Effect of heat treatment on the microstructure and properties of \textit{in-situ} Mg$_2$Si reinforced hypereutectic Al-18%Si matrix composites

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Abstract

The \textit{in situ} preparation of particle reinforced metal matrix composites (PRMMCs) can prevent the particle surface from pollution, improve the wettability of particles and matrix metals, and reduce the production cost of composites. In this paper, \textit{in situ} Mg$_2$Si reinforced hypereutectic Al-18%Si matrix composites were prepared by adding an appropriate amount of magnesium. However, the Mg$_2$Si enhanced phase often has developed dendrites, which are easy to cause stress concentration and cut apart the matrix, resulting in the decrease of the mechanical properties of the material. Therefore, in this study, necessary solution treatment and aging treatment were carried out, and the effect of heat treatment on the microstructure and properties of the prepared composites was discussed. The results showed that the \textit{in situ} Mg$_2$Si reinforced Al-18%Si matrix composites with an ideal microstructure could be prepared by adding 4% Mg. After solution treatment at 545 °C for 8 h and aging treatment at 170 ± 2 °C for 8 h, the coarse dendrites of Mg$_2$Si were broke and granulated, which improved the strength, hardness and wear resistance of the composites. Compared with the common as cast hypereutectic Al-18%Si alloy, the hardness and the strength of the prepared composites were increased by 30% and 46%, respectively. Besides, the granulation process of the \textit{in situ} Mg$_2$Si phase was explained with the Gibbs-Thomson theorem in this paper.

1. Introduction

PRMMCs are one of the most attractive materials in aviation, aerospace, automobile industry and other high-tech industries. The added reinforced particles of PRMMCs can change the microstructure of the base metals and improve or make up for the defects of the properties of the base metals [1, 2]. The common methods to prepare PRMMCs are powder metallurgy, preform impregnation, stir casting and spray co-deposition [3–6]. Onur Ertugrul et al investigated the effect of heat treatment on the microstructure and mechanical properties of Al 2024 matrix composites reinforced with Ni$_{50}$Nb$_{50}$ metallic glass particles [7]. Vineet Tirth et al studied the properties and aging parameters of aluminum matrix composites [8–10]. However, the above methods have the disadvantage of difficulty in wetting the matrix and particles due to the easily polluted surface of the added particles. Moreover, the high production cost of the above-mentioned approaches limits their development and application. The \textit{in situ} formation of reinforcement particles on the base metals in PRMMCs helps avoid the pollution of the particle surface, thus improving the wettability of particles and base metals and reducing the production cost of composites. As a result, the \textit{in situ} method has aroused great interest and becomes a research hotspot in material science. Hongyu Yang et al fabricated \textit{in situ} SiC/Al composites by the combustion synthesis and hot press consolidation technique, and characterized them [11]. CHEN Xiao et al explored the influence of Ca addition on the microstructure and mechanical properties of \textit{in situ} Mg$_2$Si/ZM5 magnesium matrix
composites [12]. Yu Huashun et al researched the microstructure and mechanical properties of Mg-Li-MgO/Mg2Si composites prepared by the reaction synthesis in liquid [13]. Hypereutectic Al–Si alloy is an ideal new type of piston alloy for automobiles, motorcycles, etc. owing to its excellent properties as diverse as small linear expansion coefficient, high dimensional stability, wear resistance, corrosion resistance, good casting performance and low casting cost. When a certain amount of Mg is added into hypereutectic Al–Si alloy melt, Mg will react with Si in the alloy to form Mg2Si, which is an ideal reinforcement phase for metal matrix composites because its density is only 1.99 kg m−3, its modulus of elasticity is high (120 GPa), and its coefficient of thermal expansion is low (CTE = 7.5 × 10−6 K−1) [14]. The in situ formation of the dispersed small-sized Mg2Si phase in the Al matrix can not only greatly elevate the strength and hardness and reduce the thermal expansion coefficient of the composites, but also promote the thermodynamic stability and good interface combination [15]. Hence, the prepared composites will be far superior to the traditional hypereutectic Al–Si alloy in the performance.

