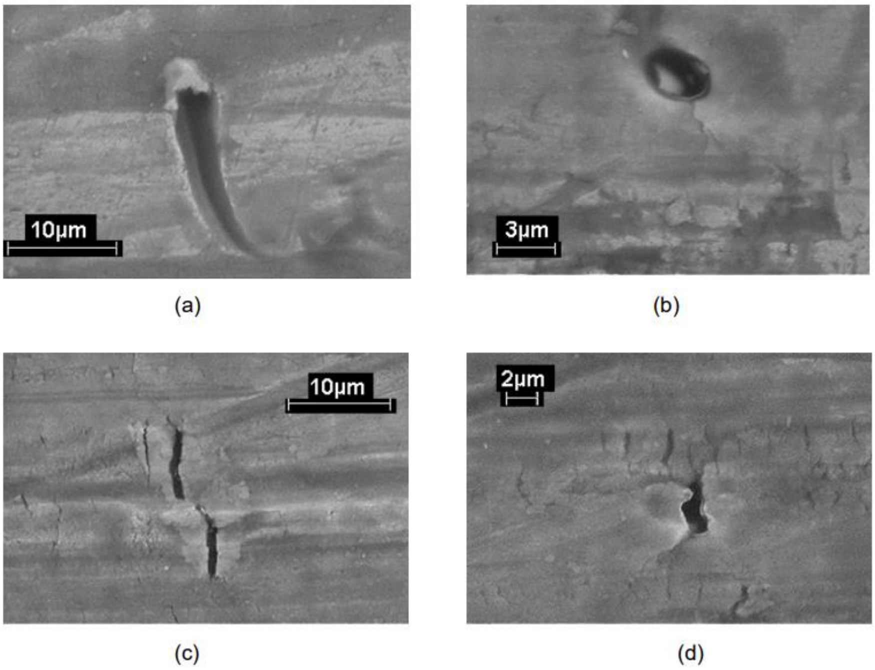


Fig. 4. Microscopic condition of the specimen surface after a 10% stretch

Due to the presence of microcracks, the crack initiation time is reduced, leading to a shorter fatigue life. Additionally, plastic deformation-induced microcracks reduce the variability in fatigue life. While there are indications that plastic deformation may influence the crack growth rate, tests have shown that this effect is marginal. Figure 5 presents an example of the crack growth rate for a specimen with a 10% pre-stretch compared to a reference specimen under a stress of 115 MPa. The crack growth rates derived from the experimental crack size versus load cycle curves are in good agreement under both conditions, suggesting that the impact of plastic deformation on the fatigue crack growth rate can be ignored in engineering treatments. The difference in total fatigue life is primarily due to the crack initiation phase.

Tests indicate that varying initial crack sizes may be necessary for fatigue crack growth analysis, depending on the degree of gross plastic deformation, stress level, and the number of cracks participating in the initiation process. Various defects were observed on the material surface for both pre-stretched and undeformed specimens. However, defects on the original material are mostly scratches and defects within the material matrix, as shown in the micrographic images in Figure 4 a and 4 b. Figure 4 a show a typical machining scratch larger than 10 µm. Impurity particle defects in the material matrix are smaller than machining scratches, as shown in Figure 4 b.

The surface condition changes significantly after substantial plastic stretching, with numerous microcracks larger than 10 µm appearing in the material matrix, as observed in Figures 4 c and 4 d. Generally, cracks formed within the grains Figure 4 c are much larger than those formed along grain boundaries Figure 4 d. Although the defects on the surface of the undeformed material are similar in size to the cracks formed after significant plastic stretching, their roles in crack initiation time are quite different.

The finite element analysis was conducted using ANSYS Mechanical 2022R2 software. The modeling process was carried out in the Static Structural module, employing a 2D analysis approach. Eight-node quadrilateral finite elements were used to ensure accurate geometric discretization. The simulation included six loading steps, allowing for a detailed assessment of the structural behavior under progressive load conditions.

A finite element analysis was conducted to identify the crack initiation mechanism using geometric and material nonlinearity models within a commercial finite element code. The analysis focused particularly on large scratch types, as shown in Figure 4 a. A plane strain deformation model was created to simulate the impact of an edged object on the material surface, assuming an isotropic material model. The impact object was modeled as a rigid surface with greater hardness than the aluminum alloy. Due to geometric symmetry, a semi-infinite model was used.

