B.TECH. PROJECT REPORT

On

Effect of Stress Ratio and Notch Sensitivity Factor on High Cycle Fatigue Strength of Al 6061

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INDIAN INSTITUTE OF TECHNOLOGY INDORE

December 2024

Effect of Stress Ratio and Notch Sensitivity Factor on High Cycle Fatigue Strength of Al 6061

A PROJECT REPORT

Submitted in partial fulfillment of the requirements for the award of the degrees

of

BACHELOR OF TECHNOLOGY

in

METALLURGICAL ENGINEERING AND MATERIALS SCIENCE

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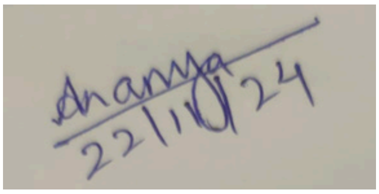
December 2024

CANDIDATE’S DECLARATION

We hereby declare that the project entitled **“Effect of Stress Ratio and Notch Sensitivity on High Cycle Fatigue strength of Al 6061”** submitted in partial fulfillment for the award of the degree of Bachelor of Technology in Metallurgical Engineering and Material Science’ completed under the supervision of **Dr. Jayaprakash Murugesan, Associate Professor, Metallurgical Engineering and Materials Science, IIT Indore** is an authentic work.

Further, we declare that we have not submitted this work for the award of any other degree elsewhere.



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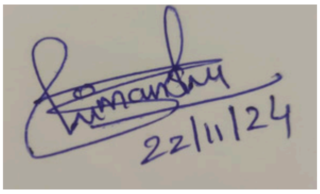

Bhimanshu Durge

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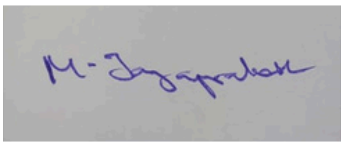
It is certified that the above statement made by the students is correct to the best of my knowledge.



Dr. Jayaprakash Murugesan
(Associate Professor)

Preface

This report on "Effect of Stress Ratio and Notch Sensitivity on High Cycle Fatigue strength of Al 6061" is prepared under the guidance of Dr. Jayaprakash Murugesan.

Through this report, we have studied the effect of stress ratio and notch sensitivity on the high cycle fatigue strength of Al 6061 alloy. The experimental approach involved subjecting the material to various stress ratios and introducing notches to assess their impact on fatigue performance. Characterization of fatigue strength was carried out using fatigue testing, microstructural analysis through optical microscopy, and SEM examination of fracture surfaces.

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Acknowledgements

We extend our heartfelt gratitude to Dr. Jayaprakash Murugesan for generously allowing us to be part of his esteemed research group. His unwavering support and guidance were instrumental in navigating the challenges of this project, especially during these unprecedented times. Dr. Murugesan's dedication and oversight not only facilitated the project's execution but also provided us with invaluable learning experiences.

A special note of appreciation goes to our lab-mates from the Welding Research Group at IIT Indore. Their constant support, camaraderie, and motivation created a collaborative atmosphere that fueled our enthusiasm throughout the journey.

We would like to express our thanks to Mr. Adarsh Gaurav for his guidance and assistance. Their mentorship played a pivotal role in shaping the direction of our research, and the friendly environment fostered in the lab enriched our understanding not only of the project but also of the broader research discourse. This project has been a collective effort, and we are grateful to each individual mentioned above for their time, efforts, and contributions that have significantly impacted our academic and research endeavors.

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Abstract

This study thoroughly investigates the impact of stress ratio and notch sensitivity factor on the high-cycle fatigue strength of aluminum alloy 6061, a material renowned for its widespread applications in aerospace, automotive, and structural engineering. Its exceptional strength-to-weight ratio, corrosion resistance, and mechanical adaptability make it a preferred choice for components requiring both durability and lightweight properties. However, these applications often expose the alloy to cyclic loading and stress concentrations, significantly reducing its fatigue life, especially in the presence of geometric discontinuities like notches. The research adopts a comprehensive experimental methodology, including tensile and fatigue testing, microstructural evaluation, and fractographic analysis, to understand the alloy's mechanical behavior under varying conditions. Specimens with different notch geometries were prepared to simulate real-world stress concentration scenarios, and these samples were subjected to cyclic loading under various stress ratios to replicate operational conditions. The findings reveal a pronounced reduction in fatigue life with increasing notch sensitivity, attributed to the amplification of localized stresses at geometric discontinuities. Additionally, stress ratio variations play a critical role, with higher stress ratios accelerating crack initiation and propagation, while lower ratios provide relatively improved fatigue resistance. The study's findings provide essential insights into optimizing aluminum alloy 6061 for high-performance applications. By understanding the relationship between stress ratios, notch sensitivity, and microstructural characteristics, designers and engineers can develop strategies to enhance the alloy's durability and reliability. This research underscores the importance of addressing stress concentration and cyclic loading during the design and manufacturing processes to improve the fatigue performance of aluminum alloy 6061 in demanding environments.

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Chapter 1

Introduction

1.1 Motivation

The motivation for this research on 6061 aluminum alloy arises from its crucial role in high-performance sectors like aerospace, automotive, and automation. This alloy is prized for its high strength-to-weight ratio, superior machinability, and excellent weldability, making it highly suitable for applications where both structural strength and manufacturing efficiency are required. These attributes allow it to meet the demands for lightweight materials in advanced engineering applications. However, despite its advantages, 6061 alloy faces limitations in environments where cyclic stresses are high, particularly when notches or stress concentrators are present. These factors contribute to its susceptibility to fatigue over extended service periods, which restricts its broader use in load-bearing structures that demand high endurance and longevity.

This research seeks to address these challenges by examining the high-cycle fatigue strength and notch sensitivity of 6061 aluminum alloy, exploring how it withstands repeated loads over long periods. High-cycle fatigue testing simulates conditions the alloy would encounter in real-world applications, where it often experiences millions of cycles at relatively low stress levels. By focusing on fatigue resistance in the presence of notches, this study aims to better understand the durability of the alloy in applications where stress concentrators are common. Notches, whether intentional (e.g., holes or design features) or unintentional (e.g., surface imperfections), can accelerate fatigue failure by concentrating stress in specific areas. Understanding how 6061 alloy responds to these factors is critical, as it could inform design strategies that mitigate fatigue effects, thereby enhancing the alloy's reliability in critical applications.

The insights gained from this study are expected to contribute to a deeper understanding of the fatigue behavior and notch sensitivity of 6061 aluminum alloy, with implications for material optimization and engineering design. By providing valuable data on the alloy's fatigue limits and how notches impact its performance, this research supports ongoing developments in materials science to enhance the durability and service life of aluminum alloys. The findings will be particularly beneficial in high-stakes fields, aligning with industry demands for materials that are not only lightweight but also resilient under cyclic loading conditions. This work ultimately aims to push the boundaries of 6061 aluminum alloy's applicability, enabling its use in environments that require both high performance and longevity, and contributing to future engineering advancements in sectors where reliability and fatigue resistance are paramount.

1.1.1 Materials Selection and Justification

The selection of materials for any manufacturing process is a critical decision that significantly impacts the final product's performance and durability. In this BTP, the choice of rolled Al6061 aluminum alloy is a strategically driven approach, aimed at studying the effects of notch sensitivity and fatigue limit in high-performance applications

Al6061 Aluminum Alloy:

Rolled Al 6061 is a widely-used aluminum alloy renowned for its excellent mechanical and metallurgical properties, making it suitable for various applications ranging from aerospace to automotive, and even in general engineering [1,2]. Here's a detailed description of its metallurgical properties, including heat treatment, alloying elements, mechanical characteristics, corrosion resistance, and other important properties. References are provided to support further research.

Metallurgical Properties:

1. Composition and Alloying Elements

Aluminum 6061 is mostly made of aluminum, with silicon and magnesium serving as its primary alloying ingredients. Al 6061's precise composition consists of:

Element	Amount (wt %)
Aluminium	96.85
Magnesium	0.9
Silicon	0.7
Iron	0.6
Copper	0.30
Chromium	0.25
Zinc	0.20
Titanium	0.10
Manganese	0.05
Others	0.05

Table 1.1 : Composition of Aluminium 6061 alloy. [3]

These components give Al 6061 its unique qualities; silicon improves casting qualities and lowers melting temperature, which makes alloying easier, while magnesium increases strength and resistance to corrosion. Grain boundary precipitation of magnesium silicide, which could otherwise cause the alloy to become brittle, is inhibited by chromium. Strength, formability, weldability, and corrosion resistance are all balanced by the combined actions of these alloying components.

2. Heat Treatment and Temper Designations

A variety of heat treatment techniques can be used to aluminum 6061 to improve its mechanical qualities. The following are the most widely used temper designations for rolled Al 6061:

The annealed condition 6061-O has the best ductility but the lowest strength.

6061-T4: A solution with moderate strength that has been heat-treated and naturally aged.
6061-T6: Solution heat-treated and artificially aged, providing exceptional machinability and strength.[4]

When alloying elements are dissolved into a solid solution by the solution treatment procedure, followed by quenching and aging, Al 6061 reaches its maximum strength in the T6 condition. Because of the creation of Mg2Si (magnesium silicide) particles that prevent dislocation movement, the aging process permits the formation of tiny precipitates, which increase strength.

While the T6 temper maximizes strength, the T4 condition offers a balance between good ductility and moderate strength. Because tempering is so versatile, grades can be chosen according to the strength and formability needed for a given application.

3. Mechanical Properties

The state of heat treatment has the biggest impact on the mechanical characteristics of rolled Al 6061. The T4 and T6 tempers, which are most frequently employed in rolled products, differ greatly in their characteristics.

- 6061-T6 Tensile and Yield Strength**:** Al 6061 has a yield strength of around 275 MPa (40 ksi) and a tensile strength of about 310 MPa (45 ksi) in the T6 temper. Because of this, it is among the strongest varieties of Al 6061 that may be used in structural applications.[5]

- 6061-T4: The yield strength is roughly 145 MPa (21 ksi) while the tensile strength is lower in the T4 temper, at about 240 MPa (35 ksi). Better formability is made possible by the increased ductility that makes up for this decreased strength.[6]

Applications where greater ductility is needed may benefit from the T4 temper's lower hardness.

4. Ductility and Elongation

In T6, the elongation of rolled Al 6061 is approximately 10–12%, but in T4, it might reach 16–18%. Higher ductility, which is preferred in forming operations, is seen in this increased elongation in the T4 condition. Better resilience to cracking during machining or forming is another benefit of high elongation.

5.Corrosion Resistance

Rolled aluminum 6061 resists corrosion well in both maritime and general air conditions. The presence of silicon and magnesium, which aid in the formation of a persistent oxide layer on the material's surface, is primarily responsible for its corrosion resistance[5].By serving as a barrier, this oxide layer stops more corrosion.

Furthermore, Al 6061 is renowned for its ability to withstand stress corrosion cracking (SCC), particularly when it is in the T6 condition. Anodizing, which thickens the protective oxide layer and increases resistance to pitting corrosion, especially in maritime conditions, can further improve corrosion resistance.

6. Machinability and Workability

One of the most machinable aluminum alloys is 6061, especially when it is in T6 state. Its high hardness prevents unnecessary tool wear and enables precise, clean cuts. Its machinability is influenced by several important parameters, including:

Outstanding Chip Control: The alloy creates short chips that lessen tool clogging and assist to keep the workspace tidy.

Decreased Tool Wear: When machining Al 6061, the tool life is longer than with softer aluminum alloys because of its moderate hardness.

Surface Finish Quality: Al 6061 responds well to machining processes, giving components that are turned or milled a high-quality finish.

Conversely, workability varies according on temperament. Al 6061 is comparatively easy to form in the T4 condition, enabling rolling, bending, and drawing operations without cracking. Because of the increased hardness in the T6 condition, formability is reduced;

however, this can be controlled by using mild heating to increase flexibility.[5]

7. Weldability

Because of its great weldability, rolled aluminum 6061 can be used for structures that need welded joints. However, because the heat-affected zone (HAZ) loses strength, the weld zone may be weaker than the underlying material. Post-weld heat treatment, particularly aging, can help to reduce this problem by restoring some of the weld region's strength [7].

Al 6061 is frequently welded using the following techniques:

For accurate control and superior welds, TIG (tungsten inert gas) welding is recommended. Because MIG (Metal Inert Gas) welding produces quicker weld speeds, it is frequently utilized in bigger assemblies.

1.1.2 Applications

6061 aluminum alloy is renowned for its versatility and is widely utilized across various industries due to its favorable mechanical properties and corrosion resistance. Its representative applications include the following sectors:

1.Aerospace Applications

Al 6061 is highly prized in the aerospace industry for its strength-to-weight ratio, which is crucial for creating lightweight components that can withstand severe stress. Because of this, Al 6061 is frequently used in frames, fittings, and structural parts where excellent structural integrity and weight reduction are essential [8].

Example: Aircraft frames and fuselage components, Al 6061 is frequently utilized in aircraft frames and fuselage components because of its strength and stiffness. For instance, it is used in lightweight aircraft, such as tiny passenger aircraft and single-engine aircraft, when durability and material weight are important considerations. Here, the T6 temper is especially preferred since it offers the most strength without appreciably adding weight.

2. Automotive Industry

Al 6061 is used to make parts for automobiles that require high strength, resilience to fatigue, and lightweight qualities. Reducing vehicle weight with aluminum components is becoming more and more crucial as fuel efficiency increases, and Al 6061 is a good option.

For instance, suspension components, Control arms, suspension links, and brackets are among the suspension parts that frequently use rolled aluminum 6061. Material that can sustain high fatigue pressures without failing is necessary for these components because they are subjected to repeated load cycles. Al 6061-T6 is appropriate for these kinds of applications due to its high fatigue strength and resistance to wear. Its resistance to corrosion also aids in withstanding environmental factors like dampness and road salt.[1,2]

3.Marine Environments

Because of its ability to withstand corrosion, particularly in the T6 temper, Al 6061 is a good choice for marine settings where other metals can be rapidly corroded by prolonged exposure to water and saline conditions. The inherent oxide coating of this alloy acts as a barrier to stop corrosion, and anodizing can improve this quality even more.

Example: Ship fittings and structural components, Ship decks, hulls, and fittings that must endure severe maritime conditions without corroding use rolled aluminum 6061. For example, it is used in yacht superstructures and small boat hulls, where buoyancy and performance depend on lightweight, durable materials.

4. Construction and Architecture

Because of its strength, ease of manufacture, and visual appeal, Al 6061 is frequently used in windows, frames, structural components, and other architectural features in construction. Because the alloy may be anodized, it can also be coated to improve its look and resistance to corrosion, which makes it perfect for exposed structures.

Example: Building Facades and Window Frames, Al 6061 is frequently utilized in contemporary construction facades where materials that are both robust and lightweight are crucial. For instance, aluminum frames in skyscraper construction offer strong support for huge glass windows while maintaining the structure's overall light weight. Even when exposed to a variety of weather conditions, these components will last a long time thanks to Al 6061's resistance to corrosion.

5. Industrial Tools and Machinery

Because of its hardness and machinability, Al 6061 is frequently used for industrial tools and machinery parts. Tool wear is decreased by its ability to tolerate wear from mechanical processes while remaining machinable due to its hardness in the T6 temper.

For instance, molds and fixtures, Al 6061 is frequently utilized in the manufacturing sector to create molds, fixtures, and jigs. Al 6061 molds, for instance, are used for prototyping in plastic injection molding because they can be machined to exact tolerances and have enough strength to withstand the pressures required in molding operations. Because aluminum is easier to machine than steel, this saves money and time.

6. Electrical and Electronic Uses

Al 6061 is also utilized in electronics for heat sinks, enclosures, and other parts that require corrosion resistance, electrical conductivity, and heat dissipation. The thermal conductivity of this alloy prolongs the life of electronic devices by minimizing heat accumulation.

Heat Sinks in LED Lighting, for instance, Al 6061 is utilized in LED heat sinks to effectively dissipate heat because of its high thermal conductivity. The metal is perfect for complex designs needed in LED lighting fixtures because of its lightweight and machinable qualities. Al 6061 heat sinks, for example, contribute to the maintenance of ideal operating temperatures, extending the life of LEDs used in high-power lighting applications.

