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| RESEARCH ARTICLE

Fatigue Reliability and Failure Mechanisms of Steel and Aluminum Alloys for Advanced Manufacturing Applications

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| ABSTRACT
Fatigue failure is important in an engineering component when it is subjected to repeated or cyclic loading, because it can fracture at stresses below the UTS of the material. The objective of this study is to investigate the fatigue reliability and failure mechanisms of steel and aluminum alloys for advanced manufacturing applications that will assist in selecting more suitable materials to make safer, longer-lasting and more reliable U.S. manufacturing and infrastructure. The experimental investigation is conducted on AISI 1018 steel, AISI 1020 steel, 6061 aluminium alloy and B16 brass as an additional laboratory reference material. Experimental evidence was created using tensile, hardness, Charpy impact, tensile-fatigue, and rotating-beam fatigue laboratory tests. The mechanical characterization test involved stress strain testing, tensile testing, hardness, impact and energy absorption testing, and fatigue testing that covered cyclic loading, fatigue life, and fracture behavior. The loading conditions are related to the fatigue-life prediction via the fatigue analysis, employing the concepts of stress amplitude, mean stress, endurance-limit, Goodman and Basquin finite-life relationship. It was decided that the rotating-beam fatigue experiment would give a direct comparison of the two materials: AISI 1018 steel and 6061 aluminum. Under the conditions tested, failure was observed at 27,700 cycles for the steel specimen and at 5,000 cycles for the aluminum specimen. The Charpy impact experiment also reported mean impact-strength values of 3819.975 for AISI 1018 steel, 2786.569 for AISI 1020 steel, 2199.397 for B16 brass, and 1098.715 for 6061 aluminum. The results here show that there are significant differences between the mechanical and fatigue properties of the materials. When assessing reliability, the study also takes into account that experimental variability, condition of specimens, measurement uncertainty, and differences between theoretical predictions and observed fatigue life can all have an impact. The desired result is a performance and failure comparison of the materials that will yield the most reliable material based on the conditions studied and will be useful in real world material selection guidelines for advanced manufacturing components. The results are used to guide engineering toward greater durability, safety, service life and reliability in extreme manufacturing and infrastructure applications, but the reliability results are based on tested environments.

| KEYWORDS

Fatigue Reliability, Fatigue Life, Failure Mechanisms, AISI 1018 Steel, AISI 1020 Steel and 6061 Aluminum Alloy

| ARTICLE INFORMATION

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I. Introduction

A. *Background*

Fatigue is one of the most significant failure mechanisms of engineering materials and parts under repeated or cyclic loading. Fatigue failure may take place in a few steps, starting with the formation of cracks, the growth of cracks, and the final fracture, whereas an immediate tensile failure occurs without the presence of any cracks. A component, therefore, might fail even if the applied cyclic stress is not exceeding the UTS. The behavior was shown in the fatigue experiments in the laboratory which were performed in the present study, both with a tensile-fatigue test and with a rotating-beam fatigue test [1]. The repeated loading was applied to a specimen in a tensile-fatigue experiment that was carried out on an MTS 810 testing system to determine how many cycles it takes for the specimen to fail. In the experiment, fatigue behavior of maximum stress, minimum stress, mean stress and surface condition were also studied. Mechanical properties of steel and aluminium alloys make it suitable for a wide variety of manufacturing applications and hence they are considered as important engineering materials. Variations in strength, hardness, ductility, toughness and fatigue response, however, can have a significant impact on the reliability and service-life of components [2]. It is important therefore in the case of advanced manufacturing that not only be selected for their static mechanical properties but also their ability to withstand repeated loading and their ability to perform consistently over a specified life. In the present study the emphasis has been laid on the characteristics of steel AISI 1018, AISI 1020 and 6061 aluminium alloy, and B16 brass has been used for comparison in the laboratory experiments. The experimental programmer offers a variety of viewpoints on material behaviour [3]. Stress–strain behavior and mechanical properties were studied by tensile testing, and resistance to indentation was studied by hardness testing using Brinell, Rockwell and Vickers test. The tensile tests gave data on the force, elongation, stress and strain of materials used to test for the elastic and plastic properties.

A. *Reliability and Failure Mechanisms of Fatigue*

Fatigue reliability is of particular importance since fatigue life is not just a function of ultimate strength of the material. The initiation and propagation of fatigue cracks can be influenced by cyclic stress conditions, surface characteristics, specimen geometry, material conditions, and experimental variability [4]. The tensile-fatigue laboratory investigation was carried out with the consideration of mean stress by Goodman criterion and the estimation of finite fatigue life by Basquin equation. These approaches serve as a basis for mapping the applied stress conditions on to the fatigue-life behavior [5]. For cyclic loading, the rotating-beam fatigue experiment gives further evidence which can be used to compare steel and aluminum. During that trial, both the AISI 1018 steel and 6061 aluminum were tested alone until fracture. The following fatigue lives were observed: 1018 steel specimen: 27,700 cycles; 6061 Aluminum specimen: 5,000 cycles. The fracture surface after failure was also observed in the experiment, which has certain significance in understanding the fatigue failure characteristics.

B. *Problem Statement*

When choosing materials for components that are to be used for a long time, it is difficult to select materials that have the required properties for tensile strength, hardness, resistance to impact and fatigue resistance. Material which gives good performance under one kind of loading may not necessarily have the same reliability under repeated cyclic loading. Furthermore, there are some differences between the theoretical fatigue-life prediction and experimental results which can make the engineering design uncertain [6]. This is shown with the laboratory results. The rotating-beam fatigue test gave fatigue lives significantly different from the predicted values, and the report pointed out that errors in the moment calculation and an Aluminium specimen that may have been defective were possible factors. Again, in the tensile-fatigue experiment, there was a real fracture after about 17,242 cycles, but the predicted fatigue life was much lower than this. The differences highlight the need to consider uncertainty and variability and use experimental evidence to evaluate fatigue performance.

C. *Research Goal*

The aim of this study is to evaluate fatigue reliability and failure mechanisms of steel and aluminum alloys for advanced manufacturing applications with a specific focus on improving the selection of materials for long-life, reliable and durable parts in U.S. manufacturing and infrastructure. The experimental study compares the three materials: AISI 1018 steel, AISI 1020 steel and 6061 aluminum alloy and B16 brass is used as a reference material in the experiments conducted in the lab. This research aims to obtain a correlation between some fundamental mechanical properties and fatigue [7]. This correlation is achieved by combining the results of tensile, hardness, Charpy impact, tensile-fatigue, and rotating-beam fatigue experiments. Special focus on the fatigue life, cycles to failure, material variability and failure characteristics observed under cyclic loading. The study also compares the experimental fatigue behaviour with theoretical fatigue life expectations, to see whether there are differences between the two that could be due to loading conditions, specimen characteristics, measurement uncertainty, material defects or any other factors [8]. The integrated evaluation will be used to determine the material with the best performance under the experimental conditions investigated and to create evidence-based material-selection guidelines. This study will aid in Designing Safer Components, Durability and Service Life of Components, and Reliable Material Selection for Advanced Manufacturing Applications.

D. *Research Objectives*

The study aims at accomplishing the following:

- To compare the fatigue life of some alloys of steels and aluminium under cyclic loading.
- To study failure mechanisms that relate to fatigue fracture [9].
- To assess the correlation among tensile properties, hardness, impact strength and fatigue resistance.
- To compare the theoretical fatigue-life prediction with the experimental fatigue life.
- To assess the reliability of materials from fatigue-life and experimental variation data.
- To determine the best material for the conditions analyzed in the experiments.
- To come up with material selection rules for long lasting manufacturing parts.

E. *Research Questions*

The study answers the following research questions:

- How does fatigue life change between AISI 1018 steel, AISI 1020 steel and 6061 aluminium alloy for the loading applied in the above?
- What failure mechanisms do the tested materials have, related to fatigue fracture? What is the relationship between Hardness, Tensile properties and impact strength with Fatigue performance?
- Which material has the best fatigue characteristics, under the experimental conditions?
- How to tie together experimental data on fatigue and mechanical properties for applications in advanced manufacturing?

F. *Significance of the Study*

The importance of this research lies in the fact that the selection of materials used in the manufacturing process can play a key role in making the manufacturing process safer and durable. The study is a combination of fatigue testing, tensile testing, hardness testing, and impact testing for a comprehensive evaluation of material performance [10]. For instance, in the Charpy impact experiment, a material that was tested and found to have measurable differences among the four materials tested, the mean impact-strength values were 3819.975 for 1018 steel, 2786.569 for 1020 steel, 2199.397 for B16 brass, and 1098.715 for 6061 aluminum. The study can give a more complete basis for material selection than could a single mechanical property since it incorporates these experimental observations with fatigue-life and failure analysis. The results will help engineers make decisions on durability, fatigue, reliability of parts and service life in advanced manufacturing and related U.S. infrastructure applications [11]. The material selection guidelines that can be derived from these will aid engineers in making decisions for selecting materials for components under repeated or high loading conditions, taking both performance and reliability into account.

