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Effect of Heat Treatment on Mechanical and Vibration Properties for 6061 and 2024 Aluminum Alloys

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ABSTRACT: This paper investigates the effect of heat treatment on the mechanical properties (yield and ultimate strength, elongation, hardness, and modulus of elasticity) and dynamic characteristics (natural frequency and dynamic response) under impulse loading for 6061 and 2024 aluminum alloys in O, T4, and T6 treatment conditions to study the effect of heat treatments. The study was conducted by implementing various techniques. The first step was to evaluate the mechanical properties and the natural frequency for the aluminum alloys; this was performed experimentally, after undergoing various heat treatment methods. In the second part of his study a numerical method (finite element) and he natural frequency was calculated for an aluminum plate after which a comparison was made with the results that were obtained experimentally, also the dynamic response for a plate under impulse load was evaluated numerically. Finally evaluating the dynamic plate response analytically by solution the general equation of motion for a plate under impulse load, then a comparison was performed on the results hat were obtained from this research the results together. When a comparison was made for normal frequency and platelet response it gave an acceptable percentage of error. Therefore, the results showed an improvement of the mechanical and dynamic properties for aluminum alloys, and that heat treatment gives acceptable results, due to the improvement of these properties that reach up to 20%.

KEYWORDS: Heat Treatment; Aluminum Alloy; Vibration Plate; Impulse Load

INTRODUCTION

Since the 1930's aluminum alloys have been the principle material for aircraft fabrication. Aeronautical manufacturing depends greatly on 2xxx and 7xxx alloys. Presently there is a growing interest in 6xxx aluminum alloys due to its numerous beneficial qualities i.e. medium strength, formability, weldability, corrosion resistance, and low cost. In addition to its wide field of aircraft fabrication which include the fuselage for aircrafts, body panels for automobiles and their bumpers as a substitute ,after suitable heat treatment, for the more expensive 2xxx & 7xxx alloys. Owing to this the fabrication method and characteristics plays an important role. [1].

Aluminum alloys are divided into two groups and they are: those that cannot be heat treated, and those that can. Those that are heat treatable can be hardened by the addition of certain alloying elements, and these elements are copper, zinc, magnesium and silicon, these elements when applied in different concentrations form compositions that display a solubility increase in aluminum at elevated temperatures it is possible conduct heat treatment on them. The process consists of heating the solution followed by quenching or aging. Conducting an appropriate sequence an agreeable ductility with a high strength can be obtained, [2]. Due the scientific importance of the 6xxx aluminum group they have undergone intensive studies because of their ability to increase in strength when subjected to precipitation hardening. These alloys are used in extrusion, construction and automobile manufacturing, because of their low density which makes them simple to shape. In addition to them being low priced they have good weld ability and good corrosion resistance making them desirable, [3].

Different precipitants can be obtained depending on the type of constituents that the alloy is formed of.. This will in turn influence and produce different mechanical properties, [4]. An attempt was made for positioning these precipitates on the phase diagram, via using the precipitates line chart, and the phases that are stable were detected. So as to acquire the best mechanical properties appropriate fabrication process is needed to be chosen. The time needed for aging, temperature, occurrence of deformation and the whole fabrication process are also needed to be taken into consideration, [5]. The significance of the time spent between solution heat treatment and aging, artificially will demonstrate that the time spent from quenching till aging will lead to the natural aging of the specimen and hence lowering its hardness in the end. In another study, [6], deformed samples between quenching and aging and they concluded that this method has positive effects on hardness and strength.

Effects of Heat Treatment

Age hardening is a heat treatment method implemented on heat treatable aluminum alloys in order to improve some their mechanical properties. the process rearranges the components that make up the alloy that detach from the aluminum during the cooling phase after it had been heated to a specific temperature during the process , the alloy's elements that are dissolvable will compose a uniform mass by solid diffusion. The alloy is quenched so as to keep the uniform condition in the quenched state. This process produces a malleable supersaturated but insecure alloy. At room temperature ,the alloying elements that form the alloy will start to precipitate from the solid solution, this will cause the alloy's hardness increase considerably. Some alloys need years in order to obtain strength and maximum hardness.

The alloys that have a slower transformation for age hardening can be sped up artificially by heating the alloy to a specific temperature and length of time depending on its dimensions, [7]. A considerable rise in yield and tensile strength is noted together with a decrease in ductility when it is subjected, after solution heat treatment, and cold work. Different compositions produce a variation of properties. Annealing is a heat treatment process used for recrystallization and/or eliminating residual stresses which are induced as a result of cold work and heat treatment. Annealing temperature for most of these alloys reach 650 0 F (343 0C).they are heated at a controlled pace depending on the thickness and which of the several types of annealing desired. The rate at which the part is cooled is not significant so long as it is not quenched as this will lead to residual stresses. [8].

Effects of Quenching

Quenching is when a metal is heated to a high temperature and then followed by rapid cooling as fast as possible by immersing the heated part in a relatively colder liquid such as oil or water. This process leads to an increase in the alloy's strength and resistance to corrosion. The alloy's structures as well as the elements that make up the alloy just prior to quenching are arrested when it is quenched. The alloy's properties are ruled by the alloy's constituents as well as its properties its cross section's thickness and he cooling rate when the alloy is quenched which depends on the quenching mediums type and temperature.

Maximum corrosion resistance can be obtained as a result of quenching in cold water and is implemented on products fabricated by tube sheet, extrusions. Quenching by rind is favored to a less severe quench in which the mechanical properties are increased. Slower quenching in mediums such as boiling water is implemented on large sections and /or hefty forgings. A low quenching rate has a more homogeneous cooling rate and produces a less distorted and cracked product which usually occur from uneven cooling. The temperature of the medium does not affect the resistance to corrosion; keep in mind the resistance to corrosion is less serious in thick parts than it is in thin parts. [9]. Since temperature has a significant effect on the mechanical properties, [10-14], and also since application of aluminum alloys are widely used; therefore it is a necessity to study the effect of heat treatment on aluminum alloys.

EXPERIMENTAL WORK

The experimental work was conducted on two types of aluminum alloys for this study, 6061-T6 and 2024-T4 alloys (chemical composition of the two alloys is shown in table (1). The work was divided into two parts. The first part was dedicated to evaluating the effect of heat treatment, for various temperatures, on the mechanical properties for aluminum alloys. Whilst in the second part the vibration characterizations for plate structure with various temperatures effect was determined in addition to these the basic mechanical properties: yield strength, ultimate stress, elongation, and, modulus of elasticity were measured. Also, the natural frequencies of a plate fabricated from these alloys were measured vibration characterizations measurement is the natural frequency of plate structure manufactured from its alloy materials, before and after heat treatment, by using vibration rig compound.