7. Recreational and Sports Gear

Al 6061 is widely used in the manufacturing of recreational equipment, particularly products that must be both lightweight and long-lasting, because of its excellent strength-to-weight ratio and resistance to corrosion.

For instance, bicycle frames are frequently made of Al 6061-T6, a material that combines strength and portability. Because of its ability to withstand corrosion, this alloy is especially well-suited for outdoor activities like mountain biking, where gear may be subjected to dirt and dampness. It is also perfect for absorbing shocks while preserving stability due to its stiffness and fatigue resistance.

8. Medical Equipment and Devices

Medical devices can benefit from the alloy's machinability and biocompatibility, especially in non-implantable applications where materials that are lightweight and resistant to corrosion are needed.

For instance, frames for medical equipment
Because it is lightweight and resistant to sterilizing treatments, Al 6061 is utilized in medical equipment stands and frames. Aluminum frames, for instance, give X-ray machines rigidity and support while facilitating easy movement of the apparatus in a medical environment.

Chapter 2

Literature Review

2.1 Fatigue

The progressive, localized, and permanent structural change that happens in materials as a result of varying loads and strains is called fatigue. After a certain number of load fluctuations have taken place, crack initiation and propagation begin. Plastic strain, tensile stress, and cyclic stress all contribute to fatigue-related fractures. It's interesting to note that fatigue cracking is initiated by cyclic stress, tensile stress, and plastic strain, but it only spreads in one of the aforementioned scenarios. In other words, cyclic stress acts as an initiator, but only if the fatigue cracking is tensile in nature does it spread. Although a load brought on by compression can occasionally result in fatigue, compression by itself cannot.

The fatigue process can be divided into three distinct stages: initial damage that leads to crack nucleation and initiation; progressive cyclic growth of a crack, or crack propagation, until the remaining uncracked cross-section becomes structurally inadequate to support applied loads; and finally, a rapid, sudden fracture of the remaining cross-section. When cyclic loads are substantially lower than the material's static yield strength, fatigue cracking commonly occurs. When the material has a high work-hardening rate, which accelerates fatigue, or when low-cycle fatigue occurs, stresses build up to a level that exceeds the static yield strength.

Cracks typically start and spread in places with high strain, frequently close to structural flaws that act as stress concentrators and encourage localized strain.

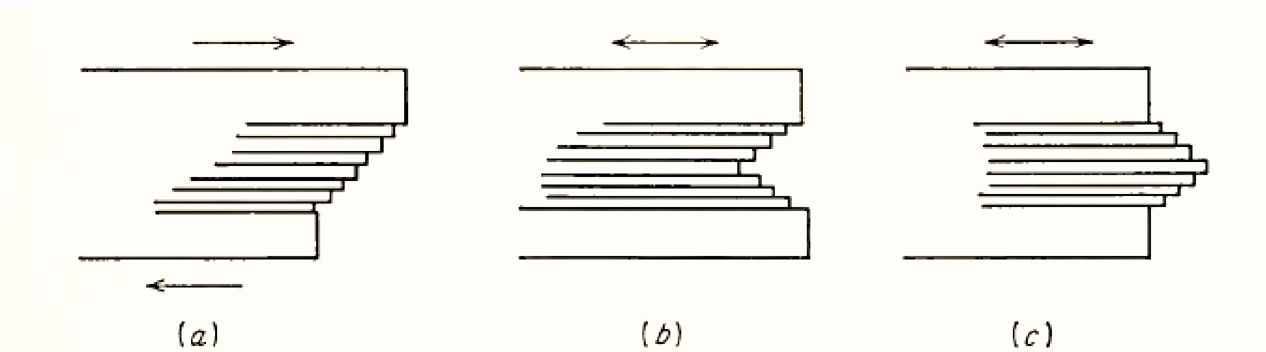


Fig 2.1 W. A. Wood's concept of micro-deformation leading to formation of fatigue crack, (a) Static deformation; (b) fatigue deformation leading to surface notch (intrusion) ; (c) fatigue deformation leading to slip-band extrusion [9].

Engineering materials always contain such defects and therefore are most susceptible to fatigue crack formation in such areas. Cyclic loading generates a plastic deformation zone at the tips of the defects. This plastic deformation zone serves as a nucleation site for fatigue cracks. These grow through the material under the applied stress until they eventually cause fracture. On a microscopic scale, crack nucleation is the most important stage in the fatigue process. It is controlled by local stress concentrations and inhomogeneities of the material [10].

2.1.1 Cyclic Stresses

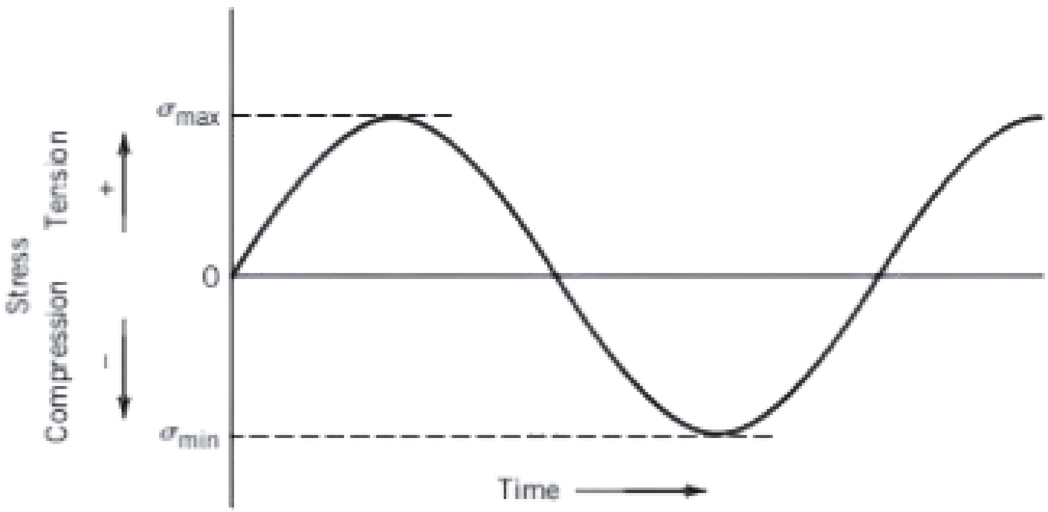
The cyclic stresses are time-dependent applied stresses often in the form of shapes of axial, (tension–compression), flexural (bending), or torsional (twisting) deformations. During cyclic material loading, three major kinds of fluctuating stress–time relations occur:

1.Reversed stress cycle:

The stress varies sinusoidally; that is, it increases and then decreases symmetrically about a mean stress level of zero. This means that the alternate stress is given by a maximum tensile stress (σ_{max}) and an equal-magnitude minimum compressive stress (σ_{min}), as shown in Fig 2.2 (a). This repeated cycle is known as a fully reversed or alternating stress cycle.

2.Repeated Stress Cycle:

In this type of loading, the maximum and minimum stresses are unsymmetrical about zero stress with nonzero tensile and compressive magnitudes. A repeated cycle is demonstrated in Fig 2.2 (b), where the stress oscillates but does not return to a completely reversed state.



(a)

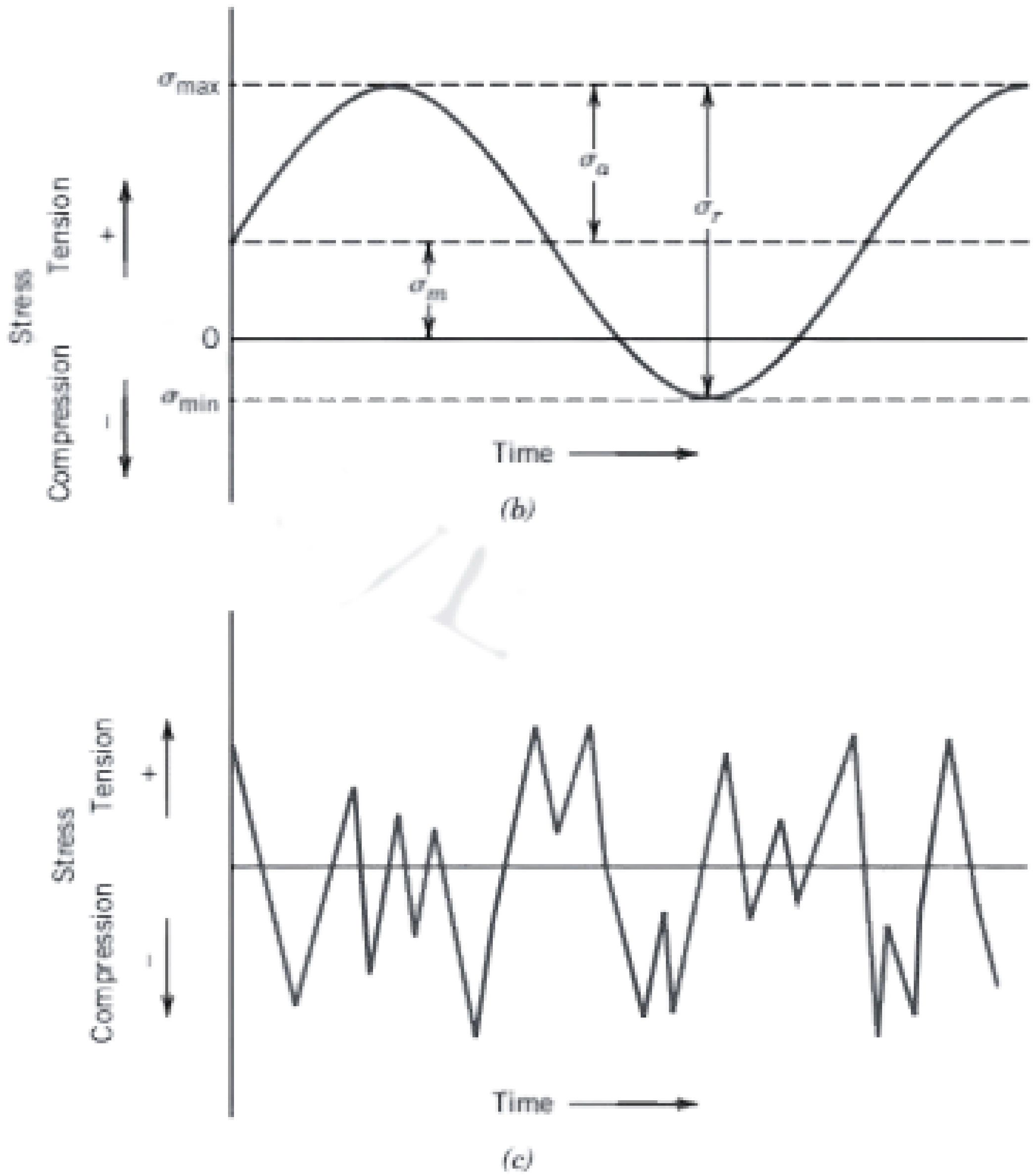


Fig 2.2 Variation of stresses with time that accounts for fatigue failures. (a) Reversed stress cycle, in which the stress oscillates from a maximum tensile stress to a maximum compressive stress of equal magnitude. (b) Repeated stress cycle, in which maximum and minimum stresses are asymmetrical relative to the zero stress level; mean stress , range of stress , and stress amplitude are indicated. (c) Random stress cycle.[11]

3.Random Stress Cycle

This cycle is marked by uneven stress fluctuations in both amplitude and frequency, with stresses that come up erratically; as depicted in Fig 2.2(c). Such loading conditions are normally met in actual applications because stresses do not follow a predictable pattern of incidence [11].

2.1.2 Forms of fatigue

Fatigue failures in materials are broadly classified under two categories: mechanical fatigue and thermal fatigue. Within each of these, there are particular types of fatigue damage that occur due to operational or environmental conditions.

1.Mechanical Fatigue

Long-term exposure to cyclic stresses produces mechanical fatigue. In fact, most components designed to resist alternating mechanical stresses—such as rotating machinery and pressure control valves—do not fail by fatigue unless they are weakened by another damage mechanism, such as impact from foreign objects or corrosion. Two common forms of mechanical fatigue are vibration fatigue and corrosion fatigue.

Vibration Fatigue

One class of mechanical fatigue results due to cyclic stresses that cause equipment or piping vibration and, consequently, their subsequent operation. For instance, operation of equipment outside predetermined integrity operating windows is considered to be vibration induced from fatigue. Poor design of some installations, inadequate support-albeit sometimes in the form of missing dampeners, especially-and excessive rigidity would become the main causes of such vibration fatigue. The two important variables that govern the fatigue damage due to vibrations are amplitude and frequency. These contribute to crack initiation and subsequent crack propagation within the material [9].

Corrosion Fatigue

Corrosion fatigue arises as a result of interaction of cyclic mechanical loads with the corrosive environment. A corrosive environment degrades the surface layer of metal, and thus the resulting corrosion damage has a function of stress raiser. Thin films and protective coatings are usually applied as a means of preventing corrosion-related damage to equipment, and are often susceptible to mechanical fatigue, which damages the outer layer of protection and allows the metal inside to experience the environment.[9]

This synergy between mechanical and chemical damage increases crack growth and causes the component to fail prematurely.

2.Thermal Fatigue

Cyclic temperature causes thermal fatigue. It is typical of tube assemblies in fired heaters or

similar equipment. Mechanical fatigue either is or can be present in thermal fatigue. This type of fatigue is most commonly linked to the start-up and shutdown operations of equipment because the rapid change in temperature that results during these operations subjects the material to thermal shock, potentially causing instantaneous failure.
The susceptibility of the material to thermal fatigue also increases with an increase in the cycling frequency and rate of temperature change. Probably the most well-known rule of thumb relates that thermal fatigue is probable if the temperature change exceeds 200°F between the operating and shut-down conditions. This cycling produces thermal stresses that can eventually lead to formation and propagation of fatigue cracks in the material [9].

Mitigation Measures for Thermal Fatigue

Thermal fatigue can be mitigated by adopting proper design and operational practices that minimize thermal stresses and thermal cycling. Key mitigation strategies include the following:

- Optimized Design to Minimize Stress Concentration: Structural designs should be made to minimize potential sites of stress concentration, which can act as initiation sites for thermal fatigue cracks. Techniques such as blending weld profiles through grinding and ensuring gradual, smooth transitions in thickness may be considered.

- Controlled heating and cooling rates: the rates of heating and cooling during start-up and shut-down operations reduce thermal gradients that lead to the accumulation of thermal stress. Gradual heating and cooling can reduce the chance of thermal shock and extend the service life of the component.

- Minimize cycle start-up and shutdown frequency: Reduces the number of thermal cycling exposures and therefore the total amount of damage through fatigue buildup.

- Reduce differential thermal expansion: In cases where there are two dissimilar metals which are joined as in bimetallic joint differential thermal expansion builds up significant stress. Providing some design flexibility, for example through differential expansion between dissimilar metals is able to minimize the associated risk of thermal fatigue.

2.1.3 Stages Of Fatigue

1.Crack Initiation:

The process of cracking initiation in metallic samples that precede fatigue failure consists of a four-step cycle. In the first stage, the material forms cell structures and becomes hardened as the applied loading is applied. Such hardening causes the newly imposed constraint on strain due to these cell structures and leads to an increase in the effective stress amplitude. Eventually, these cell structures collapse and lead to persistent slip bands. Slip within the material localizes at these PSBs, and the increased slip at these locations generates stress concentrations, which become initiation sites for crack formation. The nucleation and growth of a crack to a detectable size comprise most of the crack development process, which is why fatigue failures often seem sudden, with most internal changes in the material remaining undetectable without destructive testing. Fatigue failures even in normally ductile material often show characteristics a bit similar to those of brittle fracture.

PSB-induced slip planes create intrusions and extrusions along the surface of the material, often in paired formations. Such a phenomenon is not caused by a microstructural change but rather by the multiplication of dislocations within the material. The surface, roughened by these slip-generated intrusions and extrusions, is similar to the edge of a slightly mismatched deck of cards. The fine surface features thus formed increase the likelihood of crack initiation because of their inverse proportionality to stress concentration factors.These first steps sometimes are altogether eliminated when the cracks begin at some pre-existing stress concentrators. Examples of these include material inclusions and geometric stress features such as sharp internal corners, fillets [11].

