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Influence of heat treatment on tribological behaviors of novel wrought aluminum bronze ①

ZHANG Wei-wen(张卫文), NGAI Tungwai Leo(倪东惠), XIA Wei(夏 伟), QIU Cheng(邱 诚), CHEN Wei-ping(陈维平)

(College of Mechanical Engineering, South China University of Technology, Guangzhou 510640, China)

[Abstract] Influence of heat treatment on mechanical properties and tribological behaviors of Ti and B modified wrought aluminum bronze were studied. The results show that different strength and plasticity combination of the alloy after solution treatment can be obtained by adjusting the ageing temperature. When aged at 450 ℃, the tensile strength σ_b, yield strength $\sigma_{0.2}$, elongation δ and hardness of the alloy are 1 050 MPa, 780 MPa, 4.5%, HB282, respectively. When aged at 650 ℃, those of the alloy are 905 MPa, 600 MPa, 12%, HB232, respectively. Under boundary lubrication condition with pressure above 22.2 MPa, alloy with low temperature ageing has the best wear property. However, under the condition involving impact or shock loading, alloy with high temperature ageing is preferable. If the load is not heavy, the alloy under extrusion state is favorable for wear-resisting parts.

[Key words] aluminum bronze; heat treatment; tribological behaviors

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1 INTRODUCTION

Aluminum bronze possesses excellent physical, mechanical and tribological properties. It is available for making wear-resisting and abrasion-resisting parts. Bronze with Al content about 10% (mass fraction) has the best comprehensive properties and the widest applications in aluminum bronze. Typical alloys are QAl10-3-1.5 and QAl10-4-4. Tribological behaviors of aluminum bronze have been intensively investigated since 1970s. Some investigations were focused on the tribological behaviors of the alloy with steel as the counterpart[1~4]. Some researches were focused on the effects of adhesion and stack faults energy caused by residual stress[5, 6]. Some were emphasized on the effects of hardness on the wear of aluminum bronze[7, 8]. However, the study of the influence of the basic characteristics of aluminum bronze such as alloy composition, constituent, ratio of hard phase to soft phase and grain size on the tribological behaviors of aluminum bronze is relatively inadequate.

Based on the alloy QAl10-3-1.5, the authors developed a high-strength wear-resisting aluminum bronze with a code name KK, and systematically analyzed the influence of the microstructure on the tribological behaviors[9~11]. In order to promote the load endurance ability of KK under the lubricated condition and broaden its application fields, a novel wrought aluminum bronze based on KK and a commercial alloy QAl10-4-4 was developed. The purpose of this study is to investigate the tribological behaviors of the alloy under different heat treatment condition. This study will offer a useful foundation for proper selection of heat treatment processing according to the working conditions of the alloy.

2 EXPERIMENTAL

Composition range of the developed alloy is (in mass fraction) 9% ~ 11% Al, 3% ~ 5% Fe, 3% ~ 5% Ni, 0.5% ~ 2.0% Mn, with certain amounts of titanium and boron as modification agents and the balance is copper. The content of alloying elements examined by wet chemical analysis are 10.1% Al, 4.4% Fe, 4.6% Ni and 1.1% Mn. The alloy was prepared by melting commercial pure copper, manganese, aluminum, electrolytic nickel and master alloys in an induction furnace and then pouring into permanent mould of d 172 mm × 200 mm. The castings were extruded to d 20 mm rods at 850 ℃. The extrusion ratio was 37∶1. Samples for heat treatment were cut from the extruded rods. The heat treatment processing was solutionization and artificial ageing, which was carried out in an electric furnace. The temperature for solution treatment was 900 ± 10 ℃, the holding time was 1 h, and water at room temperature was used as the quenching media. Artificial ageing temperature was varying from 400 ℃ to 700 ℃ with the same holding time of 1 h. In this study, two ageing temperatures identified as low temperature ageing (450 ℃) and high temperature ageing (650 ℃) were emphatically investigated.