Table 1. Chemical composition of the alloys, % wt.

	Alloy	
	6061	2024
Si	0.78	0.37
Mg	1.08	1.5
Mn	0.15	0.6
Cu	0.36	4.4
Fe	0.16	0.4
Zn	0.053	0.21
Ni	0.007	----
Cr	0.35	0.1
Ti	0.025	0.09

Annealing Heat Treatment

The first thing we need to do is to eliminate all residual effects of any prior heat treatment that the plates may have been subjected to, its history was unknown this was achieved by placing both types of alloys in the form of plates in a furnace with the temperature set at (413 ºC), they were soaked at this temperature for two hours. They were then left in the furnace to cool down slowly until they had reached (250 ºC) and then onto room temperature. The process will present stress free plates (6061-T0) and (2024-T0) aluminum alloy plates.

Solution Heat Treatment

Solution heat treatment is a process where a series of heating and rapid cooling are performed on the aluminum alloys. The heat treatment can be summarized as follows:

1. Heated to a specific temperature
2. Soaked at this temperature for a specific time
3. Rapidly quenched

Aluminum alloy 6061-T0 was heated in furnace at (530°C) for a period of one hour , after which the alloy was quenched in water and returned to the furnace to be heated to (175 °C) for a period of (3 hours) to ensure diffusion of copper atoms into the aluminum , [15-16]. At the end of this process we obtained the aluminum alloy (6061- T4).

Aluminum alloy 2024-T0 had been heated in the furnace up to (494°C) for a period of (35 minutes). At the end of this time it was quenched in water and returned to the furnace and heated up to (100 ºC) for a period of (3-4 Hours) after this time had elapsed we were able to obtain (AGING)tensile test specimens were made from the two prepared alloys in tested their harness and tensile strength mechanical properties of the examined alloys.

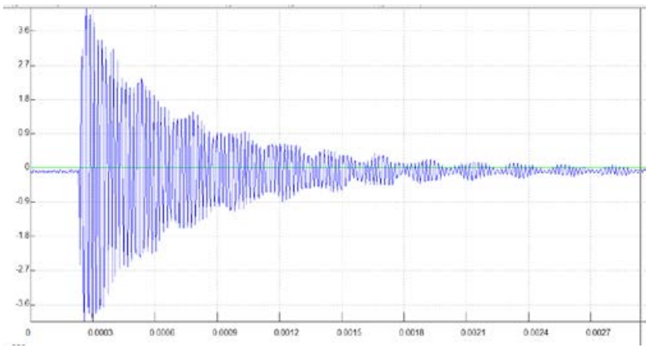
Vibration Test

Vibration tests were also conducted to find their natural frequency by using a vibration rig which was composed of the following devices, [17-21], as shown in Fig. 1

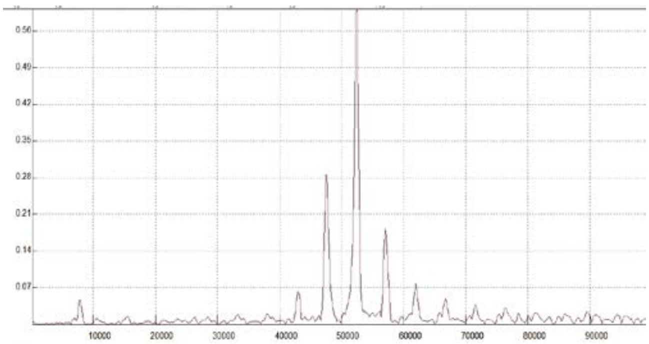
1. Plate sample
2. Structure rig
3. Supported for plate
4. Accelerometer
5. Amplifiers
6. Oscilloscope

The vibration signal was read from the oscilloscope by using the FFT technique, [22-27], the natural frequency for a plate can be calculated, as shown in Fig. 2. Where, the plate tested had the dimensions, (210*80*3 mm), and supported as a simply supported & cantilever plate.

Figure 1. Vibration Rig Compound



a. Vibration Response Signal (mv) with Time (sec) Relationship



b. Vibration Response Signal (mv) with Frequency (Hz) Relationship

Figure 2. FFT for Vibration Response Signal

ANALYTICAL TECHNIQUE

The analytical analysis included drive and solution for general equation of motion, [28-30], for vibration plate structure applied to transverse impulse loading. Where the analysis included the solution for simply supported plate structure. Therefore, the hypothesized theory of plate vibration is the "Small Deflection Plate Theory", [31]. Then, the equilibrium equation in z-direction for transverse plate vibration is,

$$D\left(\frac{\partial^4 w}{\partial x^4} + 2\frac{\partial^4 w}{\partial x^2\,\partial y^2} + \frac{\partial^4 w}{\partial y^4}\right) + \rho h \frac{\partial^2 w}{\partial t^2} = f(x, y, t) \tag{1}$$

Where,

$D = \frac{Eh^3}{12(1-\nu^2)}$, for, E: modulus of elasticity, ν: Poission’s ratio, h: plate thickness, ρ: material density, w:

transverse plate deflection, and, $f(x, y, t)$: applied load per unit plate area.

Then, to solve Eq. (1), to evaluate the natural frequency and the plate response, first evaluating the mode behavior for plate as a function of (x,y) by applying boundary conditions of plate, [32-33]. There, by applying boundary condition for plate structure supported as simply supported, get the shape faction for first mode plate behavior as,

$$w(x, y) = A \sin\frac{\pi x}{a} . \sin\frac{\pi y}{b} \tag{2}$$

Where, a and b are length and width for plate structure, and A constant. Then, by substituting Eq. 2 in to Eq. 1, and then multiplying the result by shape faction of plate, using normalized method, [31],

$$\int_0^b \int_0^a \rho h w^2 \, dx \, dy = 1 \tag{3}$$

Then, from Eq. 3 given,

$$A = \frac{2}{\sqrt{\rho hab}} \tag{4}$$

Therefore, get,

$$\ddot{w}(t) + \omega^2 w(t) = N(t) \tag{5}$$

Where,

$$N(t) = \int_0^b \int_0^a w(x, y). f(x, y, t) dx \, dy \tag{6}$$

And,

$$\omega = \pi^2 \sqrt{\left(\frac{D}{\rho h}\right)} \left(\left(\frac{1}{a^2}\right) + \left(\frac{1}{b^2}\right)\right) \tag{7}$$

Then, by applying concentrated load on plate, get,

$$N(t) = \frac{2}{\sqrt{\rho hab}} F(t) \tag{8}$$

Then, by using convolution integral, [34], and applying unit impulse load, get the response for plate structure by,

$$w(t) = \frac{2}{\omega\sqrt{\rho hab}} \sin \omega t \tag{9}$$

Thus, from the analytical solution the natural frequency can be evaluated for simply supported plate and the time response for late subjected to impulse loading, by using Eqns. 7 and 9, respectively, with various heat treatment effect of aluminum materials plate. Where, the mechanical properties for aluminum materials, with various heat treatment effect, can be used in the experimental mechanical properties calculation, [35-36]. Therefore, for agreement the experimental and numerical results were calculated, the analytical natural frequency results compared with experimental and numerical methods, and the analytical vibration time response compared with the numerical method.