2.Crack Propagation:

Most of the fatigue life of a material is usually taken up by the crack growth phase. The crack growth rate is primarily determined by the range of cyclic loading, but growth rate also depends on mean stress, environmental conditions, and overloads or underloads, which may stop crack growth if the loading is less than a certain threshold.

Cracks in materials can be started and propagate from material defects as small as 10 µm in size. When the crack growth rate increases, fatigue striations may be observed on the fracture surface. Striation widths are proportional to crack growth over one loading cycle, indicating the crack's progression of the crack tip. The striations come from localized plastic deformation near the crack tip.

When the stress intensity exceeds that of a material's fracture toughness, then, through primarily microvoid coalescence, very fast, dynamically unstable fracture results. The region of the fracture surface above final fracture frequently comprises a composite of fatigue-influenced areas and the region controlled by fast fracture [11].

Enhancement and Delaying Actions on Crack Propagation

- **Effect of Mean Stress:** When the mean stress is elevated, an increase in crack propagation rate.

- **Environment:** Environmental exposure accelerates crack growth. In aluminum, for example, the surface cracks allow atmospheric water vapor to dissociate to atomic hydrogen at the tip of the crack, thus embrittling. Cracks that break internally and, therefore, are sheltered from environmental exposure typically grow more slowly (usually a factor of order one than surface cracks.

- **Underloads:** Minor underload cycles can result in enhanced crack growth rates, thus negating any beneficial effects from overloads.

- **Overloads:** Overloads (ordinarily greater than 1.5 times maximum load in a cycle), initially increase the rate of crack growth slightly before inducing prolonged periods of reduced rates.

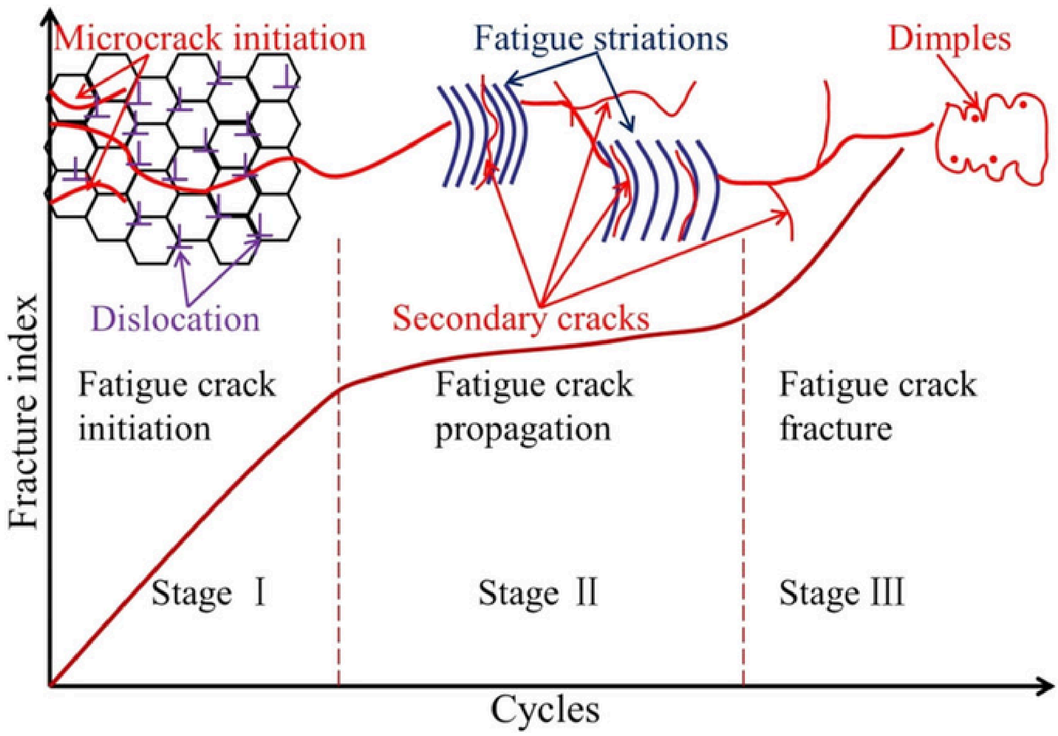


Fig 2.3 : Stages of Fatigue [12]

3.Failure:

The third and final stage of fatigue failure is known as rapid fracture or final fracture. This stage occurs when the remaining uncracked cross-section of the material can no longer support the applied load, exceeding the material's fracture toughness. At this critical juncture, the dominant crack or cracks propagate rapidly, resulting in a sudden and catastrophic failure.

During rapid fracture, the material's resistance to crack propagation is overwhelmed, and the crack accelerates in growth, often accompanied by significant plastic deformation and high strain. This stage of rapid overload fracture is a direct result of the cumulative damage incurred in the preceding stages of crack initiation and stable crack growth.

Rapid fracture is commonly observed in high-cycle fatigue (above 10^5 cycles), where the applied fatigue stresses are relatively low. Fracture surfaces from this stage frequently exhibit fine fatigue striations perpendicular in the direction of crack propagation, marking each cycle's crack advance. This stage is characterized by an abrupt increase in the crack growth rate, culminating in a rapid and catastrophic material failure.[13]

2.1.4.Factors Affecting Fatigue:

1.Effect of Stress Ratio (R), Stress Amplitude, and Stress Range in Fatigue Life

The stress ratio (R), defined as, indicates the ratio of minimum to maximum stresses in a cycle. It, along with stress amplitude (σ_a) and stress range (σ_r), significantly impacts fatigue life.

$$R = \frac{\sigma_{max}}{\sigma_{min}}$$

Stress Range: The difference between maximum and minimum stresses in a cycle. Higher stress ranges increase fatigue damage.

$$\sigma_r = \sigma_{max} - \sigma_{min}$$

Stress Amplitude: Represents half of the stress range. Higher stress amplitudes correspond to greater fatigue damage.

$$\sigma_a = \frac{\sigma_r}{2} = \frac{\sigma_{max - }\sigma_{min}}{2}$$

High Stress Ratios (e.g.,(R = 0.5)): Primarily tensile cycles lead to higher mean stresses, decreasing fatigue life by promoting crack growth.

Low or Negative Stress Ratios (e.g.,(R = -1)): Cycles with compressive components reduce crack growth, often extending fatigue life.

Effect of Mean Stress(σ_m):

$$\sigma_a = \frac{\sigma_{max+}\sigma_{min}}{2}$$

Higher mean stress (common in positive (R)) lowers allowable stress amplitude, reducing fatigue life. This relationship is described by Goodman and Gerber models, which show that as mean stress increases, fatigue strength decreases.

In summary, low or negative (R), low stress amplitude, and low stress range generally extend fatigue life, while high values for these factors increase fatigue damage and reduce life expectancy.[9]

2.The effect of stress concentration:

In real-world mechanical components, various types of notches, such as keyways, steps, threads, and grease holes, are commonly present, even though traditional fatigue strength tests are performed on smooth, machined specimens. These notches create stress concentrations that significantly increase the actual stress at their roots, often far exceeding the nominal stress that the component is designed to withstand. It is typically at these locations where fatigue failure begins.

Under ideal elastic conditions, the theoretical stress concentration coefficient (Kt) is defined as the ratio of the maximum actual stress to the nominal stress at the root of the notch, according to elastic theory.

The ratio of the fatigue limit of a smooth specimen (σ-1) to the fatigue limit of a notched specimen (σ1n) is the effective stress concentration factor (Kf), sometimes referred to as the fatigue stress concentration factor. This factor depends on a number of elements, including material qualities, production techniques, heat treatment, and the component's size and shape.[14]

Although the effective stress concentration factor is generally lower than the theoretical Kt, it increases as the notch sharpness becomes greater.

Sensitivity coefficient q for fatigue notches: The material's sensitivity level to fatigue notch is represented by the fatigue notch sensitivity coefficient, which can be computed as follows:

$$q = \frac{K_f - 1}{K_t - 1}$$

3. The Impact of the Size Factor

As the size of a component increases, its fatigue limit typically decreases due to the higher probability of failure caused by the material's inherent inhomogeneity and internal defects, such as voids or inclusions. This size effect presents a challenge when applying small-scale laboratory fatigue data to larger parts. In laboratory tests, the stress concentration and gradient present in real-world large components cannot be replicated exactly in small samples. Therefore, the fatigue damage observed in laboratory specimens may not fully represent the behavior of large parts, making the size factor an important consideration in predicting fatigue life for practical applications.

4. Influence of Loading Experience

Real-world components are rarely subjected to constant stress amplitudes; instead, they often experience overloads and secondary loading conditions, which can significantly influence their fatigue limits. Research indicates that both overload and secondary load conditions are common and affect the material's overall fatigue performance.

Overload Damage refers to the reduction in a material's fatigue limit that occurs after exposure to loads higher than the material's designated fatigue limit. The severity of this damage increases with the magnitude of the overload, requiring fewer cycles to cause fatigue failure. However, in some cases, a few cycles of overload can strengthen the material instead of weakening it, due to residual compressive stresses, crack tip passivation, and deformation strengthening. In these instances, overload cycles may actually increase the material's fatigue limit.

Sub-load Exercise describes a phenomenon where a material is subjected to stress levels below its fatigue limit, but still above a certain threshold, over an extended period. This prolonged exposure can enhance the material's fatigue limit. The impact of sub-load exercise is influenced by the material's intrinsic properties, which may either enhance or diminish the beneficial effects of this type of loading condition.

5. The Effect of Inclusions

Inclusions can be likened to tiny notches or the voids they leave behind, as they cause localized stress and strain concentrations under cyclic loading, leading to fatigue cracks and adversely affecting the material's fatigue performance. The extent to which inclusions impact fatigue strength depends on factors such as their nature, shape, type, size, quantity, and distribution, as well as the material's strength level and the magnitude and condition of the applied external stress.

Different types of inclusions exhibit varying physical and mechanical properties, which influence fatigue performance differently compared to the base material. Brittle inclusions, such as oxides and silicates, generally have a more detrimental impact on steel's fatigue properties than ductile inclusions, such as sulfides, which deform more readily. For inclusions with a higher thermal expansion coefficient than the surrounding matrix (e.g., sulfides), compressive stress in the matrix has a lesser effect, whereas tensile stress in the matrix has a greater impact on inclusions with a lower thermal expansion coefficient, such as alumina.

The impact of inclusions on fatigue behavior also varies depending on the loading conditions. Inclusions can act as localized strain concentration sites, particularly within the stress range that governs the material's fatigue limit, significantly influencing fatigue strength. However, under high-stress conditions, where plastic flow is induced in the material regardless of inclusions, their influence becomes negligible. Thus, inclusions primarily affect the material's fatigue limit, while at higher stress levels, their effect on overall fatigue strength diminishes.

The purity of the material, established during the melting process, also plays a critical role. Advanced purification methods, such as vacuum degassing, vacuum melting and electroslag remelting, can significantly reduce impurity levels in steel, thereby improving its fatigue properties.

6. Influence of Surface Properties and Residual Stress

The impact of surface condition on fatigue strength involves not only surface finish but also changes in the mechanical properties of surface and residual stress effect. Surface layer deformation strengthening, as well as alterations in chemical composition and microstructure at the surface, can significantly modify the mechanical characteristics of the surface layer.

These changes often arise from surface treatments or machining processes, which can introduce compressive residual stresses that enhance fatigue resistance.Carburizing, nitriding, and carbonitriding are examples of surface heat treatments that can improve a part's fatigue strength and wear resistance. They are particularly useful for improving corrosion fatigue and bite corrosion resistance.

The loading mode, the amount of carbon and nitrogen in the infiltration layer, the surface hardness and its gradient, the ratio of surface hardness to core hardness, the depth of the hardened layer, and the size and distribution of residual compressive stresses caused by the treatment are some of the variables that affect the fatigue strength of materials treated with surface chemical heat processes. Chemical heat treatment often improves fatigue strength, especially when there are strong notches from the initial processing stage, as many investigations have shown.

The influence of surface treatments on fatigue performance varies significantly with the loading mode. Under axial loading, stress within the surface layer and beneath it is evenly distributed due to the absence of unequal stress distribution through the layer depth. In such cases, surface treatment primarily enhances the fatigue performance of the outer layer without substantially strengthening the core material, limiting the overall improvement in fatigue strength. In contrast, under bending and torsion, stress is concentrated at the surface. Here, the residual compressive stresses introduced by surface treatments, combined with the external stress, effectively reduce the actual stress acting on the surface. This makes treatments such as carburizing, nitriding, and carbonitriding effective in improving fatigue strength under these conditions. However, if decarburization occurs during the heat treatment process, reducing surface hardness, the material's fatigue strength will be significantly diminished. Similarly, factors such as cracks in surface coatings, residual tensile stresses from coatings applied to the base metal, and hydrogen embrittlement from hydrogen exposure during plating can lead to a reduction in fatigue strength. This is commonly observed with coatings such as chromium and nickel.

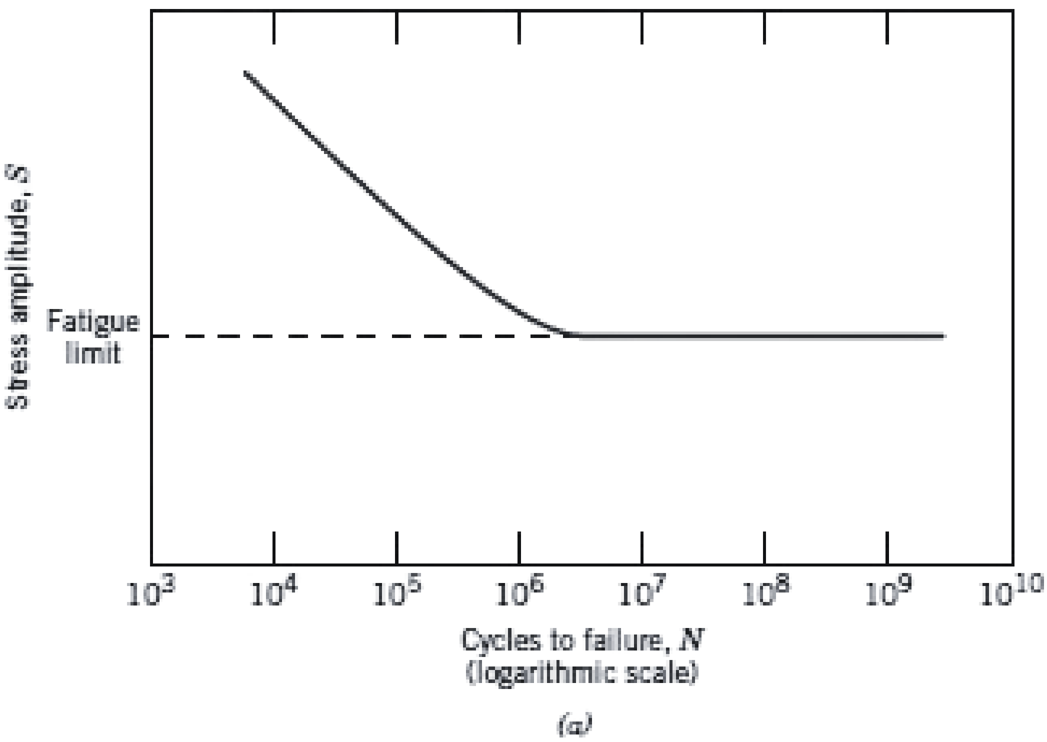
Induction quenching, surface flame quenching, and thin-shell quenching of low-hardenability steels are also effective methods for enhancing fatigue strength. These processes produce a hardened surface layer of a specific depth and induce favorable residual compressive stresses on the surface, contributing to improved performance. Surface rolling and shot peening are also effective at increasing fatigue strength by introducing residual compressive stress into the surface and creating a hardened layer at a defined depth, which enhances the material's resistance to deformation under cyclic loads.

2.1.5. S-N Curve:

The relationship between the cyclic stress amplitude (S) applied to a material and the corresponding number of cycles to failure (N) is visually represented by the S-N curve, sometimes referred to as the stress-life curve. Test specimens are subjected to continuous cyclic stress levels, and the number of cycles till failure is recorded to create this graph.