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Tensile properties and bulk hardness of the alloys were measured according to Chinese mechanical testing standards. The diameter of the tensile specimens was 10 mm. The mechanical properties of the alloy were measured using SANS CMT5105 electronic mechanical tester and HB-3000B hardness tester. An MM-200 block-on-ring friction tester was used for measuring the friction and wear behaviors of experimental alloys under lubricated condition. The block sample was the developed alloy and the ring sample was made of quenched GCr15 steel with a hardness of HRC 55. The lubricant was common engine oil. The sliding velocity was 0.877 m/s. The duration for the experiment was set to 1 h and therefore the total sliding distance was about 3 157 m. All data reported in this study were average values taken from at least three separate measurements.

PHILIPS XL-30FEG scanning electron microscopy with energy dispersive spectroscopy (EDS) was used to analyze the microstructures, fracture and wear surface of the samples.

3 RESULTS AND ANALYSIS

3.1 Mechanical properties

Mechanical properties of the alloy in different states such as extrusion, low temperature ageing and high temperature ageing are shown in Table 1. It can be seen from the table that different strength and elongation combination can be obtained by varying the ageing temperature. For extrusion state, the strength of the alloy is the lowest, but the elongation is the highest. For low temperature ageing, the tensile strength and yield strength of the alloy are 28.4% and 77.3%, respectively, higher than that of the extrusion state, but the elongation is only one-fourth of that of the extrusion state. For high temperature ageing, the tensile strength and yield strength of the alloy are 11.7% and 36.4%, respectively, higher than that of the extrusion state, and elongation is 33.3% lower than that of the extrusion state. So it can be concluded that high temperature aged alloy has the best overall mechanical properties.

3.2 Friction and wear behaviors

Fig. 1 shows the variation of the friction and wear behaviors of experimental alloys. It can be seen that the friction coefficients of the alloy increase with increasing load. On the condition of low load, the difference in the coefficients is very little. With the increase of the load, the anti-friction property of the low temperature aged alloy is the best and that of the high temperature aged alloy is the worst. As for the wear resistance, there is no obvious difference for the three states when the load is light; when the load is heavy enough such as 600 N (The pressure is no less than 22.2 MPa), the wear resistance of the extrusion alloy is obviously worse than that of the heat-treated alloy. The low temperature aged alloy has the best wear resistance and the alloy of high temperature ageing is a little worse than that of the low temperature aged alloy.

Table 1 Mechanical properties of alloys

Ageing temperature	Tensile strength σ_b/MPa	Yield strength $\sigma_{0.2}$/MPa	Elongation δ/%	Brinell hardness (HB)
Extrusion state	810	440	18	204
Low temperature ageing(450 ℃)	1 050	780	4.5	282
High temperature ageing(650 ℃)	905	600	12	232

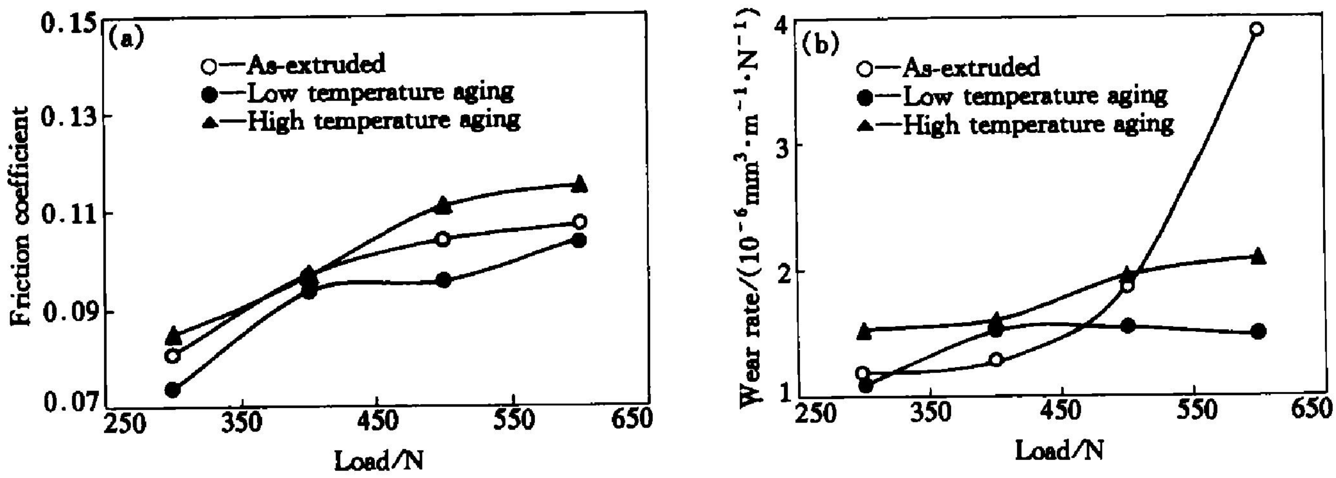

Fig. 1 Tribological behaviors of experimental alloys
(a) —Friction coefficient against load; (b) —Wear rate against load