NUMERICAL TECHNIQUE

The numerical method is an important method used to give approximate results and compared with other experimental and analytical results to give agreement for results calculated by other methods . There are several theories that give numerical analysis, but for dynamic behavior and rigid radicalization of structures, a finite element can be used to produce acceptable and reliable results, [37-40].

Any structure subjected for analysis by using the finite element method , the type of element must be selected for analysis, which depends on the structure geometry and problem application, then the mechanical properties for structure is then required which can be taken from the experimental work, and then, applying the load and solving the problem for structure. Thus, the element type that can be used for plate vibration is (Shell 281), [27], in which the element has six degrees of freedom in addition to other dynamic characteristics. Then, after selecting the element types must be mesh the structure to select the best number for element, after this the load is applied and solve the problem selected. Then the results are evaluated by numerical method the natural frequency and time response of platelets that are exposed to an impulse load, after which the natural frequency's results are then compared with that of those obtained experimentally and theoretically results of the process and theoretical. Also the plate's response to time is compared with the theoretical results that were obtained [41, 42].

RESULT AND DISCUSSION

The results for this paper was divided into two parts, the first is the mechanical properties for materials, whilst the second was for the dynamic characteristics for plate structure supported as a simply supported plate and cantilever plate, which included the natural frequency and the time response for plate subjected to an impulse load. Results were calculated for two aluminum alloys (6061 and 2024 alloy) with the effect of various heat treatments.

Mechanical Properties for Materials

The mechanical properties for 2024 and 6061 aluminum alloy calculated, with the effect of various heat treatment, are

1. Hardness
2. Yield strength
3. Ultimate strength
4. Modulus of elasticity
5. Elongation

Where, its properties presenting through Figs. 3 to 17, there, Figs. 3 and 4 show the effect of heat treatment on the hardness for two types of aluminum alloys used, respectively, Fig. 5 shows the comparison for hardness with heat treatment effect between alloys 2024 and 6061. Then, Figs. 6 and 7 show the behavior for yield strength with heat treatment effect for the two types of alloys, also, Fig. 8 gives a comparison on the effect for heat treatment on the yield strength for two alloys. Also, Figs. 9 and 10 present the relationship between the ultimate strength and heat treatment, then, Fig. 11, presents the comparison for two alloys with heat treatment effect. In addition, Figs. 12 and 13 show the effect of heat treatment on the modulus of elasticity of two alloys types used, respectively, and, Fig. 14 shows the comparison between the 2024 and 6061 alloy with heat treatment effect.

Therefore, from Figs. 3 to 14 it can be seen that heat treatment increases the properties presented with best temperature at T4 for alloy 2024, but its properties increased with T6 more than the other temperature for alloy 6061. Also, from this figure it can also be seen that heat treatment modifies its properties for 2024 alloy more than modifying the same properties 6061 aluminum alloy. Finally, Figs. 15 and 16 show the elongation for 2024 and 6061 aluminum alloy materials with heat treatment alloy, and the comparison between elongation for its materials is shown in Fig. 17. Where, from these figures can be see that heat treatment decreases elongation for these two types of alloys, but, the decrease for 2024 alloy was more than the decreasing for 6061 alloy elongation. Therefore, from this study it can be concluded that the 2024 aluminum alloy is better than 6061 aluminum alloy, and, the modifying for its properties for 2024 aluminum alloy is better than for 6061 alloy.

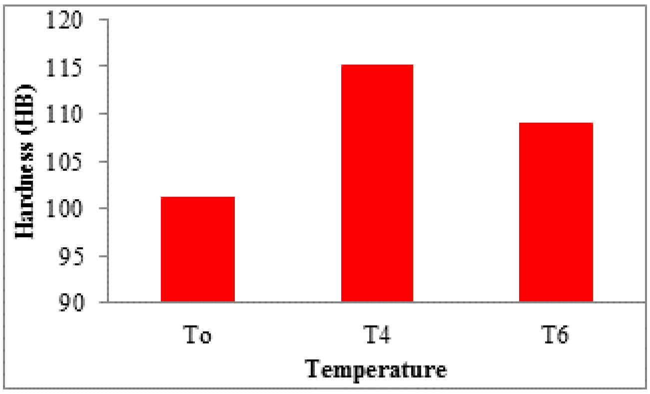


Figure 3. Hardness for 2024 Aluminum Alloy with Various Heat Treatment

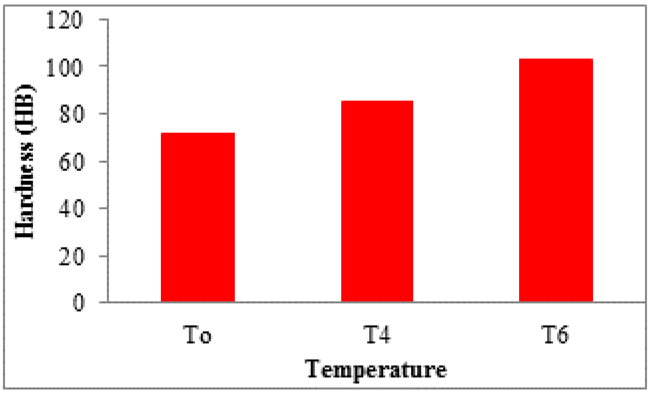


Figure 4. Hardness for 6061 Aluminum Alloy with Various Heat Treatment

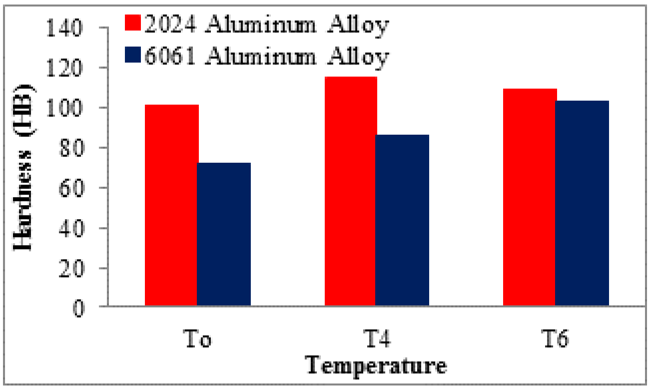


Figure 5. Hardness Comparison Between Different Aluminum Alloy with Various Heat Treatment Effect