II. LITERATURE REVIEW

A. *Fundamentals of Fatigue and Fatigue Failure Mechanisms*

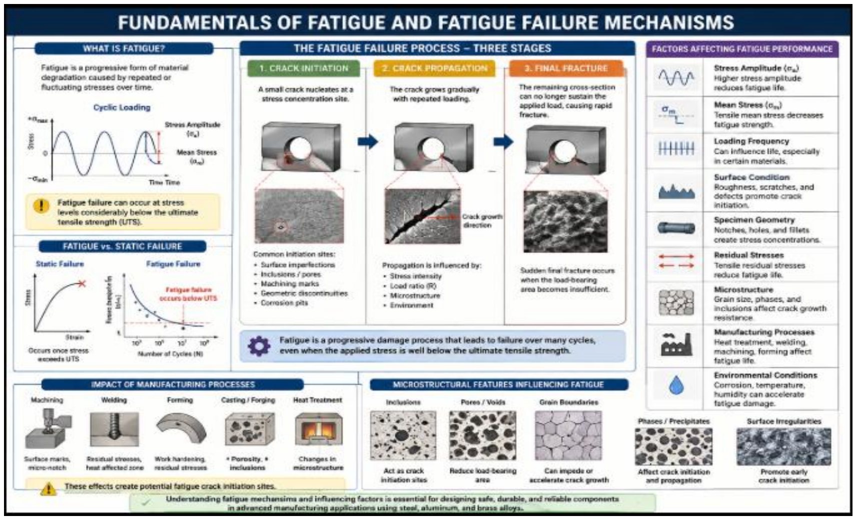

Figure 1: This image demonstrates the progression of fatigue, the factors that can affect fatigue, and mechanisms of crack initiation during manufacture

The basic process of fatigue failure and the key factors that affect the fatigue performance of engineering materials are shown in figure 1. The diagram first separates the fatigue from static failure, and demonstrates that fatigue can develop under cyclic stresses that are less than the ultimate tensile strength [12]. The central section shows the 3 major phases of fatigue failure: crack initiation, crack growth and final fracture. It pinpoints typical locations where cracks are likely to form, such as surface flaws, inclusions or pores, machining marks or geometric discontinuities [13]. Also, stress amplitude, mean stress, loading frequency, surface condition, specimen geometry, residual stresses, microstructure, manufacturing processes, and environmental conditions are important factors that influence fatigue, and are summarized in the figure. Lastly, it focuses on the mechanisms that manufacturing processes and microstructural features can give rise to or exacerbate fatigue damage.

B. *S–N Relationships, Fatigue Life and Fatigue Mean Stress Effects*

Typically, fatigue life is referred to as the number of cycles to failure of a material at a given failure criterion. The most popular way to determine fatigue properties is the stress–life (S–N) method, where the number of cycles to failure is correlated with the amplitude of stress. The S–N curve is very useful for high cycle fatigue problems where the stress is relatively low and the number of cycles applied to the component is large [14]. The shape and slope of an S–N relationship can be very informative of the sensitivity of a material to cyclic loading. Fatigue data typically show a large scatter in the results, though, due to the influence of specimen condition, surface quality, microstructure, defects and testing variation on fatigue failure [15]. The Basquin relationship is a mathematical representation of the relationship between stress amplitude and the number of cycles to failure. It is written as a power law between cyclic stress and number of cycles to failure. The Basque-type relationships are still widely employed for the analysis of stress–life data in the modern literature on fatigue. They are especially useful in the high cycle fatigue regime. Other factors that are important include mean stress, as the cyclic loading may not fully be reversed. Fatigue resistance can be decreased by a positive mean stress, while varying mean stresses can lead to varying fatigue lives with similar stress amplitudes [16]. The Goodman criterion is an often-used linear correction applied when using fatigue calculations that include mean stress. It correlates alternating stress, mean stress, ultimate tensile strength and fatigue strength of the material [17]. The theoretical background for comparison of the prediction and experimental fatigue behavior in this research is based on the S–N approach, Basque approach and Goodman approach [18]. It is important to compare calculated and laboratory fatigue life because there are approximations in the theoretical models, and they should be compared with the actual experimental performance.

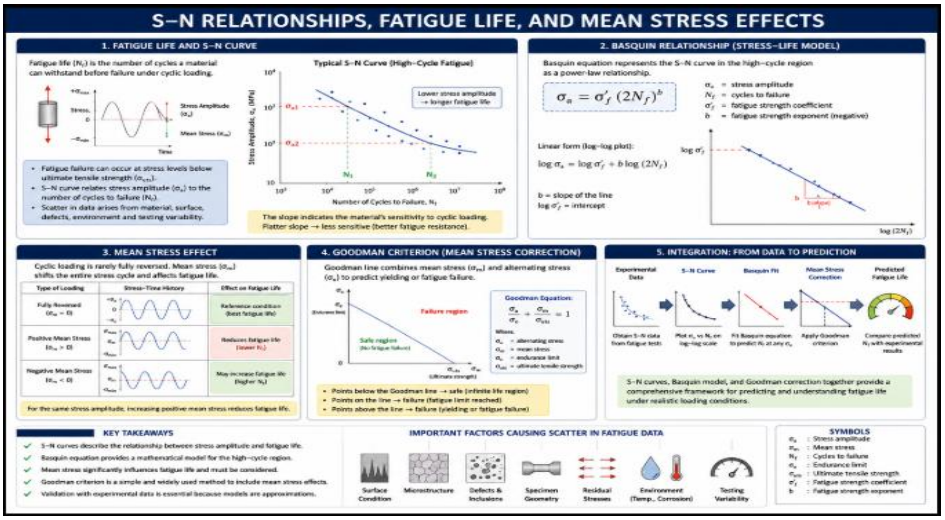

Figure 2: This image shows the S–N curves, Basquin modeling, mean stress effects, and Goodman fatigue-life prediction

The S–N approach for cyclic stress/fatigue life relationship is shown in Figure 2. It specifies fatigue life in terms of number of cycles to failure, and shows that lower stress amplitudes typically equate to longer fatigue lives. The figure is a mathematical stress–life model of the Basquin relationship and demonstrates that the model can be expressed as a log–log relationship. It also discusses how mean stress affects fatigue life; that positive mean stress tends to decrease fatigue life [19]. The Goodman criterion is given as a technique for correcting fatigue calculations for mean stress. The image relates experimental fatigue data to S–N curves, Basquin fitting, Goodman correction, and fatigue life prediction, and identifies some of the factors that cause experimental scatter.

C. *Mechanical Properties of Steel, Aluminum, and Brass Alloys*

Service conditions, processing history, microstructure and composition are each important factors in the mechanical behavior of metallic materials. Some common steel grades used for engineering and manufacturing are referred to as low carbon steels, and include AISI 1018 and AISI 1020. While the compositions are fairly comparable, variations in carbon content and the condition of the material may affect their mechanical response [20]. It is possible to compare the two steels and see how small variations in material properties can affect the fatigue, hardness, tensile and impact properties [16]. AISI 1018 is of particular interest to the current research since it is tested directly for its fatigue response using rotating-beam tests [17]. A total of 6061 aluminum alloy is also used in the experimental programmer as it is one of the most commonly used alloys for applications with high demands on low density and weight reduction [18]. It has light weight, which may make it appealing for use in manufacturing applications that require lightweight materials, but its fatigue response should be assessed depending on the loading and material [19]. The fatigue performance of 6061 aluminum is compared with AISI 1018 steel as observed during the use of the rotating-beam fatigue machine. B16 brass is added as a reference material to serve as another basis for mechanical / impact comparison. Incorporation of this would expand the material comparison beyond steel and aluminum, and will further illustrate the differences in response to mechanical loading for different alloy systems [20]. Mechanical properties should thus be treated as a whole and not separately. The properties of a material, measured in its ability to withstand tension, hardness, ductility, impact and fatigue, are described by tensile strength, hardness, ductility, impact resistance and fatigue. When choosing materials for manufacturing components with cyclic loads, it is important to conduct experimental comparison as it is possible that a material with high static strength may not have the highest fatigue resistance.

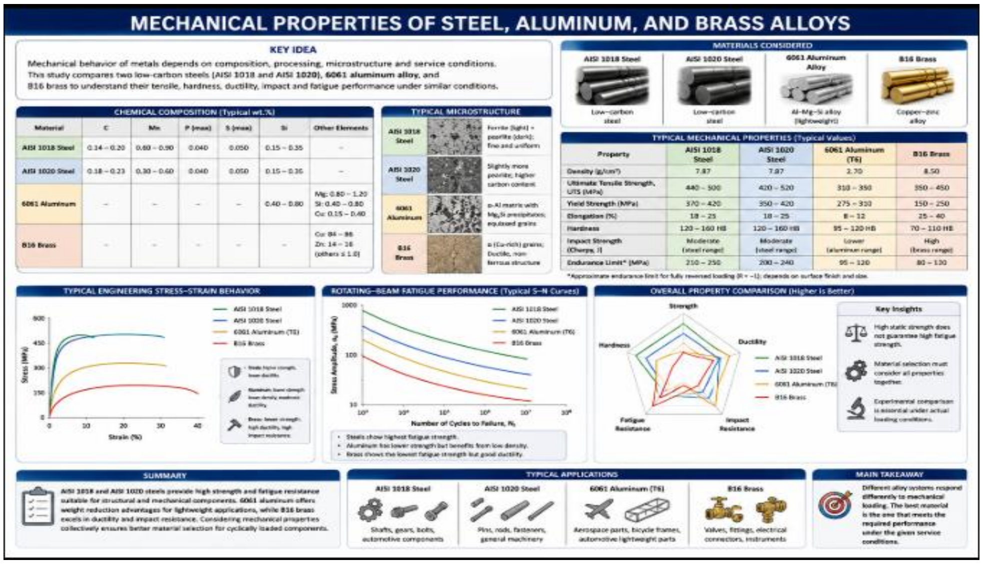

Figure 3: This image compares mechanical properties of steel, aluminum and brass alloys for engineering use

Figure 3 shows a comparative overview of mechanical properties of AISI 1018 steel, AISI 1020 steel, 6061 aluminum alloy and B16 brass. It outlines their average chemical composition, microstructural features and significant mechanical characteristics such as density, tensile strength, yield strength, elongation, hardness, impact strength, and endurance limit. Rotating-beam fatigue performance is also compared to the typical engineering stress–strain response by means of S–N curves. A radar chart is useful for a general visual comparison of strength, ductility, impact resistance, fatigue resistance and hardness. Representative engineering applications are identified and it is made clear that the selection of the materials should involve more than one mechanical property and also take into account the actual service condition.