3.3 Microstructures

Fig. 2(a) shows the micrograph of the alloy under the extrusion state, which is characterized by α-matrix and κ phases. α phase is a copper-based substitutional solid solution and κ phases are basically Fe-rich and Ni-rich intermetallic compounds with four different types named κ_{I}, κ_{II}, κ_{III}, and κ_{IV}. Under normal casting conditions, the κ_{I} precipitates have a dendritic morphology, which can only be observed in the alloy containing a higher iron content (relative to Ni). The κ_{II}, which also has a dendritic morphology, has a composition based on Fe_3Al and DO_3 structure. The κ_{III} is the product of eutectoidal decomposition and has a lamellar or globular morphology based on NiAl and κ_{IV} forms as relatively small equiaxed precipitates in the α-matrix[12, 13]. The studied alloy was extruded at 850 ℃. The stable β phase will appear in the alloy at this temperature according to the phase diagram[12]. After extrusion, the stable β phase will transform into $\alpha+\kappa_{III}$ if the cooling rate is not very slow[13]. From Fig. 2(a), it can be seen that both lamellar and spherical shaped κ_{III} particles and κ_{IV} are dispersed in the α-matrix of the alloy. Moreover, there are many fine holes in the α-matrix in which small dendritic shape κ_{II} phase is embedded. Because Ni content is higher than Fe content in the studied alloy, κ_{I} phase doesn't appear in Fig. 2(a).

After solution treatment, the stable β phase in the alloy will transform to martensitic β' phase. When the alloy is aged at low temperature such as 450 ℃, β' phase will transform into $\alpha+\gamma_2+\kappa_{III}$ eutectoid. When the alloy is aged at 650 ℃, the eutectiodal products of β' phase become $\alpha+\kappa_{III}$. Fig. 2(b) shows the morphology of the low temperature aged alloy. Obviously, the microstructure of the alloy changes sharply after heat treatment. Between the needle-like α phase, there are many $\alpha+\gamma_2+\kappa_{III}$ eutectoid, which forms a network. Furthermore, there are also some holes in which κ_{II} particles exist, but its amount is relatively less than that of the alloy in extrusion state. Fig. 2(c) shows the microstructure of the high temperature aged alloy. The main feature is that either the homogeneous dot-like or rod-shaped κ_{III} phases distribute in the α-matrix, meanwhile, the hole and the κ_{II} phase in the hole still exist in the alloy.

Figs. 3(a), (b) and (c) show the fracture morphologies of the alloy under the extrusion state, low temperature ageing and high temperature ageing, respectively.

The characteristic fracture morphology of the extruded alloy is that there are many tiny and severely deformed dimples in which there are some hard particles. EDS analysis proves that the compounds are κ phases. Some of the κ phases remain in the dimples and some of them have been torn out. The morphology shows a typical ductile fracture feature.

Experimental results demonstrate that the mechanical properties of the alloy have taken great change after heat treatment. This change is attributed to the variation of the alloy's microstructures. For the alloy of low temperature ageing, the eutectoid reaction of β' martensite transforming to $\alpha+\gamma_2+\kappa_{III}$ will cause the increase in strength and decrease in plasticity because of the appearance of brittle and hard γ_2 phase. It can also be proved from Fig. 3(b) that the fracture surface of the alloy is planar and there are no obvious dimples. Only a great amount of holes remain in the fracture surface due to the cracking of the brittle γ_2 phase. It is a typical brittle fracture feature. However for the alloy of high temperature ageing (650 ℃), eutectoid transformation of $\beta' \to \alpha+\gamma_2+\kappa$ is interrupted and β' martensite trans-