In this paper, different proportions of Mg was added into the Al–18%Si alloy to prepare in situ Mg2Si reinforced hypereutectic Al–18%Si matrix composites. Besides, the effect of the addition amount of Mg on the microstructure of the formed Mg2Si was studied. However, the in situ Mg2Si with large dendrites and shaped as Chinese characters, as well as the slender needle-shaped eutectic silicon in the alloy can easily lead to stress concentration and make the matrix to break. Consequently, the prepared materials have poor mechanical properties at room temperature and high temperature, and thus cannot meet the actual production needs [16–18]. Therefore, it is necessary to carry out in-depth research on the solution and aging treatment of the matrix composites, and study the effect of heat treatment on the microstructure and properties of the prepared composites.

2. Materials and methods

2.1. Materials
The industrial pure aluminium (containing 99.7% Al) and aluminium silicon alloy (containing 50% Si) were melted in SG2–3–10 resistance furnace, with the melting temperature controlled at 720 °C by KSW–4D–11 resistance furnace temperature controller. After reaching the set temperature, 8%, 6%, 4% and 2% Mg were added separately, and the mixtures were modified with 0.6% Sr (the amount was proved to be ideal by the previous test) meanwhile. During the test, Mg was wrapped with aluminium foil and pressed into a certain depth below the alloy liquid surface with a bell jar until it was completely melted. After the melt was degassed and refined by 0.4% C2Cl6, it was poured into the metal mold to afford ingots with a size of φ70 mm × 120 mm at the casting temperature of 700 °C. The prepared samples were numbered as a, b, c and d. The composition (mass fraction) of the samples obtained was tested by the Magix (PW2424) x-ray fluorescence spectrometer, and shown in table 1.

| Sample number | a  | b  | c  | d  |
|---------------|----|----|----|----|
| Si            | 17.63 | 18.11 | 18.72 | 17.76 |
| Mg            | 8.12 | 6.73 | 4.31 | 2.25 |
| Al            | margin | margin | margin | margin |

2.2. Test methods
A 10 mm-thick disc with the arc length of about 25 mm was cut out from each sample as a metallographic section. After pre-grinding, rough grinding, fine grinding and polishing, the metallographic section was etched with 10% HF aqueous solution, and the metallographic structure of the section was observed with Zeiss axioskop2 optical microscope. It was determined whether the in situ Mg2Si reinforced hypereutectic Al–18%Si matrix composites could be prepared by adding an appropriate amount of Mg. The phase composition of the composites with an ideal microstructure was analyzed by x-ray diffraction (XRD).

The cast samples of the prepared composites were put into the box resistance furnace for solution treatment for 4 h, 6 h and 8 h at 535 °C and 545 °C, respectively. Then, the samples were treated by water quenching at 20 °C for no more than 10 s. The obtained samples were numbered as 1, 2, 3, 4, 5 and 6. After quenching, the samples were immediately put into a drying oven (101–3 type) with air circulation for aging treatment at 170 ± 2 °C for 8 h, followed by air cooling. Subsequently, the metallographic sections were prepared, and the effect of heat treatment on the microstructure of the prepared composites was investigated by SEM.
The hypereutectic Al–Si alloy composites after heat treatment were cut and processed into tensile samples (the size is shown in figure 1), hardness samples with a size of 30 mm × 30 mm × 20 mm and wear-resistant samples with a size of 40 mm × 10 mm. The tensile strength and elongation of the alloy were measured by universal testing machine. The wear test was carried out with M-2000 wear testing machine (GCr15 steel ball) at a working pressure of 750 N and normal temperature. The test lasted for 3 min and was under a dry friction condition. During the test, the sample was fixed and rubbed by the grinding wheel. The wear performance was expressed by mass loss. The weights of the sample before and after wear were measured by the electro-optic analytical balance (with an accuracy of 0.1 mg), and the weight loss of each sample was calculated as \( \Delta m \). It must be noted that the oil stain must be completely removed, dried and weighed before and after the test. Otherwise, the residual oil stain will affect the accuracy. The hardness of the alloy was measured by HB-3000 Brinell hardness tester (ball diameter \( d = 5 \) mm, load \( P = 250 \) Kg) based on the following calculation formula:

\[
HB = \frac{2P}{\pi D(D - \sqrt{D^2 - d^2})}
\]

(1)

where \( P \) is load (Kg), \( D \) is ball diameter (mm) and \( d \) is indentation diameter (mm).

In order to improve the accuracy of the test, the experiments were carried out in triplicate and the average values of hardness, tensile strength and wear resistance were taken as the final results.