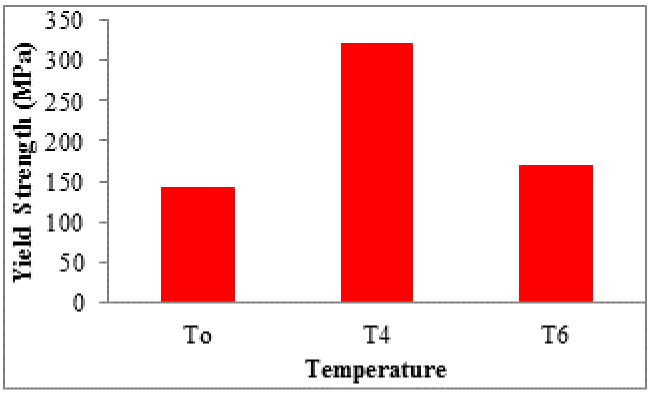


Figure 6. Yield Strength for 2024 Aluminum Alloy with Various Heat Treatment Effect

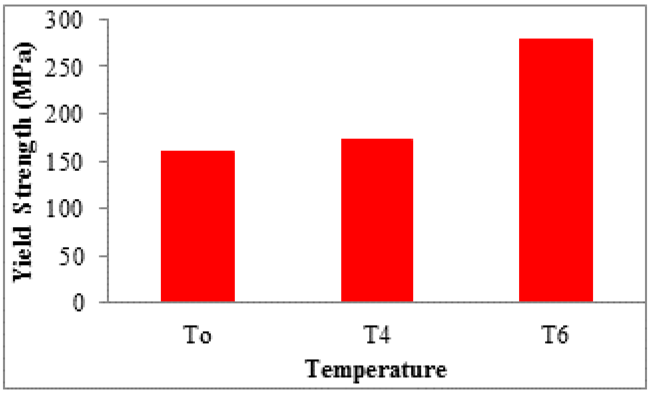


Figure 7. Yield Strength for 6061 Aluminum Alloy with Various Heat Treatment Effect

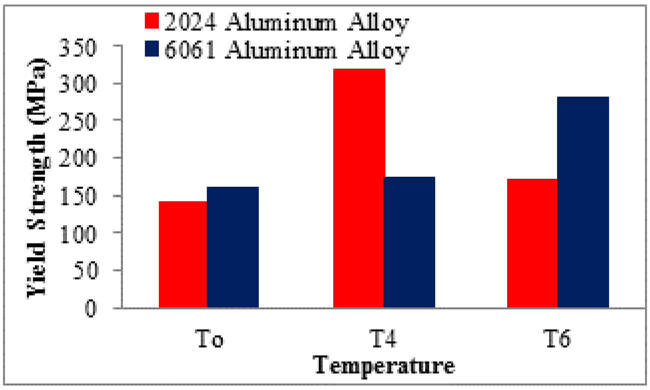


Figure 8. Yield Strength Comparison Between Different Aluminum Alloy with Various Heat Treatment Effect

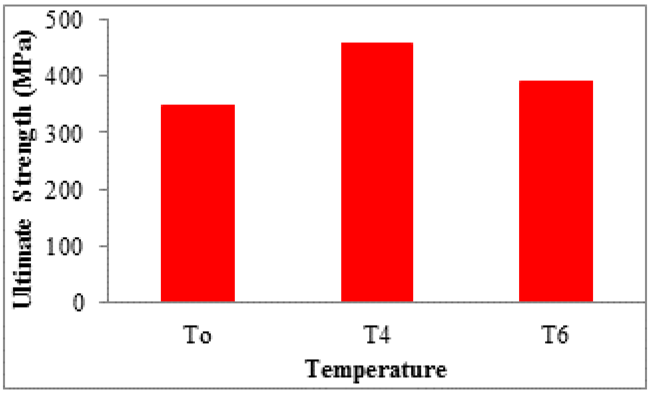


Figure 9. Ultimate Strength for 2024 Aluminum Alloy with Various Heat Treatment Effect

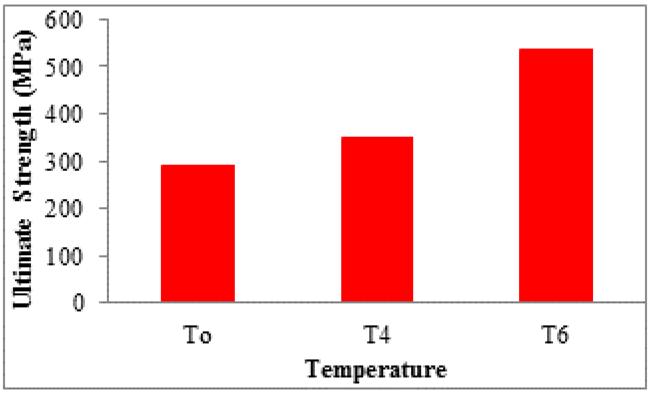


Figure 10. Ultimate Strength for 6061 Aluminum Alloy with Various Heat Treatment Effect

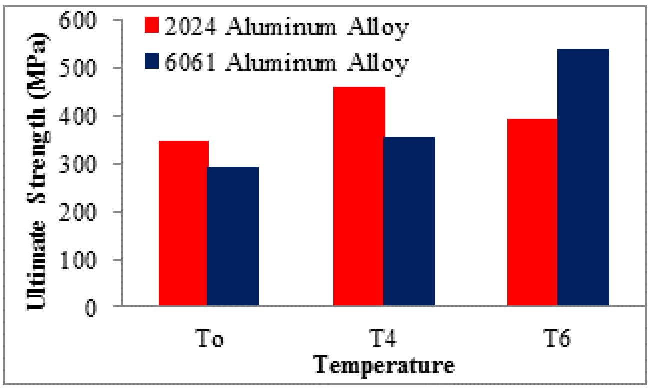


Figure 11. Ultimate Strength Comparison Between Different Aluminum Alloy with Various Heat Treatment Effect