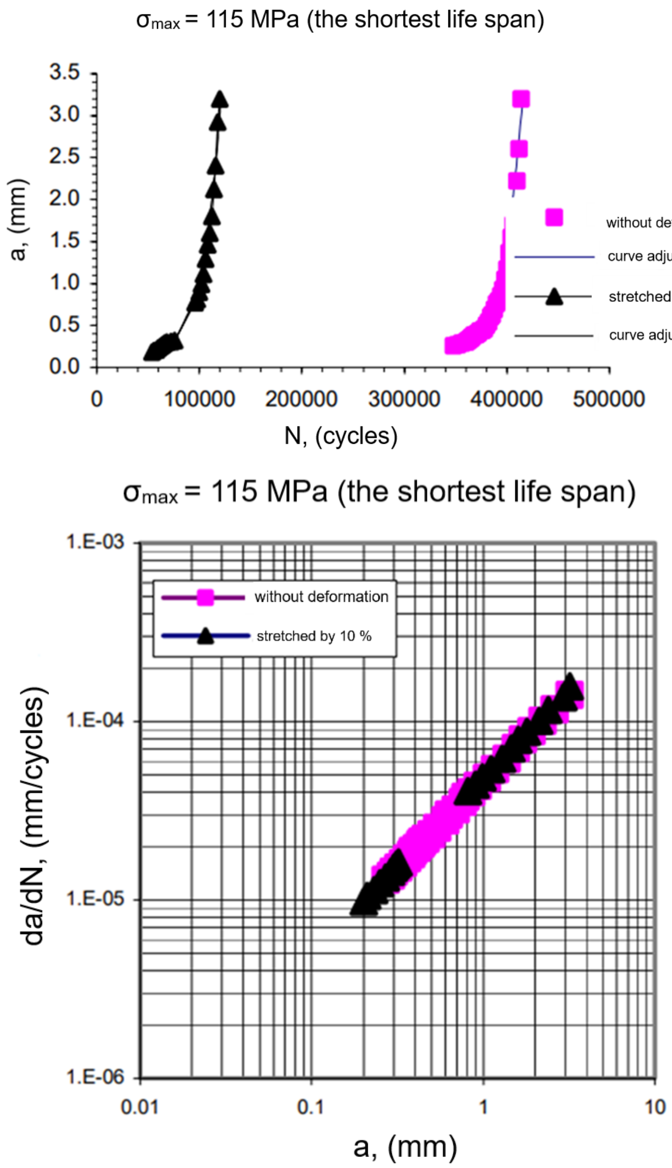



Fig. 5. Fatigue crack growth rate graphs

A six-step simulation was performed, and the results are presented in Figure 6, illustrating the opening stresses (Mode I) at the notch base during each simulation stage. The first step simulates the impact of a rigid edge with a rounded tip. This hard edge penetrates the material, creating an indentation similar to that shown in Figure 4(a). When the edge is removed in the second step, a residual compressive stress is created, leaving an indentation on the material surface. The residual stress amplitude is -600 MPa, exceeding the yield limit due to the plane strain condition that induces a two-dimensional stress state.

The residual stress prevents crack initiation until the applied stress exceeds 85% of the initial yield limit (400 MPa). This residual stress is present at the bottom and sides of the indentation. When a fatigue load is applied, the residual stress state at the indentation ensures that the fatigue crack can only initiate on the opposite side of the material. As shown in Figure 6, residual stress can be relieved by applying significant compressive loads, such as a compression of 400 MPa. Compressive plastic flow generated by stress concentration can release much of the residual compressive stress.

After compression, for instance, the residual stress on the bottom surface of the indentation is reduced. However, the subsurface residual stress remains significant, creating a condition where a fatigue crack can initiate on the lower surface of the indentation due to stress concentration. Nonetheless, the crack must still overcome some of the residual compressive stress by penetrating into the material before fully initiating a fatigue crack. This residual stress can halt crack propagation.

The analysis provides a clear explanation for the observation that fatigue cracks initiate further from machining scratches. Figure 7 shows a microscopic inspection of a specimen's notch. Despite numerous scratches at the bottom of the notch, the fatigue crack is observed to initiate away from these scratches on a smooth surface in the material matrix.