D. ***Hardness, Tensile Behavior and Impact Toughness in Fatigue Assessment***

Hardness, tensile properties, and impact toughness do not give the same information about material behavior, but can help in the interpretation of the fatigue characteristics [21]. Hardness is a measure of the resistance of a material to localized permanent deformation and is often used as a measure of the condition and resistance of a material to the permanent deformation caused by an indentation. The original experimental program involved making Brinell, Rockwell and Vickers measurements to characterize the difference between the tested materials [22]. The results on Brinell measurements indicated that the mechanical response depended on the material type and processing condition (hot-rolled steel, cold-rolled steel and 6061 aluminum). Tensile testing can be used to learn about elastic deformation, yielding, strain hardening, UTS, elongation, necking and fracture. The properties are helpful in determining the underlying mechanics of a material prior to studying its fatigue behavior [23]. Fatigue is not simply a function of tensile strength, however, and is an accumulation of repeated loading, crack initiation and crack propagation. In the tensile fatigues experiment described in the study, it is clear that it is worth comparing the static and cyclic behavior [24]. Another view comes from impact toughness, which is analogous to Charpy, in that it is the amount of energy absorbed as the material fractures under sudden loading. The experimental ranking reported was AISI 1018 steel, AISI 1020 steel, B16 brass and 6061 aluminum [25]. However, impact toughness and fatigue life are the two different failure mechanisms and are not interchangeable properties. Thus, a combination of the hardness, tensile properties, impact properties and fatigue properties would offer a better foundation for material evaluation [26]. This is especially applicable to the selection of materials for advanced manufacturing where the selection of material is required to meet both static mechanical requirements and resistance to cyclic and impact loading.

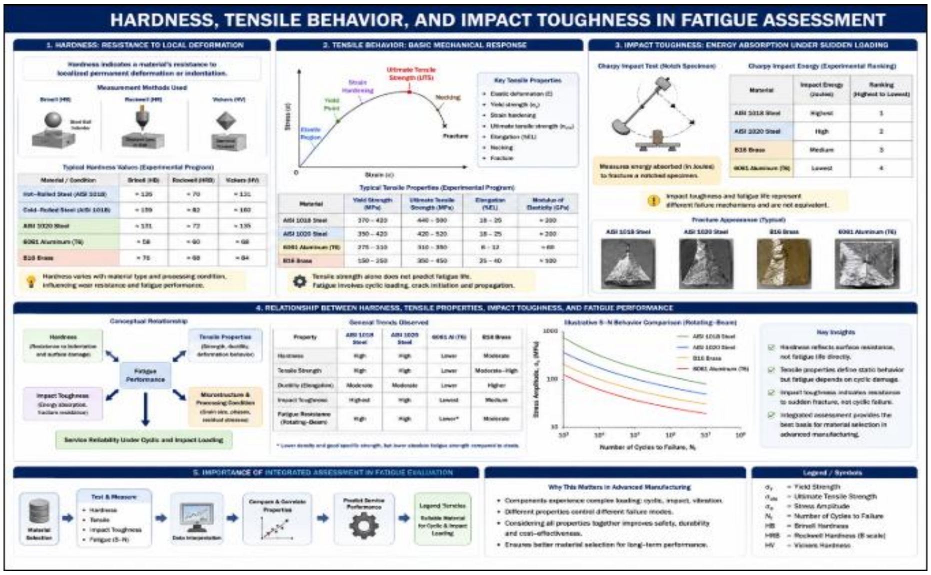

Figure 4: This image shows integrated material selection for hardness, tensile, impact and fatigue

The results of the integrated assessment of hardness, tensile behavior, impact toughness and fatigue performance for AISI 1018 steel, AISI 1020 steel, 6061 aluminum alloy and B16 brass are shown in figure 4. The figure shows the three main hardness measurement techniques (Brinell, Rockwell and Vickers) and a summary of the typical hardness values. The tensile section is shown to exhibit stress and strain characteristics such as elastic deformation, yielding, strain hardening, ultimate tensile strength, and necking and fracture [27]. The Charpy impact section illustrates impact testing and compares the impact-energy performance of the four materials, relative to each other. There is a conceptual link between hardness, tensile properties, impact toughness, and microstructure and fatigue performance [28]. The latter parts focus on integrated material assessment for advanced-manufacturing applications with reliable performance.

E. *Fatigue Reliability and Material Selection for Advanced Manufacturing*

Fatigue reliability analyzes fatigue life and incorporates uncertainty and probability of failure under certain loading conditions. The reliability analysis takes into account the variation which is usually linked with fatigue failure, and asks if a component can withstand a certain number of cycles with an acceptable level of confidence [25]. This distinction is important because fatigue tests conducted on nominally identical specimens may yield varying lives of failure for two or more specimens as a result of variations in material microstructure, surface condition, specimen geometry, defects, and experimental conditions. From the literature, it can be seen that fatigue design becomes more and more difficult as the lifetime of the component increases. Modern research on probabilistic S–N relationships has focused on taking into account scatter in fatigue data, as opposed to being based on a sole deterministic fatigue-life value. The influence of defects is important because often fatigue cracks can start from defects on the surface or inside of the component, and this can dramatically impact service life predictions. The fatigue life is therefore important in addition to the tensile strength, hardness, impact toughness, ductility, surface condition, manufacturing process, and loading conditions when selecting materials for advanced manufacturing applications [26]. Such comparisons could be made considering the experimental results obtained within the present study, and the differences between the theoretically predicted and the measured fatigue life indicates the need for experimental validation [27]. There is evidence in the literature to support a multidimensional fatigue reliability approach. None of the mechanical properties is enough to predict fatigue. Rather, the integration of mechanical characterization, fatigue testing and failure-mechanism analysis as well as experimental uncertainty is essential for reliable material selection. This is a framework to help compare the results of the present research involving AISI 1018, AISI 1020, 6061 aluminum and B16 brass.

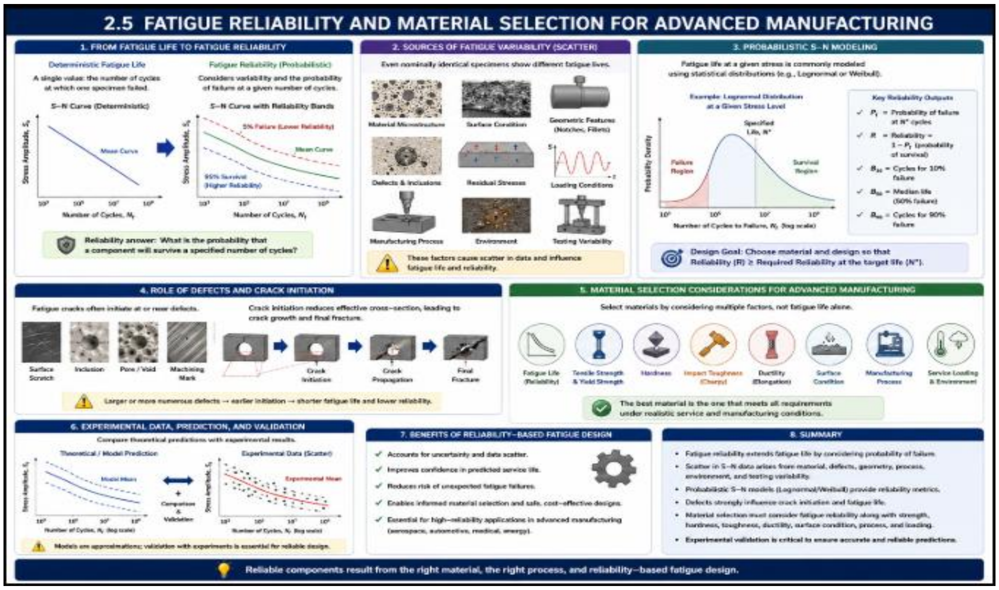

Figure 5: This image showed fatigue reliability, variability, defect effects and material selection for advanced manufacturing applications

Fatigue-life analysis can be extended into a reliability-based approach for advanced manufacturing applications as shown in figure 5. It separates the deterministic fatigue life from probabilistic fatigue reliability, and it reveals variations in fatigue data, such as those due to material microstructure, surface condition, geometric features, defects, residual stresses, manufacturing processes, and environmental conditions, as well as testing variability [28]. The figure shows probabilistic S–N modeling and reliability measures which can be used for failure and survival probability estimation. It also illustrates how defects can create and grow fatigue cracks [29]. A material selection framework considers fatigue life, tensile strength, hardness, impact toughness, ductility, surface condition, manufacturing processes, service environment and includes these. Finally, experimental validation is highlighted for reliable fatigue prediction and design.

F. *Existing Research and Research Gap*

In the article "Significant Advancements in Numerical Simulation of Fatigue Behavior in Metal Additive Manufacturing—Review", Gandhi et al. (2022) examined the advancements of Numerical Simulation for Fatigue behavior in Metal Additive Manufacturing, especially focusing on developments in fatigue properties, numerical simulation, and reliability of additively manufactured components. The authors reviewed various types of metal Additive Manufacturing technologies, materials, lattice structures, fatigue properties and numerical simulation methods such as Finite Element Methods [1]. Their review highlighted that while additive manufacturing offers great design freedom, light weight structures, and complex component manufacturing, the mechanical behavior and reliability of additively manufactured components is still difficult to characterize. The authors also pointed out the need for the validation of the numerical fatigue simulation with experimental data and limitations encountered by the current simulation methods and commercial software. The main focus of the review is on the use of additive manufacturing (AM) materials and numerical modelling, and not a comparison of the fatigue performance and mechanical properties of engineering alloys manufactured by conventional methods under controlled laboratory conditions. This generates a research gap which is filled by the present study using experimental testing of the AISI 1018 steel, AISI 1020 steel and 6061 aluminum on the following tests: tensile, hardness, Charpy impact, and tensile-fatigue and rotating-beam fatigue. The present study offers practical evidence that establishes a relationship between mechanical properties, fatigue performance and failure mechanisms by comparing the experimental fatigue life with theoretical fatigue life predictions and analyzing the failure behavior.

In the article "Improvement of the Fatigue Resistance of Super Duplex Stainless-Steel (SDSS) Components Fabricated by Wire Arc Additive Manufacturing (WAAM)," Sales et al. (2022) investigated methods for improving the fatigue performance of super duplex stainless-steel components fabricated using wire arc additive manufacturing. The authors investigated the effect of interposes temperature, microstructure, internal defects and deposition direction on the fatigue properties. Internal defects, including porosity, were characterized using micro-computed tomography and fatigue testing showed that fatigue performance of the weaker transverse direction could be enhanced by increasing the interpose temperature. Fatigue anisotropy was still observed even if the basic mechanical properties under monotonic loading were fairly comparable, which emphasizes manufacturing direction and processing conditions for fatigue performance. The influence of residual stresses, manufacturing defects and process parameters were also noted as key influences on fatigue resistance by the authors [2]. The study however, is limited to the super duplex stainless steel produced by WAAM and does not offer a more general experimental comparison of various engineering material manufactured by WAAM and subjected to various mechanical and fatigue tests. In the present study an attempt has been made to experimentally investigate the above three materials in terms of tensile, hardness, Charpy impact, tensile-fatigue, and rotating-beam fatigue tests. The data obtained in this study, which compares the theoretical fatigue predictions with experimentally determined fatigue lives and mechanical properties, offers an expanded experimental evaluation of fatigue behavior and failure mechanisms of these materials for applications in advanced manufacturing.