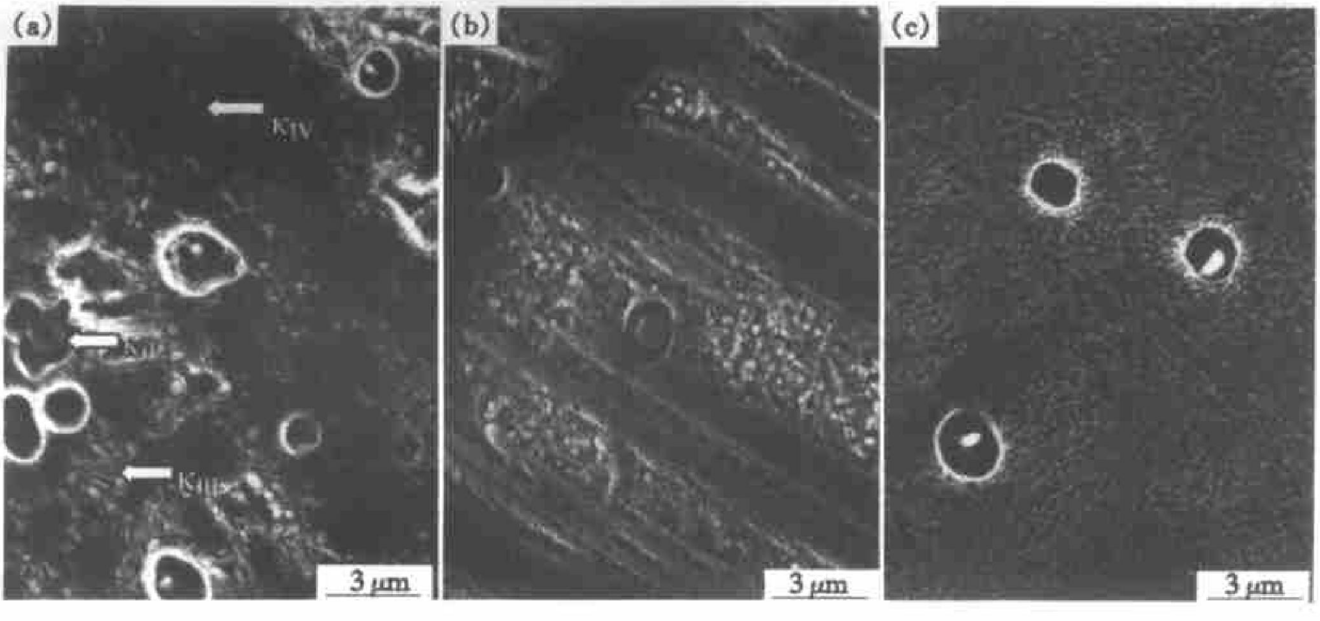

Fig. 2 Microstructures of alloys
(a) —Extrusion state; (b) —Low temperature aged; (c) —High temperature aged

