1. Introduction

From decades ago, the effectiveness of materials improved, new forms have played a key role in the development of science and technology. Advances in physics and technology are difficult without the use of advanced effective materials. To meet their needs, the researchers manufactured and handled materials in the development process. However, an appropriate correlation has not been settled between the properties of a quantity with materials of nanomaterials size. Thus, in current technology researchers are repetitively researching, investigating and trying to get used to new innovative materials. And the necessary scientific research has been conducted related to the improvement of mechanical properties and the factors that affect them, especially stirring temperature and specific amounts of metal nanoparticles added to alloys.

2. Literature review and problem statement

There are many investigations dealing with several aspects related to improving mechanical properties and factors such as stirring temperature, stirring time and particle distribution, which can affect the material properties. Nanocomposites were synthesized by the method to manufacture nanoparticles evenly distributed in metallic matrix composites. This produces a significant improvement in Young’s modulus and hardness due to the addition of a low weight fraction of A nanometric [1]. The influence of using Al2O3, TiO2, and ZrO2 nanoparticles with a size of 40 nm on a base metal matrix (A356 aluminum cast alloy) was studied in [2, 3]. With various fraction ratios ranging from 0 % to 5 %, they were stirred in the A356 matrix, by weight at variable stirring speeds varying from 270 to 2150 rpm in both the semisolid of 600 °C and liquid of 700 °C states applying a fixed stirring time of a minute. This investigation presented that the properties of nano-reinforced castings were improved for the castings applying Al2O3, TiO2, and ZrO2 nanoparticles, with a size of 40 nm. The 850 °C stirring temperature (ST) with 9 wt % Al2O3 with 850 °C stirring temperatures has the best properties. It was also revealed that the 850 °C stirring temperature (ST) with 9 wt % Al2O3 composite provide an increase in tensile strength, VHN and reduction in ductility by 20 %, 16 % and 36.8 % respectively, compared to zero-nano. Also, the fatigue life at the 90 MPa stress level increased by 17.4 % in comparison with 9 wt % nanocomposite at 800 °C (ST). Uniform distributions were observed for all nine microstructure compositions.

Keywords: 6061 aluminum alloy, Al2O3 nanoparticles, nanocomposites, stirring temperatures, stir casting method, mechanical and fatigue properties.
Furthermore, [4] investigated the influence of adding reinforcements into the metallic matrix on the mechanical properties. The major points derived from this study state that increasing the reinforcement ratio and decreasing the size of reinforcement particles considerably improves the properties of metal matrix composites. In addition, wear resistance and creep have been studied as other important factors that are not often discussed. Increasing the $\text{Al}_2\text{O}_3$ fraction reduces the fracture toughness of AMCs. The addition of zircon advances the strength of AMCs. Moreover, in [5], 10 wt % of $\text{Al}_2\text{O}_3$ nanomaterial were added to AA6061 in applying the stir casting method for producing nanocomposites. The comparison between 6061 aluminum alloy matrix and 10 wt % $\text{Al}_2\text{O}_3$ nanocomposites revealed that there is a 12.8 % improvement in the fatigue strength at 10$^7$ cycles due to 10 wt % nano-reinforcement. The accumulative fatigue life of 10 wt % nanocomposite was improved by 33.37 % and 39.58 % for low-high and high-low loading sequences, respectively. The results showed that the addition of nanomaterials increased the strength of both constant and cumulative fatigue and fatigue life.