Typically, the S-N curve demonstrates that higher stress amplitudes result in fewer cycles to failure, while lower stress amplitudes enable longer fatigue life. For certain materials, the curve levels off at a specific stress value known as the fatigue limit or endurance limit, below which the material is theoretically capable of enduring an infinite number of cycles without failing. In contrast, some materials exhibit an S-N curve that continuously slopes downward, indicating that failure will eventually occur even at very low stress amplitudes.

The curve is generally divided into two main regions: low-cycle and high-cycle fatigue. These regions reflect distinct fatigue behaviors depending on the number of cycles to failure and the type of deformation the material experiences under cyclic loading.[9,11]



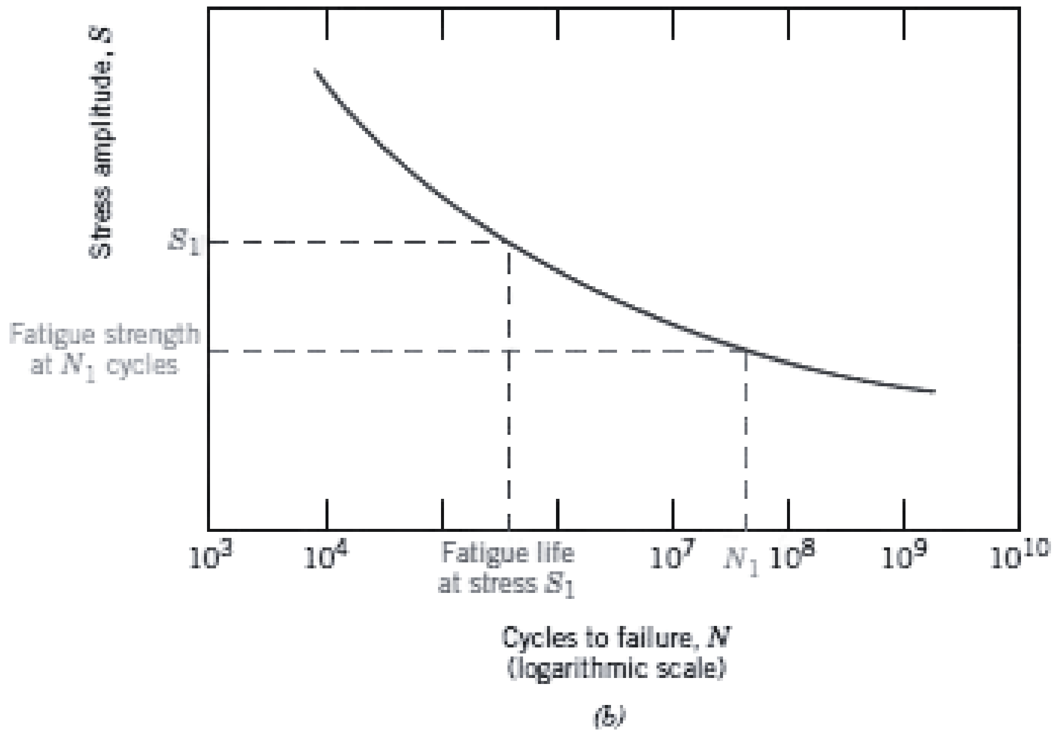


Fig 2.4 Stress amplitude (S) versus a logarithm of the number of cycles to fatigue failure (N) for (a) a material that displays a fatigue limit and (b) a material that does not display a fatigue limit.[11]

1. Low-Cycle Fatigue (LCF)

- **Cycles:** Low-cycle fatigue generally occurs at fewer than 10^4 to 10^5 cycles.[15]
- **Stress Levels:** It occurs at relatively high stress levels, often approaching the material's yield strength.
- **Deformation:** The high stress levels in LCF produce both elastic and plastic strains during each load cycle. This means the material undergoes some permanent deformation with each cycle.
- **Characteristics:** LCF is characterized by shorter fatigue lives because the plastic strain contributes significantly to material degradation and crack initiation. This region is typical of applications where components are subjected to high loads or dynamic forces such as in structural or mechanical parts that experience large load variations.
- **Failure Mechanism:** In LCF, plastic deformation accelerates crack initiation, leading to earlier failure.

2. High-Cycle Fatigue (HCF)

- **Cycles:** High-cycle fatigue typically involves more than 10^5 cycles, often reaching up to millions of cycles.[15]

- **Stress Levels:** HCF occurs at lower stress levels, usually well below the yield strength, so that deformations remain entirely within the elastic range.

- **Deformation:** The cyclic stresses in HCF produce only elastic strain, meaning the material does not undergo permanent deformation with each cycle.

- **Characteristics:** Since the deformations are purely elastic, the material can endure many more cycles before failure. This is typical for components subject to lower, repetitive stresses over long periods, such as in rotating machinery or components in aerospace applications.

- **Failure Mechanism:** In HCF, fatigue failure is primarily due to the gradual initiation and growth of microscopic cracks, which eventually propagate, leading to failure after a large number of cycles.

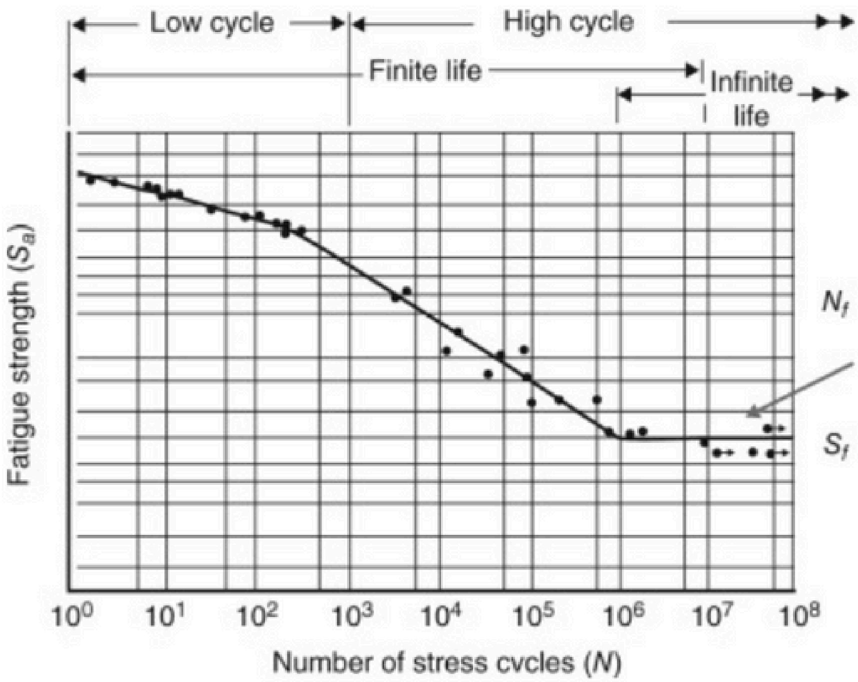


Fig 2.5 S-N curve showing High cycle and Low cycle region [16]

2.1.6. Fractography:

Fractography is the study of fracture surfaces, essential in determining the causes and progression of material failure. Metal fractography has evolved over centuries, with techniques and tools improving, particularly with the advent of SEM, which provides high-resolution, in-depth analysis of fracture surfaces. This process aids in identifying stress points, environmental interactions, and mechanical failures in metals.[17]

Primary Metal Failure Mechanisms:

Ductile Fracture of Metals

Characteristics :

Ductile fracture happens with a significant amount of plastic deformation before the material fails. As such, it requires considerably much energy to initiate and continue propagating. This is why a large degree of stress typically is necessary to initiate and propagate ductile fractures.

A fracture surface generally appears rough and fibrous with a dimpled surface when magnified. Such a dimpled surface is the hallmark of ductile fractures, which result from micro-void coalescence, where small cavities start to form and enlarge until they connect together and fracture the material asunder.[18]

Mechanism:

1.Micro-void Nucleation: The initiation of the process of ductile fracture follows micro-void nucleation at stress concentrators, such as inclusions, impurities, or other material defects within its structure. In a pure metal, voids can nucleate along grain boundaries or dislocation sites.

2.Micro-void Expansion: When stress is applied, these voids expand across grain boundaries because the surrounding metal undergoes plastic deformation.

3.Micro-voids coalesce to become a crack, which continues to propagate through the material. Such micro-void coalescence is characteristic of ductile fractures and creates a dimpled appearance.

Fracture Surface:

- At the microscopic level, ductile fractures exhibit dimples that are cup-shaped (associated with tensile loading) or shear-oriented (associated with torsional or bending loads).

- The orientation and size of these dimples can provide insights into the direction and magnitude of the forces that caused the fracture. For instance, dimples aligned in one direction may indicate shear loading, while equiaxed dimples suggest pure tensile loading.

Conditions Favourable to Ductile Fracture:

Ductile fractures are seen more in materials whose toughness is very high, such as mild steel and many others are ductile, but are subjected at room temperature or at higher temperature. Ductile fracture usually occurs in structural applications wherein materials are expected to deform rather than break suddenly. This property is advantageous as it gives a warning before failure so interventions may be made to prevent catastrophic breakdowns.

Applications:

Knowing about ductile fracture is important for applications wherein it is required that materials undergo plastic deformation without sudden failure, just like in structural engineering and automotive components wherein safety and gradual failure are preferred.

Brittle Fracture in Metals

Characteristics:

The brittle fracture is different from the ductile fracture as the latter occurs at little to zero plastic deformations. When a material is stressed, it will snap sharply with minimal energy absorption, and the fracture surface appears relatively flat and shiny.
This type of fracture occurs over some particular crystallographic planes, known as cleavage planes of cleavage fracture, in materials which display brittleness at certain conditions. Metals with BCC and HCP structures such as ferritic steels and titanium alloys are prone to brittle fracture mainly at temperatures below ambient temperature .[18]

Mechanism:

- Crack Initiation: Brittle fractures often initiate at stress concentrators like scratches, sharp notches, or existing microcracks, as well as material defects such as inclusions.

- Crack Propagation: Once a crack initiates, it can rapidly propagate through the material without significant deformation, especially if the crack reaches a critical size where the stress intensity exceeds the material's fracture toughness.

- Trans-granular and Intergranular Fracture: Brittle fractures can be trans-granular (cracking through grains) or intergranular (cracking along grain boundaries). Trans-granular fractures show cleavage facets aligned along crystallographic planes, while intergranular fractures reveal grain boundaries, often due to embrittlement or environmental degradation like corrosion.

Fracture Surface:

Cleavage Facets-Transgranular brittle fracture types have the cleavage facets formed along the crystallographic planes of the metal grain, thus appearing rather reflective and shiny.
Chevron Patterns: These V-shaped markings on the fracture surface point reverse to the initiation of fracture showing the crack propagation direction.
River Patterns: Lines that look like rivers are often found on the cleavage facets; however, such lines indicate the crack growth direction and serve as visual indications of the stress conditions at the time of fracture.

Favorable Conditions of Brittle Fracture:

Metals can fail by brittle fracture at low temperatures or high-strain-rate loadings because both limit atomic mobility, challenging plastic deformation under the circumstances .
High-carbon steels and other metals that have a BCC or HCP crystal structure are more prone to brittle fracture, especially at low temperatures (referred to as the "ductile-to-brittle transition temperature").

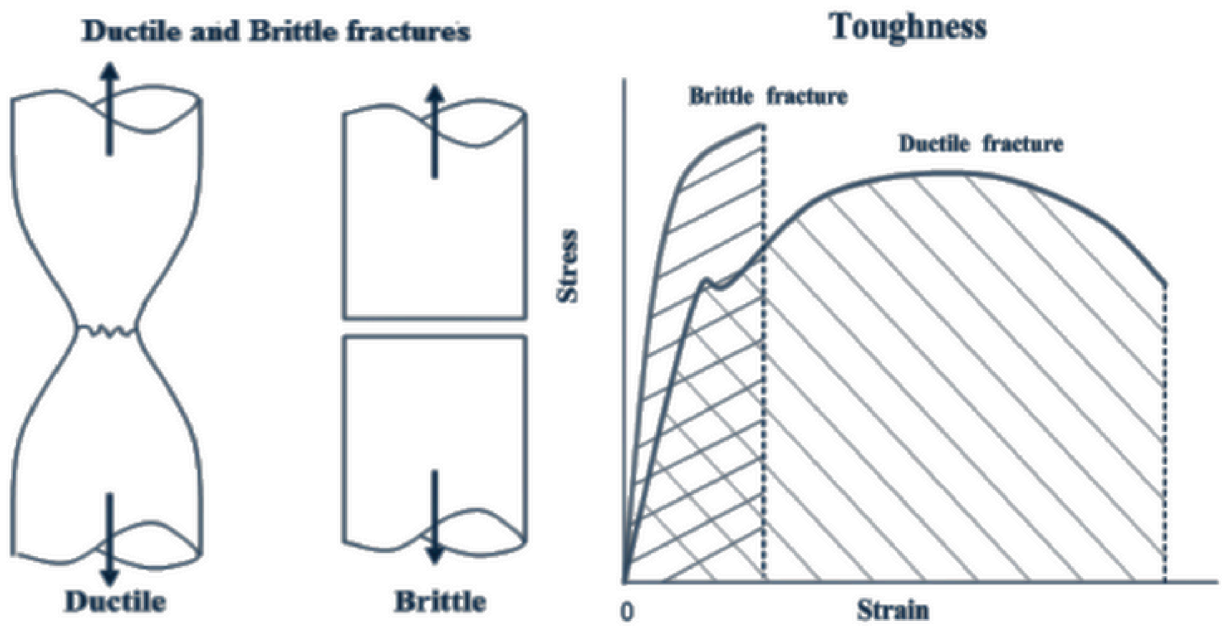


Fig 2.6 Mechanical behavior of brittle and ductile fractures [19]

Applications and Implications:

Brittle fractures are dangerous in safety-critical applications since brittle fractures occur without any warning. Engineers should take care of operating temperature, notch sensitivity, and loading conditions if critical structures such as bridges, pipelines, and pressure vessels are to be free from brittle fracture.
Ductile-to-brittle transition is a phenomenon critical to material selection for variable temperature applications-like offshore structures and aerospace components that work at extreme colds.

Environmental Influence on Metal Fracture:

The impact of the environment on metal fracture includes hydrogen embrittlement, which happens when hydrogen atoms pierce metal, leaving it brittle and prone to breaking under stress. Intergranular fracture and characteristic "fisheye" patterns on fracture surfaces are the usual outcomes.
Corrosion: Metal is broken down by electrochemical processes, which frequently start near grain boundaries or stress concentrators. Combining chemical and mechanical forces, corrosion fatigue shortens fatigue life and produces pits and striations.

Analysis and Testing Techniques:

Optical and Scanning Electron Microscopy (SEM):

- SEM allows high-magnification imaging of fracture surfaces, essential in detecting microstructural details such as dimples, cleavage facets, and striations.

Nondestructive Testing (NDT):

- Techniques like ultrasonic testing, radiographic inspection, and magnetic particle testing are critical for detecting subsurface flaws and microcracks in metals without damaging the sample. [20]

Elemental Analysis:

- Energy Dispersive X-Ray Spectroscopy (EDS) with SEM provides elemental composition insights, useful in identifying contamination or alloy composition anomalies contributing to failure.

Common Causes of Failure in Metals:

- Design Issues: Poor design choices, such as sharp corners, cause stress concentrations, leading to early fracture initiation.
- Manufacturing Defects: Residual stresses from welding, machining, and forming can weaken the material, making it prone to failure. Porosity, inclusions, and voids act as stress concentrators.
- Service Conditions: Exposure to cyclic stresses, corrosive environments, or extreme temperatures can accelerate metal fatigue, SCC, and embrittlement.

