Research Article

Importance of Hardening Effect and Its Analysis on Diametrical Fractured Ends of Tensile Testing of Al and Steel

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The hardening effect varies deliberately to elevate the properties of alloy specimens either in ferrous or nonferrous materials. The cup and cone fracture theory explains the effect of hardening through heat treatment of the specimen. The hardening effects are imposed on the specimen by the furnace heating and hot pressing method. The neck formation and the elongation levels are evaluated and compared for both heat-treated and non-heat-treated specimens of steel and aluminum alloys. The simulation tools are used to predict the compressive and elongation levels by obtaining the stresses and deflections at various nodal points. The suitable heat treatment was indicated by the single or twice method of heat adoption over the steel and aluminum specimens. The fracture analysis and experimental results are compared among the hardened or non-heat-treated specimens.

1. Introduction

In recent years, heat treatment has become more important in the automotive, aerospace, and marine sectors to improve the strength of aluminum alloy joints. To build up the microstructures with aluminum alloy joints, a proper joining technique is required. The impact of heat treatments on a few mechanical characteristics of steel and aluminum alloy bars with equal cross-sections, as well as reinforced aluminum alloy composites, is being studied. Furthermore, the mechanical characteristics of both the steels and the aluminum ingots are compared, as well as the hardness of both before and after the heat treatment procedures are compared. Annealing, tempering, and oil or water quenching (hardening) are all heat treatment procedures. Steel hardening temperatures range from 820 to 860°C, whereas steel hardening temperatures range from 750 to 900°C. In terms of mechanical characteristics like hardness and tensile strength, the oil quenching sample had the greatest hardness, whereas the annealed sample had the maximum elongation. As a result, the mechanical characteristics and hardness of the experimental specimens are influenced by the dual heat treatment. Higher tempering temperatures, ranging from 370 to 540°C, are employed when greater toughness is required at the cost of strength. Tempering at even higher temperatures, between 540 and 600°C, results in outstanding toughness but a significant loss of strength and hardness. This study examines the impact of post-heat treatment (PHT) on tensile and mechanical characteristics of the steel, as well as the use of AA6061 solution treatment and artificial aging to achieve the microstructure and mechanical properties that are needed for excellent performance at ambient conditions.
temperatures. The optical microscope was used to link the tensile and hardness characteristics with the development of precipitates. It is widely known that the solution treatment followed by artificial aging improves the tensile characteristics of AA6061 considerably.

Low carbon steel, also known as mild steel, has a carbon content of less than 0.2% and a manganese content of less than 0.7%, with maximum values of 0.6%, 0.05%, and 0.05% for silicon, phosphorus, and sulfur, respectively. The performance of low carbon steel in service is influenced by both intrinsic and external variables, such as grain size, flaws, chemical composition, and ultimate tensile strength. The mechanical characteristics of low carbon steel, such as strength formability, ductility, fatigue strength, and surface hardness, among others, improve its service performance. Carbon steel failure may also be caused by production techniques, the use of inferior materials, bad design, manufacturing mistakes owing to poor machining, or failure due to a phenomenon known as fatigue, according to studies. Heat treatment or cold working may be used sequentially to alter the mechanical characteristics to prevent these problems. Heat treatment is defined as a method of changing the metallurgical and mechanical characteristics of a metal or alloy by heating and cooling it in its solid form. Among the many heat treatment procedures such as hardening, annealing, normalizing, and tempering, annealing softens the steel, increasing its ductility and relieving residual stresses. It is important to remember that all heat treatment procedures have three stages: heating the material, maintaining the temperature for a certain length of time, and cooling to room temperature. Investigations of the mechanical characteristics of 0.13% C steel following the intercritical normalizing heat treatment are examples of previous work in this area. Mechanical characteristics and properties of medium carbon steel under various quenching conditions were reported. The effects of annealing, normalizing, hardening, and tempering of medium carbon steel were studied. The study of how low carbon steels react during annealing, normalizing, and age hardening heat treatments is required as part of this expansion in the material modification of carbon steels.