### 3. Results and discussion

#### 3.1. Preparation of in-situ Mg2Si reinforced hypereutectic Al-18%Si matrix composites

Figures 2(a)–(d) are the metallographic structures of Al-18%Si matrix composites added with 8%, 6%, 4% and 2% magnesium, respectively. In the Al-Mg-Si ternary alloy system, Al, Mg and Si constituted a pseudo binary eutectic system, of which the temperature was 595 °C and the composition was Al-8.9%Mg2Si [19, 20]. According to the ternary phase diagram of Al-Mg2Si-Si [21, 22], the near spherical white area in figure 2(a) is the primary \( \alpha \)-Al structure, the gray fibrous dense structure is eutectic silicon, the blue or black block is the primary Mg2Si phase, and there are a little irregular Chinese character-shaped or fibrous eutectic Mg2Si. The Al-18%Si matrix composites containing 8% Mg were mostly shaped as irregular and large blocks because Mg and Si proned to combine and form a large amount of fully grown Mg2Si due to the high Mg content. Only a few Mg2Si structures were shaped as Chinese characters or fibers [23].

Figure 2(b) is the microstructure of the composites added with 6% Mg. With the decrease of Mg content, the amount of primary Mg2Si in the material also declined slightly. Besides, a part of eutectic Mg2Si appeared [24]. The morphology of primary Mg2Si changed from large-scale blocks to small-scale polygons, and the eutectic Mg2Si was in the shape of Chinese characters or five star petals. It can be seen from the figure that the microstructure of the Mg2Si was close to the eutectic composition of the Al-Mg2Si pseudo binary eutectic system, but there were still some primary Mg2Si phases. It indicated that a large amount of eutectic Al-Mg2Si was generated [25]. Due to the low formation temperature of the Mg2Si phase in the pseudo eutectic structure, atoms in the solid phase were difficult to diffuse and easy to nucleate on the grain boundary. As a result, most Mg2Si either grew into Chinese character-shaped or fibrous eutectic Mg2Si in the \( \alpha \)-Al phase or at \( \alpha \)-Al phase interface, or attached to the primary Mg2Si phase to grow large. Therefore, the Mg2Si phase in the pseudo eutectic structure was much smaller than the primary Mg2Si phase.

The structure composition of Al-18%Si matrix composites containing 4% magnesium (figure 2(c)) was similar to the eutectic composition of the Al-Mg2Si pseudo binary system. The black or blue structure in the figure is the binary eutectic Mg2Si, and the more complete network structure is \((\alpha \text{-Al} + \text{Mg}_2\text{Si} + \text{Si})\) ternary eutectic. The eutectic Mg2Si was shaped as developed Chinese characters, dendrites, or fishbone. Under the actual non-equilibrium solidification condition, a large number of binary eutectic structures \((\alpha \text{-Al} + \text{Mg}_2\text{Si})\) were formed, and the binary eutectic Mg2Si was pushed to the grain boundary by the binary eutectic \( \alpha \)-Al that
attached to the primary \( \alpha \)-Al to grow \([26, 27]\). The formation of eutectic structures was also affected by diffusion. With the decrease of the crystallization temperature, the diffusion resistance of Mg and Si elements increased. Under the condition of non-equilibrium solidification, most of the binary eutectic structures did not have time to grow big, and the first precipitated Mg\(_2\)Si particles tends to grow slowly. Therefore, the primary Mg\(_2\)Si structure in figure 2(c) was relatively small, and the eutectic Mg\(_2\)Si was in the shape of Chinese characters, fishbone or dendrites. Such a structure was deemed as ideal for \textit{in situ} Mg\(_2\)Si reinforced hypereutectic Al-18\%Si matrix composites.

Figure 2(d) shows the microstructure of the composites containing 2\% Mg. Due to the low Mg content, the microstructure was composed of the primary \( \alpha \)-Al, eutectic silicon and a small amount of primary silicon. A very small number of Mg\(_2\)Si enhanced phases were scattered in the shape of strips.

