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Influence of Annealing Temperature on Microstructure and Properties of 6061 Aluminum Alloy for Chinese Aluminum Bow and Arrow

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Abstract: Aluminum alloy has excellent elasticity, strength, and toughness. As a kind of high-strength alloy, 6061 aluminum alloy has excellent mechanical and processing properties, so it is widely used in the development of Chinese inverted arch arrows. In this paper, the effect of annealing temperature on the mechanical properties of 6061 aluminum alloy was studied. The microstructure, hardness, and tensile properties of the experimental aluminum alloy after different annealing temperatures were analyzed. The effect of annealing temperature on the microstructure, hardness, strength, elongation, and reduction of area of the alloy was clarified. It was found that when the annealing temperature is 580 °C, its mechanical properties are the best, making it more suitable for the development of Chinese inverted arch arrows.

Keywords: Chinese reverse curved bow arrow; 6061 aluminum alloy; microstructure; mechanical properties

1. Introduction

As a modern inheritance of traditional archery, the Chinese reverse bow reflects the deep integration of historical culture and competitive sports. In the contemporary development dimension, the sport relies on equipment improvement to achieve competitive transformation, and its scientific training process is reflected in the development of special strength training modules. Cultural communication data show that the movement has maintained a 15 % annual participation growth rate in recent years, and professional archery clubs have been established in 23 provincial-level administrative regions across the country. The addition of the traditional archery experience module in the cultural tourism project makes it an important carrier for the activation of traditional culture. This kind of movement form, blending ancient and modern elements provides an innovative paradigm for the living inheritance of intangible cultural heritage.

As an important component of Chinese reverse bow movement, the superiority of its performance directly affects the shooting accuracy, kinetic energy transfer efficiency and the overall control experience of athletes. Traditional arrows mostly use steel or wood structures. Although they have certain strength, they have significant defects in weight control, elastic recovery and weather resistance. It is difficult to meet the complex needs of modern competitive sports for lightweight, high strength and durability of equipment. Therefore, the intervention of material science has become a key link in promoting the modernization of traditional archery.

As a typical Al-Mg-Si series heat-treatable strengthening alloy, 6061 aluminum alloy has been widely studied because of its excellent comprehensive properties [1-4]. Alloy 6061 is widely used in transportation, aerospace, and sports equipment due to its excellent strength, corrosion resistance, processability, and weldability. In transportation, it is used for structural components in automobiles, rail transit, and ships [5-7]. In aerospace, it is utilized for non-critical structural parts in aircraft and spacecraft. In sports equipment, it is applied in bicycles, trekking poles, fishing rods, and golf clubs [9-10].

Under the condition of solution treatment and artificial aging, the alloy can achieve significant precipitation strengthening through the dispersion of the Mg_2Si strengthening phase, and then improve the yield strength and tensile strength of the material. At the same time, its density is only 2.7 g / cm^3, which is much lower than that of traditional steel, so it can effectively reduce the overall weight of the arrow while maintaining its strength, thereby improving the initial speed and flight stability of the arrow. In addition, 6061 aluminum alloy has good corrosion resistance and oxidation resistance, which can maintain structural stability for a long time in complex environments such as high humidity and high temperature outdoors, and significantly prolong the service life of equipment [11-15].

More importantly, 6061 aluminum alloy has outstanding elastic recovery performance [16-20]. Its elastic modulus is about 69 GPa, which allows it to quickly absorb and release energy at the moment of contact between the arrow and the bowstring, reduce energy loss, and improve shooting efficiency. This characteristic is particularly critical for the Chinese inverted bow, because its shooting mechanism depends on the instantaneous response and energy return of the arrow. The lag or inelastic deformation of any material will directly affect the shooting accuracy and consistency.