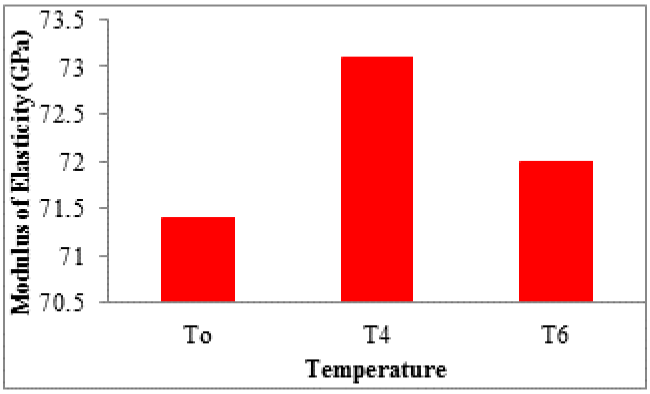


Figure 12. Modulus of Elasticity for 2024 Aluminum Alloy with Various Heat Treatment Effect

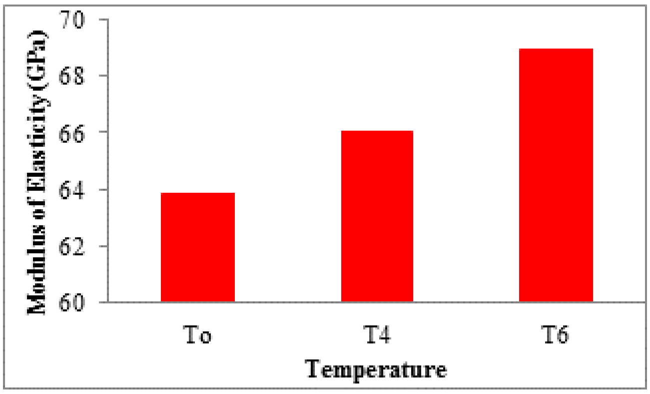


Figure 13. Modulus of Elasticity for 2024 Aluminum Alloy with Various Heat Treatment Effect

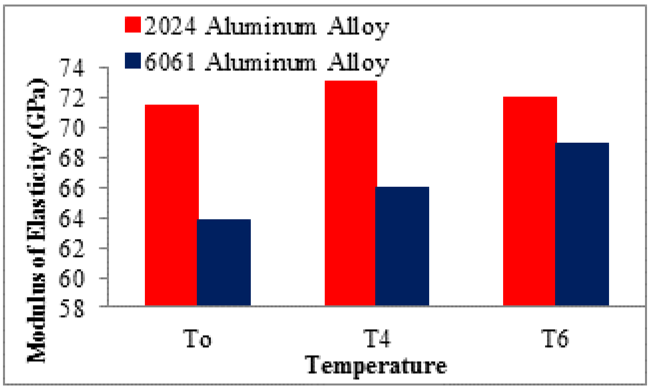


Figure 14. Modulus of Elasticity Comparison Between Different Aluminum Alloy with Various Heat

Treatment Effect

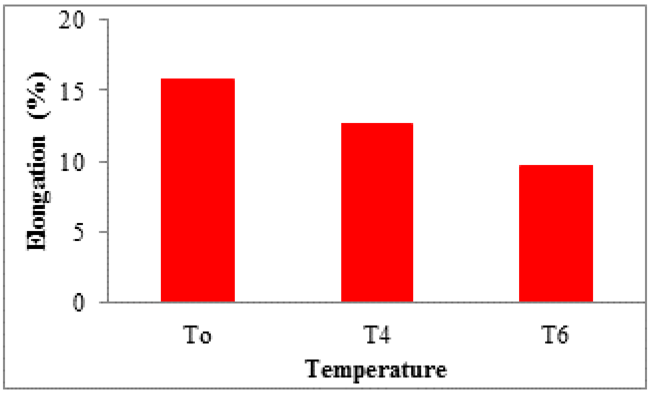


Figure 15. Elongation for 2024 Aluminum Alloy with Various Heat Treatment Effect

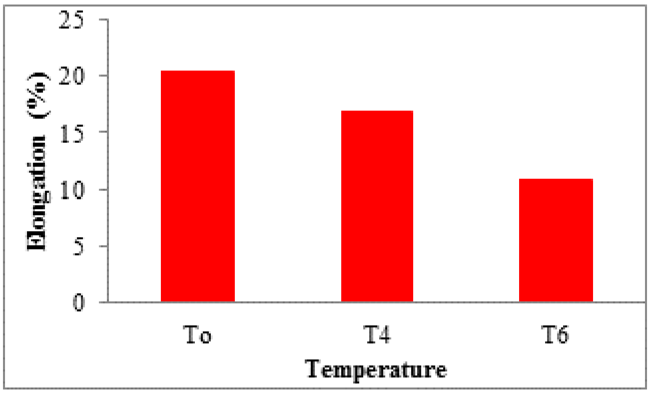


Figure 16. Elongation for 6061 Aluminum Alloy with Various Heat Treatment Effect

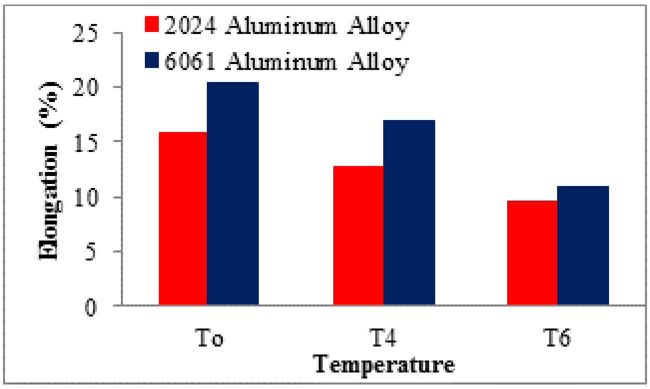


Figure 17. Elongation Comparison Between Different Aluminum Alloy with Various Heat Treatment Effect

Natural Frequency for Plate

The first part for dynamic characteristics include evaluating the natural frequency of the two types of alloys (2024 and 6061 aluminum alloy) with various heat treatment effect. Thus, firstly, a comparison between the results evaluated by analytical solution with numerical and experimental results for simply supported plate, as shown in Figs. 18 and 19, for 2024 and 6061 alloy materials, respectively. Then, a comparison between the natural frequencies for the two alloys with different heat treatment effect, as shown in Fig. 20. There, from this figure can it can be seen that modifying the natural frequency for 2024 alloy, with heat treatment, is better than modifying for 6061 alloy plate materials. In addition to this it can also be seen that the best temperature for 2024 alloy is T4 heat treatment.