According to the phase diagram of Mg-Si binary alloy at the equilibrium state \([28]\), the eutectic reaction occurred at 638.8 \( ^\circ \)C, \( L \rightarrow \alpha (\text{Mg}) + \text{Mg}_2\text{Si} \). The Si content of eutectic alloy was 1.34\%, and the contents of two phases in the eutectic alloy were 95.9\% and 4.1\%, respectively. In hypereutectic Al-18\%Si matrix composites, Si content was more than 1.34\%, so the primary phase was Mg\(_2\)Si. The eutectic reaction occurred when the temperature dropped to 638.8 \( ^\circ \)C. Combined with the microstructure shown in figure 2, the Mg\(_2\)Si phase formed by binary eutectic and ternary eutectic reactions was in the shape of irregular Chinese characters, and the eutectic \((\alpha - \text{Al} + \text{Mg}_2\text{Si} + \text{Si})\) generated in the ternary eutectic reaction was distributed as net. In the process of crystallization, the Mg\(_2\)Si phase was crystallized before the initiation of the binary eutectic reaction \( L \rightarrow \alpha (\text{Al}) + \text{Mg}_2\text{Si} \) and the ternary eutectic reaction \((\alpha - \text{Al} + \text{Mg}_2\text{Si} + \text{Si})\). The primary Mg\(_2\)Si phase was block- or polygon-shaped, while the Mg\(_2\)Si phase produced by binary eutectic and ternary eutectic reactions was like irregular Chinese characters or fishbone. In the composites, with the increase of magnesium content, both the quantity and size of the Mg\(_2\)Si phase increased. When 4\% Mg was added, the structure composition was similar to the eutectic composition of the Al-Mg\(_2\)Si pseudo binary eutectic system. In this case, fine primary Mg\(_2\)Si structures were formed, and the eutectic Mg\(_2\)Si was in the shape of Chinese characters, fishbone or dendrites. Such a structure was considered as ideal for the composites. The XRD of the composites with an ideal microstructure is shown in figure 3.

Figure 2. The microstructure of \textit{in situ} Mg\(_2\)Si reinforced hypereutectic Al-18\%Si matrix composites (a) 8\% magnesium (b) 6\% magnesium (c) 4\% magnesium (d) 2\% magnesium.
3.2. Microstructure after heat treatment

The metallographic structure after different heat treatments is shown in figure 4. After heat treatment, the microstructure of the alloy changed greatly. The primary Si and eutectic Si became more fine, blunt and uniform. Some of the eutectic Si was spherical, vermicular and grainy. Especially, with the prolongation of the treatment time, the morphology of coarse prismatic dendritic Mg2Si gradually changed. The sharp corners of the Mg2Si phase began to be passivated after 4 h of heat treatment (figures 4(a) and (b)). When treated for 6 h, most dendrites were dissolved, and a few bald branches and some passivated granular Mg2Si phases were left (figures 4(c) and (d)). A part of these passivated granular Mg2Si phases were generated from the original developed dendritic Mg2Si phases, and the other part were formed by the rounding of dissolved prismatic dendrites after breaking away from the primary axis or secondary axis. After 8 h of heat preservation, the original coarse prismatic dendrites no longer existed, and the Mg2Si phases were smaller, mostly granular and distributed uniformly (figures 4(e) and (f)). Under the same solution temperature, the longer the solution time, the better the heat treatment effect. It can be concluded from figure 4 that the heat treatment effect after 8 h of solution treatment was obviously better than that after 6 h of solution treatment, and the effect of 4 h of solution treatment was not satisfactory. The effect of heat treatment on the same material also varied with solution temperature. When other conditions were the same, the microstructure was slightly better at the solution temperature of 545 °C than that at 535 °C.

3.3. Mechanism analysis

In the composites, Si atoms could only spread through the Mg2Si-α-Al interface [29]. Jin Yunxue et al [30] explained the melting and spheroidizing processes of TiC dendrites under the heat treatment by using the microchemical composition inhomogeneity caused by Gibbs-Thomson theorem and the theory of colloidal equilibrium, and established the melting model. According to Gibbs-Thomson theorem, the curvature of the dendrite surface fluctuated due to the variations of the temperature field and the solute field, and the solute concentration in the matrix section with large curvature was higher than that in other parts. The concentration of silicon in prismatic dendrites and the Mg2Si phase with large curvature of the composites can be expressed by the following formula [31]:

\[
\ln \frac{C_{\alpha}(r)}{C_{\alpha}(\infty)} = \frac{2\sigma V_B}{k_B T} r
\]

where \(C_{\alpha}(r)\) is the concentration of silicon at the matrix part with curvature radius of \(r\), \(C_{\alpha}(\infty)\) is the concentration of silicon at the flat interface, \(\sigma\) is the surface tension, \(V_B\) is the volume of silicon atoms, \(T\) is the absolute temperature, and \(k_B\) is the shape-related coefficient. According to Formula 2, the smaller the curvature radius, the greater the silicon concentration.