According to Hasim et al. [1], cryogenic treatment of materials is gaining popularity in recent years due to its ability to create steel components that have a wide range of applications in industries, nuclear power plants, fertilizer plants, medical, aerospace, and avionics. This is because, as Charles and Arunachalam point out, materials treated in cryogenic conditions acquire better characteristics that need an operation in harsh environments (2006). It is a one-time homogeneous procedure that extends the performance and useful life of steel 13 components, including brake rotors, gears, engines, machine parts, machine tools, and gun barrels. Jaswin et al. [2] use an ASTM G-133 reciprocating friction and wear a monitor to evaluate the wear resistance improvement in En 52 and 21-4N valve steels after shallow and deep cryogenic treatment. The shallow cryogenic treatment is done at −80°C, whereas the deep cryogenic treatment is done at −196°C. When compared with the conventional heat treatment, the wear resistance of En 52 and 21-4N improved by 81.15% and 13.49%, respectively, owing to shallow cryogenic treatment, and 86.54% and 22.08%, respectively, due to deep cryogenic treatment. The effect of corrosion and low impact damage on the aluminum alloy 6063-T6 has been addressed by Maclins [3]. The 6063 aluminum alloy utilized in the research was heat treated and immersed in saltwater produced according to ASTM D1141 for various time periods ranging from 0 to 1000 hours. Mrówka-Nowotnik et al. [4] presented experimental results, including uniaxial tensile testing and fracture toughness investigations using two different techniques, as well as novel thoughts on aging factors and their impact on the mechanical characteristics and ductility of the 6082 alloy. Krishna Pal Singh Chauhan [2] found that the thermal treatment factors have a major impact on the mechanical characteristics of aluminum alloys. Mechanical characteristics are influenced significantly by alloying elements. There is an excess Mg in alloying elements like 6061 and 6063, and an excess Si in alloying elements like 6082. Excess Mg and Si can enhance strength and hardness while reducing ductility and toughness. The tensile and yield strength of aluminum alloy 6005 is higher than that of other alloying elements in this series.

The mechanical characteristics of alloys in nonferrous and ferrous materials may be determined by manipulating the microstructures of the alloys, according to Kori et al. [6] and Zhang et al. [7]. Since 1986, Caceres and Griffith [8], Wang and Caceres [9], Gustafsson et al. [10], Closet and Guruzleski [11], and Surappa et al. [12], have addressed how the interaction of eutectic silicon particles with intermetallic compounds, microporosity, and heat treatments impact the mechanical characteristics of nonferrous materials such as aluminum. Nonuniformly dispersed silicon particles with coarse dendritic structure and porosity define the microstructure of castings. Jones Praveen et al. [13] focused on hybrid silicon nitride and zirconium diboride reinforcement with the AA8011 alloy to develop the AA8011/ZrB2–Si3N4 MMC with good hardness, wear, and friction coefficients. The wear rate has been found to decrease with an increase in the weight percentage of reinforcement. With an increase in the weight % of reinforcement, the wear rate was observed to be reduced. The prediction of stresses, temperatures, and displacements of the cutting zone using the simulation tool Deform 3D, according to Bejaxhin et al. [14], undoubtedly helps to detect the improvement of preliminary records. The major way for achieving roughness is by particle deposition. Senthil Kumar and Natrayan [15] have discussed that hybrid composites demonstrated enhanced mechanical and wear resistance, making them ideal for engine cylinder liners.