Also, the behavior for cantilever plate structure presented in Figs. 21 and 22 to show comparison between the numerical and experimental natural frequency results for two types of alloys with different heat treatments. The effect of heat treatment on natural frequency for different alloy materials for plate structure is shown in Fig. 23. Where, from this figure it can be seen that the effect of heat treatment on the natural frequency is similar to the effect of heat treatment on frequency for simply supported plate structure.

In addition, from Figs. 18 and 19, can be seen that the analytical, numerical and experimental results is in agreement with maximum error between analytical and numerical method and does not exceed around (1%), and the percentage error between analytical and experimental method is about (10%). Also, the comparison for numerical and experimental natural frequencies results presented in Figs. 21 and 22, for cantilever plate, show that the maximum error between its results are around (10%). Then, from the results presented we find that the 2024 aluminum alloy is better than the 6061 aluminum alloy and the modification for the 2024 alloy is better than that of the 6061 alloy with heat treatment effect.

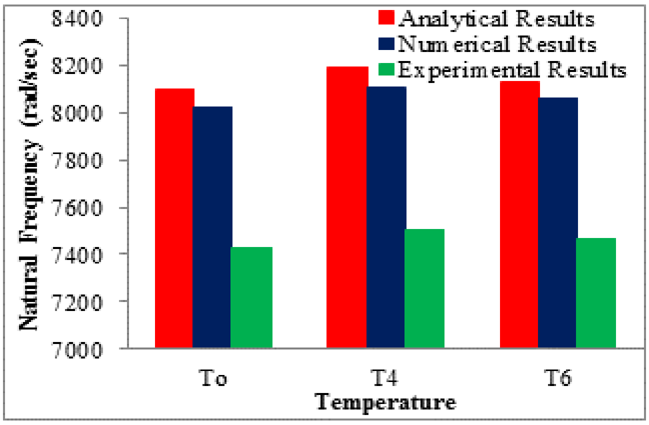


Figure 18. Comparison of Natural Frequency for Simply Supported Plate of 2024 Aluminum Alloy, Evaluated by Different Techniques

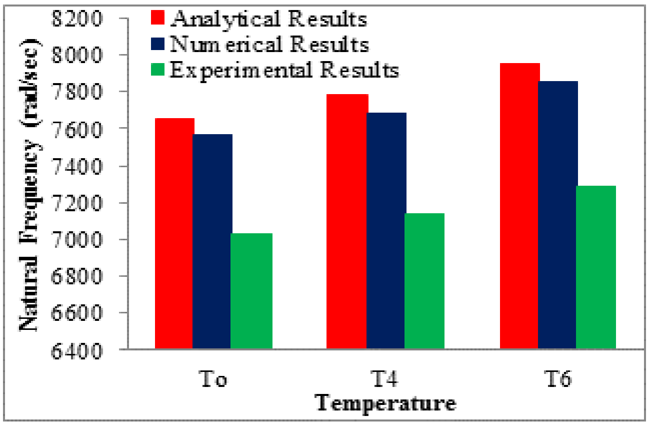


Figure 19. Comparison of Natural Frequency for Simply Supported Plate of 6061 Aluminum Alloy, Evaluated by Different Techniques

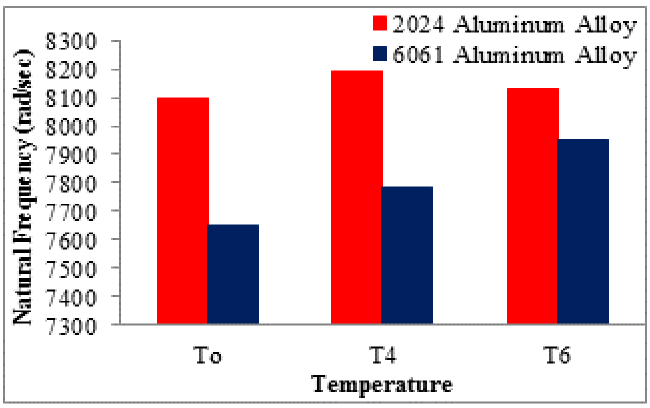


Figure 20. Natural Frequency for Various Aluminum Alloy Simply Supported Plate, with Different Temperature Effect

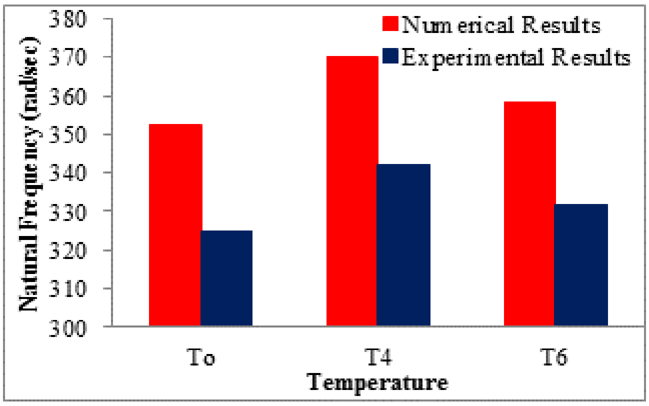


Figure 21. Comparison of Natural Frequency for Cantilever Supported Plate of 2024 Aluminum Alloy, Evaluated by Different Techniques

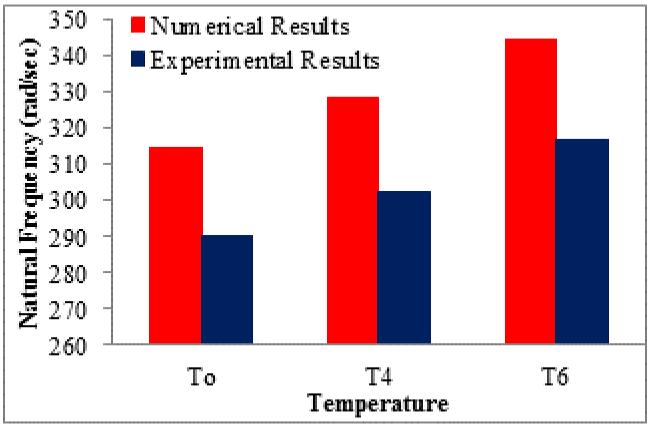


Figure 22. Comparison of Natural Frequency for Cantilever Supported Plate of 6061 Aluminum Alloy, Evaluated by Different Techniques