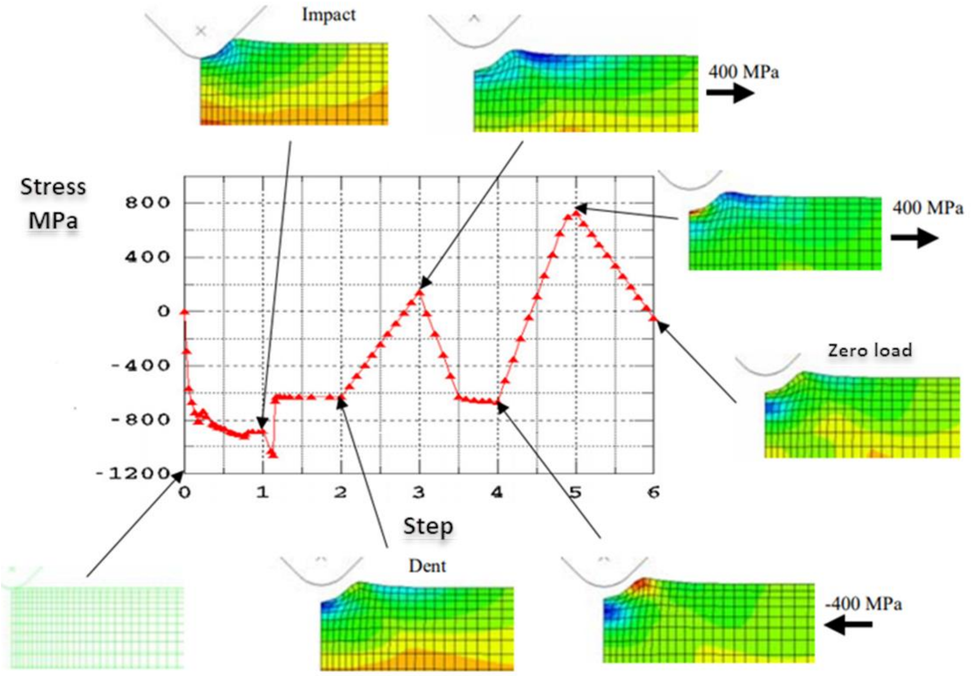


Fig. 6. Finite element simulation diagram of the impact effect on local stress

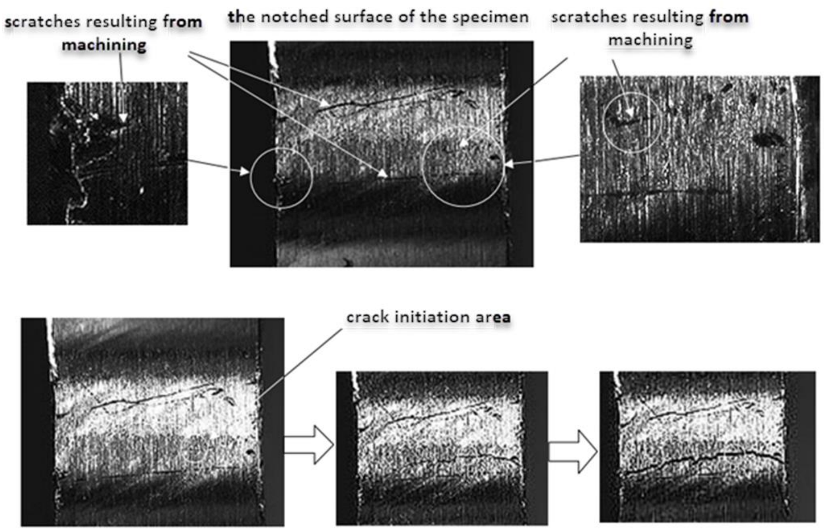


Fig. 7. Fatigue crack initiation site

Interestingly, this analysis might also explain the differences between the reference test results and those from the AGARD project. The AGARD test specimens were prepared using a chemical process to remove a layer of material from the notch, eliminating residual stress and scratches from the notch base. This likely also removed the beneficial effects of the scratches, resulting in a slightly shorter fatigue life compared to the reference tests with the original notch surface condition, as shown in Figure 3.

### 3.2. The impact of local plastic deformation on the fatigue strength of notched specimens made from 2024-T3 aluminum alloy

Figure 8 illustrates the curves for untreated holes and the specimens with circular and elliptical cold-worked holes for both R=-1 and R=0 conditions. For R=-1, it is observed that the LR orientation for untreated holes exhibits greater fatigue resistance than the TR orientation. For R=0, tests were conducted only for the LR orientation. Additionally, the beneficial effect of a 4% cold expansion is clearly evident. Notably, using the Type E mandrel results in a greater improvement in fatigue resistance compared to the Type C mandrel. In the

R=-1 condition, the effect of specimen loading direction on fatigue resistance was significantly reduced for expanded holes. Only four curves were used for the six experimental conditions. The number of cycles to failure for the Type E mandrel shows nearly identical values for LR and TR orientations at σ = 109 MPa. Similarly, for the Type C mandrel, nearly the same number of cycles to failure was observed at σ = 95 MPa and 100 MPa.