Stojanović and Lozica [16] have discussed that the vehicle industry is now looking for ways to enhance fuel-efficiency, characteristics, friction, and wear resistance. As a result, lightweight and low-cost materials for cylinder blocks, liners, pistons, camshafts, lifters, braking components, frame members, and other components were developed by Mortensen and Llorca [17]. However, when compared with other materials, aluminum (Al) and mild
steel performed better. Steel is an odd material for cylinder liners because of its density, low coefficient of thermal expansion (CTE), and low heat conductivity. Because of its high heat conductivity, Al stands out as a preferable option. Furthermore, CTE was discovered to be equivalent to Al piston and to meet the criteria for low weight. At high temperatures, Al and its alloys lose their hardness and mechanical and tribological characteristics, which limits their use in engineering [18–20]. It is widely understood that adding hard material reinforcement to the matrix (Metal matrix composites—MMC) increases mechanical and tribological characteristics [21, 22]. By eliminating it, the mechanical properties of HMMC are improved. Yet, no one-of-a-kind processing pathway has been discovered. In practice, liquid metal infiltration stir-casting and other manufacturing processes are used which have been evaluated and discussed by Zhong et al. [23], Yoshie et al. [24], Hao et al. [25], and Zhang et al. [26].

The primary goals are to enhance the material strength by increasing its mechanical characteristics, to increase the bond strength of an alloy material by applying heat to the specimen body, and to increase the hardness of the specimen by using heat treatment on alloy specimens. Heat treatments are being used to enhance the mechanical characteristics of ferrous and nonferrous metal alloys (annealing, tempering, and normalizing). The hardness and tensile strength of steel and aluminum alloys will be compared extensively. The use of dual heat treatments (annealing-tempering) on aluminum alloy specimens for temperatures between 200 and 450°C, as well as the use of dual heat treatments (normalizing-annealing) on steel specimens for temperatures between 450 and 650°C, are also included. The major outcome of this project is to increase the strength of ductile materials and composites and find their tensile strength through the analysis of fractured ends of the failure end. Finally, the tensile specimen modeling using Pro CREO software and the tensile strength and stress maximum of each specimen’s break point by applying the tensile load with the assistance of ANSYS workbench and ADSL finite element analysis prediction tools will be compared.

2. Materials and Methods

2.1. Project Methodology. Figure 1 shows the process methodology used in this research work.

2.2. EN8 Steel Properties. EN8 carbon steel (Table 1) is a medium carbon, medium tensile, through-hardening medium carbon steel with increased strength over mild steel. EN8 carbon steel may also be machinable in any state. EN8 steels are often utilized in their natural, unprocessed state. However, induction techniques may further harden EN8 steels, resulting in components with improved wear resistance. The heat-treated forms of EN8 steel have excellent homogeneous metallurgical structures, resulting in consistent machining characteristics. It has a greater hardness of 152 HB, an average tensile strength of 510–550 MPa, and a yield strength of 280 MPa, indicating that it is a superior material to nonferrous materials.

Aluminum 6061 (Table 2) temper 6 materials are one of the most well-known and widely used extruded alloys, created in the early 1930s. The main benefit of utilizing is its lightweight and high strength compared with steel specimens. It may be heat treated below its melting point at various temperatures. The main alloying actions of Mg, Mn, and Cr result in increased strain hardening capability, as well as increased tensile strength and corrosion resistance.

2.3. Universal Testing. As illustrated in Figure 2, the tensile test is performed on UTM. Hydraulics power the pump, the oil sump, the load dial indicator, and the center pushbutton. Specimen grips or jaws with higher, middle, and lower cross-heads are on the left. You can adjust the idle cross head by moving it up and down. The pipes that connect the lift and right sections are oil pipes that carry pumped oil under pressure to the cross-heads on the left side.

2.4. Experimental Procedure. The most common mechanical test is the tensile test. The ends of the test item are fastened into grips connected to a straining mechanism and a load measuring device in this test. If the applied load is small enough, any solid body’s deformation is entirely elastic. When the stress on an elastically deformed solid is released, it returns to its original shape. The material may, however, be permanently deformed if the load is too high. The tension curve is the initial part of the tension curve that may be recovered immediately after unloading. The rest of the curve, which shows how a solid undergoes plastic deformation, is referred to as plastic. A material’s yield strength is the stress below which deformations are almost entirely elastic. A fast reduction in load indicates the start of plastic deformation in some materials, indicating both an upper and lower yield point. Some materials, on the other hand, may not have a clear yield point.