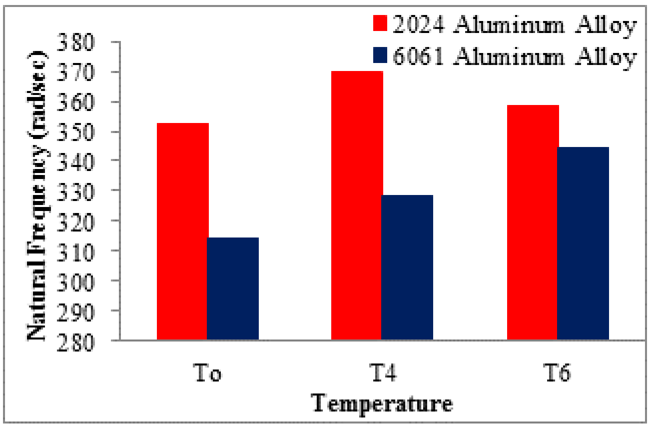


Figure 23. Natural Frequency for Various Aluminum Alloy Cantilever Supported Plate, with Different Temperature Effect

Time Plate Response

These results represent the second part of the dynamic characteristics for aluminum alloy structure with effect of heat treatment on its alloy. Figs, 24 to 29, for the two alloys with different heat treatment effect. Show that the analytical response results for simply supported plate structure with various materials used (2024 and 6061 aluminum alloy) are agreement with maximum error did not exceed (1.2%).

Then, after agreement evaluation for response results, presenting the effect for heat treatment on the maximum simply supported plate response for 2024 and 6061 aluminum alloy, as shown in Figs. 30 and 31, respectively, and comparing its response for 2024 and 6061 alloy plates, as shown in Fig. 32, with different heat treatment effect. Therefore, from the results presented in Figs. 30 to 32, we note that the response for plate structure decreases with heat treatment for the two alloys, but, the decrease response for 2024 alloy plate is more than the decrease for 6061 alloy plate. Therefore, it can be conclusion that the modifying for 2024 alloy with heat treatment material is better than the modifying for 6061 alloy, with dependent on the dynamic response plate behavior.

Found that heat treating (2024 and 6061) alloys improves their mechanical properties and he dynamic behavior of these plates, thus the dynamic behavior of structures made from these alloys are improved when undergoing heat treatment. But the 2024 alloy is better than the 6061 alloy when heat treated.

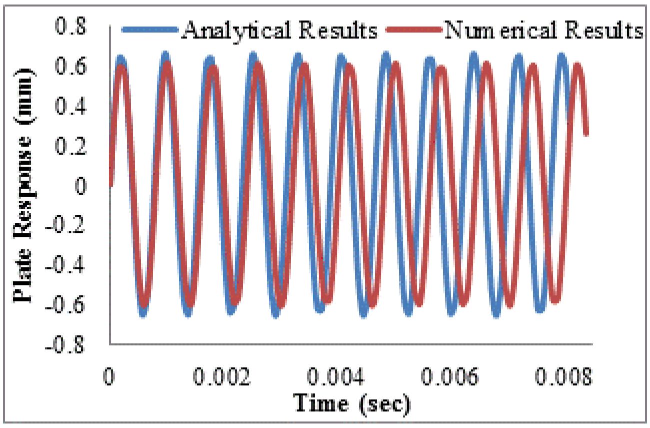


Figure 24. Comparison Between Analytical and Numerical Plate Response Results with To Temperature Effect of 2024 Aluminum Alloy

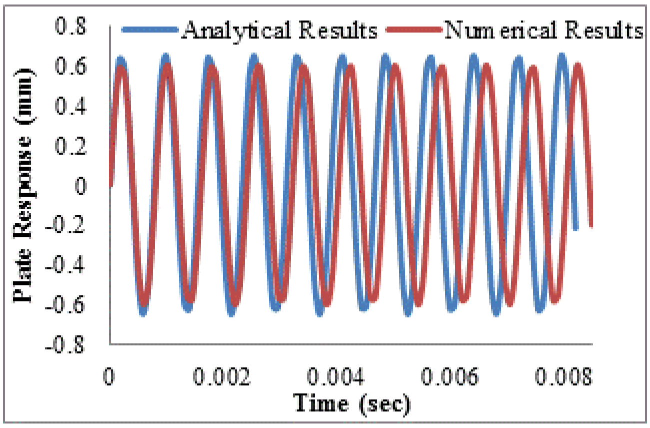


Figure 25. Comparison Between Analytical and Numerical Plate Response Results with T4 Temperature Effect of 2024 Aluminum Alloy

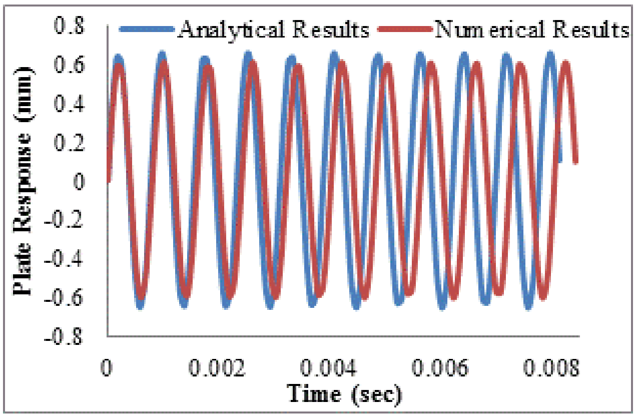


Figure 26. Comparison Between Analytical and Numerical Plate Response Results with T6 Temperature Effect of 2024 Aluminum Alloy

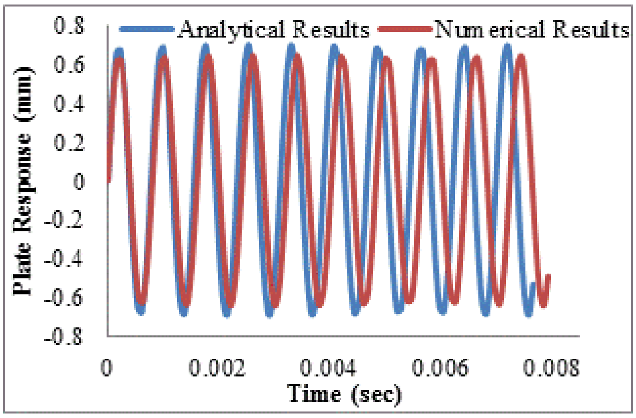


Figure 27. Comparison Between Analytical and Numerical Plate Response Results with T0 Temperature Effect of 6061 Aluminum Alloy