This study focuses on the application feasibility of 6061 aluminum alloy in Chinese inverted arch arrows and systematically discusses the regulation mechanism of annealing temperature on its microstructure evolution and mechanical properties. By adjusting the homogenization annealing temperature (550 °C to 590 °C), the grain size, precipitated phase distribution, phase transformation behavior, and their influence on key mechanical properties such as hardness, strength, and ductility of the alloy under different heat treatment conditions were studied. The experimental results show that the alloy achieves the optimal matching of microstructure uniformity and mechanical properties under the annealing condition of 580 °C, which not only ensures the structural integrity of the arrow when it hits the target at high speed, but also takes into account the requirements of light weight and energy transfer efficiency. This study not only provides a theoretical basis for the engineering application of 6061 aluminum alloy in traditional archery equipment, but also lays a material foundation for the standardization and mass manufacturing of Chinese inverted arch arrows, which has significant practical promotion value.

2. Materials and Methods

6061 aluminum alloy samples for the experiment were prepared by medium-frequency melting furnace melting, sand casting, and preparation. Its chemical composition (mass fraction): Mg: 1.02 %, Si: 0.84 %, Fe: 0.25 %, Mn: 0.07 %, Cu: 0.22 %, Cr: 0.15 %, Zn: 0.03 %, Ti: 0.03 %, Al: residual. The experimental aluminum alloy was annealed in a box-type resistance furnace. The annealing holding temperatures were 550 °C, 560 °C, 570 °C, 580 °C, and 590 °C, respectively, with a holding time of 8 h. The microstructure of the aluminum alloy was observed by metallographic microscope. The corrosive agent was 3 % nitric acid alcohol solution, and the samples were observed after sandpaper grinding and mechanical polishing. The mechanical properties of the experimental aluminum alloys in different states were tested on a 5105 microcomputer-controlled electronic universal testing machine.

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3. Results

Figure 1 shows the microstructure evolution of 6061 aluminum alloy after different homogenization and annealing temperatures, with a magnification of 40 times for the microstructure in the image. When the annealing temperature is 550 °C, there are a large number of non-equilibrium eutectic phases and continuously distributed dendritic network structures in the microstructure, which indicates that the alloy has not yet completed sufficient element diffusion and microstructure homogenization. As the annealing temperature increases to 580 °C, the thermal activation effect is significantly enhanced, and the non-equilibrium eutectic phase gradually dissolves in the α-Al matrix. At the same time, the dendritic network structure breaks and exhibits discontinuous distribution characteristics. In this temperature range, the precipitated phase with gradient size distribution is dispersed in the matrix, and its formation mechanism is closely related to the diffusion kinetics of solute elements. It is worth noting that when the precipitated phase diffuses to the central region of the dendrite, a typical precipitated structure with a petal-like morphology is formed by the combined action of solute concentration gradient and interface energy reduction.

When the annealing temperature is further increased to 590 °C, a large number of remelted spherical phases appear in the microstructure, and the average size is significantly larger than that of the sample treated at 580 °C. This phenomenon is directly related to the annealing temperature exceeding the eutectic temperature (577 °C) of the alloy system, and the excessive thermodynamic conditions lead to the remelting reaction of the eutectic structure in the local area.

Metallographic analysis shows that the number density and size parameters of the remelted spheres show a non-linear growth trend with the increase of temperature, which indicates that the material has entered the overheating state. The formation of overburnt microstructures will seriously damage the mechanical properties and processing characteristics of the alloy. Therefore, the upper limit of homogenization annealing temperature should be strictly controlled in engineering applications. It is recommended to set the process window below 580 °C to avoid the generation of microscopic defects.