Moreover, [6] investigated the influence of pouring temperature of the slurry produced by weak electromagnetic stirring. Also, the morphology and size of the primary particles in the A356 Al alloy were investigated by analyzing the influence of superheat temperature. In this work, they obtained a semi-solid slurry of metal with a particle as a primary phase by utilizing appropriate weak electromagnetic stirring and increasing pouring heat temperature, which produces a low superheat pouring. Moreover, they have concluded that an increment in pouring temperature by 15–35 °C above the liquidus temperature combined with a weak electromagnetic stirring results in the same size and shape properties of the primary phase. The study showed the effect of stirring the alloy mixture and without stirring, and focused on stirring temperatures rather than other properties. Furthermore, [7] examined the influence of stirring speed and pouring temperature on the properties of A16061-Cu reinforced SiC MMC by the stir casting process. It was observed from scanning electron microscope (SEM) analysis that at a stirring speed of 400 rpm, an improved homogeneity could be achieved evaluated to that of 200 and 600 rpm. The study concentrated on the stirring speed of the alloy, and it was found that at a certain limit, the mechanical properties change drastically in the direction of not getting better. Besides, [8] studied evaluation emphasizes the optimization of stirring speed and pouring temperature for the properties of aluminum metal matrix composites. Several heights of pouring temperatures at a constant pouring speed of 2.5 cm/s were studied as input parameters throughout. The experimental results indicate that a pouring temperature range of 700 °C to 750 °C and 400 to 600 rpm stirring speed offered developed mechanical properties. So, the focus of this analysis is to optimize the pouring speed, the stirring speed and the pouring temperature for mechanical properties. In addition, [9] studied the optimum conditions for preparing composites reinforced with 5 wt % nanoparticles cast at 850 °C. The study concluded that the optimum conditions for the fabrication of composites after several experiments with reinforced nanoparticles cast have homogeneity in the micro-structures and exhibit increased mechanical properties such as hardness and tensile strength. That is why we found that the improvement takes place in a certain percentage, after which these properties change without improve-

3. The aim and objectives of the study

The aim of this study is to determine the effect of stirring temperature (ST) on the AA6061/$\text{Al}_2\text{O}_3$ nanocomposite. To achieve this aim, the following objectives are accomplished:

- to improve the mechanical properties, including the hardness, tensile strength and fatigue strength of 6061 aluminum alloy;
- to prepare nanocomposites at three stirring temperatures with a uniform distribution in certain cases.

4. Materials and methods

6061 aluminum alloy is applied in the present study as it is widely utilized for different purposes in the aerospace and transportation industries. The chemical composition of AA6061 is as follows: Cu 0.31, Mg 0.98, Zn 0.17, Cr 0.22, Ti 0.09, Fe 0.52, Mn 0.11, Si 0.66, and Al balance. The reinforcement nanomaterial $\text{Al}_2\text{O}_3$ had a density of 3.62 g/cm$^3$ and a particle size between 20 and 30 nm [11].

The stir casting method adopted for fabricating nanocomposites is as follows: AA6061 was cut into cubes with 1 to 2 cm$^3$, then washed with alcohol and followed by distilled water five times. The washed parts were then dried by the stream of hot air at a temperature of 100 °C, later the dried parts were heated to approximately 200 °C using an electric heater. Argon gas was pumped into the oven and heated to 800, 850 and 900 °C stirring temperature, and preheated the $\text{Al}_2\text{O}_3$ particles to 200 °C. Then finally, nanomaterials were added into the molten aluminum alloy with a gas pump. The furnace temperature was initially elevated over the liquid temperature of aluminum about 800, 850, and 900 °C. The first 800 °C, the second sample was heated to about 850 °C and the third sample was mixed at 900±10 °C to melt the aluminum alloy totally and then cooled down just below 650 °C.

The stirring time was designed for 4 minutes at 450 rpm stirring speed. The $\text{Al}_2\text{O}_3$ particles were added to the melt in the furnace, and then the mixing temperature was raised to 800 °C±10 °C. The liquid was poured into molds to acquire an aluminum rod for the composites that are shaped in the
The tensile test was carried out using a WDW-100 tensile machine that has a maximum capacity of 100 kN. Eighteen specimens were used from the fabricated round rods of diameter ($\phi$)≈10 mm and length ($L$)≈160 mm. The deformations were recorded by measuring devices and automatic control. The data were plotted by the plot device. The tensile curves (stress-strain) were employed for predicting the material behavior under different loading.

The standard tensile specimens were made according to the American Society for Testing and Materials (ASTM E8/E8M-09), as shown in Fig. 2, where all the appeared dimensions were measured in (mm). While the tensile test rig is illustrated in Fig. 3. In this paper, Vickers hardness numbers (VHN) were measured using polished samples with different stirring temperatures (800, 850, and 900 °C).

All fatigue tests were carried using a rotating fatigue test rig (ISTRON) as presented in Fig. 3.

