ASJET

Al-Salam Journal for Engineering and Technology
Journal Homepage:
http://journal.alsalam.edu.iq/index.php/ajest
e-ISSN: 2790-4822 p-ISSN: 2958-0862

Computational Investigation into The Influence of Heat Treatment processes on The Mechanical Behavior of 6061Aluminum Alloy

Thaier A. Tawfiq[1] and Abdulsattar M. Jassim[2]*

[1]Alshaab University, Baghdad, IRAQ.
[2]Alsalam University College, Baghdad, IRAQ.

*Corresponding Author: Abdulsattar M. Jassim

DOI: https://doi.org/10.55145/ajest.2025.04.02.008
Received July 2025; Accepted August 2025; Available online August 2025

ABSTRACT: This study emphasises the advantages of simplicity, cost-effectiveness, and significant enhancement of material properties. It investigates the influence of heat treatment on the structural behaviour of an aluminium alloy through numerical simulation, focusing on its impact on performance assessment in future operational conditions. A comparative analysis was conducted between thermally treated and untreated aluminium alloy samples, evaluating key mechanical properties including stress resistance, strain, elongation, and fatigue life. The finite element model was developed, meshed, and analysed using Ansys Workbench 2020 R1. Compared to the overall experimental results reported in previous studies, the simulation outcomes demonstrated that heat treatment led to an improvement of roughly 21% in stress capacity and at least 75% in fatigue performance.

Keywords: 6061 Al alloy, Heat treatment, Mechanical properties, Ansys Workbench, Heavy Structural Applications

1. INTRODUCTION

Heat treatment can alter and reorganize a material's microstructure, resulting in modifications to its mechanical properties such as strength and strain capacity. However, during thermal processing, preheating must be carefully controlled in both temperature and duration to prevent the development of internal and residual stresses. Due to its advantageous properties, including corrosion resistance, low density, and ease of processing, aluminum alloys are widely used in various engineering applications, such as food packaging, automotive manufacturing, aerospace structures, and more. Among these, the 6061 aluminum alloy, which contains magnesium and silicon, is one of the most commonly used due to its low cost, moderate strength, good toughness, excellent corrosion resistance, and suitability for forming and welding [1–4]. Recent studies have focused extensively on Al 6061 for its relatively high hardness. Nevertheless, a key limitation of this alloy is its lower strength compared to alternative materials such as titanium and steel.

Heat treatment is increasingly being employed to improve the undesirable properties of 6061 aluminum alloy [5,6], as well as those of other materials [7]. Common heat treatment techniques include precipitation strengthening, quenching, case hardening, annealing, and tempering.

Numerous researchers have investigated the effects of heat treatment on the mechanical properties of metals and alloys. In particular, the influence of heat treatment on the fatigue resistance of the 6061 aluminum alloy has been the focus of several recent studies.

Zheng et al. [8] examined a novel surface-level solid-solution treatment of Al 6061 using electro-pulse techniques. Their findings showed a 15-second increase in the dissolution rate, which resulted in enhancements of 6.8% in tensile strength and 7.2% in Vickers hardness.

Additionally, Ozturk et al. [9] studied the age-hardening response of AA6061 at various ageing conditions, reporting notable improvements in its mechanical properties. Peak-aged conditions in the alloy were achieved after 120

*Corresponding author: abdulsattar.m.jassim@alsalam.edu.iq

minutes of heat treatment at 200 °C. The study revealed that, among the various microstructural transformations occurring during ageing, the formation of "β″ precipitates had the most pronounced impact on mechanical performance, specifically by significantly increasing the yield strength while reducing strain-hardening capacity.