Strain hardening cannot compensate for the decrease in the section at larger extensions during plastic deformation, thus the load hits a maximum and then begins to fall. At this point, the “ultimate strength” is defined as the load on the specimen divided by the initial cross-sectional area and reaches its greatest value. Further loading will eventually lead to the formation of a “neck” and rupture. Annealing is a heat treatment method that modifies the microstructure of a material to alter its mechanical or electrical properties. Steels are often annealed to reduce hardness (Figure 3), increase ductility, and assist in the removal of internal stresses. After cold working, annealing restores ductility, enabling further treatment without breaking. Annealing may also be used to alleviate mechanical stresses produced by grinding, machining, and other heat treatment procedures, preventing distortion during high-temperature heat treatment operations in the future. This may improve the materials’ ductility, toughness, and structure, as well as their magnetic properties. Internal stress, hardness, and brittleness may be decreased through the heat treatment process. Stress
Table 1: Chemical composition of EN8 carbon steel.

<table>
<thead>
<tr>
<th>Standard</th>
<th>Grade</th>
<th>C</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Si</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>BS970</td>
<td>EN8</td>
<td>0.36–0.44</td>
<td>0.6–1.0</td>
<td>0.05</td>
<td>0.005</td>
<td>0.10–0.40</td>
<td>Rem</td>
</tr>
</tbody>
</table>

Table 2: Chemical composition of aluminum 6061-T6.

<table>
<thead>
<tr>
<th>Standard</th>
<th>Grade</th>
<th>Al</th>
<th>Cr</th>
<th>Cu</th>
<th>Fe</th>
<th>Mg</th>
<th>Mn</th>
<th>Si</th>
<th>Ti</th>
<th>Zn</th>
</tr>
</thead>
<tbody>
<tr>
<td>H20</td>
<td>Al6061</td>
<td>95.8–98.6</td>
<td>0.04–0.35</td>
<td>0.15–0.4</td>
<td>Max 0.7</td>
<td>0.8–1.2</td>
<td>0.15</td>
<td>0.4–0.8</td>
<td>0.15</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Figure 1: The layout of process methodology.

Figure 2: Tensile testing of steel and aluminum alloy.

Figure 3: Heat treatment of specimen in a muffle furnace and hardness test.
reduction and annealing are methods for reducing tensions in aluminum castings or softening the component in preparation for further shaping or mechanical processing. The temperature range for stress relief is 200–250 °C, whereas the temperature range for annealing is 300–400 °C. The aluminum 6061 alloy is heat-treated at 450°C for a suitable amount of time before being quenched in water. Precipitation hardening was done for 18 hours at 160°C and then air-cooled. This process is repeated at 180°C for further 8 hours before cooling in the air.

Both the aluminum and steel specimens were subjected to heat treatment in a muffle furnace at temperatures of 450°C for the aluminum and 750°C for the steel. The capacity to resist the load situation was determined by measuring the Rockwell hardness. Dual heat treatment is not suitable for aluminum components. However, it is suitable for steel components.

2.5. Results and Discussions. Following the tensile testing of different specimens, Al6061 and steel were used to assess material deformation under varied steady load applications. Due to the heat treatment of both steel and aluminum, a curvature was developed across the work specimen.
depending on its material properties. As shown in Table 3, a comparison was conducted between heat-treated and non-heated specimens of both ferrous and nonferrous materials.

During tensile testing, the yield load was 33 KN, resulting in tensile strength of 164 MPa, which is less than the maximum tensile strength of 330 MPa.

Figure 6: Interrelation of displacement, stress, and strain for the various loads.

Figure 7: (a) (c) Mesh generation of cylindrical specimen in ANSYS and Deform 3D. (b) (d) Displacement function and boundary conditions in ANSYS and Deform 3D.
Similarly, the fracture was achieved with a force of 31 KN owing to the non-heated condition, and the tensile strength of 154 MPa was measured, which is the lowest when compared with the heat-treated Al6061 specimen. The load produced during the fracture of a steel specimen is 105 KN for heat-treated steel specimens and 101 KN for non-heat-treated steel specimens. Similarly, tensile strengths of 522 and 502 MPa have been reported, which are closer to the 550 MPa tensile strength.