The melting and spheroidizing processes of Mg2Si dendrites during the heat treatment of the composites are shown in figure 5. A silicon concentration gradient was formed between Mg2Si phases with high and low curvature. Since the Mg2Si phase itself was a prismatic dendrite, silicon with increased activity moved from the high concentration area with high curvature to the low concentration flat interface when the alloy was heated to
Figure 4. Microstructure of in situ Mg$_2$Si reinforced hypereutectic Al-18%Si matrix composites after different heat treatments (a) 535 °C × 4 h solution treatment, 170 ± 2 °C × 8 h aging treatment (b) 545 °C × 4 h solution treatment, 170 ± 2 °C × 8 h aging treatment (c) 535 °C × 6 h solution treatment, 170 ± 2 °C × 8 h aging treatment (d) 545 °C × 6 h solution treatment, 170 ± 2 °C × 8 h aging treatment (e) 535 °C × 8 h solution treatment, 170 ± 2 °C × 8 h aging treatment (f) 545 °C × 8 h solution treatment, 170 ± 2 °C × 8 h aging treatment.

Figure 5. The dissolution and spheroidizing processes of Mg$_2$Si dendrites.
535 °C, which destroyed the local silicon concentration balance. In order to restore the balance, Mg2Si in the area with small curvature dissolved to supplement the deficiency of silicon concentration, while Mg2Si might precipitate in the α-Al matrix at the flat interface due to the supersaturation of silicon. This process was repeated continuously until the region with large curvature was dissolved. Therefore, the Mg2Si phase first dissolved and passivated at the sharp corner, and the polygonal massive Mg2Si phase in the structure first spheroidized (figures 4(a) and (b)). As the Mg2Si phase had pits at the root of the secondary or tertiary dendrite arm, the curvature was large, and the solid solution in contact with the pit wall had high solubility. With the extension of the treatment time, silicon diffused and the prismatic dendrites precipitated near the flat interface in the form of Mg2Si. In order to maintain this type of metastable equilibrium, the Mg2Si phase sharp angles on both sides of the pit gradually dissolved, which increased the radius of curvature and destroyed the equilibrium of the surface tension of the Mg2Si phase. For maintaining the balance of surface tension, the Mg2Si phase was dissolved continuously to deepen the pit until the entire ‘neck’ was broken. As there must be a pit in the broken ‘branch’, the Mg2Si phase sharp angles were dissolved, followed by the Mg2Si phase precipitation and growth at the flat interface and Mg2Si spheroidization successively. Ultimately, granular Mg2Si with uniform curvature were formed (figures 4(e) and (f)).

3.4. Properties
Table 2 shows the properties of the prepared composites after different heat treatments. The composites were treated by solid solution at 545 °C for 8 h, water quenched, aged at 170 ± 2 °C for 8 h, and then air cooled. The tensile strength and Brinell hardness of the composites were 350.2 Mpa and 146.5, respectively, 46.2% and 30.1% higher than those of the Mg2Si reinforced hypereutectic Al–18%Si.

It can be seen from table 2 that the heat treatment tremendously improved the strength, the hardness and wear resistance of the prepared composites, but the plasticity slightly decreased. Through the heat treatment, the solution structure was improved, the influence of coarse Mg2Si phases was eliminated, and more reinforcement phases precipitated. During the solution treatment, the solute elements in the Al–Si alloy dissolved in the lattice of the solvent, and formed the solid solution after cooling, thus lowering the strength and improving the plasticity of the material. During the aging treatment, the solute elements precipitated from the solid solution, segregated and formed the hardening region, which increased the strength and reduced the plasticity of the material.

During the test, it was also found that too long residence time at room temperature after quenching of the alloy significantly reduced the strengthening effect of artificial aging. The relationship between the strength after aging and the aging temperature is shown in figure 6. The strength gradually increased first and then decreased as the aging temperature increased. Under the condition of the same aging time, the ideal aging temperature range of hypereutectic Al–Si alloy was shown to be 160–180 °C in previous research. Therefore, the aging treatment was carried out at 170 °C immediately after quenching.