In the article "Influence of Rotation Speed on Interfacial Bonding Mechanism and Mechanical Performance of Aluminum 6061 Fabricated by Multilayer Friction-Based Additive Manufacturing," Tang et al. (2023) investigated the influence of rotation speed on the interfacial bonding, microstructure, material utilization, and mechanical performance of 6061 aluminum fabricated using friction extrusion additive manufacturing (FEAM). The authors noted that rotation speed of 400 rpm yielded a more stable and reliable multilayer deposition process with relatively consistent layer dimensions, and also resulted in better material utilization [3]. The study also demonstrated that the flow of metals, formation of the interface, recrystallization and recovery, grain structure and the resulting mechanical properties of the deposited material were affected by changes in rotation speed. The results prove that process conditions of the additive manufacturing can have a significant impact on the microstructure and mechanical properties of 6061 aluminum. The study, however, mainly concentrates on the interfacial bonding and mechanical performance of the friction-based additive manufacturing process and doesn't fully investigate the fatigue performance of the 6061 aluminum and other engineering materials under controlled cyclic loading conditions. This paper fills this gap by experimentally testing 6061 aluminum and AISI 1018 and AISI 1020 steels by tensile, hardness, Charpy impact, tensile-fatigue, and rotating-beam fatigue tests. A correlation between mechanical properties and experimentally observed fatigue life and failure behavior enabled a wider understanding of material behavior for applications in fatigue resistant and advanced manufacturing.

III. Materials and Methodology

The reliability and failure behaviour of metallic material in fatigue is assessed from experimental data from laboratory tests [7]. The materials studied were AISI 1018 steel, AISI 1020 steel, 6061 aluminum alloy and B16 brass, and the materials were evaluated by complementary mechanical and fatigue experiments [8]. The methodology included tensile-fatigue, tensile, hardness, Charpy impact and rotating beam fatigue testing. The stress–strain behavior and mechanical properties, such as strength and deformation properties, were characterized by tensile testing [9]. The hardness testing data gave information on resistance to indentation, and the Charpy impact testing data gave the energy absorbed and impact strength of the steel, aluminum and brass specimens. AISI 1018 steel and 6061 aluminum specimens were used in the rotating-beam fatigue experiment, which involved repeated bending until failure, measuring number of cycles to failure and examining fracture surfaces [10]. The data obtained were then compared to evaluate material fatigue life, mechanical characteristics, variation and material reliability in the conditions studied.

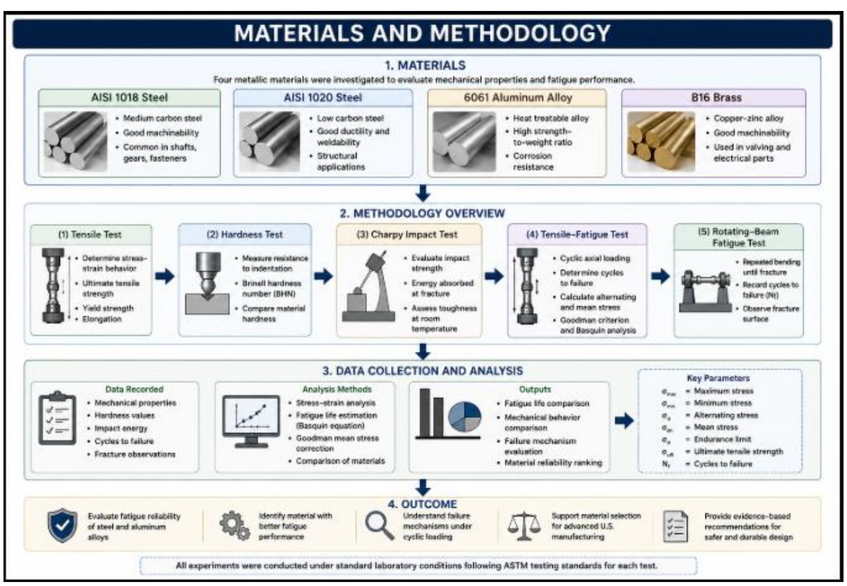

Figure 6: This image is of the materials, experimental testing, and data analysis and reliability evaluation framework

The figure presents the overall materials and methodology framework used to investigate fatigue reliability and failure mechanisms. Four materials are studied, namely AISI 1018 steel, AISI 1020 steel, 6061 aluminum alloy and B16 brass. A range of five experimental tests, tensile, hardness, Charpy impact, tensile-fatigue and rotating-beam fatigue tests are contained within the methodology [11]. The framework then illustrates a set of mechanical properties, hardness values, impact energy, cycles to fatigue and fracture observations [12]. Stress–strain evaluation, estimation of fatigue-life, Goodman mean-stress correction, Basquin analysis and material comparison are used to analyze these data [13]. The results can be used to perform fatigue-reliability evaluation, identify improved materials, understand failure mechanisms and recommend material selection for advanced U.S. manufacturing applications based on evidence.

A. *Research Design*

Steel and Al alloys fatigue reliability evaluation and failure mechanisms for advanced manufacturing applications is carried out in this study by an experimental research design [14]. The research involves a comparative analysis of the mechanical characterization done in the lab and fatigue testing [15]. The main materials studied are AISI 1018 and AISI 1020 steels and 6061 aluminum alloy [16]. The additional material B16 brass has been added as reference as it has been evaluated in the laboratory experiments [17]. The experimental approach aimed at investigating the behaviour of the material from several angles and not only based on fatigue life. Stress – strain behaviour and mechanical properties were characterized by tensile test; resistance to indentation was evaluated by hardness test; energy absorption and impact strength was determined by Charpy impact test and cyclic loading behaviour and cycles to failure was determined by fatigue test [18]. These experimental results are integrated to evaluate the material performance, understand the difference in failure mechanism and give some recommendations for material selection in advanced manufacturing applications.

B. *Experimental Materials*

Four engineering materials were included in the laboratory investigation: Material:

Material	Material Type	Role in Study
AISI 1018 Steel	Low-carbon steel,	Primarily used for fatigue and mechanical-property materials
AISI 1020 Steel	Low carbon steel	Comparative material Aluminum alloy
6061 Aluminum alloy	Aluminum alloy	Primary lightweight-material comparison
B16 Brass	Brass alloy	Additional experimental references

These were specifically tested: B16 brass, AISI 1020 steel, AISI 1018 steel, and 6061 aluminum, in the Charpy impact experiment. The rotating-beam fatigue experiment was a direct comparison of AISI 1018 steel and 6061 aluminum.

C. *Laboratory Experimental Program*

The experimental program comprised a series of laboratory tests aimed at describing various aspects of material behavior.

1) Tensile Fatigue Testing

This is a tensile fatigue experiment where a specimen was cyclically loaded in an MTS 810 testing machine. Displacement, force and time to fracture were monitored throughout the test. The specimen was treated with smoothing and cleaning, then dimensioned, the resistance element was installed, the specimen was checked and then cyclic loading was applied with the MTS 810. Fatigue data obtained were analyzed for the correlation between applied stress and cycles to failure [21]. The experiment also furnished data on the fracture characteristics and ductility.

2) Hardness Testing

Hardness was determined by three methods, Brinell, Rockwell and Vickers. All the specimen surfaces were cleaned and prepared prior to testing and several measurements were taken for each specimen surface for consistency in observations [22]. Hardness was determined with a Brinell test performed with a hardened ball indenter and a 2000 kg load; and a Rockwell test was used to measure the depth of the indentation made by the indenter under the minor load and then under the major load [23]. The Vickers test employed a diamond-pyramid indenter, and the diagonals of the resulting indentation were measured.

3) Tensile Testing

A tensile experiment was performed to analyze the stress–strain response and mechanical properties. The dimensions of the specimens were taken before the test, the testing equipment was calibrated, and force and displacement data were taken as the specimen was loaded until it fractured [24]. Crosshead displacement was measured in place of the use of an extensometer. The laboratory report noted that the crosshead movement must also account for machine and specimen deformation, and thus took into account the stiffness of the machine in the analysis. These data were then applied to the generation of stress–strain curves and to the analysis of elastic behaviour, yield behaviour, ultimate strength, resilience, toughness and fracture behaviour.

4) Charpy Impact Testing

The materials were tested for their energy absorbing capacity prior to fracturing by using Charpy impact testing. The specimen was released from a known angle and the difference measured between the angle released and the angle after impact to calculate the energy absorbed by the specimen. All specimens were taken to be measured before testing and the pendulum was run with no specimen to compensate for machine friction [25]. The specimens were subsequently tested one by one and the impact strength was determined by dividing the absorbed energy by the cross sectional area.

5) Rotating-Beam Fatigue Testing

The fatigue experiment with the rotating beam was a test of the fatigue behavior under fully reversed bending loading. The AISI 1018 steel and 6061 aluminum specimens were individually mounted, aligned and loaded in a rotating beam fatigue machine [26]. The rotational speed was slowly increased from 0 to about 5000 rpm and each specimen was tested until broken. Post-fracture, the specimens were retrieved and the fracture surfaces were examined and documented for further analysis.

D. *Specimen Preparation and Measurement*

An important part of the experimental procedure was the preparation of the specimens and the dimensional measurement [27]. The dimensions of the specimens such as the overall length, the diameter of grip, the length of the test section and the diameter of test section were measured prior to testing in the fatigue experiment. The size of the test section was needed to calculate the stress condition of the specimens. Specimen surfaces in tensile-fatigue were abraded with abrasive materials of increasing fineness, and cleaned of contaminants [28]. The specimens were examined for cracks, misalignment and other defects prior to testing.