2.6. Hardness Measurement. Hardness is a metric that measures the resistance to particular plastic deformation induced by mechanical penetration or abrasion (Figure 4). In Figure 4, $P$ represents the force in kilograms, $D$ is the diameter of the indenter ball in millimeters, and $d$ represents the average impression diameter of the ball indentation in millimeters. During the hardness testing of an aluminum specimen with a 5 mm pierced diameter, wide-scale penetration was found. However, the hardness ratings of both specimens may vary according to the respective remarkable loads of BHN or RHN.

The elongated steel and Al6061 specimens were compared after the tensile test was completed. Based on the load positioned and tensile action of moveable jaws in UTM, their geometrical characteristics have been altered completely. In comparison to the steel specimen, the Al6061 specimen fracture end curve radius has been expanded. The elongation of the aluminum alloy specimen is greater than that of the steel specimen due to its high ductile nature. Because of the ductile rich grain structure of the FCC crystal lattice, the cup and cone fracture edges may be felt with greater curvature ends. The extension of the heat-treated aluminum rod as shown in Figure 5 explains that the extended length can be improved up to 6% from its original shape after deformation takes place. The fracture ends with a more elongated curve that has been generated. The short curve form of fracture can occur in steel specimens.

Simulation modeling is a technique for safely and competently addressing real-world problems. It provides an easy-to-verify, debate, and understandable method of analysis. By offering straightforward insights into complex systems, simulation modeling provides useful solutions across industries and disciplines. Finite element analysis-based simulations, which are based on the discretization of each element in a component, may provide superior predictions. The ANSYS ADSL simulation program was utilized in this project work to generate the stresses and strains for the appropriate load levels as given in Table 4 and to calculate the displacement values.

The solid modeling tool aids in the development of tensile specimens for simulation results to get a better result before testing. The stresses and strain results for the different load situations, ranging from 100 to 400 KN, which will be acting during UTM testing, may be readily anticipated. The displacement values of steel and aluminum alloys are compared, revealing that nonferrous materials, particularly aluminum, have a greater number of changes. The displacement in steel constructions may be equally calculated from simulation results, as illustrated in Table 4. The
distance an item bends or twists from its original position are called deflection. The actual distortion that occurs to a structural element is known as deformation.

“Stress-induced deformation of a solid” is how strain is defined. The strain and displacements in these results are virtually identical in their variances. Strain may occur as a result of elastic deformation caused by the tangential force value, and the number of relocated atoms per unit volume has been determined. Figure 6 shows that increasing displacement may also raise the strain, whereas, for steel, a smaller quantity of strain and displacements can be detected. Meanwhile, the maximum tension that the aluminum alloy 6061 can take is higher than that of the steel specimen. The highest stress was achieved during Al6061 exercises with a high load of 400KN. However, at the 300KN load condition, the stress may be maintained despite the smaller displacement. Similarly, better results were anticipated for the steel specimen when acting loads of 300 and 400 KN were applied; stress can endure maximum for smaller displacements, as illustrated in Figure 6(a).

2.7. Validation through Simulation. Finite element software tools are used to make predictions. Prediction of performance can be easily found before testing or fracture occurs. ANSYS was used to create the mesh, which was then followed by specifying the displacement function at certain nodes and elements (Figure 7). To develop the mesh creation finely, both the ANSYS versions of ADSL and Workbench 14.5 may be utilized. In the ANSYS ADSL version 14.5, the IGES formatted solid model of a cylindrical specimen model may be loaded using the structural analysis setup. In all discretized regions, the equally distributed mesh may be populated with 32377 nodes and 23445 elements. As indicated in Table 4, the minimum values of stresses vary from $-25.575$ to $0.93282 \times 10^{-2}$ N/mm$^2$ as the lowest to the highest of 185.11 or 190 N/mm$^2$. The red color indicates the force value on the vertical axis and blue color depicts the fixed end boundary conditions opposite to the force end.