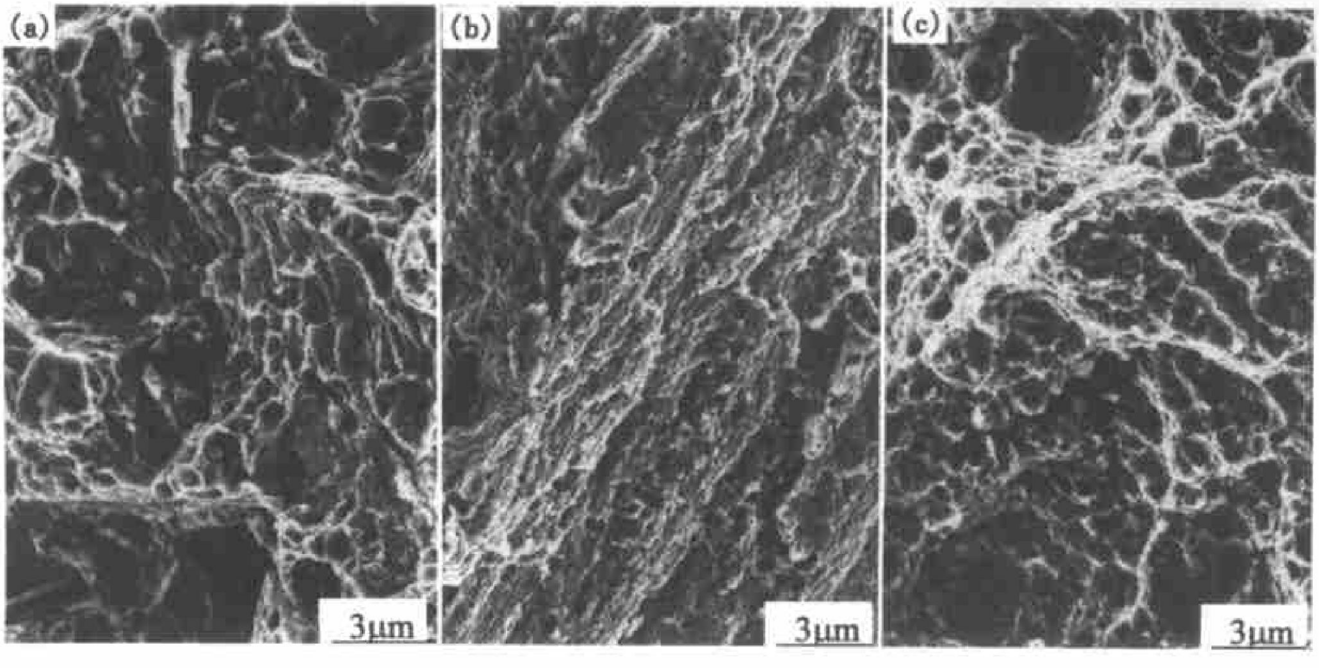

Fig. 3 Fracture morphologies of alloys
(a) —Extrusion state; (b) —Low temperature aged; (c) —High temperature aged

forms into $\alpha+\kappa_{III}$. The ductile fracture appears because the κ phase precipitates disperse in the α-matrix and no γ_2 phase appears in the alloy.

Figs. 4(a), (b), and (c) show the morphologies of the wear surface of the alloy in the states of extrusion, low temperature ageing and high temperature ageing, respectively, after block-on-ring wear testing of 60 min. It can be concluded that the dominant wear mechanism of the samples is abrasive wear, but the wear surfaces are not the same in the alloys under different states. For the extrusion alloy, serious plows, scrape and concave can be found because of the large amount of soft α grain and the tear off of the κ phases. After low temperature ageing, the increase of the alloy strength ensures the resistance of deformation and reduces the degree of abrasive wear. After high temperature ageing, the large amount of dispersed κ phases increase the strength and the resistance to plastic deformation of the α-matrix. So only minor plows and very mild abrasive wear can be seen from the wear surface of the samples.

3.4 Relationship between mechanical properties and tribological behaviors

Under boundary lubrication condition, many researches have been done on the tribological behaviors of wear-resisting aluminum bronze against the steel counterpart[1, 2, 5~8]. Most researches concern factors which affect the tribological behavior of copper alloy including loads, sliding velocity, lubricating media, etc. Besides these external factors, basic characteristics of the alloy itself such as microstructures, grain size also play an important role[9~11]. So proper heat treatment not only improves the mechanical properties of the alloy, but also influences the friction and wear behaviors. From the above experimental results, it can be found that the strength of the alloy can be remarkably increased and different combination of strength and plasticity can be obtained by solution treatment followed by different temperatures ageing. The tribological behaviors of the heat-treated alloy depend on the working conditions. Under boundary lubrication condition, the wear and friction behaviors of the heat-treated alloy are not significantly different from that of the alloy without heat treatment when the load is light, because the resistance to deformation of α-matrix is strong enough to prevent severe abrasive wear in this case. While the load is heavy, the advantage of heat-treated alloy on the tribological property shows up, as shown in Fig. 1. The alloy heat-treated by solutionization and artificial ageing has caused great changes in microstructures. A great deal of brittle and hard γ_2 phase found in the alloy after the low temperature ageing and dispersion of κ phases after high temperature ageing are the main microstructure that causes the increase of deformation resistance of the soft matrix. This decreases the possibility of tearing out of the hard particles from the α-matrix, thus, the wear resistance of the alloy is improved. Although the low temperature ageing of the alloy is useful for the wear resistance, the plasticity of the alloy is very poor, which is unsuitable for the alloy to be used in the case of wear accompanying heavy impact or shock. On this occasion, the alloy of high temperature ageing is just available because of the high toughness of the alloy. If the load is not very heavy, the as-extruded alloy shows very good friction and wear performance, thus heat treatment is unnecessary for the alloy.