Shrivastava et al. [10] investigated the effects of heat treatment under different conditions on the corrosion behavior of heat-treatable Al-6061 alloy reinforced with varying weight fractions of α-alumina nanoparticles. In their study, Al-6061 alloy powder, with particle sizes ranging from 0.02 to 0.04 mm, was used as the matrix material. The results indicated that the resolved composite exhibited superior corrosion resistance, attributed to the formation of a single-phase structure and improved uniformity between aluminum and the alloying elements. Furthermore, the study concluded that incorporating 0.5 wt% of nanoparticles in the composite under resolved conditions provides an optimal concentration for achieving maximum corrosion resistance. Chanyathunyaroj et al. [11] investigated the rotating bending fatigue life of 6061 aluminum alloy in a corrosive environment of 3.5% NaCl solution, aiming to assess the impact of corrosion on fatigue performance. Their findings showed that exposure to this environment led to a drastic reduction in fatigue by more than 51 times, reducing the lifespan from several days to just a few hours. The study also revealed that this concentration of NaCl induces the formation of corrosion pits on the surface of the 6061 aluminum alloy specimens, which serve as initiation sites for fatigue cracks. This study investigates the effect of heat treatment on the structural behavior of aluminum alloy using numerical simulation with Ansys Workbench 2020 R1, highlighting its significance for performance assessment under prospective operational conditions.

2. METHODOLOGY

In this study, a three-dimensional model of the specimen was first designed and developed using Ansys Workbench 2020 R1 to simulate and visualise the effects of heat treatment on the mechanical properties of 6061 aluminium alloy intended for heavy-duty applications. The heat treatment process involved heating the specimens to 490 °C, followed by oil quenching to ambient temperature within three hours [12]. A numerical parametric study was subsequently conducted to evaluate key mechanical properties, including strength, strain, and fatigue performance.

3. GOVERNING EQUATIONS AND ANALYTICAL METHOD

The resulting stress fields arise from the combined effects of dynamic loading, vibratory stresses, and thermal gradients. To calculate the thermal stress, the following equation is used [12,13]:

$$\sigma = E\,\alpha\,\Delta T \tag{1}$$

Where σ, ε ($\varepsilon = \alpha\,\Delta T$), and E represent the stress, strain, and elasticity matrix, respectively. α and ΔT are the thermal expansion factor and temperature gradient, respectively. The material considered in the present study is isotropic 6061 aluminium alloy (Table 1). Since the applied stress remains within the elastic deformation range, the stress–strain relationships are expressed in Cartesian coordinates, as shown in Equations (2–4) [11] [13] [14].

Table 1 6061 Al Alloy (Isotropic Elasticity)

Young's Modulus, MPa	Poisson's Ratio	Bulk Modulus, MPa	Shear Modulus, MPa
2.83e+10	0.33	6.696e+10	2.56e+10

$$\varepsilon_x = \frac{1}{E}\left[\sigma_x - V_p\left(\sigma_y + \sigma_z\right)\right] + \alpha\Delta T(x, y, z) \tag{2}$$
$$\varepsilon_y = \frac{1}{E}\left[\sigma_y - V_p\left(\sigma_x + \sigma_z\right)\right] + \alpha\Delta T(x, y, z) \tag{3}$$
$$\varepsilon_z = \frac{1}{E}\left[\sigma_z - V_p\left(\sigma_x + \sigma_y\right)\right] + \alpha\Delta T(x, y, z) \tag{4}$$

Where E is the Young modulus, α, is the coefficient of thermal expansion, and V_P is Poisson's ratio. The temperature gradient, determined from the CFD aerodynamic results, at points (x, y, z) is represented by ΔT(x, y, z).

4. NUMERICAL ANALYSIS AND FE MODEL

The numerical method is a widely used approach for obtaining reasonably accurate results, which can then be validated against analytical or experimental data to ensure consistency. Among various numerical techniques, Finite Element Analysis (FEA) is particularly prominent, as it provides detailed insights into rigid body behaviour and dynamic structural responses. FEA is regarded as one of the most reliable and accurate methods for structural analysis and design validation [15,16].

The first step in FEA, following the selection of the material type (Fig. 1), is typically the selection of the element type. This choice depends on the nature of the application and the geometry of the model (Fig. 2).