Chapter 3

Objective:

The objective of this thesis is to investigate the effects of stress ratio (R) and notch sensitivity factor (Kt) on the high-cycle fatigue strength of Al 6061 alloy to understand and improve its performance under cyclic loading conditions. This study aims to characterize the fatigue behavior of Al 6061 by analyzing how varying stress ratios and geometric discontinuities (notches) influence fatigue life, endurance limits, and overall structural integrity. Special emphasis is placed on quantifying the role of stress concentration caused by notches and examining how increasing the notch sensitivity factor exacerbates fatigue strength reduction, thereby providing critical insights into material limitations. Additionally, the research explores the relationship between applied stress ranges, stress ratios, and the number of cycles to failure, providing a comprehensive understanding of the material's response under different loading scenarios. By integrating experimental findings with practical applications, the thesis aims to generate valuable engineering insights that can guide the design of fatigue-resistant components, optimizing the use of Al 6061 alloy in high-performance industries such as automotive, aerospace and structural engineering, where reliability and fatigue resistance are of paramount importance.

Chapter 4

Experimental Work:

4.1 Material and Sample Design

Aluminum alloy 6061 specimens were designed to represent real-world structural conditions where geometric discontinuities, such as notches, holes, or abrupt changes in cross-sectional area, can induce localized stress concentrations. These stress concentrators are critical factors in fatigue studies, as they significantly influence the material's fatigue life by amplifying stress in localized regions. Using AutoCAD, three distinct specimen geometries were created to investigate this effect on fatigue behavior systematically.

We calculated the Kt values using the Peterson formula and observed the number of cycles to failure, taking into account different loading conditions. This comprehensive approach allowed us to analyze the relationship between notch geometry, applied loads, and fatigue performance.

The Peterson Formula[21] to calculate the Kt values is :

$$K_t = 1 + \left[\frac{\frac{t}{r}}{1.55\left(\frac{H}{d}\right) - 1.3}\right]^n \qquad n = \frac{\left(\frac{H}{d} - 1 + 0.5\sqrt{\frac{t}{r}}\right)}{\left(\frac{H}{d} - 1 + \sqrt{\frac{t}{r}}\right)}$$

where, t = Depth of notch ,H = width of gauge, r = radius of notch, d = H- 2t

The specimen configurations are as follows:

- Notched Sample 1: This sample was designed with sharp notches, yielding a calculated notch sensitivity factor (Kt) of 3.2. This high Kt value represents a significant stress concentration factor, simulating scenarios where the component experiences abrupt geometric discontinuities, such as holes or sharp corners.

- Notched Sample 2: This specimen featured moderate notches, resulting in a Kt value of 2.5. This design represents a scenario with milder geometric discontinuities, which still produce notable but less severe stress concentrations compared to Notched Sample 1

- Un-Notched Sample: Serving as the control, this specimen was fabricated without any notches or geometric discontinuities. This smooth configuration provides a baseline for assessing the inherent fatigue characteristics of the material without the influence of stress concentrators.

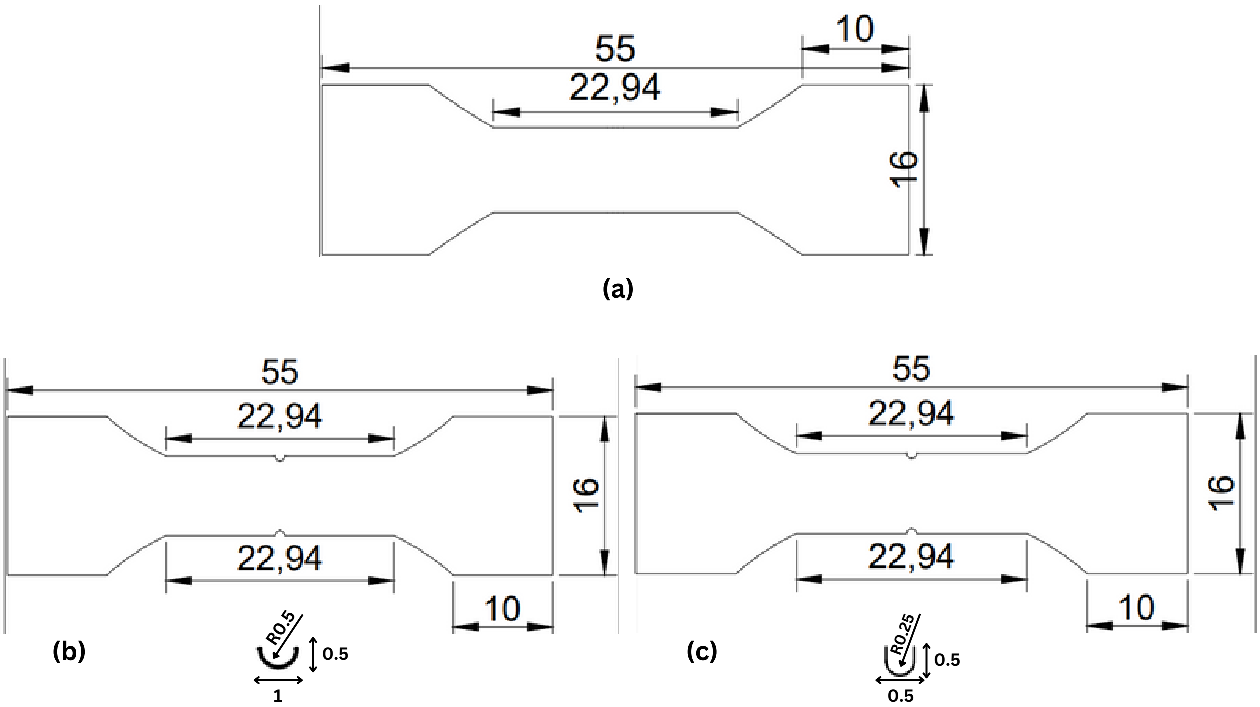


Fig.4.1 Tensile geometry (a) Un-notched, (b) Notched(Kt = 2.52), (c) Notched(Kt=3.2)

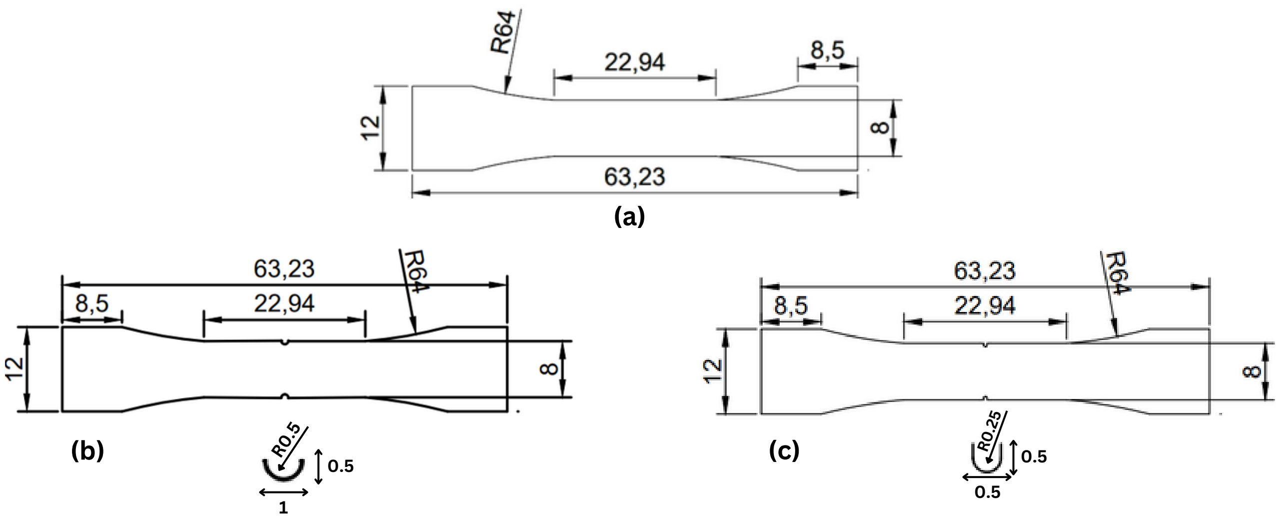


Fig.4.2 Fatigue geometry (a) Un-notched, (b) Notched(Kt = 2.52), (c) Notched(Kt=3.2)

4.2 Sample Cutting and Preparation

The aluminum 6061 alloy specimens were precisely cut from a rolled sheet using Electrical Discharge Machining (EDM). This method was selected to maintain the original microstructure and mechanical properties of the material, particularly around the notch regions. By preventing thermal alteration, EDM ensured that the samples retained their intrinsic characteristics, which is essential for accurate fatigue testing results. This careful preparation preserved the reliability of the data by minimizing any potential influence of machining-induced changes on the material’s behavior under cyclic loading conditions.

Polishing for Surface Enhancement

We improved the sample's surface smoothness by using a polishing machine with emery paper of different roughness levels (from 220 to diamond polishing). For subsequent testing to yield accurate and trustworthy results, this painstaking polishing procedure is essential.

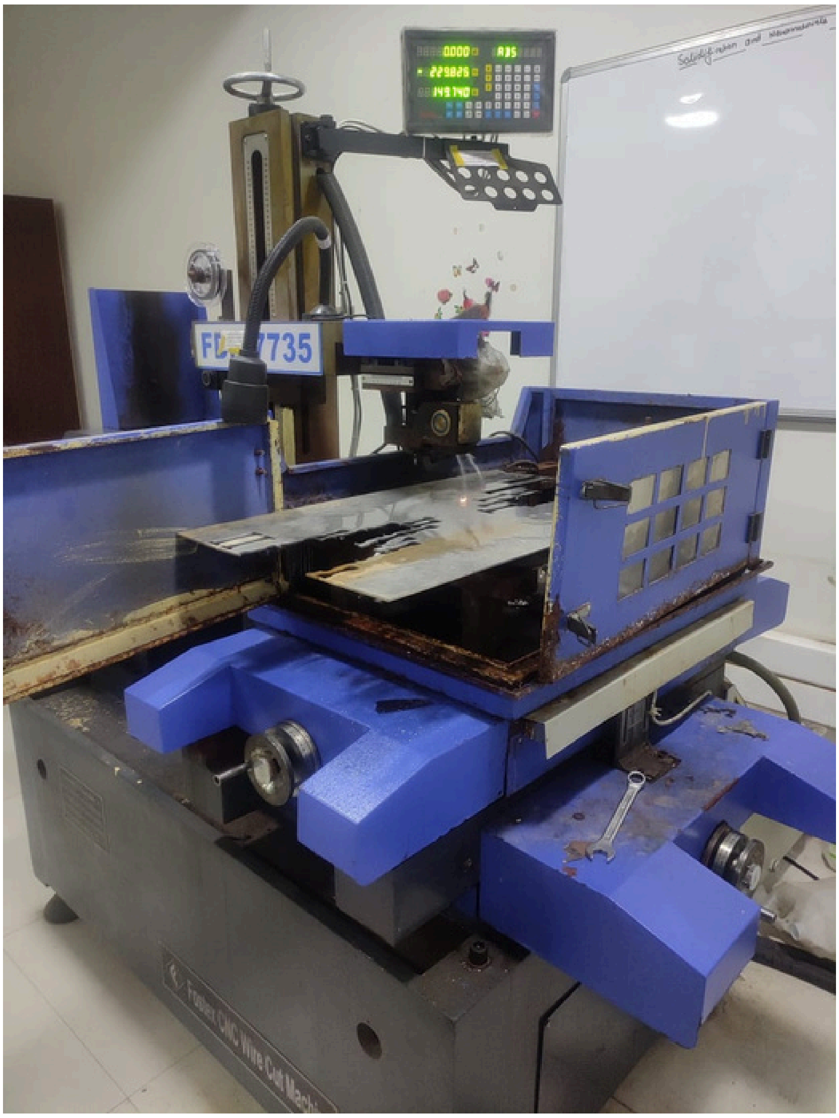


Fig 4.3 EDM Machine

Fig 4.4 Sample Cutting via EDM Machine

4.3 Tensile Testing Procedure

Purpose and Setup

The tensile testing was conducted to determine the Ultimate Tensile Strength (UTS) of the aluminum 6061 alloy samples, providing a basis for setting load levels in subsequent fatigue tests. By establishing the UTS, the tensile test allowed for calibrated load application in fatigue testing, enabling the examination of the material's performance under cyclic stresses proportional to its tensile strength.

To conduct the tensile tests, each sample was securely mounted in a fatigue testing machine which is designed to apply controlled tensile forces along the longitudinal axis of the specimen. A strain rate of 0.1 mm/min was used to ensure gradual loading, thereby minimizing the risk of sudden stress surges that could affect the accuracy of the results. This slow strain rate also allowed for precise capture of the stress-strain relationship as the load was applied progressively until fracture occurred.

Testing Steps

- Loading and Fracture: The UTM applied tensile force to each sample incrementally until fracture, recording data at each stage to ensure accurate capture of the material's response under increasing stress.

- Recording Stress-Strain Data: During the test, stress and strain data were continuously recorded. This data provided critical information on the material's behavior under load, and it was used to calculate the UTS for each sample type.

- Guiding Fatigue Testing: The UTS values derived from the tensile tests were subsequently used to determine load levels for the fatigue tests. By using UTS as a basis for fatigue loading, the testing procedure could accurately simulate the cyclic stresses that materials would encounter in practical applications, providing a realistic assessment of the alloy's fatigue performance.

Tensile Test Parameters

The tensile test was performed at a strain rate of 0.1 mm/min to ensure gradual loading and avoid sudden stress surges. This controlled rate allowed accurate stress-strain data collection. Two types of samples were tested: notched and smooth. The notched samples helped study the effect of stress concentrators, while the smooth samples served as a baseline for the material's inherent tensile properties.

The Ultimate Tensile Strength (UTS) values obtained from the tensile tests were used to determine the load levels for the subsequent fatigue tests. These UTS values provided a realistic basis for setting the cyclic loads in fatigue testing, accurately reflecting the material's performance under operational conditions.

This tensile testing process was crucial for establishing a reliable foundation for the fatigue tests, ensuring that the cyclic loads applied during fatigue testing were proportionate to the material's inherent tensile strength. By calibrating fatigue loads based on UTS, the study accurately reflected the operational conditions aluminum 6061 alloy might encounter, enhancing the validity of the fatigue life assessments obtained through subsequent testing.

4.4 Fatigue Testing

Fatigue Testing Machine Overview

The fatigue tests in this study were conducted using a BISS Nano Fatigue Testing Machine, a high-performance device specifically designed for cyclic loading applications. Fatigue testing is essential in materials science to evaluate how materials behave under repetitive loading conditions, a frequent scenario in engineering structures where components are subjected to fluctuating stresses over time. The BISS Nano machine allows precise control of critical testing parameters such as load frequency, amplitude, and stress ratios, and it accurately records cycle counts and stresses to measure fatigue life.

The machine's advanced capabilities enable the study of material durability, identifying the number of load cycles a material can withstand before failure. This knowledge is critical for structural applications, especially in industries such as aerospace and automotive, where materials often face variable loading and must exhibit reliable fatigue resistance.

Fig 4.5 BISS Nano Fatigue Testing Machine

Machine Specifications and Key Features:

The BISS Nano Fatigue Testing Machine used in this study has the following specifications and features:

- **Load Capacity:** Rated at 25 kN, the machine is capable of handling high-strength materials, including aluminum alloys, under varying load levels. This capacity ensures it can apply significant forces, simulating real-world stress conditions accurately.

- **Output Power:** The machine operates with an output power of 16 Amp, providing the stability and consistency required for sustained cyclic loading. This steady output helps maintain accurate loading without deviations, which is essential for long-term fatigue testing.

- **Frequency:** The machine is configured to apply cyclic loads at a constant frequency of 15 Hz, ensuring uniform application of load cycles throughout each test. This frequency mimics operational conditions, providing data relevant to the expected loading frequencies encountered in actual service environments.

- **Software Interface:** The BISS Nano includes a dedicated software interface that facilitates user-friendly operation and enhances testing precision. It allows researchers to set specific stress ratios and load values accurately, enabling automated control over fatigue testing parameters. Real-time data logging further supports accurate monitoring and analysis, ensuring comprehensive data on each sample's fatigue performance.