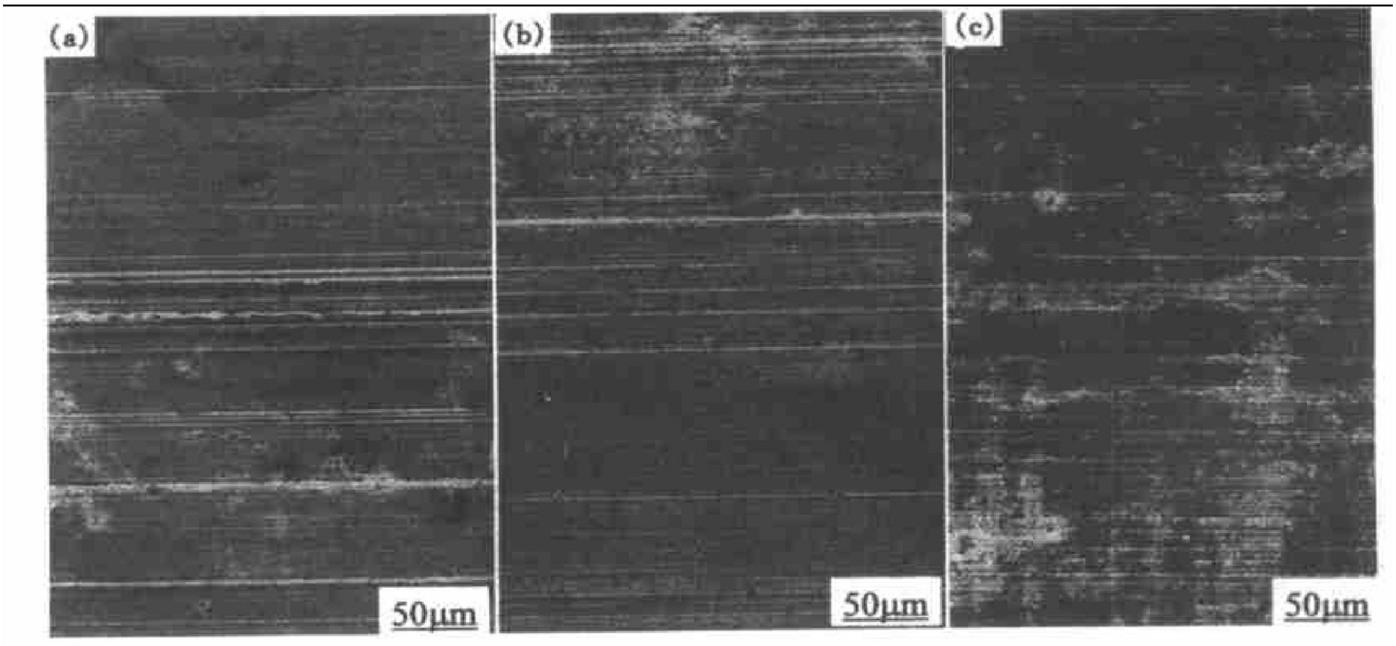

Fig. 4 Wear surfaces of alloys
(a) —Extrusion state; (b) —Low temperature aged; (c) —High temperature aged

4 CONCLUSIONS

1) The wrought aluminum bronze modified by Ti and B is a high-strength and wear-resisting alloy, whose mechanical properties can be improved remarkably by proper heat treatment. Through the solution treatment followed by low temperature ageing (450 ℃) or high temperature ageing (650 ℃), different combinations of strength and plasticity can be achieved.

2) Although the mechanical properties of the alloy can be improved by heat treatment, the tribological behaviors are not the same. Microstructures and the working condition of the alloy play a very important role. Under boundary lubrication condition, the low temperature aged alloy has the best friction and wear behaviors when the alloy is charged by relatively heavy load without impaction and shock, otherwise the high temperature aged alloy is suitable. If the load is not heavy, heat treatment of the alloy has no obvious advantage on the tribological behaviors.

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