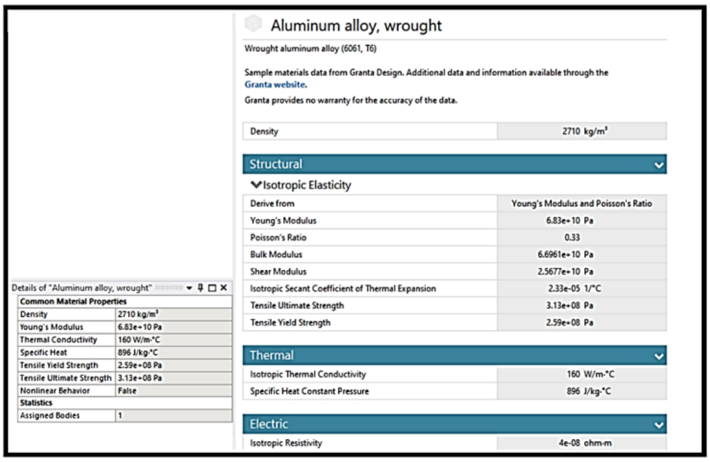

FIGURE 1 Specifying the Al6061 alloy in Ansys Workbench/Material assignment

The mechanical properties of the geometry or structure under investigation are typically obtained from materials handbooks or determined experimentally. Subsequently, the magnitudes, types, and directions of the applied loads must be defined. The model can then be solved using the appropriate governing equations, as illustrated in Fig. 3.

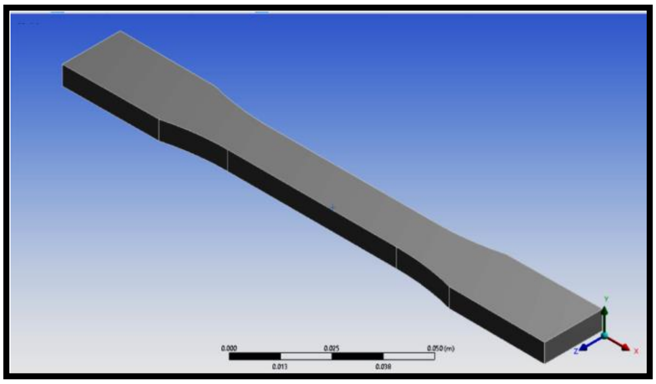

FIGURE 2 The model geometry

Accordingly, the element of (SOLID186), [17] was selected in the current work as it has six degrees of freedom, as well as some other dynamic physical characteristics.

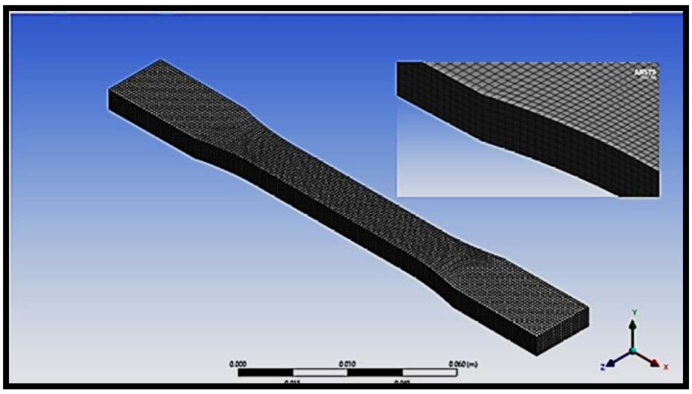

FIGURE 3 Structural mesh, using the assigned element type, with a close-up view of the refined mesh of the model

In addition to the element type, the number of elements used to generate the mesh is a critical factor. A coarse mesh with larger elements results in fewer elements, which can compromise the simulation accuracy. Conversely, a tiny mesh with a large number of elements increases computational time and effort without necessarily improving the accuracy of the results. Therefore, a mesh sensitivity analysis should be performed to determine an optimal balance between computational efficiency and result accuracy, as illustrated in Fig. 4.

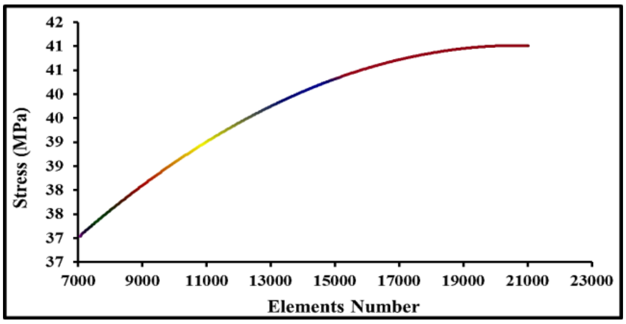

FIGURE 4 Mesh sensitivity to correctly choose the required number of assigned elements

Once this step is completed, the load type and magnitude can be applied, as shown in Fig. 5, and the model becomes ready for solution using the governing equations. Subsequently, the obtained results should be evaluated by comparing them with experimental or analytical data to ensure that the applied methodology was appropriately selected and accurately executed.