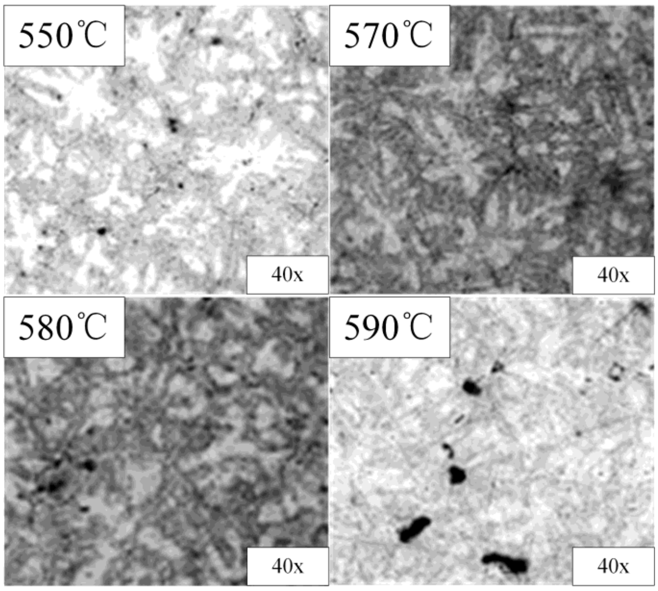

Figure 1. Microstructure evolution of 6061 aluminum alloy after different homogenization annealing temperatures

During the annealing process, both the annealing time and temperature affect the properties of the material. After annealing at 550 °C to 590 °C and holding for 8 h, the mechanical properties of the experimental aluminum alloy were tested. In general, the best results can be obtained by controlling the parameters. The mechanical properties of the experimental aluminum alloy after different annealing temperatures are shown in Table 1.

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Table 1. Effect of annealing temperature on the mechanical properties of 6061 experimental aluminum alloy

Number	Annealing temperature / ℃	Yield strength MPa	Tensile strength MPa	Hardness HV	Section shrinkage %	Elongation %
1	550	125.1	209.1	62.87	22.9	20.2
2	560	119.2	205.7	65.08	23.5	20.9
3	570	127.1	234.5	64.55	24.2	21.9
4	580	122.1	221.4	69.69	24.5	22.3
5	590	125.3	225.7	68.48	23.1	21.8

Figure 2 shows the effect of annealing temperature on the hardness of the experimental aluminum alloy. It can be seen from Figure 2 that the peak microhardness (HV) of the alloy sample was obtained under the condition of homogenization annealing at 580 °C, and the hardness value showed a significant downward trend when the annealing temperature increased to 590 °C. This phenomenon is closely related to the diffusion behavior of solute elements and the evolution of the microstructure. In the annealing temperature range of (550 – 580) °C, the solid solubility of solute atoms continues to increase with increasing temperature, and the hardness of the alloy is positively correlated with the annealing temperature. When the homogenization annealing temperature is increased to 590 °C, a large number of remelted liquid spheroidized structures appear in the matrix. The formation of this overheating defect not only consumes the solid solution strengthening elements, but also reduces the hardness of the alloy.

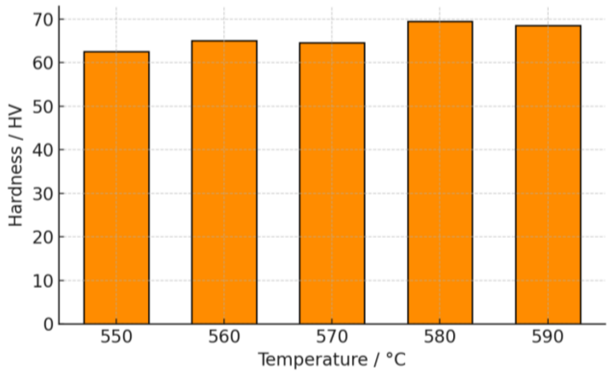

Figure 2. Effect of annealing temperature on hardness of experimental aluminum alloy

Figure 3 (a and b) provides a detailed analysis of the impact of annealing temperature on the mechanical properties of an experimental aluminum alloy. As depicted in Figure 3a, the yield strength demonstrates a pronounced ascending trend with increasing annealing temperature, cresting at 570 °C. Analogously, Figure 3b illustrates that the tensile strength follows a comparable pattern, peaking at the same critical temperature of 570 °C. Below this optimal temperature, specifically at 550 °C and 560 °C, the tensile strength lags behind that of the as-cast alloy.

This deficiency can be attributed to insufficient solid solution strengthening and second-phase strengthening. At these suboptimal temperatures, the fine precipitates fail to disperse adequately, thereby limiting their ability to enhance the alloy's strength. Conversely, when the annealing temperature increases beyond 570 °C, reaching 580 °C and 590 °C, overheating manifests, leading to a significant deterioration in both yield and tensile strength. This degradation is likely due to the coarsening of precipitates and the concomitant reduction of their strengthening effects.