In this paper, the heat treatment followed the T6 state, i.e. solid solution + complete artificial aging. In the process of solution treatment, the reinforcement phase was completely dissolved in the solid solution, and the supersaturated solid solution was obtained after quenching. From the thermodynamics point of view, the supersaturated solid solution was an unstable phase, which, therefore, precipitated in the subsequent aging process at 170 ± 2 °C. Meanwhile, the brittle phases such as Mg2Si were completely dissolved, greatly improving the hardness and strength of the alloy.

Through the above and previous experiments, we have successfully prepared in situ Mg2Si reinforced hypereutectic Al–Si alloy composites and summarized the reasonable heat treatment process. We are trying to prepare hypoeutectic Al–Si alloy composites and have made some progress. These research results can be applied to the actual industrial production as appropriate. Hypereutectic alloy is applicable to the production of wear-resistant parts such as pistons and cylinders. Hypoeutectic alloy is employed to automobile wheel hubs and other parts to improve the performance of the alloy. To prepare similar composites with aluminum–magnesium alloy, magnesium alloy and other alloys can also markedly improve the performance of existing alloys.

4. Conclusions

(1) When 4% magnesium is added to hypereutectic Al–18%Si alloy, the in situ Mg2Si shows a shape of developed Chinese characters, dendrites, fishbone or even five star petals. Such a structure is an ideal reinforcement phase. To summarize, in situ Mg2Si reinforced hypereutectic Al–18%Si matrix composites can be prepared by adding 4% Mg.

(2) After solution treatment at 545 °C for 8 h, water quenching, aging treatment at 170 ± 2 °C for 8 h, and air cooling, large prismatic dendritic Mg2Si is dissolved and granulated, improving the strength, hardness and wear resistance of the in situ Mg2Si reinforced hypereutectic Al–18%Si matrix composites. Compared with
Table 2. The properties of in situ Mg2Si reinforced hypereutectic Al-18%Si matrix composites after different treatments.

| Sample number | Solution temperature (°C) | Solution time (h) | Aging temperature and time | Brinell hardness HB | Tensile strength $\sigma_b$ (MPa) | Elongation $\delta$ (%) | Wear loss $\Delta m$ (g) |
|---------------|---------------------------|-------------------|----------------------------|---------------------|---------------------------------|------------------------|--------------------------|
| 1             | 535                       | 4                 | $170 \pm 2^\circ C \times 8$ h | 109.8               | 282.2                           | 1.93                   | 0.056                    |
| 2             | 535                       | 6                 | $170 \pm 2^\circ C \times 8$ h | 113.7               | 295.6                           | 1.87                   | 0.052                    |
| 3             | 535                       | 8                 | $170 \pm 2^\circ C \times 8$ h | 136.2               | 324.1                           | 1.81                   | 0.046                    |
| 4             | 545                       | 4                 | $170 \pm 2^\circ C \times 8$ h | 124.4               | 305.3                           | 1.89                   | 0.050                    |
| 5             | 545                       | 6                 | $170 \pm 2^\circ C \times 8$ h | 138.3               | 328.5                           | 1.82                   | 0.039                    |
| 6             | 545                       | 8                 | $170 \pm 2^\circ C \times 8$ h | 146.5               | 350.2                           | 1.76                   | 0.036                    |
ordinary as cast hypereutectic Al-18%Si alloy, the hardness and strength of \textit{in situ} Mg$_2$Si reinforced hypereutectic Al-18%Si matrix composites were higher by 30% and 46%, respectively.

3. According to Gibbs-Thomson theorem, a higher Si concentration in the solid solution near the sharp angle of Mg$_2$Si phases and a lower Si concentration in the solid solution near the flat interface cause the diffusion of Si at high temperature, resulting in the constant dissolution of Mg$_2$Si at the sharp angle, and the continuous precipitation of Mg$_2$Si at the flat interface. Consequently, a granular or spherical Mg$_2$Si reinforcement phase with uniform curvature is generated.

4. In the heat treatment process of the prepared composites, the long residence time at room temperature after quenching significantly reduces the strengthening effect of artificial aging. As the aging temperature increases, the strength increases gradually and then decreases after reaching the maximum value.

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**Figure 6.** The relationship between the strength after aging and the aging temperature.
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