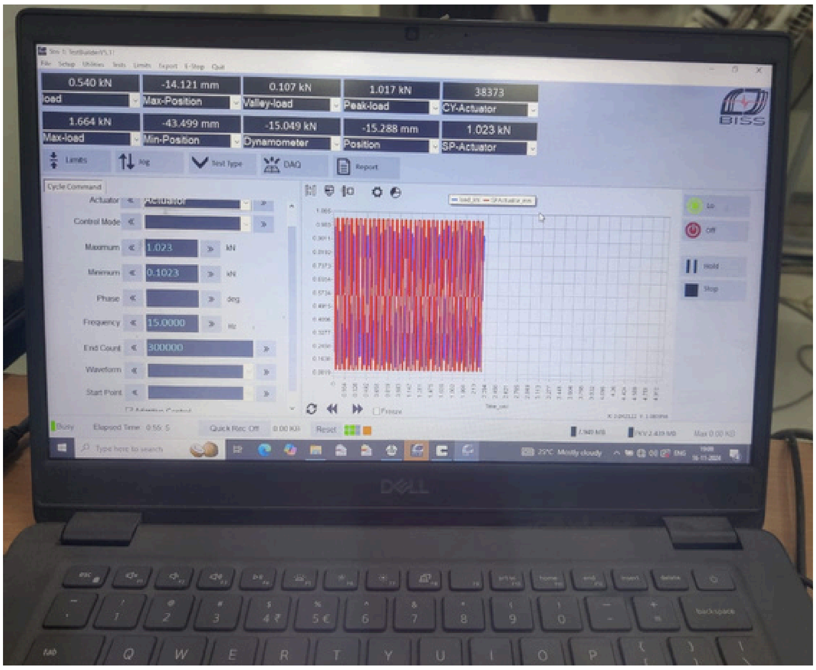


Fig 4.6 Software Interface of Fatigue Testing Machine

Machine Operation for Fatigue Testing:

The BISS Nano Fatigue Testing Machine applies cyclic loading using a servo-hydraulic actuator, which allows high-frequency load applications while maintaining precise load control. This actuator mechanism enables the machine to deliver consistent load cycles with high accuracy, ensuring that the applied stresses align closely with pre-set parameters. The machine's software interface permits real-time adjustments and monitoring of stress ratios, load amplitude, and cycle counts, which is essential for maintaining consistent test conditions.

During operation, the machine maintains a steady frequency of 15 Hz, simulating typical operational frequencies encountered in engineering applications. The software interface logs each cycle and provides real-time data on load variations, stresses, and cycles, making it possible to closely observe material response under cyclic loading. This feature allows researchers to assess fatigue life based on accurate cycle counts and stress measurements, enhancing the reliability of the data obtained. The machine's automation also minimizes user intervention, reducing the potential for human error and ensuring consistency across tests

(a)

(b)

Fig 4.7 Fatigue Testing on samples

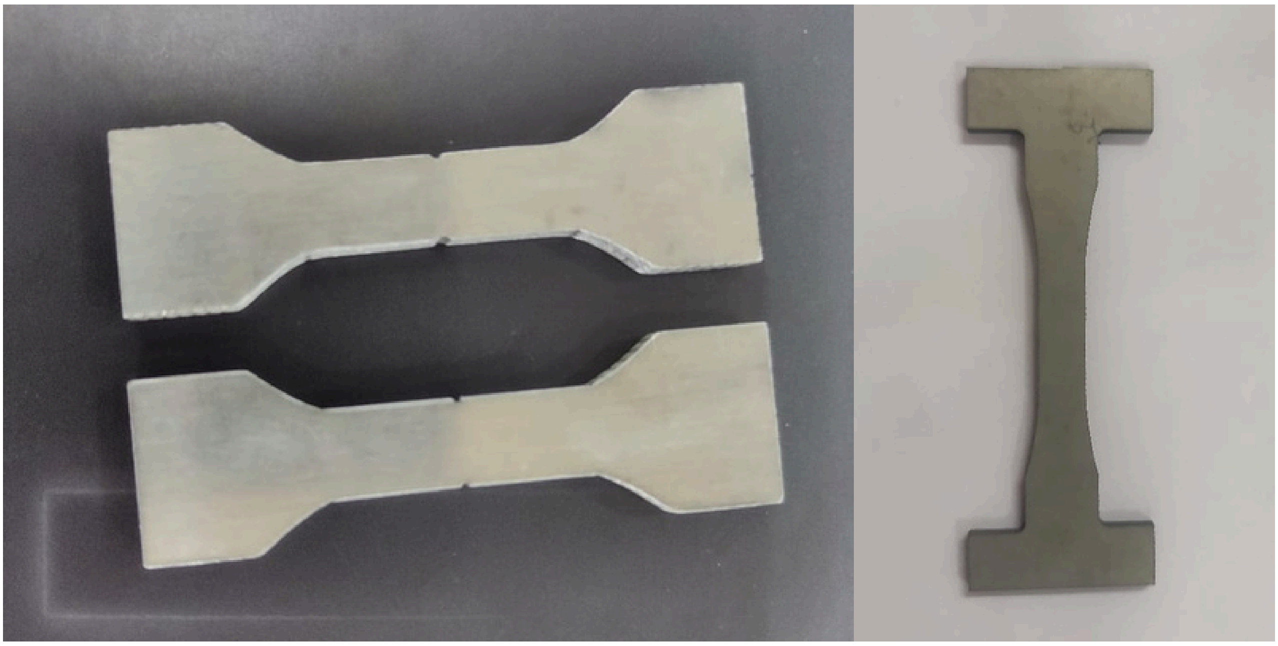
Stress Ratios and Load Setup

Fatigue testing was performed under different stress ratios to simulate a variety of loading conditions that a material might experience in real-world applications. The stress ratios used in this experiment were $R = 0.1$ and $R = 0.3$, which represent different cyclic loading conditions:

- $R = 0.1$ corresponds to a loading scenario where the minimum load is 10% of the maximum load, reflecting a relatively high tension state with a slight compressive phase during the loading cycle.

- $R = 0.3$ corresponds to a higher minimum load (30% of the maximum load), which introduces a greater level of compressive loading in the cycle, testing the material's response under more significant compressive conditions.

These ratios were chosen with attention in order to monitor the material's performance under various cyclic loading levels. The many loading situations are pertinent to engineering applications in the real world, as materials frequently experience varying loading circumstances based on operational settings. A deeper comprehension of the alloy's fatigue behavior under various tensile and compressive circumstances was made possible by the variation in loading cycles.



(a) (b)

Fig 4.8 (a) Tensile and (b) Fatigue samples ready for testing

Fatigue Test Parameters:

In addition to the stress ratios and notch sensitivity factors, other critical fatigue test parameters include:

- **Frequency:** The tests were conducted at a constant frequency of 15 Hz, ensuring that the load cycles were uniformly applied throughout the test. This frequency mimicked real-world conditions where materials are subjected to constant cyclic loading during service.

- **Load Levels:** The fatigue tests used the Ultimate Tensile Strength (UTS) values determined from the tensile tests to set the load levels. The UTS values were used to calculate the peak load levels for the fatigue tests, ensuring that the cyclic stresses were proportionate to the material's tensile strength and suitable for investigating the fatigue life under realistic conditions.

- **Environmental Conditions:** The fatigue tests were performed in controlled environmental conditions to reduce the impact of external factors such as temperature and humidity on the material's behavior. By maintaining a stable environment, the testing conditions were kept consistent to ensure reliable and repeatable results.

4.5 Experimental Procedure for Plotting the S-N Curve

The S-N curve was constructed based on fatigue test results performed on aluminum 6061 samples. Tests were conducted for two stress ratios (R=0.1 and R=0.3), and the corresponding stress amplitudes (S) and cycles to failure (N) were recorded for each specimen. The data was plotted with the number of cycles to failure (N) on the y-axis and the applied stress amplitude (S) on the x-axis, both axes using a logarithmic scale to better visualize the material's cyclic stress behavior. Stress levels for the fatigue tests were determined using the Ultimate Tensile Strength (UTS) obtained from tensile testing, ensuring the loading conditions were appropriate. A curve, typically an S-N curve, was fitted through the data points to illustrate the relationship between maximum stress and the number of cycles to failure. This curve was analyzed to evaluate how notch sensitivity and stress ratios influenced the fatigue life of the samples. Notched specimens which have higher stress concentration factors (Kt) exhibited significantly reduced fatigue life compared to smooth specimens. Additionally, the S-N curve was used to estimate the fatigue limit, representing the stress level below which smooth samples could theoretically endure infinite cycles without failure. Overall, the S-N curve offered critical insights into the material's fatigue characteristics and its response to repeated loading.

4.6 Comprehensive Testing

The sample was put through a variety of tests, such as microstructure analysis, XRD (X-ray diffraction), fractography, and tensile strength. A thorough grasp of the characteristics and behavior of the material was made possible by these testing.

Chapter 5

Results and Discussion

5.1. Microstructure Analysis:

This study undertakes an in-depth investigation of the microstructure of aluminum alloy 6061. The primary aim is to understand the evolution of microstructural components during thermal processing, which includes solution treatment and artificial aging. These processes are critical in tailoring the alloy's mechanical properties, making it highly sought after in industries such as aerospace and automotive.
The microstructure of Al 6061 comprises the following major phases:

- **Primary Aluminum Matrix (α-Al):** This is the continuous phase, forming the base of the alloy. It provides high ductility and contributes to the alloy's light weight.

- **Mg_2Si Precipitates:** However, some small amount of precipitates of Mg_2Si formed which is confirmed by EDS and XRD test which will be discussed in later sections, strengthening precipitates are distributed uniformly throughout the matrix.

- **Grain Boundaries:** The grain boundaries are well-defined and exhibit precipitate segregation. This segregation enhances the alloy's resistance to grain boundary sliding and improves high-temperature performance.

Grain Structure:

The grain size is a function of the thermal history and mechanical working of the material. Solution treatment results in equiaxed grains, while cold working produces elongated grains. The aging process leads to fine, dispersed precipitates at the grain boundaries, contributing to higher strength. In some cases, recrystallization is observed depending on processing conditions, especially in extruded or rolled samples.

Mechanical Significance:

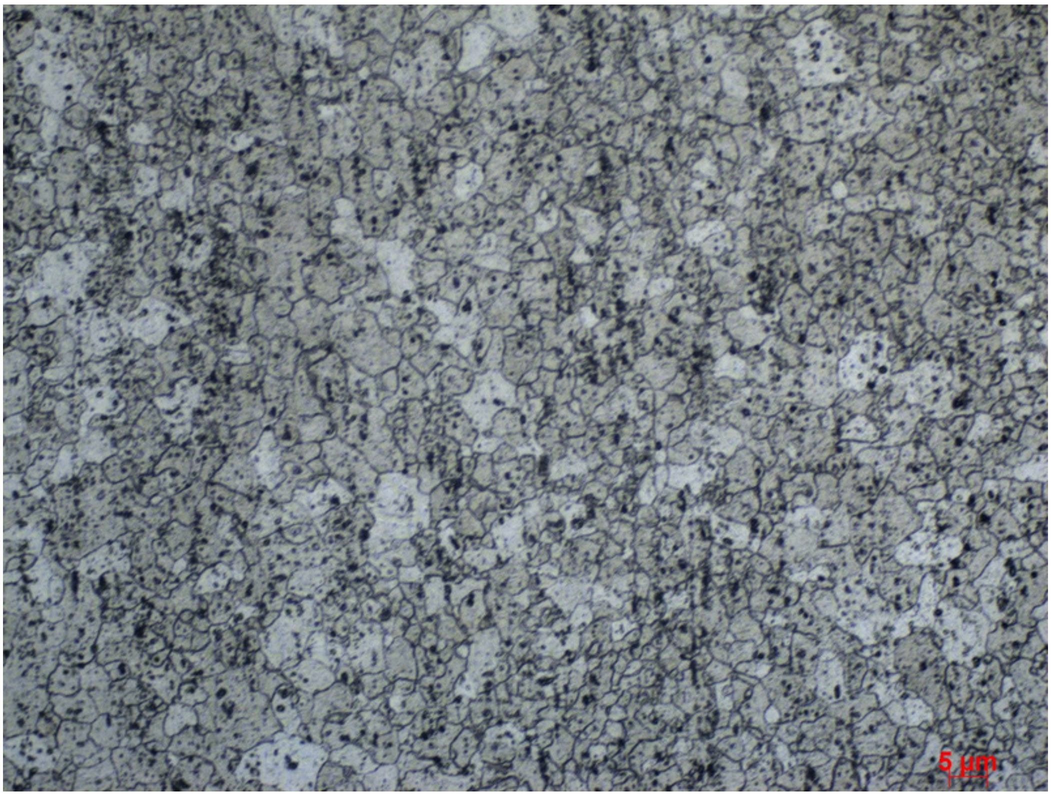
The distribution of Mg_2Si precipitates plays a pivotal role in determining the material's yield strength and fatigue resistance. Grain refinement contributes to the Hall-Petch strengthening effect, while intermetallic phases provide thermal stability and wear resistance.

this detailed exploration of the microstructure of Al 6061 highlights the intricate relationship between processing conditions, microstructural evolution, and resultant properties, reinforcing its importance in high-performance structural applications.

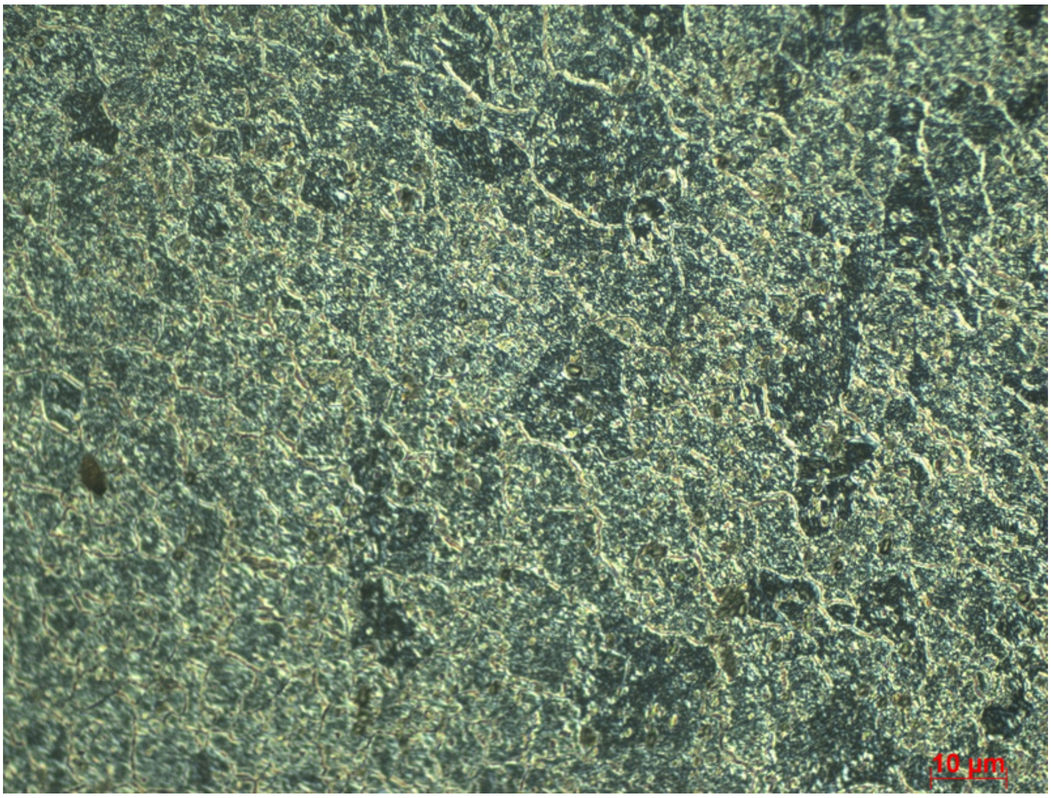
Etchant Used: Kellers Etch(Distilled water-190 ml,Nitric acid-5 ml,Hydrochloric acid-3 ml, Hydrofluoric acid-2 m)

Etching Time: 15 sec

Optical Images: Micrographs provide clear visualization of the Mg_2Si precipitates, intermetallic inclusions, and grain boundary characteristics.