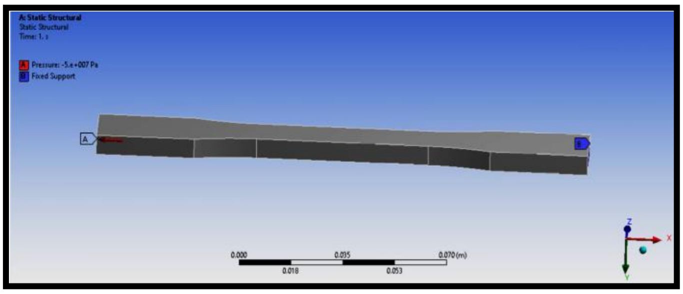

FIGURE 5 Applied load on the designed model

In this study, the results pertain to the analysis of stress, strain, deflection, and fatigue. Fig. 6 presents these steps in the form of a flowchart.

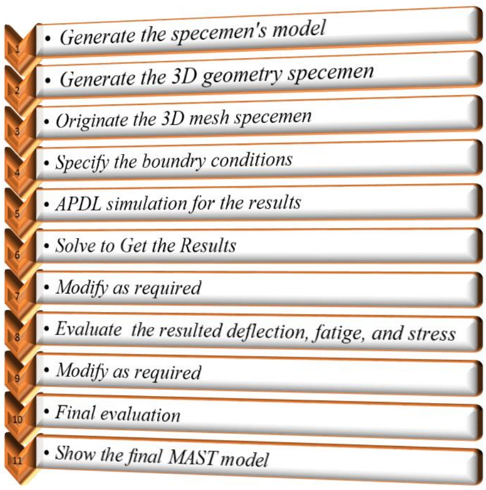

FIGURE 6 Overview of the analysis procedures followed for the current simulation

5. VALIDATION OF THE NUMERICAL STUDY

This study aims to numerically investigate the effect of heat treatment on selected mechanical properties of 6061 aluminum alloy, including von Mises stress, maximum principal stress, maximum principal strain, and fatigue parameters such as fatigue life and damage. The analysis was performed using Ansys Workbench, a widely recognized software based on the Finite Element Technique (FET).

6. RESULTS AND DISCUSSIONS

In this study, a finite element analysis (FEA) of a 3D model of Al 6061 alloy was conducted to assess the impact of heat treatment on its mechanical properties. Figure 7 illustrates the von Mises stress, elastic strain, total deformation, and maximum principal stress for the alloy model before heat treatment. As shown, fixing one end of the specimen and applying a tensile force to the opposite end resulted in noticeable stress concentration, accompanied by strain and deformation distributed unevenly along the specimen's body. These effects were associated with relatively high values. For instance, maximum stress values reached approximately 8.3 MPa for von Mises stress and 10.05 MPa for maximum principal stress, both observed near the midsection of the specimen.

Furthermore, a significant portion of the specimen was colored in shades ranging from yellow to red, indicating that a large area of the material was affected by the applied tensile load. Similarly, these color distributions were observed in the strain contours, reflecting the deformation caused by the loading. This widespread response suggests a limited capacity of the alloy to withstand such tensile stresses in practical applications.

The total deformation of the specimen is also presented in this study. As shown in the contour plot, the maximum deformation occurred at the free end of the specimen, reaching approximately 6.3 µm. In contrast, the minimum deformation, around 0.7 µm, was observed at the fixed end. This range of deformation, particularly the high values along most of the specimen, may be considered unfavorable, indicating potential structural limitations of the alloy under tensile loading.