E. *Stress and Strain Analysis*

The mechanical response of the tensile specimens was evaluated by performing a stress–strain analysis. The applied force and original cross-sectional area were used to calculate the engineering stress:

$$\sigma = \frac{F}{A_0}$$

Where σ is engineering stress, F represents applied force and

A_0 Represents the original cross sectional area.

Engineering strain was determined from the change in specimen length

$$\epsilon = \frac{\Delta L}{L_0}$$

Where ϵ is engineering strain, ΔL is the change in length and L_0 is the original gauge length

The resulting stress–strain relationship was used to determine the plastic behavior, yield behavior, elastic region and fracture behavior [29]. These mechanical properties were assessed by the tensile laboratory experiment using stress–strain data.

F. *Stiffness and Modulus of Elasticity Analysis*

To analyze the force–displacement response, the experiment with tensile test was also taken into account the stiffness of the machine and the stiffness of the specimens. Since crosshead displacement was measured, machine and specimen deformations could add to the measured displacement. The stiffness of the machines were thus added to the analysis based on the laboratory procedure [30]. The corrected force–displacement relationship was used to evaluate material stiffness and modulus of elasticity. The results were then compared with the actual stress–strain behaviour.

G. Basquin Fatigue-Life Model

The theory is to use the Basquin curve and Goodman's Criteria to be able to determine the fatigue of failure acting upon the specimen [31]. To begin first, have to use the following equations in order to calculate separate values of stress acting upon the specimen.

σ_e: Endurance Limit - This can be determined using the given equation and table

The established material endurance limit $\sigma_e=0.27(\sigma_{ult})$.

Surfaces	s_e
Ground	$0.44s_{ult}$
Machined	$0.37s_{ult}$
As-rolled	$0.27s_{ult}$
As-forged	$0.20s_{ult}$

σ_m: Average Applied Stress - $(\sigma_{min} + \sigma_{max})/2$

σ_{range}: Range Stress - $\sigma_{max} - \sigma_{min}$

σ_a: Stress Applied - $(\sigma_{max} - \sigma_{min})/2$ or $\sigma_a = \sigma_{max} - \sigma_m$

Once the values are gathered, use them to find the infinite life region by plugging them into the Goodman equation.

$1/n = \sigma_a/\sigma_e + \sigma_m/\sigma_{ult}$

Interpret and apply the **Basquin finite life equation** using the given data:

$\sigma_f = AN^B$

$A= (0.9\ \sigma_{ult})^2/\sigma_e$

$B=-1/3 \log (0.9\sigma_{ult}/\sigma_e)$

σ_f = fatigue strength at a given number of cycles N

σ_u = ultimate tensile strength

σ_e = endurance limit

N = number of cycles to failure

A, B coefficients

The detailed step-by-step test procedures are provided below

- **Smooth the specimen parts** using various abrasive grids. Start with a coarser grid to remove larger imperfections and gradually move to finer grids to achieve a smooth and even surface [32]. This step ensures that the specimen is prepared for accurate measurements and proper bonding of the resistance element.
- **Clean the specimen parts** thoroughly using a specific cleaning solution, such as acetone or isopropyl alcohol, to remove any dust, oil, or contaminants. This cleaning process is essential to ensure there is no residue that could interfere with the adhesive or the accuracy of the measurements during testing.
- **Measure the dimensions of the specimen parts** using a pencil and scale. Accurately mark the exact center of each specimen part, as this is where the resistance element will be placed [33]. Proper measurement is critical for ensuring uniform stress distribution during testing and for accurate data collection.

- **Connect the positive and negative terminals** of the resistance element to the respective leads, ensuring correct polarity to avoid any errors in measurement during testing [34]. Make sure the connections are secure and that there is no risk of disconnection during the fatigue test.
- **Apply a small amount of adhesive** to the center of the specimen to secure the resistance element in place. Allow sufficient time for the adhesive to set and bond the resistance element securely to the specimen [34]. This step ensures that the resistance element will stay in place during fatigue testing.
- **Shoulder the specimen parts together** using specific tools and iron. Carefully apply force to ensure the parts are aligned properly, ensuring a solid bond [35]. This step is crucial to prevent any misalignment or weaknesses that could affect the integrity of the specimen during testing.
- **Inspect the specimen for any defects**, such as cracks, misalignment, or imperfections in the bonding. Any issues identified during the inspection should be addressed and corrected before proceeding with the testing to ensure the accuracy and reliability of the results.
- **Perform the fatigue testing** using the MTS 810 machine. [36] Apply cyclic loads to the specimen, carefully monitoring and recording data such as displacement, force, and time to fracture. This data will be analyzed to determine the material's fatigue life and tensile strength.

H. *Hardness Testing*

The hardness of the given specimen was measured using three different methods: Brinell, Rockwell, and Vickers hardness tests [37]. These tests were performed to compare the hardness values obtained using different indenters and loading conditions while following standard laboratory procedures. Before conducting the tests, the specimen surface was cleaned and prepared to ensure accurate indentation results [38]. The hardness testing machines were checked for proper calibration, and the test surface was made smooth and free from visible defects.

1) Brinell hardness Test

The Brinell hardness test was conducted to determine the hardness of the specimen by measuring the diameter of an indentation produced by a hardened steel ball under a high applied load [39]. A load of 2000 kg was applied during this test.

The detailed step-by-step test procedures are provided below:

- Measure and record the dimensions of the specimen.
- Place the specimen securely on the anvil of the Brinell hardness testing machine.
- Select the appropriate ball indenter and set the load to 2000 kg.
- Bring the indenter into contact with the specimen surface gradually.
- Apply the load smoothly and maintain it for the specified dwell time.
- Release the load slowly after the dwell time is completed [40].
- Measure the diameter of the indentation using the optical measuring device.
- Record the Brinell hardness number (BHN).
- Repeat the test at different locations on the specimen.

2) Rockwell Hardness Test

The Rockwell hardness test was performed to determine the hardness of the specimen by measuring the depth of penetration under a minor and major load [41]. This test allows for quick and direct hardness readings.

The detailed step-by-step test procedures are provided below:

- First, calibrate the Rockwell Testing Machine using the calibration testing materials.
- Measure and record the dimensions of the specimen.
- Place the specimen properly on the anvil of the Rockwell hardness testing machine.
- Select the appropriate Rockwell scale and enter.
- Apply the minor load to set the reference position [42].
- Apply the major load and allow it to dwell for the specified time.
- Remove the major load while maintaining the minor load.
- Read and record the hardness value directly from the machine dial or display.

- Repeat the test at different points on the specimen surface.

3) Vickers Hardness Test

The Vickers hardness test was conducted to determine the hardness of the specimen by measuring the diagonal lengths of a square-shaped indentation produced by a diamond pyramid indentation.

- The detailed step-by-step test procedures are provided below:
- Measure and record the specimen dimensions.
- Place the specimen on the stage of the Vickers hardness testing machine.
- Select the appropriate test load.
- Bring the diamond pyramid indenter into contact with the specimen surface.
- Apply the load gradually and maintain it for the specified dwell time.
- Release the load carefully after the dwell time [43].
- Measure the two diagonals of the indentation using the microscope.
- Calculate and record the Vickers hardness number (VHN).
- Repeat the test at multiple locations for accuracy.

I. *Statistical and Reliability Analysis*

Experimental results were compared by means of the mean values, standard deviations, fatigue-life results and comparison of the material properties [44]. The experimental data were evaluated taking into account the statistical variation resulting from the fact that when the same nominal testing conditions are applied to a series of specimens, they can yield different results. The number of cycles to failure, obtained from experiments, were compared to the theoretical or expected fatigue-life behavior for fatigue reliability [45]. The differences between predicted and measured fatigue lives were investigated and related to possible experimental error, specimen condition, loading calculations and material variability [46]. As the number of fatigue specimens tested was not large enough, the results were treated as experimental evidence under the laboratory conditions as opposed to as being statistically reliable distributions of reliability for the materials.

J. *Failure-Mechanism Analysis*

The evaluation of failure mechanisms has been carried out based on the behavior of material response in tensile and fatigue tests and the observation of the fracture surface after fatigue failure. Tensile testing gave evidence of elastic deformation, yielding, plastic deformation, strain hardening, the ultimate strength and fracture behaviour [47]. These stages are referred to as the stress–strain response of ductile materials in the tensile laboratory report. The fractured surfaces of the specimens tested for fatigue were also examined after failure [48]. The special requirement of the rotating-beam fatigue experiment was that the fractured specimens be removed after testing, labeled and then examined. This examination was employed to aid in the interpretation of fatigue crack initiation, propagation and final fracture behavior.

K. *Comparative Material Evaluation*

The last step of the methodology was the merging of the data from tensile, hardness, impact, tensile fatigue and rotating beam fatigue tests. Mechanical strength, hardness, impact strength, fatigue life, deformation behavior and characteristics of failure observed were used for comparing the materials [49]. The comparison was developed to compare and contrast the relative merits and deficiencies, as compared to steel, of aluminum alloys for advanced manufacturing requirements [50]. The 1018 grade of AISI steel and 6061 aluminum are highlighted in the fatigue comparison as they were specifically tested in the rotating-beam fatigue test; the additional comparative information for mechanical and impact tests was provided by the AISI 1020 steel and the B16 brass.

IV. RESULTS AND ANALYSIS

The experimental results have been used to compare the mechanical, impact and fatigue properties of the materials studied in the laboratory program [51]. The analysis integrates tensile-fatigue, hardness, tensile, Charpy impact and rotating-beam fatigue observations, to analyze material performance and reliability. The results show that there are significant differences between the AISI 1018 steel, AISI 1020 steel, 6061 aluminum alloy, and B16 brass. Special focus is placed on fatigue life as the load is cyclic and it is a key research goal [52]. The fatigue test results indicate that the fatigue life of the AISI 1018 steel is significantly greater than the 6061 aluminum for the conditions tested, as the fatigue life of the steel is shown to be in the millions of cycles. The Charpy impact values also show variation in impact properties amongst the four materials [53]. These findings are discussed separately in the next few subsections.