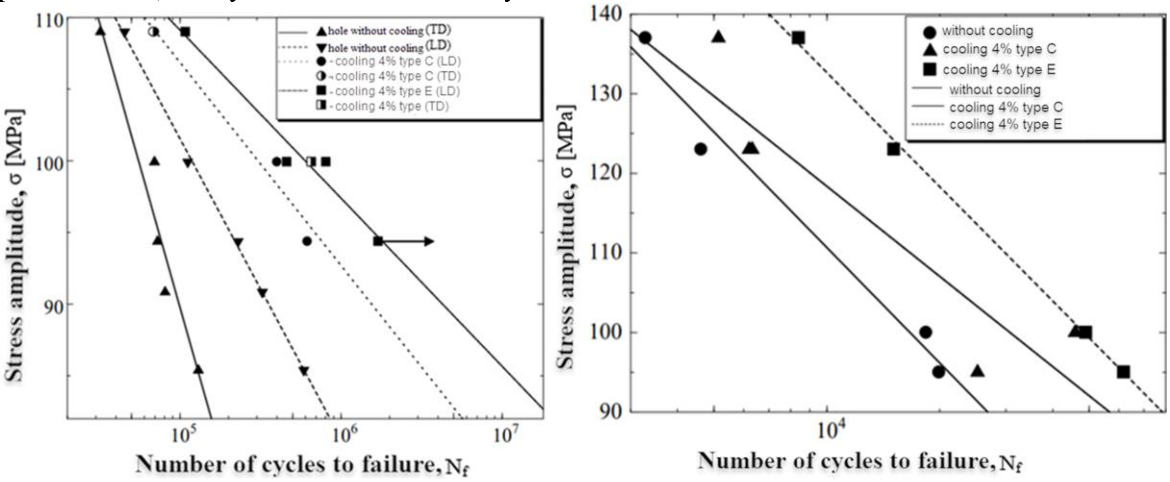



Fig. 8. Graph for untreated holes and 4% cold-expanded holes under R=-1 and R=0 conditions

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For R=0, the fatigue resistance is almost identical to that for R=-1. The fatigue resistance of the specimen was enhanced by cold expanding the holes. It was also highlighted that using a Type E (elliptical) mandrel increased fatigue resistance more than using a Type C (circular) mandrel.

## 4. CONCLUSIONS

An investigation was conducted to evaluate the effect of plastic deformation on the fatigue properties of metallic materials. Fatigue tests were performed under constant amplitude loading on simply notched specimens made from 2024-T3 aluminum plates, both undeformed and plastically deformed. The tests indicate that plastic deformation significantly affects the material's fatigue life, depending on the stress level. A reduction of over 20% in fatigue life was observed near the fatigue limit, with little or no reduction at higher stress levels. Crack initiation and propagation were monitored using laser or white light and recorded with a CCD camera. Microscopic and scanning electron microscope inspections were performed on both the specimen surfaces and fractured surfaces to identify the mechanisms of crack initiation and growth for both undeformed and plastically deformed materials. The research shows that plastic deformation reduces fatigue life by creating numerous microcracks in the material matrix, accelerating crack initiation, and reducing fatigue life dispersion. Although there are indications that plastic deformation might affect the crack growth rate, fatigue tests showed only a marginal impact. In engineering applications, the effect of plastic deformation on the fatigue crack growth rate can be ignored. The investigation suggests that different initial crack sizes might be necessary for analyzing fatigue crack growth, depending on the stress level and the number of cracks participating in the initiation process.

The finite element analysis emphasizes the critical role of residual stress and plastic deformation in influencing crack initiation and propagation. Residual stress, represented as compressive stress generated by the penetration of a rigid object, effectively delays crack initiation by raising the stress threshold needed for cracking. This stress is particularly pronounced at the bottom and sides of the indentation, serving as a barrier to crack propagation.

Plastic deformation, modeled as the material's response to stress concentration and compressive loading, significantly impacts the distribution of residual stresses and the location of crack initiation. The analysis shows that compressive plastic flow reduces residual compressive stress on the surface while preserving substantial subsurface stresses, which can alter crack initiation points. These findings highlight the combined impact of residual stress and plastic deformation on crack mechanisms and fatigue life.

The results align with experimental observations, providing a detailed understanding of how residual stresses and plastic deformation shape crack behavior. The study emphasizes the need to account for these factors in fatigue life predictions and suggests that controlled plastic deformation techniques can enhance the durability of structural components. Cold expansion of rivet holes, a common technique used in aircraft to improve fatigue strength, was also examined. The application of a 4% cold expansion using both circular and elliptical mandrels enhanced the fatigue resistance of the specimens. The elliptical mandrel (Type E) was particularly effective, showing greater improvement in fatigue resistance compared to the circular mandrel (Type C). The beneficial effects of compressive residual stress introduced by cold expansion were evident, as these stresses delayed the fatigue crack initiation process.

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