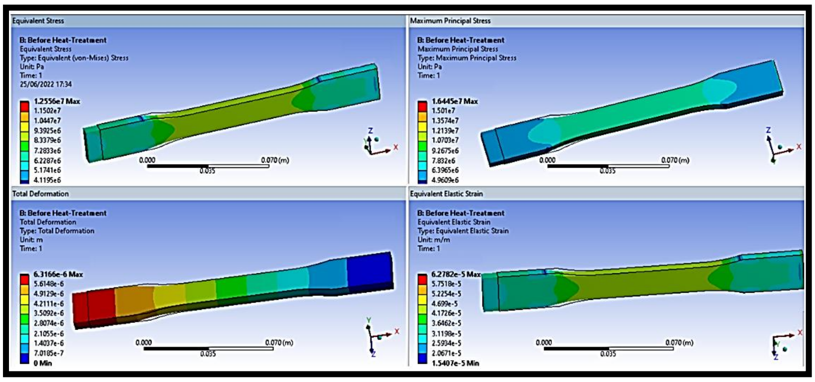

FIGURE 7 Structural tool (equivalent stress, maximum principal stress, total deformation, and equivalent strain) before conducting the heat treatment

Similarly, Fig. 8 presents the fatigue-related metrics for the untreated alloy model, including fatigue life, damage, safety factor, and biaxiality indication. Under the same boundary conditions described earlier, the model demonstrated a fatigue life of approximately 9 million cycles. However, the damage distribution indicates that a substantial portion of the specimen experienced significant material degradation due to the applied loading.

The safety factor, a critical measure for assessing a structure's resilience against sudden or excessive loads, was found to be approximately 0.4 across most of the specimens. Only a few localized regions exhibited higher values, reaching 190%. Such low values across the majority of the model suggest insufficient resistance to overload conditions. Additionally, the biaxiality indicates a parameter that evaluates the multiaxial stress state, further emphasizing the need for structural improvements. Collectively, these fatigue assessment tools underscore the inadequacy of the current untreated alloy model to endure conditions beyond its intended design scope, thereby highlighting the necessity for further enhancement.

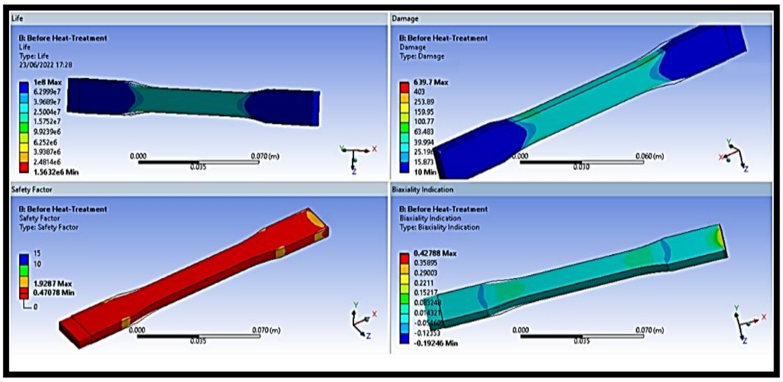

FIGURE 8 **Fatigue tool (life, damage, safety factor, and biaxiality indication), before conducting the heat treatment**

Based on the initial results, heat treatment was applied to the model, and the same boundary conditions (BCs) were maintained to assess its influence on the mechanical parameters. Following the same methodology, Figure 9 illustrates the distribution of von Mises stress, elastic strain, total deformation, and maximum principal stress for the heat-treated Al 6061 alloy model.

The results indicate a more uniform stress and strain distribution across the specimen, accompanied by comparatively lower stress values than those observed in the untreated model. For instance, the maximum values recorded were approximately 6.7 MPa for the von Mises stress and 8.7 MPa for the maximum principal stress; both stresses are concentrated near the midsection of the specimen. The remainder of the specimen displayed stress values ranging from 4.2 to 8.05 MPa for von Mises stress and from 5.1 to 6.3 MPa for maximum principal stress, represented by a blue-to-yellow color gradient. This improved stress distribution reflects the beneficial impact of heat treatment on the alloy’s mechanical behavior.

Similarly, the strain contours showed consistent coloration patterns, indicating a uniform strain response across the specimen. This further supports the conclusion that heat treatment enhanced the alloy’s ability to withstand mechanical loads, making it more suitable for practical applications.

Furthermore, the total deformation of the heat-treated model is presented in the current analysis. The deformation contour reveals a marked improvement, with the maximum deformation observed at the free end being approximately 5.1 µm, while the minimum deformation at the fixed end was around 0.051 µm. These relatively low deformation values, along with the positive effect on most regions of the specimen, confirm the advantages of the applied heat treatment in enhancing the alloy’s structural integrity.