(a)



(b)

Fig 5.1 Microstructure of Al 6061 alloy

5.2. SEM and EDS Analysis:

Al6061 is an aluminum alloy primarily composed of aluminum (Al), magnesium (Mg), and silicon (Si), along with smaller amounts of elements like iron (Fe), copper (Cu), manganese (Mn), chromium (Cr), zinc (Zn), and titanium (Ti). These elements contribute to the alloy's mechanical properties, corrosion resistance, and machinability.

Scanning Electron Microscopy (SEM) Results:

The SEM analysis was performed to study the microstructural features of the rolled Al6061 alloy. The high magnification allowed for a detailed examination of grain morphology, grain boundaries, and surface defects. The SEM image clearly reveals the following features:

- **Grain Structure:** The grains appear well-defined with a uniform morphology, indicating proper rolling and heat treatment. The grain sizes are within the micrometer range, consistent with the alloy's typical processing conditions.

- **Grain Boundaries:** Grain boundaries are prominent and suggest that the alloy may have undergone significant deformation during rolling. The boundaries could act as pathways for crack propagation under mechanical loading.

- **Surface Defects:** Minor surface imperfections and inclusions are visible, which might arise from impurities or secondary phases during alloying.

Energy-Dispersive X-ray Spectroscopy (EDS) Results:

The EDS analysis complements SEM by providing elemental composition data for different regions of the alloy. The analysis identified the following:

- **Grains:** The grains primarily consist of aluminum, with a nearly pure composition (100% Al). This indicates the aluminum matrix is largely free from secondary phases or precipitates within the grains.

- **Grain Boundaries:** The grain boundaries contain minor amounts of magnesium (0.9 wt%) and silicon (0.7 wt%), along with aluminum (96.8 wt%). This suggests the presence of Mg_2Si precipitates, which are typical strengthening phases in Al6061. These precipitates form at grain boundaries due to segregation during processing.

- **Inclusions:** Small inclusions were observed, likely composed of Fe and Mn, which are common impurities in aluminum alloys. These inclusions can slightly impact the alloy's mechanical properties but are generally controlled during processing.

Significance of the Findings:

- Microstructure Control: The grain size and morphology, coupled with the distribution of Mg_2Si precipitates, play a critical role in determining the mechanical properties of Al6061. Fine grains contribute to higher strength, while the presence of precipitates enhances the alloy's hardness and tensile strength.

Phases	Elements	Weight %
Grain boundary	Al	96.8
	Mg	0.9
	Si	0.7
Grain	Al	100

Table 5.1 : EDS Chemical composition (wt%)

- **Chemical Composition:** The EDS results confirm that the alloy adheres to its standard composition, ensuring its suitability for structural applications. The segregation of Mg and Si at grain boundaries suggests effective precipitation hardening.

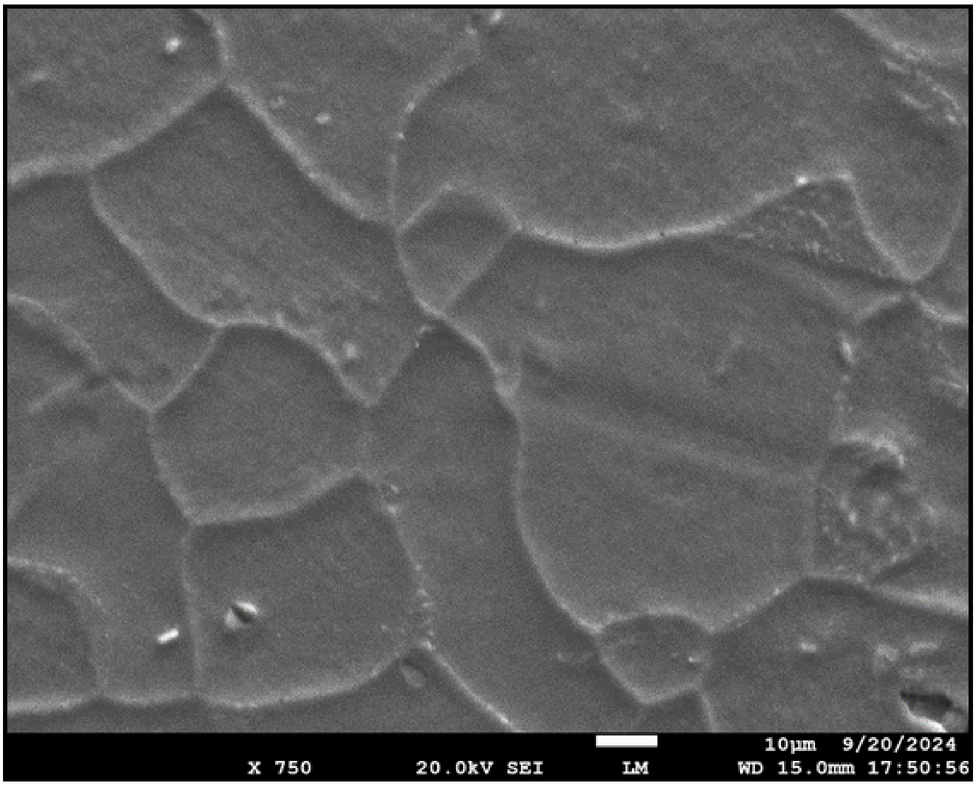


Fig 5.2 SEM image of Al 6061 alloy

5.3. XRD Test

The XRD analysis of the rolled Al 6061 demonstrates a prominent FCC aluminum matrix (α-phase), with diffraction peaks at 38°, 45°, 65°, and 78° (2θ) corresponding to the (111), (200), (220), and (311) planes. These sharp and intense peaks reflect the dominant crystallographic structure and a well-crystallized matrix. Additionally, the presence of smaller peaks at higher angles indicates the formation of Mg_2Si precipitates (β-phase), which are essential for precipitation hardening. The relatively low intensity of these β-phase peaks suggests a small volume fraction of precipitates, typical of the as-rolled state. This result highlights the potential for further optimization of the alloy's mechanical properties through aging treatments to enhance the density and distribution of Mg_2Si. These findings align with literature reports, where the rolling process induces a crystallographic texture in the aluminum matrix, while Mg_2Si contributes to the alloy's strength by impeding dislocation motion.

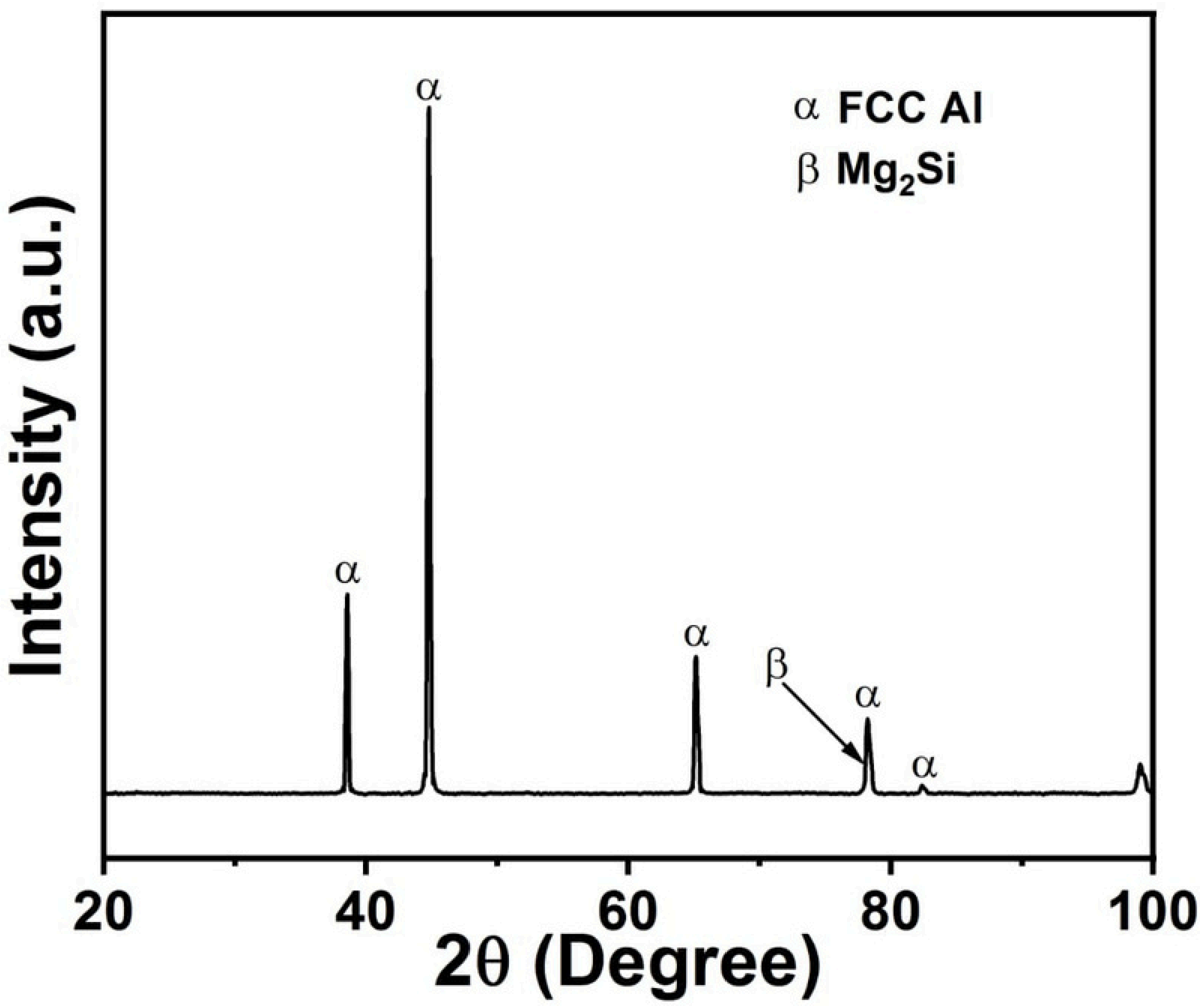


Fig 5.3 XRD pattern for Al 6061 alloy

5.4.Tensile Test

The ultimate tensile strength represents the maximum stress the material can withstand before failure. The un-notched sample exhibits the highest UTS of 321.68 MPa, indicating superior resistance to applied stress. This is expected since the absence of notches eliminates stress concentration, allowing the material to perform to its full potential.

For the notched specimens, the UTS decreases as the notch severity increases. The notched sample with Kt=2.76 has a UTS of 309.09 MPa, while the sample with Kt=3.2 shows the lowest UTS of 306 MPa. The reduction in UTS with increasing Kt occurs due to higher stress localization at the notch, which reduces the material's ability to withstand maximum stress. Despite the differences, the decrease in UTS is relatively small, indicating that aluminum 6061 retains good tensile strength even under notch-induced stress concentration.

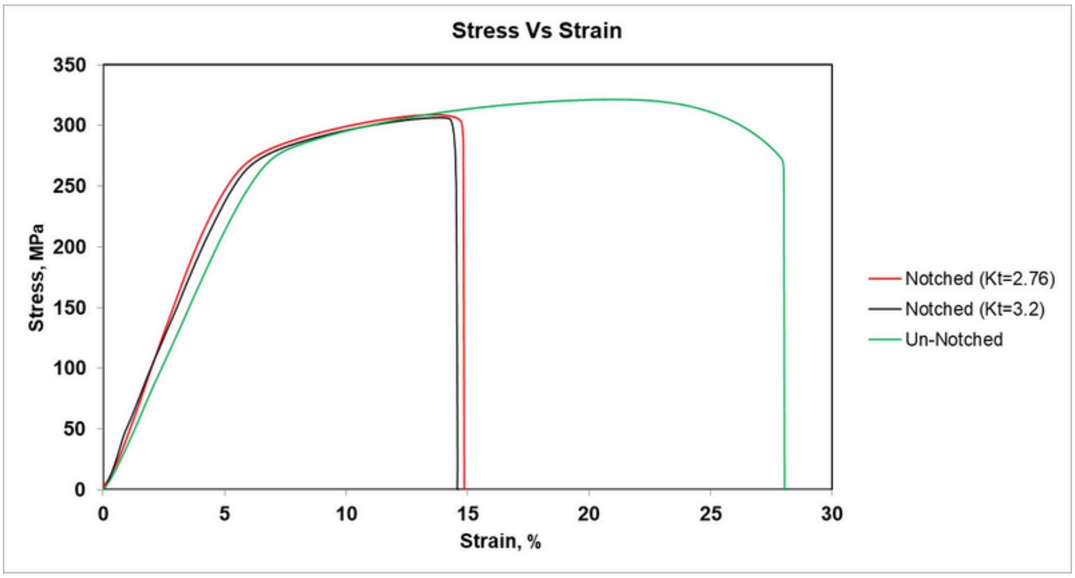


Fig 5.4 Stress vs Strain Curve for Un-notched and Notched (Kt = 2.76 ,3.2) samples

Type of Specimen Rolled Al 6061	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Percent Elongation (%)
Un-notched	255.32 ± 8	321.68 ± 6	24.93 ± 3
Notch (Kt = 2.76)	241.33 ± 6	309.09 ± 10	14.91 ± 3
Notch (Kt = 3.2)	241 ± 7	306 ± 8	~14.6

Table 5.2 Tensile Test results for Al 6061 alloy Un-notched and Notched(Kt =2.76, 3.2) samples

5.4.1. Yield Strength

The yield strength, measured as the stress at which the material begins to deform plastically, shows a consistent trend across all specimens, with only slight reductions in the notched samples. The un-notched sample demonstrates a yield strength of approximately 255.32 MPa, while the notched samples have slightly lower values, such as 241.33 MPa for Kt=2.76. This small reduction indicates that the material's resistance to the onset of plastic deformation is only marginally affected by notches. The yield strength behavior reflects aluminum 6061's uniform response under elastic conditions, even when localized stress concentration is introduced.

Elongation at Break

The elongation at break is a measure of the material's ductility, showing how much it can stretch before fracture. This parameter varies significantly between the un-notched and notched specimens. The un-notched sample has the highest elongation at break, around 24.93%, indicating superior ductility and capacity for plastic deformation. This high ductility is characteristic of aluminum alloys, which are known for their ability to deform extensively under tensile loads.

In contrast, the notched specimens show markedly lower elongation values. The sample with Kt=2.76 exhibits an elongation of 14.91%, while the sample with Kt=3.2 has an elongation of approximately 14.6%. This sharp reduction highlights the effect of notches in promoting premature failure by concentrating stress, which limits the material's ability to undergo plastic deformation. Higher Kt values correspond to more significant reductions in elongation, indicating an increasingly brittle-like behavior under tensile loads.

5.5. Fatigue Test

S-N Curve

The S-N curve (Stress vs. Number of cycles) is a fundamental representation used to understand the fatigue behavior of materials. For Al 6061, a commonly used structural alloy,

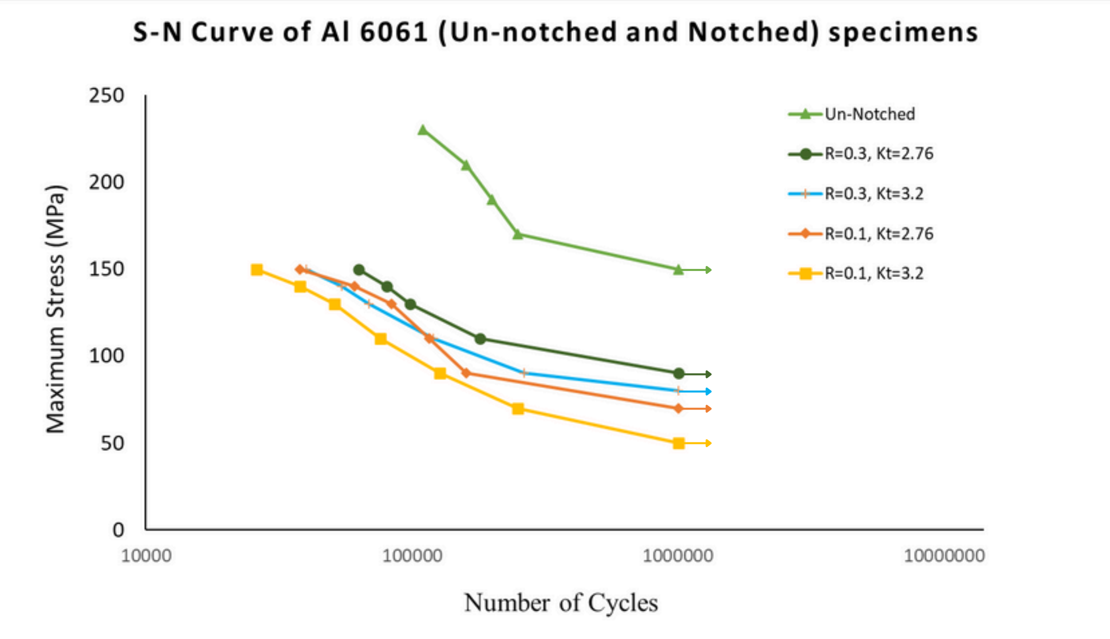


Fig 5.5 S-N curve for Al 6061 alloy Un-notched and Notched(Kt=2.76,3.2) samples at stress ratio(R= 0.1 and R= 0.3)

the S-N curve is influenced by various factors, including the presence of notches (which introduce stress concentration) and the applied stress ratio (R), defined as the ratio of the minimum stress to the maximum stress in a loading cycle. This comparative study examines the fatigue performance of different samples — un-notched, and notched with Kt=2.76K and Kt=3.2 — under two distinct stress ratios (R=0.1 and R=0.3).