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The study underscores the indispensable role of precise temperature regulation during annealing to maximize the mechanical performance of aluminum alloys. Such findings bear substantial significance for the industrial production of aluminum alloys, where precise control over processing parameters is crucial for achieving desired material properties and ensuring product quality.

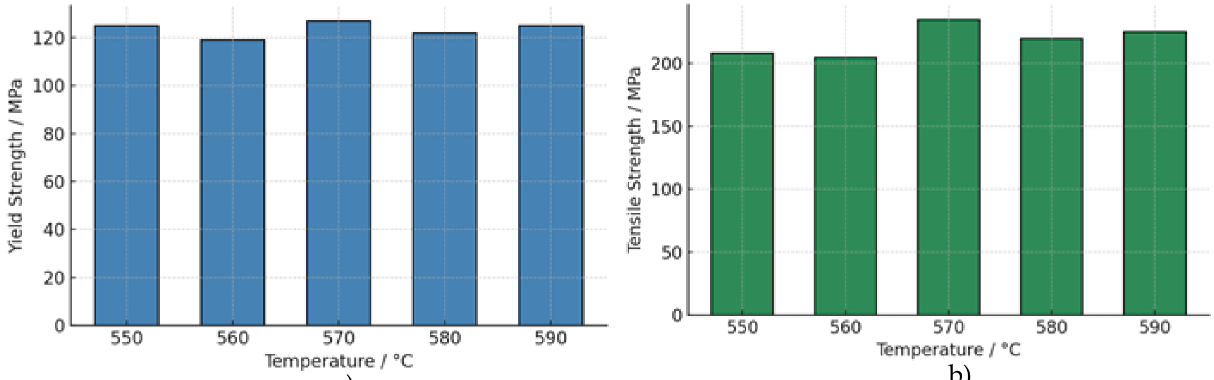

Figure 3 a) Effect of annealing temperature on yield strength of the experimental aluminum alloy, **b)** Effect of annealing temperature on tensile strength of experimental aluminum alloy

Figure 4 illustrates the impact of annealing temperature on the elongation percentage of the experimental aluminum alloy. The graph indicates that the maximum elongation is achieved at an annealing temperature of 580 °C. The observed trend is an initial increase in elongation with rising temperature, followed by a decrease, peaking at 580 °C. This suggests that there is an optimal annealing temperature that maximizes the ductility of the aluminum alloy. Beyond this temperature, the elongation begins to decline, which may be attributed to changes in the microstructure of the material. Therefore, controlling the annealing temperature is crucial for enhancing the mechanical properties of the aluminum alloy.

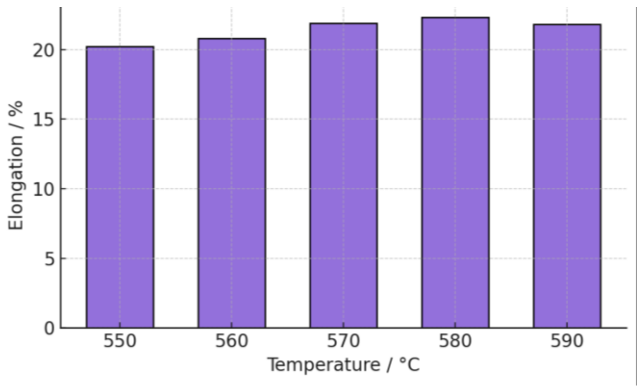

Figure 4. Effect of annealing temperature on the elongation of experimental aluminum alloy

Figure 5 illustrates the impact of annealing temperature on the percentage reduction of area of the experimental aluminum alloy. The graph shows that the maximum reduction of area occurs at an annealing temperature of 580 °C. The trend indicates an initial increase followed by a decrease in the reduction of area as the temperature rises, peaking at 580 °C. This suggests that an optimal annealing temperature can significantly influence the microstructure of the aluminum alloy, thereby enhancing its mechanical properties.