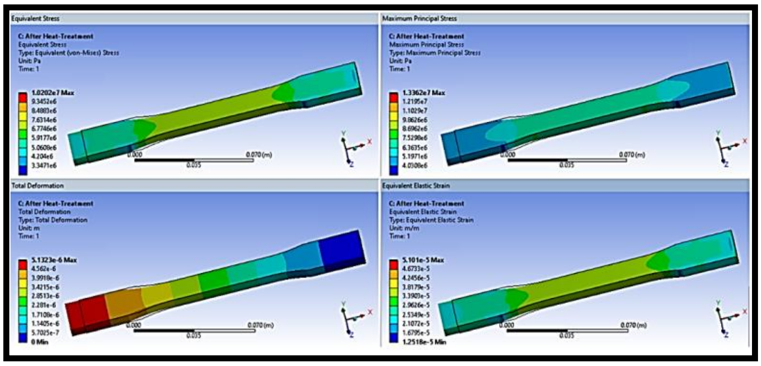

FIGURE 9 **Structural tool (equivalent stress, maximum principal stress, total deformation, and equivalent strain) after conducting the heat treatment**

The fatigue behavior of the Al 6061 alloy model following heat treatment represents the fourth key parameter evaluated in this study. Figure 10 presents the corresponding fatigue metrics: fatigue life, accumulated damage, safety factor, and stress biaxiality.

The results demonstrate that heat treatment significantly improves the fatigue life of the alloy. Numerically, the entire model was capable of withstanding more than 100 million loading cycles, indicating a substantial enhancement in service life and durability for demanding applications. The corresponding damage analysis revealed negligible damage under the applied loading conditions, further confirming the effectiveness of the thermal treatment. This suggests that the model, post-treatment, operates well within its fatigue limits, with failure only expected at significantly higher loads.

The safety factor also exhibited a marked improvement. Before heat treatment, the safety factor for most of the models was approximately 0.4, indicating poor performance under stress. After treatment, this value increased significantly, with most of the models displaying a safety factor of approximately 2.8. A minimum safety factor of 0.6 was observed only at the midsection of the model, which remains an acceptable value in comparison to the untreated state.

Although the stress biaxiality distributions remained largely similar between the treated and untreated models in terms of numerical values, the spatial distribution of these stresses was notably affected. The heat-treated specimen exhibited a lower overall biaxiality index across critical regions, indicating a more favorable stress state. This shift in stress behavior underscores the beneficial impact of heat treatment on the fatigue performance and structural integrity of the alloy under cyclic loading.

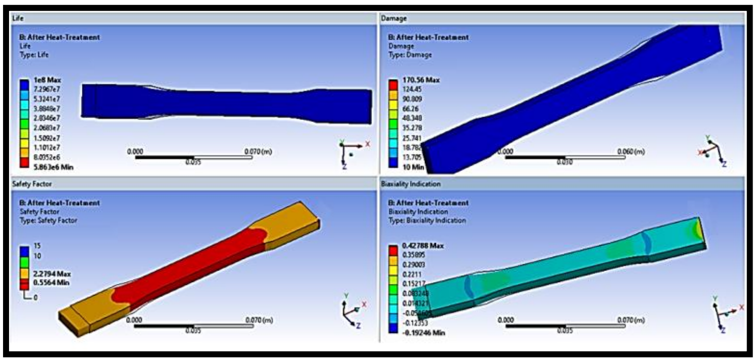

FIGURE 10 Fatigue tool (life, damage, safety factor, and biaxiality indication), after conducting the heat treatment

7. CONCLUSIONS

This study examined the impact of heat treatment on the mechanical properties of 6061 aluminum alloy under various tensile loads using three-dimensional FEA. The effect of heat treatment on stress distribution, deformation behavior, and fatigue-related parameters was systematically evaluated. The main conclusions drawn from this research are as follows:

1. Heat treatment significantly influenced both the deformation and stress responses of the alloy, as well as fatigue-related indicators. At a given tensile load, the heat-treated model exhibited a maximum increase of approximately 17% in deformation and 21% in stress. Furthermore, the fatigue life and damage parameters showed improvements of about 9% and 7%, respectively, under the same boundary conditions.

2. Stress concentrations were primarily observed in the central region of the specimen, suggesting that this area experienced the most substantial mechanical response and thus benefited most from the applied heat treatment.