The uniform distribution of Al$_2$O$_3$ into a matrix and relatively lower porosity in the casting led to high-density dislocations leading to an enhancement of mechanical properties. It can be concluded that 6061 Al alloy-based composites with 9 % Al$_2$O$_3$ possess better mechanical properties. All the fabricated nanocomposites show improvement in hardness and ductility. The 9 % Al$_2$O$_3$ composite shows an optimal improvement in hardness and ductility at 850 °C stirring temperature. The hardness of 9 % Al$_2$O$_3$ at 850 °C increased by 16 %, while the ductility enhanced by 36.8 %. These findings are somehow aligned with [13], where they fabricated and examined 2024/Al$_2$O$_3$ nanocomposites to obtain the improvement in mechanical properties.
The results of the VHN hardness of the matrix are shown in Fig. 7. Important developments in mechanical properties and hardness were recorded from adding Al₂O₃ in the matrix. The reason could be that Al₂O₃ particles act as obstacles to the motion of dislocations and Al₂O₃ particles work as a barrier to crack initiation and slip band [14, 15]. In addition, Al₂O₃ particles are harder than those of the base metal leading to the improvement of mechanical properties and VHN of the composites. The fairly distributed particles of Al₂O₃ resulted in the development of the mechanical properties of the composites [16].

The results of ductility tests show that an increase in Al₂O₃ leads to ductility reduction. The maximum decrease occurred for the composite including 9 wt% Al₂O₃ achieved at 850 °C stirring temperatures. Once again, the result is confirmed by [17], who have found that increasing the amount of Al₂O₃ improves UTS and VHN. Nevertheless, the ductility tends to reduce, and the peak reduction is obtained at 6 wt% Al₂O₃ with 850 °C stirring temperature. An improvement in mechanical properties and hardness with a reduction in ductility may be due to the thermal mismatch between the base metal and Al₂O₃ particles [18, 19].

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The specimen has a round cross-section and is affected by the employed load from the perpendicular axis to the right side of the workpiece, improving the bending moment. Hence, the surface of the workpiece is under compression and tension stress when it rotates. Three samples were tested for each stress level. The results showed that the samples manufactured at 850 °C (ST) have a longer fatigue life than others, as shown in Table 3. The outcome of these experiments can be applied to the relationship between the stresses used and the number of cycles to failure.

### Table 2

<table>
<thead>
<tr>
<th>Al₂O₃, wt %</th>
<th>UTS (MPa)</th>
<th>YS (MPa)</th>
<th>VHN</th>
<th>Ductility</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>151.22</td>
<td>137.53</td>
<td>92.26</td>
<td>16%</td>
</tr>
<tr>
<td>5%</td>
<td>170.54</td>
<td>144.23</td>
<td>105.42</td>
<td>14.90%</td>
</tr>
<tr>
<td>7%</td>
<td>178.56</td>
<td>154.54</td>
<td>108.23</td>
<td>12%</td>
</tr>
<tr>
<td>9%</td>
<td>186.23</td>
<td>164.44</td>
<td>112.67</td>
<td>10.70%</td>
</tr>
</tbody>
</table>

Fig. 4. UTS, YS, with the percentage at stir casting Temp. 800 °C of the weight percentage of Al₂O₃

Fig. 5. UTS, YS, with the percentage at stir casting Temp. 850 °C of the weight percentage of Al₂O₃

Fig. 6. UTS, YS, with the percentage at stir casting temp. 900 °C of the weight percentage of Al₂O₃

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Table 3

<table>
<thead>
<tr>
<th>Stress level (MPa)</th>
<th>N_f at 800 °C (ST)</th>
<th>N_f at 850 °C (ST)</th>
<th>N_f at 900 °C (ST)</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td>201,000</td>
<td>243,366</td>
<td>207,000</td>
</tr>
<tr>
<td>110</td>
<td>155,000</td>
<td>151,100</td>
<td>160,000</td>
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<tr>
<td>130</td>
<td>94,000</td>
<td>84,800</td>
<td>91,800</td>
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<tr>
<td>150</td>
<td>42,800</td>
<td>35,833</td>
<td>33,600</td>
</tr>
<tr>
<td>180</td>
<td>10,200</td>
<td>14,266</td>
<td>11,000</td>
</tr>
</tbody>
</table>

Therefore, the S-N curve was plotted depending on the values obtained from the fatigue equations for the three cases (800, 850, and 900 °C) of stirring temperatures as shown above in Fig. 9.