Effect of R=0.1 and R=0.3 on Fatigue Life

For both un-notched and notched specimens, the S-N curves at R=0.1 exhibit a relatively steeper slope in the sloped portion of the diagram. This indicates a consistent decrease in fatigue strength as the number of cycles increases. At R=0.1, the stress range is wider due to a lower mean stress, which results in a more pronounced stress fluctuation between the maximum and minimum stresses. In this scenario, the fatigue life is predominantly influenced by the stress range ($\Delta\sigma$), as the material experiences a greater differential between tensile and compressive loading phases. Consequently, the fatigue strength is reduced at higher stress levels, but the specimens still exhibit a defined endurance limit beyond 10^6 cycles.

Our results demonstrate that increasing the stress ratio from R=0.1 to R=0.3 led to an improvement in the fatigue life of the Al 6061 samples. At the same stress amplitude, the samples at R=0.3 were able to endure more cycles before failure compared to those tested at R=0.1. This improvement can be attributed to the higher mean stress in each cycle at R=0.3, which likely contributed to a more stable crack propagation behavior. The presence of a positive mean stress can reduce the severity of cyclic loading by keeping the material in a more favorable stress state during each load cycle. As a result, the sample could withstand a higher number of fatigue cycles before failure, demonstrating a more resilient response under cyclic stress conditions. This trend indicates that, for Al 6061, a higher stress ratio might enhance fatigue life under specific loading conditions.

Comparative Analysis of R=0.1 and R=0.3

The comparative behavior observed between the two stress ratios highlights an important aspect of fatigue performance in Al 6061. At R=0.1, the compressive portion of the stress cycle mitigates crack propagation to some extent, allowing the material to endure a greater number of cycles, particularly in the high cycle fatigue region. The fatigue strength at this lower R value suggests that the material is less affected by the tensile loading phase alone and that the overall stress range ($\Delta\sigma$) is a key factor in determining fatigue life.

In contrast, the S-N curve at R=0.3 demonstrates a shift to the right, especially for surface-induced fractures in notched specimens. This shift indicates a increase in fatigue life.

life is influenced by both the maximum stress and the mean stress, rather than just the stress range, making these factors crucial in understanding the behavior of Al 6061 under cyclic loading.

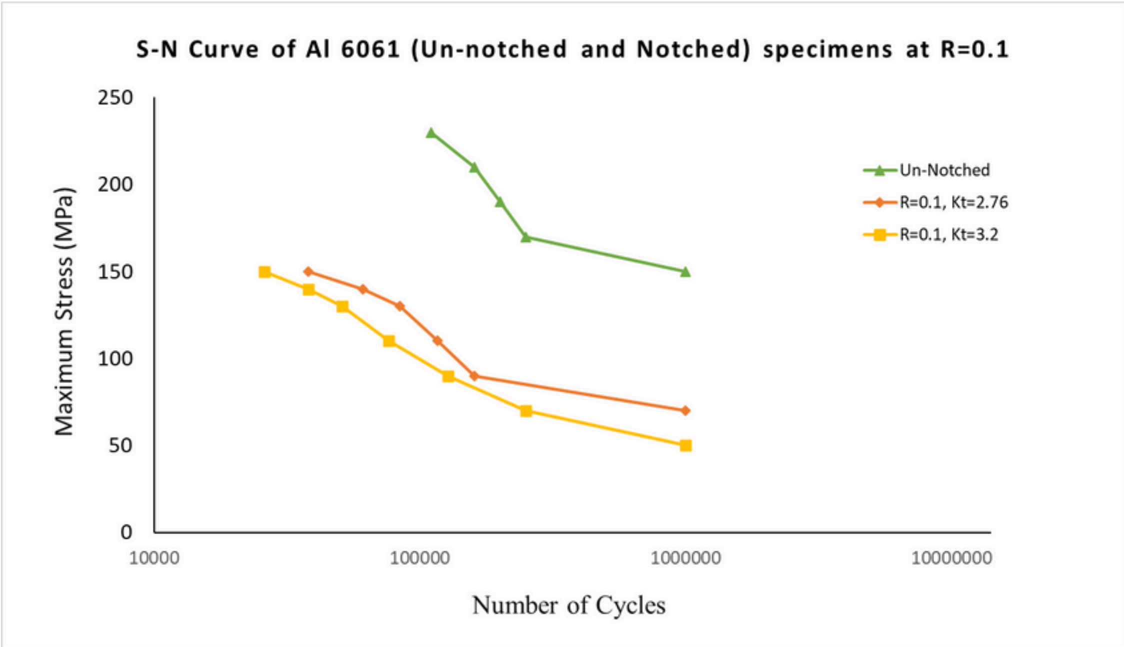


Fig 5.6 S-N curve for Al 6061 alloy Un-notched and Notched(Kt=2.76 ,3.2) samples at stress ratio(R= 0.1)

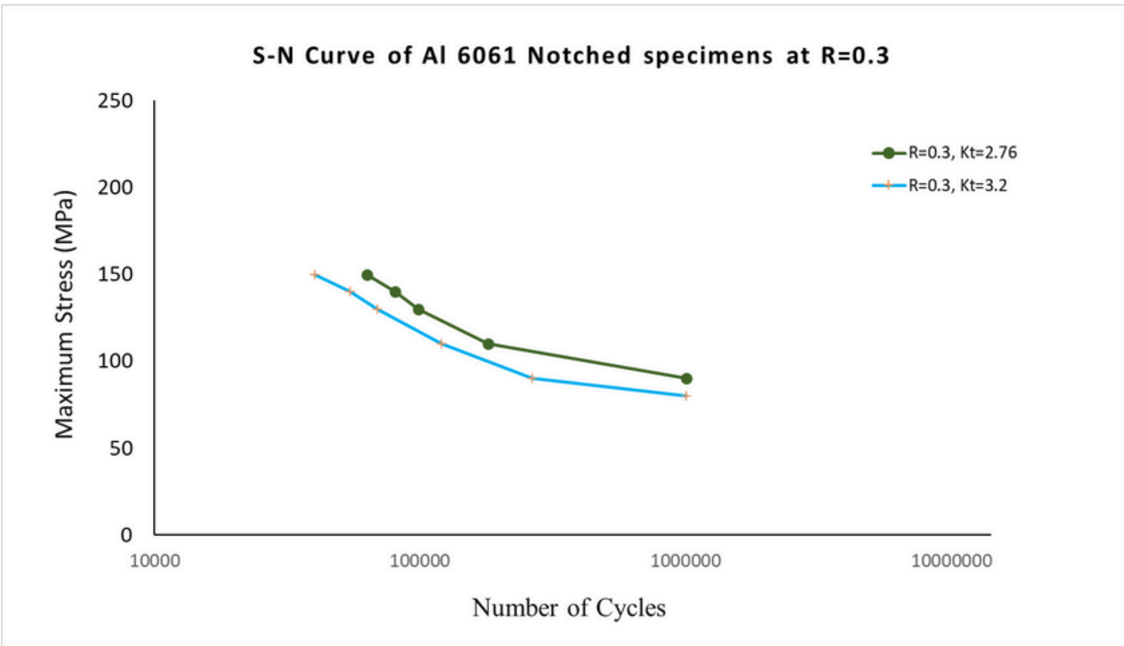


Fig 5.7 S-N curve for Al 6061 alloy Un-notched and Notched (Kt=2.76 ,3.2) samples at stress ratio(R= 0.3)

Effect of Notch Factor (Kt) on Fatigue Life

For the un-notched specimens, the S-N curve exhibits the best fatigue performance, characterized by the highest fatigue strength and longest life. The absence of a notch means there is no localized stress amplification, allowing the material to experience a more uniform stress distribution throughout the loading cycle. As a result, the un-notched samples can endure higher maximum stress levels and sustain a greater number of cycles before failure, especially in the high cycle fatigue region (beyond (10^6) cycles). This behavior suggests that, in the absence of geometric stress risers, Al 6061 can develop a distinct endurance limit, where it can theoretically resist infinite cycles if the applied stress remains below a certain threshold.

When a notch is introduced, increasing the notch factor to (Kt = 2.76), the S-N curve shifts downward, indicating a noticeable reduction in fatigue life. The notch acts as a stress concentrator, amplifying the local stresses at the root of the notch. This stress amplification leads to an increased likelihood of crack initiation, especially under cyclic loading conditions. In the low cycle fatigue region (up to approximately (10^5) cycles), the maximum stress levels that the (Kt = 2.76) specimens can withstand are significantly lower than those for the un-notched samples. Despite this reduction in fatigue strength, the (Kt = 2.76) specimens still demonstrate a moderate endurance limit, suggesting that the stress concentration is not yet severe enough to completely eliminate the potential for high cycle fatigue resistance.

As the notch factor increases further to (Kt = 3.2), the S-N curve undergoes a more dramatic downward shift. The increased notch severity results in higher stress concentrations, which not only accelerate crack initiation but also promote rapid crack propagation once a crack has formed. This leads to a substantial reduction in fatigue strength across the entire range of cycles. In the high cycle fatigue region, the (Kt =3.2) specimens exhibit a significantly lower endurance limit compared to both the un-notched and (Kt = 2.76) specimens. The steeper slope of the S-N curve at (Kt = 3.2) indicates that the material's ability to resist fatigue loading diminishes quickly as the notch severity increases.

Comparative Analysis of Notch Factor (Kt) Effects

The comparative behavior of the S-N curves for different Kt values highlights the critical impact of stress concentration on the fatigue life of Al 6061. The un-notched specimens, show the highest resistance to cyclic loading, as the material is subjected to uniform stresses without localized intensification. This allows for higher fatigue strength and longer life, particularly in the high cycle fatigue region, where an endurance limit can be observed.

In contrast, the notched specimens (Kt = 2.76) and (Kt = 3.2) exhibit progressively lower

Specimen Type	Notch Factor (Kt)	Stress Ratio (R)	Fatigue Strength Trend	Observations
Un-Notched	No notch	R=0.1	Highest fatigue strength across all samples	Longer fatigue life and higher stress resistance, especially at lower cycle counts. No significant drop observed at high cycle fatigue region.
Notched	Kt=2.76	R=0.1	Reduced fatigue strength compared to un-notched	Moderate reduction in fatigue life. The effect of the notch is more prominent as the stress level increases.
Notched	Kt=3.2	R=0.1	Lowest fatigue strength among all samples	Significant reduction in fatigue life, especially at high stress levels. The higher Kt value leads to earlier crack initiation.
Notched	Kt=2.76	R=0.3	Lower fatigue strength compared to R=0.1	Higher stress ratio leads to shorter fatigue life. Increased mean stress exacerbates crack growth.
Notched	Kt=3.2	R=0.3	Substantial reduction in fatigue life	Highest sensitivity to both high Kt and high R. Fatigue life is severely reduced due to combined effects of increased notch severity and mean stress.

Table 5.3 Comparative Study for fatigue results of Al 6061 alloy samples

fatigue strengths and shorter fatigue lives as the notch factor increases. The introduction of a notch significantly alters the stress distribution, creating areas of high localized stress that serve as preferential sites for crack initiation. This effect is magnified as (Kt) increases, resulting in a pronounced decrease in the maximum stress levels that the material can sustain without failure. The difference in fatigue behavior between the (Kt = 2.76) and (Kt = 3.2) specimens emphasizes the exponential impact of increasing stress concentration, where even a small increase in (Kt) can lead to a substantial reduction in fatigue life.

Influence of Notch Factor on Crack Initiation and Growth:

The presence of a notch introduces a stress concentration factor that greatly influences the fatigue crack initiation phase. In the un-notched specimens, crack initiation is typically delayed due to the uniform stress distribution, allowing the material to withstand a higher number of cycles before crack growth becomes a concern. However, in notched specimens, the high localized stresses at the notch root facilitate the early formation of micro-cracks. For (K_t = 2.76), the stress concentration is sufficient to initiate cracks earlier than in the un-notched case, but the material still retains some degree of resistance in the high cycle region.

At (K_t = 3.2), the increased stress concentration leads to a more rapid transition from crack initiation to crack growth. The cracks formed at the notch root are subjected to greater opening forces during each loading cycle, which accelerates the propagation phase and reduces the number of cycles to failure. This behavior is particularly evident in the high cycle fatigue region, where the endurance limit of the (K_t = 3.2) specimens is significantly lower, indicating that the material can no longer sustain prolonged cyclic loading without failure.

Chapter 6

Conclusion

- Un-notched specimens demonstrated the highest fatigue strength and longest fatigue life due to the absence of stress concentrators, with a yield strength of 255.32 MPa, ultimate tensile strength of 321.68 MPa, and 24.93% elongation. These values indicate superior ductility and extended fatigue life, particularly beyond 10^6 cycles, where the material reaches its endurance limit.

- In contrast, notched specimens exhibited lower mechanical properties, with yield strength, tensile strength, and elongation reduced as the notch factor (Kt) increased. For Kt = 2.76, yield strength dropped to 241.33 MPa, ultimate tensile strength to 309.09 MPa, and elongation to 14.91%. For sharper notches (Kt = 3.2), these values further decreased, resulting in the lowest fatigue strength and life.

- Interestingly, increasing the stress ratio from R = 0.1 to R = 0.3 improved the fatigue life of notched specimens, contrary to typical expectations. For instance, at a maximum stress of 150 MPa, the fatigue life nearly doubled for specimens with a stress concentration factor (Kt) of 2.76 and increased significantly for those with Kt = 3.2. This behavior highlights the unique fatigue response of the Al 6061 alloy under these specific conditions.

- Microstructural analysis revealed fine grains, with small amounts of Mg (0.9 wt.%) and Si (0.7 wt.%) at grain boundaries, which impeded dislocation motion and crack propagation, enhancing fatigue resistance.

- XRD analysis confirmed the presence of the FCC aluminum (α) phase as the dominant matrix phase, with trace amounts of the Mg2_22Si (β) phase. The β-phase particles, distributed at grain boundaries, contributed to secondary strengthening mechanisms but also acted as potential crack initiation sites under cyclic loading.

Chapter 7

Future Scope

- Research should explore how different notch shapes (U, V, circular, etc.), sizes, and aspect ratios influence stress concentrations and fatigue life. Finite element analysis (FEA) and experiments can be used to study their effects on crack initiation and propagation under cyclic loading.

- Studies should differentiate the effects of notches in high-cycle fatigue (HCF) with small stresses over many cycles and low-cycle fatigue (LCF) with plastic deformation at fewer cycles. Material-specific behavior and variable amplitude loading transitions also require attention.

- Temperature, corrosive environments, and humidity significantly impact fatigue life. Elevated or cryogenic temperatures alter material strength, while corrosion and moisture accelerate crack growth. Long-term testing and protective measures like coatings are essential.

- Data-driven approaches, including machine learning, can correlate notch geometry, loading, and environmental factors. Multiscale models integrating material and structural behavior will inform design guidelines for fatigue-resistant components in critical industries.

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