A. *Variability in Charpy Impact Strength*

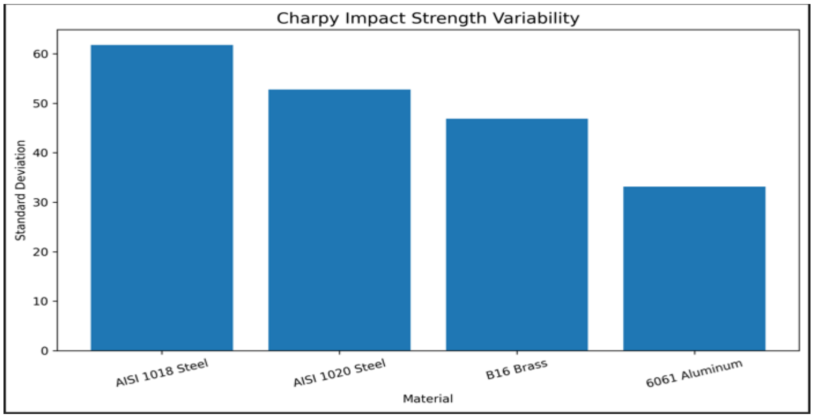

Figure 7: This image shows the Charpy impact-strength variation in four tested engineering materials

The figure shows the standard deviation of Charpy impact strength for AISI 1018 steel, AISI 1020 steel, B16 brass and 6061 aluminum. The maximum standard deviation is found in the AISI 1018 steel with a value of 61.8, which means that the measured impact strength results are the most variable [1]. AISI 1020 steel has a standard deviation of about 52.8 and B16 brass has a lower standard deviation of about 46.9. The lowest standard deviation (~33.1) which is obtained for the 6061 aluminum alloy indicates that the impact-strength measurements are more consistent across the experimental observations [2]. The range in measured impact-strength values for the materials tested appears to be very large, given the small range from AISI 1018 steel to 6061 aluminum [3]. The standard deviation, however, is a measure of consistency of the experimental measurements and not a measure of absolute material performance [4]. The lower variation of 6061 aluminum should not be an indication of higher impact resistance. These results, however, are valuable data regarding experimental consistency and should be interpreted in conjunction with the mean impact strength and other mechanical characteristics.

B. *Comparison of Expected and Observed Rotating-Beam Fatigue Life*

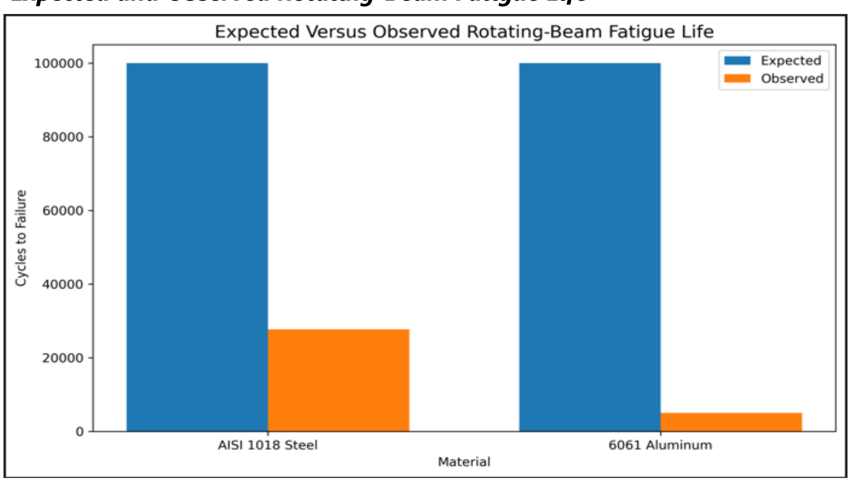

Figure 8: This image shows the expected fatigue life in steel and aluminum specimens, compared to the observed fatigue life

The rotating-beam fatigue life of AISI 1018 steel and 6061 aluminum alloy are compared in Figure 8, both experimentally and theoretically. For both materials the expected number of cycles to fatigue was about 100,000. But the experimental data were much less for both materials. AISI 1018 steel had reached approximately 27.7% of its expected life (cycles) while 6061 aluminum had reached approximately 5% of its expected life (cycles). The difference between production and performance is significantly greater for aluminum 6061 than for AISI 1018 steel. The results shown here show that the theoretical fatigue life predictions can vary widely from the actual performance in the laboratory under certain conditions [5]. The results show that the fatigue life of AISI 1018 steel is significantly longer than that of 6061 aluminum in this experiment [6]. The laboratory report noted, however, that there are uncertainties in the calculations performed as well as uncertainties associated with the specimens themselves and that these results should be viewed as experimental observations of the condition, rather than a universal material property.

C. *Comparison of the mean Charpy impact strength*

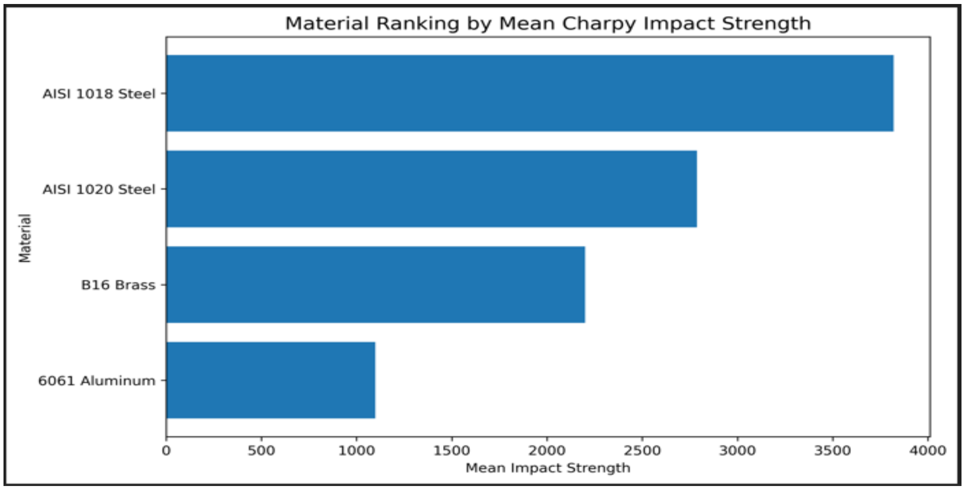

Figure 9: This image shows how materials compare in terms of their mean Charpy impact strength

The mean Charpy impact strength of the four materials tested is shown in the rankings in Figure 9. The AISI 1018 steel has the highest mean impact strength of about 3819.98, which represents the best impact performance for the materials in this study. AISI 1020 steel is second in the list with a mean value of 2786.57. B16 brass falls at number 3 with a mean impact strength of around 2199.40, and 6061 aluminum is at the bottom with a mean impact strength of 1098.72. The effects of the steel alloys and the aluminum alloy on impact resistance are clearly different. Based on the experimental values, AISI 1018 steel can have about 3.5 times the mean values of impact strength of 6061 aluminum [7]. The ranking suggests that AISI 1018 had the highest resistance to impact loading conditions during the testing [8]. Impact strength is resistance to sudden loading and is not an accurate indicator of fatigue reliability. These, therefore, should be considered in conjunction with fatigue-life and other mechanical-property results.

D. *Comparative Analysis of Mean Brinell hardness*

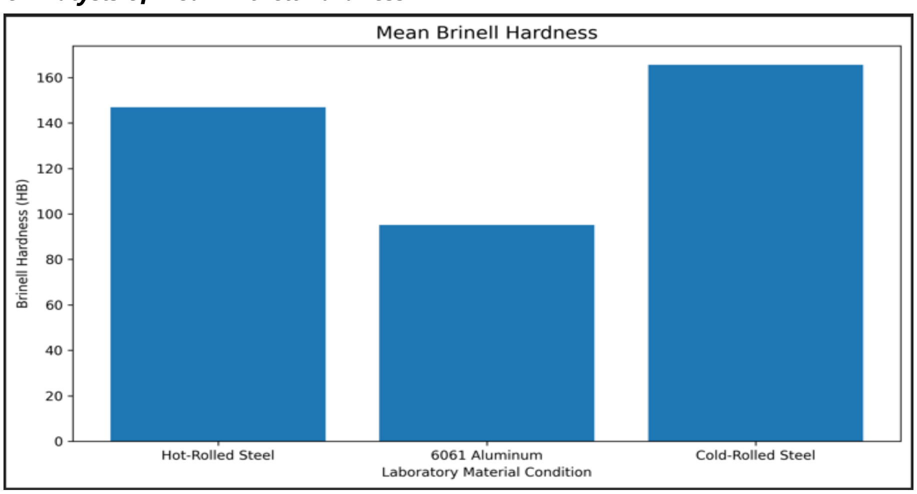

Figure 10: This image displays the differences in mean Brinell hardness for steel conditions in comparison with 6061 aluminum

The mean Brinell hardness values for the different conditions of the tested material are compared in figure 4. The cold-rolled condition has the highest mean hardness, around 165.61 HB indicating the highest resistance to indentation of the 3 conditions displayed [9]. The mean hardness of hot-rolled steel is about 146.88 HB, and the lowest mean hardness is that of 6061 aluminum, which is about 95.10 HB is. The difference between the steel conditions and 6061 aluminum indicates that the tested steel specimens exhibited greater indentation resistance under the Brinell testing conditions [10]. The mean hardness of the cold-rolled steel was about 74% higher than that of the 6061 aluminum, and the hot-rolled steel was about 54% harder than the 6061 aluminum. Results show that the material processing condition can affect the measured hardness since the hardness of the two steel conditions is different [11]. The results of these analyses may be useful to consider in the context of the overall fatigue-reliability analysis [12]. The fatigue life and reliability, however, are not just determined by hardness; other factors such as cyclic stress, surface condition, material microstructure, defects, and loading conditions influence fatigue performance.