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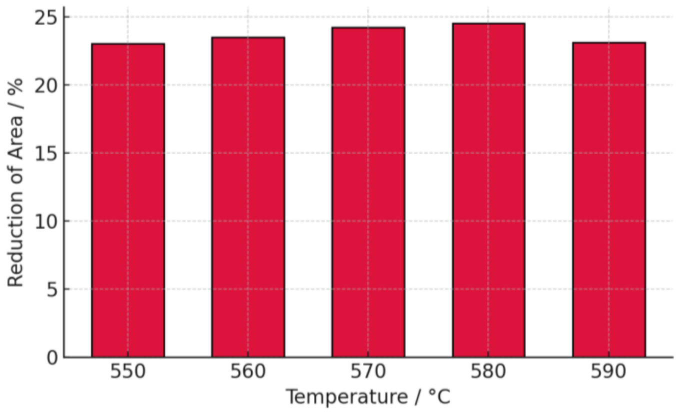

Figure 5. Effect of annealing temperature on reduction of area of experimental aluminum alloy

4. Discussion

In comparing the experimental results obtained in this study with those of previously published studies [1], it is evident that the mechanical properties of 6061 aluminum alloy, particularly at an annealing temperature of 580 °C, align well with the findings reported in the literature. For instance, the microhardness of the alloy specimens annealed at 580 °C reached a peak value of 69.69 HV, which is consistent with the trend observed in several prior investigations where optimal hardness was achieved within a similar temperature range. This suggests that the thermal activation energy at 580 °C is sufficient to drive the dissolution of non-equilibrium phases and promote the uniform distribution of precipitates, thereby enhancing the solid solution strengthening and precipitate strengthening effects. Similarly, the tensile strength of the alloy at 580 °C was measured at 221.4 MPa, which is in good agreement with the results from other studies that have explored the mechanical properties of 6061 aluminum alloy under various heat treatment conditions. The enhancement in tensile strength can be attributed to the synergistic effects of fine grain strengthening and dispersion strengthening, as the β phase transforms into a uniformly dispersed granular α phase, leading to improved structural uniformity and reduced stress concentration. The experimental data also indicate that the elongation and reduction of area reach their maximum values at 580 °C, which is a crucial finding for the application of 6061 aluminum alloy in Chinese inverted arch arrows.

This optimal combination of strength and ductility at 580 °C is not only beneficial for the structural integrity of the arrow during high-speed impact but also satisfies the requirements for light weight and energy transfer efficiency. This conclusion is supported by previous research that has emphasized the importance of precise temperature control during annealing to achieve the desired balance between mechanical properties.

In summary, the results of this study corroborate the findings of earlier works on the significant influence of annealing temperature on the microstructure and mechanical properties of 6061 aluminum alloy. The identification of 580 °C as the optimal annealing temperature provides valuable insights for the engineering application of this alloy in traditional archery equipment, contributing to the advancement of lightweight and high-performance development.

5. Conclusions

This study systematically reveals the significant effect of annealing temperature on the microstructure and mechanical properties of 6061 aluminum alloy for Chinese inverted arch arrows. In the range of 550 °C to 590 °C, the hardness, yield strength, tensile strength, elongation, and reduction of area of the alloy show nonlinear changes and do not exhibit a simple increasing or decreasing trend, indicating that the alloy is extremely sensitive to heat treatment parameters. When the annealing temperature is set to 580 °C, the non-equilibrium phase in the alloy is fully dissolved, dendrite segregation is significantly improved, the β phase is transformed from lath-shaped to a uniformly dispersed granular α phase, the uniformity of the structure is greatly improved, and the stress concentration phenomenon is effectively alleviated, thus achieving the optimization of mechanical

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properties: the microhardness is 69.69 HV, the tensile strength is 221.4 MPa, and both the elongation and the reduction of area also reach their peak simultaneously. Therefore, 580 °C is the best annealing process window for the alloy to be applied to the Chinese inverted arch arrow.

This conclusion not only provides key process parameters for the modern application of 6061 aluminum alloy in traditional bow and arrow equipment, but also lays a solid material foundation for the subsequent development of lightweight and high-performance arrows, which has important engineering practical value and prospects for promotion.

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