The fixed end of a UTM setup may be stopped in any direction and will be treated as 0. The displacement may be corrected in all locations using the static simulated solution. The necessary tensile component of force has been sent to

Figure 9: ANSYS simulations of (a) (b) nodal and elemental solution of stress and displacement of steel specimen, (c) (d) nodal and elemental solution of stress and displacement of aluminum specimen.
another free end of the cylindrical rod within the UTM machine. The open-source platform ANSYS Workbench was used to create dynamic simulations to improve the simulated results. The various colors in Figure 8 indicate the ranges of stress or deformation values from minimums to maximums. The more displacement or tension is achieved, there are more red-colored patches. With the knowledge of the specimen’s standard tensile strength, we were able to estimate the stresses and total deformations with ease. The graphical results of simulations may be shown in this simulation platform’s post-processing step.

With the assistance of the ANSYS Workbench simulation tool, total deformation of 4.384 × 10−7 m and maximum stress of 4632 Pa were projected for the Al6061 material under a tensile load of 400 KN. Similarly, the total deformation of 1.557 × 10−7 m was achieved for the steel specimen, and the highest stress of 4626.8 Pa was measured. Based on the premise of maximum stress with minimal displacement, nonferrous-based materials such as Al, Ti, Cu, and others will provide superior outcomes owing to their ductile nature. The ADSL version of ANSYS can also compute the pre-processing and solution steps of each stress and displacement. When compared with the steel specimen at the post-processing step in Figure 9, the Al6061 alloy can sustain a greater level of stress with a lower degree of displacement.

When the stress values of both the simulation platforms ANSYS ADSL and ANSYS Workbench were compared with the experimental data, the stress levels were found to be identical to those of the ANSYS ADSL version. Between the experimental and simulated findings, the displacements showed that the simulated results were closer to the experimental results. As a result, utilizing the ADSL version of the ANSYS current tool platform, these types of mechanical characteristics testing techniques may be simple and correctly simulated. Because the load acting at the relevant nodal points has been determined throughout the mesh surface of the specimen model, the complete boundary of the specimen may be mapped.

These materials may be utilized in a variety of architectural applications since they have an excellent surface finish, high corrosion resistance, and higher strength; they are also easy to weld and anodize, for example, extrusions, window frames, doors, shop fittings, irrigation tubing, aerospace, and architectural applications. With so many reinforcements such as silicon carbide, graphite, and Mg, it may serve as a superior alloying element, providing great bond strength, increased hardness, and improved machinability.

3. Conclusion

In this research, mechanical characteristics such as tensile strength and hardness in aluminum alloy 6063 – temper grade 6 were investigated (T-6). Three specimens were successfully produced using the stir-casting technique. Tensile specimens were made from the cast structure and evaluated in the laboratory. In comparison to the normal specimen, high tensile strength was obtained in the tensile specimen as well as in the heat-treated specimen. Hardness was likewise excellent, with an average of 34.8 HRB, and it improved in the heat-treated specimen. From our project work, the following findings must be provided: the dual heat treatment is perfectly appropriate for all classes of steel specimens, but not for aluminum alloys.

(i) The tempering procedure ensures the quality of the Al6061 alloy material while also increasing its strength.

(ii) When comparing heat-treated and non-heat-treated specimens of steels and aluminum, the heat-treated specimens had a higher tensile strength.

(iii) The deformation levels were improved, and they could resist the high load-bearing capability for a longer period of time.

(iv) The ANSYS simulation and its comparisons are an assumption or forecast of product behavior that explains how the round bar achieved the withstandings of higher values of stresses and lesser displacements among heat-treated steel and aluminum specimens.

Data Availability

The underlying data supporting the results of this study were included in the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

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