E. *Mean Charpy Impact Strength is compared*

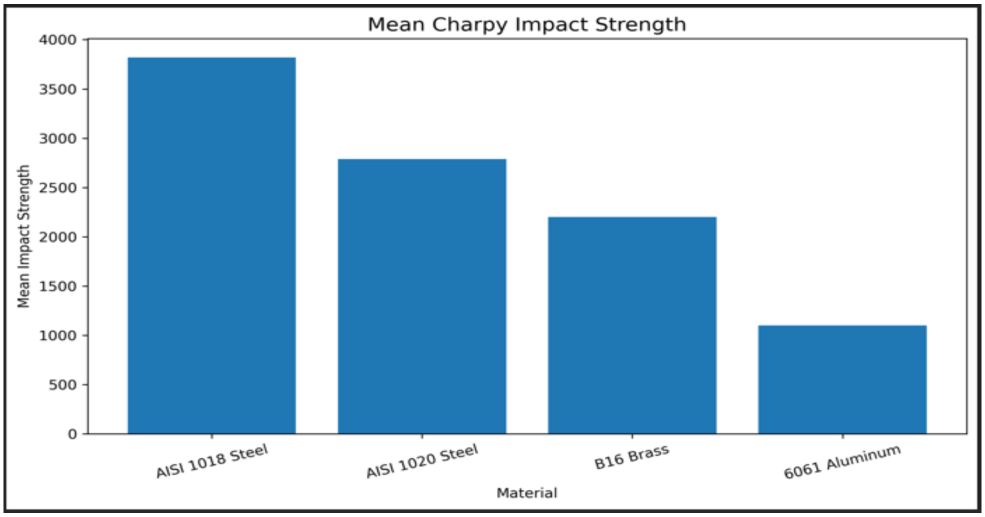

Figure 10: This image depicts the average Charpy impact strength of four different engineering materials subjected to experimental tests

Figure 10 is a comparison between average Charpy impact strength of AISI 1018 steel, AISI 1020 steel, B16 brass, and 6061 aluminum. The AISI 1018 steel has the highest mean impact strength of 3819.98, indicating the highest impact performance of the tested materials. AISI 1020 steel ranks second with approximately 2786.57, followed by B16 bras at approximately 2199.40. The lowest mean impact strength of this alloy is approximately 6061 aluminum at 1098.72. The outcomes show that there is a significant distinction in performance of the materials under Charpy impact conditions [13]. In comparison with the experimental mean values, the impact strength of AISI 1018 steel is about 3.48 times higher than that of 6061 aluminum [14]. The relatively high impact strength of both steel materials suggests that they have a higher resistance to the sudden impact loading in this experiment, whereas the lower value of 6061 aluminum shows that it has comparatively low energy absorption under the impact conditions used in this experiment [15]. The results of these tests are useful as supporting data for material selection analysis [16]. It is important to note that impact strength is different to fatigue reliability as resisting a single impact does not necessarily lead to a long-term performance under repeated cyclic loading.

F. *Analysis of Observed Tensile-Fatigue Life*

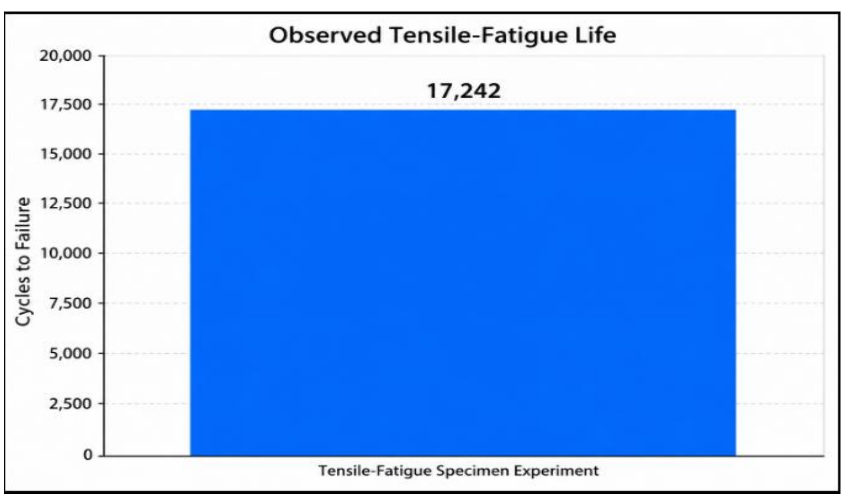

Figure 11: This image represents the actual tensile fatigue life of the specimen before total failure

The tensile-fatigue life of the test specimen, in terms of number of cycles to failure, is shown in Figure 11. The specimen fractured after about 17243 cycles. This is a good example that the material had the capacity to endure a significant amount of repeated loading cycles without reaching full fatigue failure [17]. The observed fatigue life is an important experimental parameter for assessing the resistance of the material to cyclic loading [18]. In contrast to the immediate failure under applied load, the specimen underwent progressive failure in fatigue until the occurrence of failure [19]. The result shows that fatigue-life analysis is important for assessing the reliability and durability of engineering materials in manufactured applications [20]. The observed value can also be compared to the theoretical fatigue-life prediction from the fatigue-life model, to give an indication on the accuracy of the prediction to determine the experimental variability [21]. But this number is only for one experimental specimen and therefore should not be regarded as a statistically representative fatigue-life distribution. Further samples and retesting would be needed to get good estimates of reliability and measures of variability.

G. *Relative Observed Fatigue Life (ROFL) Comparative Analysis*

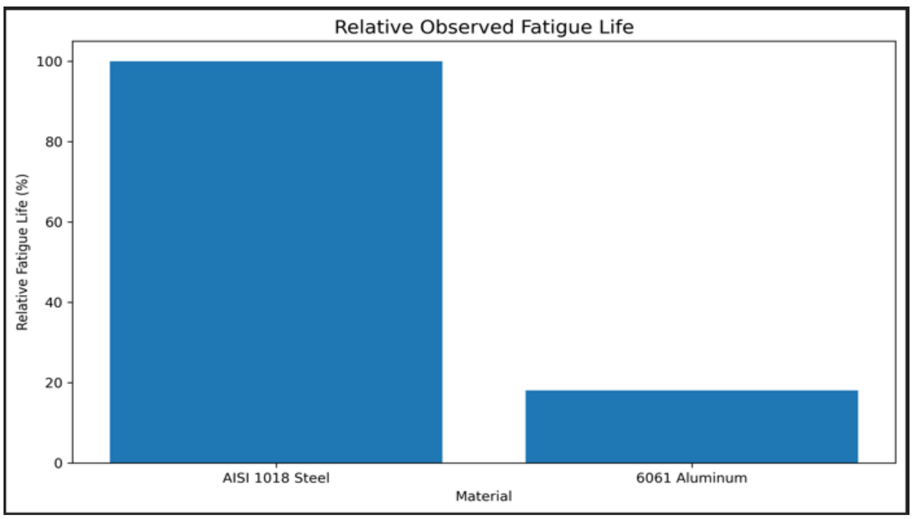

Figure 12: This image shows relative observed fatigue life of AISI 1018 steel and 6061 aluminum

The results of this rotating-beam fatigue experiment are shown in figure 12, which is a comparison of the relative observed fatigue life of AISI 1018 steel and the 6061 aluminum alloy. AISI 1018 steel is used as the reference material, and is therefore considered to have a 100% relative fatigue life (or observed failure life of 27,700 cycles). By comparison, 6061 aluminum had about 5,000 cycles and experienced a relative fatigue-life value of about 18.05% of the AISI 1018 steel value [22]. Different from the experimental conditions, therefore, the steel specimen exhibited a fatigue life that is about 5.54 times the observed fatigue life of the aluminum specimen [23]. This large difference suggests that AISI 1018 steel has higher resistance to cyclic fatigue failure under the tested condition in the rotating-beam experiment [24]. The comparison, however, was based on experimental observations which do not necessarily imply a universal ranking of the two materials [25]. Fatigue results may be affected by specimen condition, loading calculations, material defects and experimental procedure [26]. Thus, this relative measure of fatigue life should be considered in conjunction with other mechanical properties and experimental uncertainty for determining the overall reliability of a material.

H. *Comparative Analysis of Fatigue Life of Rotating-Beam*

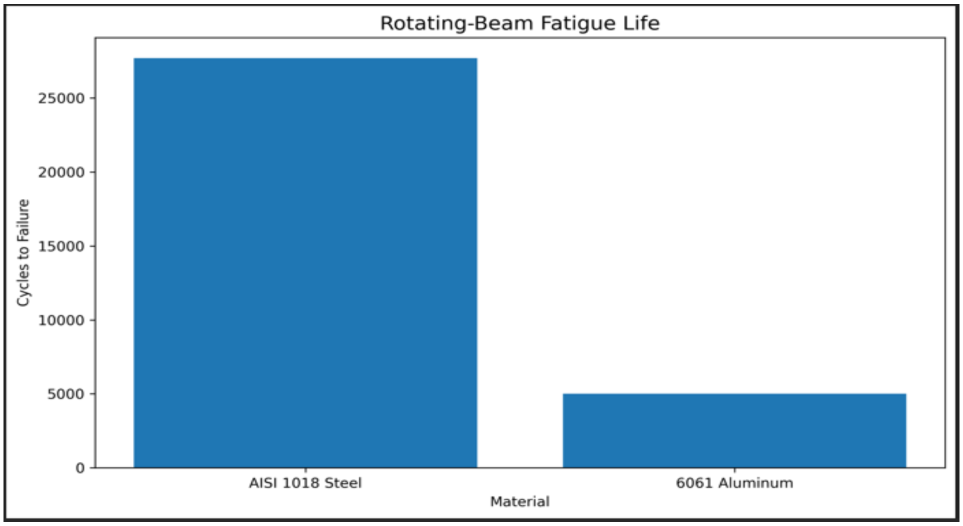

***Figure 13: The image displays a comparison of rotating-beam fatigue life between steel specimens and aluminum specimen*s**

The fatigue life for rotating beam test, cycles to failure, of the AISI 1018 steel and 6061 aluminum alloy are compared in Figure 13. AISI 1018 steel shows an order of magnitude higher fatigue life of ~27,700 cycles until failure. The 6061 aluminum sample, on the other hand, achieves about 5,000 cycles with the same reported experimental conditions [27]. The difference shows that the AISI 1018 steel sample experienced about 22,700 more cycles than the aluminum sample. The steel specimen endured about 5.54 times as many cycles as the 6061 aluminum specimen [28]. This finding implies that AISI 1018 had higher cyclic bending failure resistance in the rotating-beam test. The difference observed is significant for fatigue-reliability analysis as one of the important points to consider while choosing materials for repeated loading components [29]. The results should be treated with caution when viewed in the context of the experiment, as there were a number of uncertainties identified in the lab report regarding the moment calculation and condition of the aluminum specimen [30]. Thus, further repeated testing would enhance the reliability comparison.