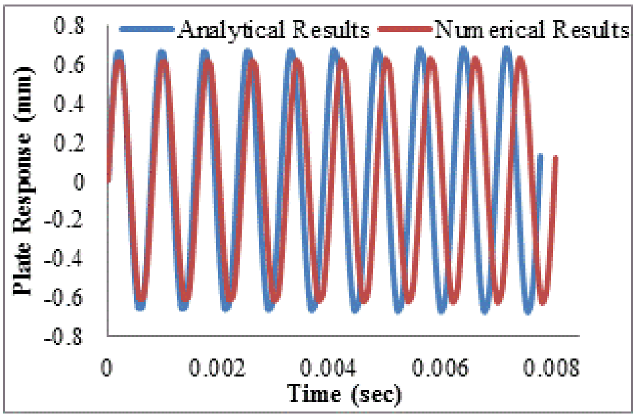


Figure 28. Comparison Between Analytical and Numerical Plate Response Results with T4 Temperature Effect of 6061 Aluminum Alloy

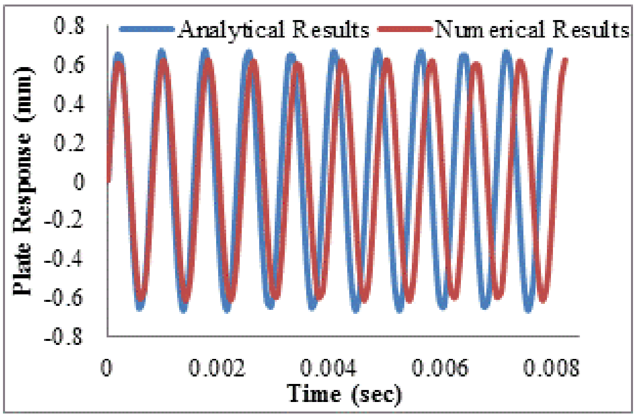


Figure 29. Comparison Between Analytical and Numerical Plate Response Results with T6 Temperature Effect of 6061 Aluminum Alloy

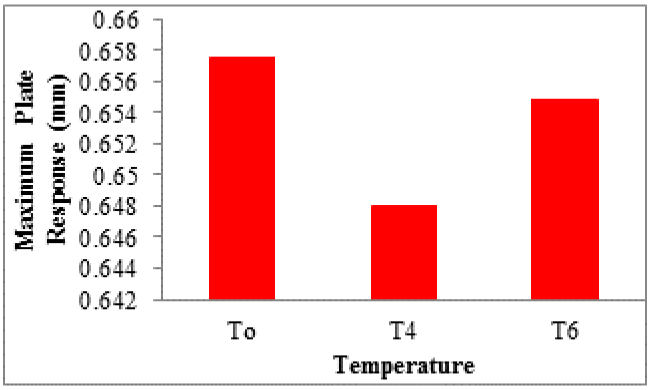


Figure 30. Maximum Plate Response with Different Temperature Effect for 2024 Aluminum Alloy, with Unit Impulse Load Effect

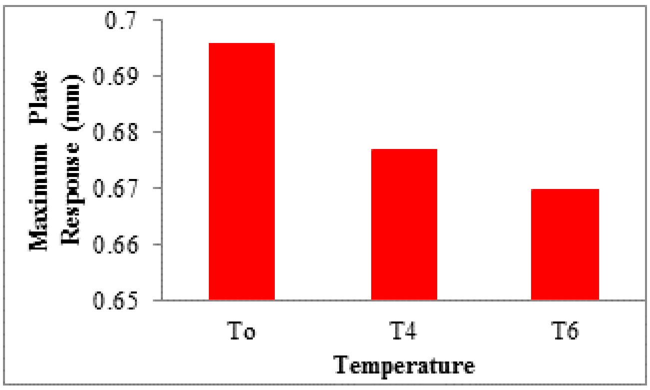


Figure 31. Maximum Plate Response with Different Temperature Effect for 6061 Aluminum Alloy, with Unit Impulse Load Effect

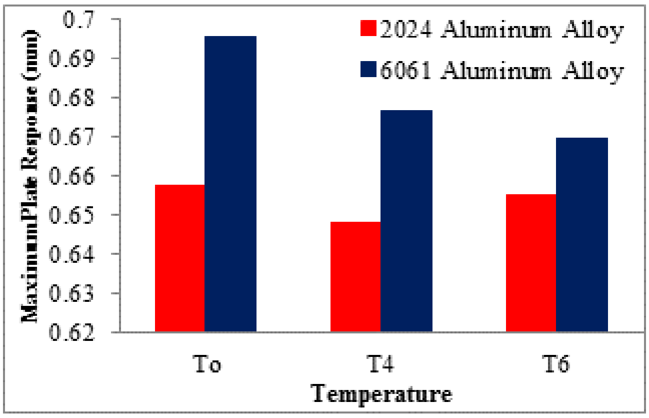


Figure 32. Maximum Plate Response for Various Aluminum Alloy with Different Temperature Effect, with Unit Impulse Load Effect

CONCLUSION

From the presenting work, the effect of heat treatment (To, T4, and T6) on the mechanical properties and dynamic characterizations for plate structure of 2024 and 6061 aluminum alloy materials, can be conclusion the following important points, as

Heat treatment modifies the mechanical properties for aluminum alloy materials, where, the best temperature treatment for 2024 alloy is T4 and T6 for 6061 alloy.

The mechanical properties for 2024 aluminum alloy material is better than mechanical properties for 6061 aluminum materials., also modifying the mechanical properties of 2024 alloy by heat treatment is better than the modification of the mechanical properties for 6061 alloy.

The dynamic characteristics for simply supported and cantilever plate structure made of 2024 and 6061 aluminum alloy materials can be modified by the use of heat treatment.

The dynamic characteristics for 2024 alloy plate are better than the dynamic characteristics for 6061 alloy materials plate structure, for different supported and various heat treatment effects.

The analytical solution technique is a perfect solution and can be used to evaluate the dynamic characteristics (natural frequency and response) for simply supported plate structure, with different parameters effect on the mechanical properties of plate materials.

The comparison between analytical, numerical and experimental techniques used for evaluating the natural frequency for plate structure gave good results with accepted percentage error. Also, the comparison between numerical and experimental plate response results gave a good agreement for its results.

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