3. Fatigue initiation and damage were also most pronounced at the midsection of the specimen, coinciding with the regions exhibiting the highest stress levels.

4. The findings underscore that structural analysis using FE modeling is an effective tool for evaluating fatigue life, deformation, and stress distribution in both heat-treated and untreated specimens. However, it is important to note that this study did not analyze the heat treatment process itself. Instead, a parametric investigation was conducted focusing on two key aspects: (i) the magnitudes of stress and deformation, and (ii) the spatial regions most affected by these mechanical responses.

FUNDING

None

ACKNOWLEDGEMENT

The authors would like to thank the anonymous reviewers for their efforts.

CONFLICTS OF INTEREST

The authors declare no conflict of interest

REFERENCES

[1] I. Guzmán, C. Guzmán, et al., "Comparative in mechanical behavior of 6061 aluminum alloy welded by pulsed GMAW with different filler metals and heat treatments," Materials, vol. 12, no. 24, p. 4157, 2019.
[2] N. Z. Nasir, et al., "The effect of heat treatment on fatigue and mechanical properties of 6061 aluminum alloy," Applied Mechanics and Materials, vol. 699, pp. 227–232, 2015.
[3] S. H. Lee, et al., "Microstructures and mechanical properties of 6061 aluminum alloy processed by accumulative roll-bonding," Materials Science and Engineering: A, vol. 325, no. 1–2, pp. 228–235, 2002.
[4] Y. H. Kim, et al., "An analysis of the forging processes for 6061 aluminum-alloy wheels," Journal of Materials Processing Technology, vol. 123, no. 2, pp. 270–276, 2002.
[5] O. Nejadseyfi, et al., "Combining equal-channel angular pressing and heat treatment to obtain enhanced corrosion resistance in 6061 aluminum alloy," Journal of Alloys and Compounds, vol. 648, pp. 912–918, 2015.
[6] B.-M. Sim, et al., "Analyzing the effects of heat treatment on SMAW duplex stainless steel weld overlays," Materials, vol. 15, no. 5, p. 1833, 2022.
[7] D. Šeruga, et al., "Heat treatment consideration in structural simulations of machine elements: Analysis of a starter clutch barrel," Technologies, vol. 9, no. 4, p. 73, 2021.
[8] Y. S. Zheng, et al., "Effect of electro pulse on solid solution treatment of 6061 aluminum alloy," Journal of Alloys and Compounds, vol. 615, pp. 849–853, 2014.
[9] F. Ozturk, et al., "Influence of aging treatment on mechanical properties of 6061 aluminum alloy," Materials and Design, vol. 31, no. 2, pp. 972–975, 2010.
[10] V. Shrivastava, G. K. Gupta, and I. B. Singh, "Heat treatment effect on the microstructure and corrosion behavior of Al-6061 alloy with influence of α-nano alumina reinforcement in 3.5% NaCl solution," Journal of Alloys and Compounds, vol. 775, pp. 628–638, 2019.
[11] K. Chanyathunyaroj, et al., "Fatigue characteristics of 6061 aluminum alloy subject to 3.5% NaCl environment," International Journal of Fatigue, vol. 133, p. 105420, 2020.
[12] N. E. Dowling, Mechanical Behavior of Materials: Engineering Methods for Deformation, Fracture and Fatigue, 4th ed. Boston, MA: Pearson, 2013, p. 457.
[13] P. Guillaume, "Modal analysis," Dept. of Mechanical Engineering, Vrije Universiteit Brussel, Pleinlaan, vol. 2, pp. 4–6, 2006.
[14] D. Maisonnette, et al., "Effects of heat treatments on the microstructure and mechanical properties of a 6061 aluminum alloy," Materials Science and Engineering: A, vol. 528, no. 6, pp. 2718–2724, 2011.
[15] K. L. Lawrence, Ansys Workbench Tutorial Release 14, Mission, KS: SDC Publications, 2012.
[16] T. Stolarski, Y. Nakasone, and S. Yoshimoto, Engineering Analysis with ANSYS Software, Oxford, UK: Butterworth-Heinemann, 2011.
[17] ANSYS CFX-Solver Theory Guide, ANSYS Inc., Canonsburg, PA 15317, SAS IP, Inc., 2011.