V. Discussion and Analysis

The results of the experiments give a comprehensive picture of the fatigue behaviour, mechanical properties and reliability of the materials studied in this work [31]. The tensile fatigue experiment showed that the specimen would not break immediately, but rather evolve as the cycles continued to be applied; the tested specimen failed after about 17,242 cycles, thus confirming the typical sequence of fatigue damage crack initiation, crack propagation and final fracture [32]. The tensile test also showed significant plastic deformation and necking prior to fracture, indicative of ductile behavior and that static tensile response is different, but related, to cyclic fatigue response [33]. The most significant difference in stress fatigue between the principal steel and aluminum specimens was found to occur when exposed to the same number of stress cycles in the rotating-beam test setup, with AISI 1018 steel lasting about 27,700 cycles while 6061 aluminum failed after about 5,000 cycles, under the reported experimental conditions. Hence the steel specimen has seen about 5.54 times the number of cycles as the aluminum specimen, which suggests that it has demonstrated greater resistance to cyclic bending in this experiment [33]. This one result should not be used for a fatigue-life ranking of all AISI 1018 and 6061 aluminum products, however, since the laboratory report contained some uncertainties regarding the moment calculation and the condition of the aluminum specimen, the test should be repeated and a more reliable comparison made. A comparison of the theoretical and experimental fatigue life again highlights the need for experimental validation [34]. The fatigue life of both AISI 1018 steel and 6061 aluminum was about 100,000 cycles, but the actual tested fatigue life for both materials was much lower: 27.7% of expected life for AISI 1018 steel and 5% of expected life for 6061 aluminum. As these differences suggest, fatigue-life models are not to be considered as a true representation of laboratory or service performance but rather as an approximation [35]. These may be due to specimen condition, uncertainty in calculation, surface characteristics, variability of the material, machine alignment, loading conditions etc. Hardness results are also indicative of mechanical response differences. The tested steel specimens did exhibit higher resistance to an indentation test than the 6061 aluminum specimen, providing an indication that hardness can be used to provide useful information as to material condition and resistance to localized deformation, although it is not a direct indicator of fatigue reliability [36]. AISI 1018 steel was the best steel followed by AISI 1020 steel, B16 brass and 6061 aluminum. Although this ranking is helpful in understanding the resistance to sudden impact loading, impact toughness and fatigue life are not the same since they refer to different loading and failure mechanisms [37]. The results from both experiments thus show that there is a need to evaluate fatigue performance using more than one mechanical property. Tensile strength gives data on static load bearing capacity, hardness gives data on resistance to local deformation, impact test gives data on energy absorbed in sudden fracture and fatigue test gives data on response to repeated loading [38]. Reliability becomes a significant consideration in this case since the same nominally identical specimens can have different fatigue lives due to microstructural variation, surface condition, defects, geometry, manufacturing processes, residual stresses, environmental conditions and experimental variability [39]. The study thus confirms the use of the reliability-based evaluation instead of the exclusively deterministic fatigue-life evaluation. The results are immediately applicable for advanced manufacturing in material selection [40]. Materials and manufacturing processes must be chosen for components that are subject to repeated loading, vibration, thermal variations and/or rotating stresses to ensure adequate fatigue resistance and predictable service life [41]. Alloys of steel may offer benefits in terms of strength and fatigue resistance, whereas alloys of aluminum may offer key benefits for weight-reduction and other production benefits [42]. The analysis also shows that the selection of mechanical properties depending on the combination of required properties can be useful, as specific mechanical response of B16 brass demonstrates. Instead, fatigue life, tensile properties, hardness, impact resistance, ductility, specimen and surface conditions, manufacturing variations, loading conditions, and service life should be taken into account when selecting the most appropriate material [43]. Due to the small number of fatigue specimens used in the study and the known experimental uncertainties, results should be interpreted as being condition specific experimental data and not as material properties. Future reliability assessment would benefit from greater sample sizes, better measurement techniques, more accurate, validated S–N databases, and a detailed fracture-surface analysis.

VI. Ethical Issues and Restrictions

In experimental materials research it is important to be concerned with ethical issues as the measurements that are taken may be inaccurate and the interpretation may not be the correct one, and the resulting engineering decisions are then incorrect [44]. The same applies to all experimental observations in this study: They should be presented clearly, even if they are unexpected or fail to work out or if measurements are problematic. Two specimens of steel intended to be AISI 1018 were subjected to the Charpy test and produced incorrect 0° readings, and were not included in the analysis of the laboratory records. These exclusions should be explicitly stated and not just the results reported to support a desired answer [45]. Fatigue lives for the rotating-beam experiment were very low compared to the value of 100,000 cycles that was expected: it was suggested that possible causes may be calculation errors and that the aluminum specimen may be defective. Laboratory safety is also an ethical responsibility as fatigue and tensile specimens have a tendency to break without warning, proper equipment operation, specimen alignment, protective equipment, and safe testing procedures are necessary [46]. There are also some limitations to this study. Fatigue-life distributions could not be drawn from a statistically sound number of fatigue specimens. Furthermore, testing was conducted directly on the AISI 1018 steel and 6061 aluminum in the rotating-beam fatigue experiment, but not for all of the materials used in the larger experimental program of this study [47]. There may have been errors in calculation of moments and the defective aluminium specimen may have affected the results of fatigue. In addition, it is noted that elongation was measured during the tensile experiment since an extensometer was not available, which could have an impact on the results of elongation. Thus, the results are a matter of experiment and conditions and not general material reliability values.

VII. Future Work

The experimental investigation should be extended in the future to give a more detailed and statistically valid assessment of fatigue reliability and failure mechanisms of steel and aluminium alloys in advanced manufacturing applications. While the present study offers useful comparative evidence, the rotating-beam fatigue experiment involved only small numbers of specimens - AISI 1018 steel and 6061 aluminium were tested separately [48]. Further tests should then be conducted under the same loading conditions to further enhance the reliability and reproducibility of the results. A recording of cycles to fracture and examination of the fracture surfaces after testing is already a part of the laboratory procedure that can be expanded to include an investigation of fatigue. The number of fatigue specimens should be increased in the future for each material, especially in AISI 1018 steel, AISI 1020 steel and 6061 aluminum alloy. Multiple tests could be performed in order to determine more meaningful averages, standard deviations, and fatigue-life distributions. If enough observations were obtained, the statistical reliability techniques could be used to calculate the probability of survival for a given number of loading cycles. This would enable the best material to be identified and minimize the impact of specimen behaviour. An additional area of interest is the improvement of more fully developed S–N fatigue curves [49]. The present rotating-beam test measured the actual fatigue life value and compared it to an estimated value of about 100,000 cycles, but in both tests the specimens failed before reaching the expected fatigue life. It was determined that the source of the discrepancy might be in the calculations of the moments in the laboratory and possibly from a defective aluminum specimen. Additional fatigue tests should be performed after future work should confirm loading calculations, machine calibration, specimen dimensions, specimen alignment or material condition [50]. A further investigation of the surfaces of fatigue fracture must also be carried out with higher resolution techniques. Visual inspection and recording of the fracture surfaces was part of the existing experiment. Microscopic investigation may yield more information about crack initiation, crack propagation, defects in the surface and the final fracture characteristics [51]. This would enhance the understanding of the fatigue performance mechanisms that cause fatigue performance differences. Future studies also should include environmental and manufacturing conditions. Surface finishes, manufacturing processes, residual stresses, temperature and other service conditions might be examined to see how they affect the fatigue life of the product [52]. This would yield a more representative set of findings of actual advanced manufacturing applications. Finally, future studies should incorporate tensile, hardness, impact and fatigue measurements into a single material-selection process [53]. Elastic and plastic behaviour, such as yielding, necking and fracture, have already been observed in the tensile experiments [54]. These properties together with increased fatigue data would assist in the development of more sound engineering guidelines for choosing more durable materials. This could help ensure the safety, service life, reliability and performance of components in U.S. manufacturing and infrastructure applications.

VIII. Conclusion

The fatigue reliability and failure mechanisms of steel and Al alloys for advanced manufacturing applications were studied using an integrated experimental evaluation of their tensile, tensile-fatigue, hardness, Charpy impact, and rotating-beam fatigue properties. The results showed that the behaviour of the materials is very different with different kinds of loading and different mechanical properties. The tensile-fatigue test revealed that the specimen failed at about 17,242 cycles, and the tensile test showed that there was considerable necking and plastic deformation before failure; the former test was used to check the fatigue behavior, and the latter to check the ductile behavior; the experimental results confirmed the ductile behavior. The rotating-beam fatigue experiment was a direct comparison of the fatigue characteristics of AISI 1018 steel and 6061 aluminum. AISI 1018 steel was able to endure about 27,700 cycles whereas 6061 aluminum failed after about 5,000 cycles. Therefore, the steel specimen is expected to last about 5.54 times longer than the aluminum specimen in these particular experimental conditions. The test results were well below the expected theoretical fatigue life of 100,000 cycles and are a reminder of the need to examine theory predictions of S–N and fatigue life experimentally. The hardness test results also showed differences between the materials as the Brinell hardness values reported show a greater resistance to indentation of the tested steel specimens compared to 6061 aluminum. The average impact strength of AISI 1018 steel was the highest of all the above followed by AISI 1020 steel, B16 brass and 6061 aluminum as shown by Charpy impact result. The results showed that hardness, tensile strength, impact resistance and fatigue life are complementary measures of material properties. In general, the study shows that there is no single mechanical property that can be used to predict fatigue reliability. Fatigue life, tensile properties, hardness, impact resistance, specimen condition, loading conditions and manufacturing variability are all factors to be taken into account when selecting material for advanced manufacturing. Because of the small number of fatigue specimens and the known experimental uncertainties, the results are not generalizable. The conclusions derived from the study would be more reliable if larger sample sizes were used, better measurement techniques were employed, validated S–N data were used, and fracture surface analysis was conducted. However, the present results are still valuable experimental data for assessing material behavior and for fatigue sensitive material selection.

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