5.2. Uniformity of AA6061/Al₂O₃ nanocomposites

After preparing the nanomaterials according to weight and inserting them into the alloy, the Al₂O₃ nanoparticles acted as barriers of dislocations leading to an improvement of fatigue behavior and mechanical properties. Moreover, the interaction between the nanoparticles and dislocations plays a significant role in developing the mechanical and fatigue properties [20].

Concerning the scanning electron microscope (SEM) testing, Fig. 11 presents the SEM photographs of a: zero-nanoparticles at 850 °C; b: 9 wt % Al₂O₃ at 850 °C; and c: 9 wt % Al₂O₃ at 900 °C.

The findings refer to the improvement of the properties by reassuring that the Al₂O₃ nanoparticles acted as dislocation barriers leading to improved fatigue behavior and mechanical properties. The features of the proposed method indicate that the properties of the new composites give an improvement in the exact case. This was observed in Fig. 5. It is possible to observe the significant increase in ultimate tensile strength (UTS) and yield stress (YS). The results of the VHN hardness of the matrix shown in Fig. 7 can also be observed enhancing up to 16 %, while the ductility enhanced by 36.8 %, as shown in Fig. 8. The maximum enhancement for ultimate tensile strength, yield stress, hardness and ductility occurs when the composite is produced with the addition of 9 wt % of the nanomaterial to a mixture at 850 °C.

This method can be considered a great advantage in improving mechanical properties. But the nature, purity and cost of nanomaterials can be an impediment to successful outcomes. Therefore, research and studies must be conducted to obtain pure and cost-effective nanomaterials.

The limitations of this method can be represented in obtaining a uniform distribution of nanomaterials unless there is an in-depth study of the molecular structure, which enhances the results gained.

One of the focal disadvantages related to nanomaterials is considered to be inhalation exposure. This concern stems from studies in humans that suggest that nanomaterials can cause adverse effects on the lungs. Therefore, caution should be taken when conducting experiments.

The research can be considered useful, as the results have given important indications to the improvement of many properties compared to the untreated alloy. Because of this improvement, this alloy can be used in numerous applications, which use AA6061.

This research is a continuation of many research studies in which many kinds of nanomaterials have been used in different proportions and multiple methods of preparation. These studies were concerned with the improvement of the mechanical properties of alloys. The development of this method can be used for various aluminum alloys, which may enhance the mechanical and fatigue properties with different quantities of nanomaterials depending on the interaction between the aluminum alloys and the ratio of nanoparticles.

6. Discussion of experimental results of determining the effect of stirring temperature (ST) on the AA6061/Al₂O₃ nanocomposite

The present investigation revealed with an indication of qualitative or quantitative indicators of research results that the 850 °C stirring temperature with 9 wt % Al₂O₃ composites reveal a uniform particle distribution and low agglomeration and few clusters at inter-dendrite regions. However, the best uniformly distributed is 9 wt % Al₂O₃ at 850 °C. Also, adding Al₂O₃ into the base metal melt develops the viscosity of the melt and this retards the movement of Al₂O₃. It is significant to control the solidification rate to attain high distribution of Al₂O₃ in the process of stir casting [21, 22].

7. Conclusions

1. The present investigation revealed with an indication of qualitative or quantitative indicators of research results that the 850 °C stirring temperature with 9 wt % Al₂O₃ compos-
ites provides better mechanical properties, hardness and fatigue properties than the other stirring temperature of 800 °C and 900 °C and the stirring temperature has an important effect on the above properties. The composite with 9 wt % Al₂O₃ stirring at 850 °C exhibits the highest hardness and lowest elongation compared to the other stirring temperature.

2. Analysis of SEM showed evidence for incorporating the Al₂O₃ nanoparticles with the metal matrix. And the AA6069 / wt % Al₂O₃ nanocomposite with 850 °C (ST) exhibited high strength and fatigue life compared to the other produced nanocomposites and base metal.

References


Acknowledgments

The authors acknowledge the Iraqi Ministry of Higher Education and Scientific Research for their support of this research.