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Effect of heat treatment on microstructure and properties of hot-extruded nickel-aluminum bronze

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Abstract: The effect of heat treatment on the microstructure and properties of a hot-extruded nickel-aluminum bronze was investigated. Experimental materials were heat treated through different processes, including quenching, normalizing, aging and annealing, and their microstructure, corrosion resistance and mechanical properties were characterized. It is found that quenching causes all β phase transformed into β' phase, however, normalizing causes β phase transformed into β', α and κ phases. When the quenched sample is aged, fine κ phase is precipitated from the as-quenched microstructure of β' phase. Annealing causes the transformation of β' into α and κ phases. The results of mechanical property tests show that quenching, normalizing and aging improve the tensile strength and hardness of the experimental material, with a corresponding fall in elongation. Annealing raises the elongation but reduces the tensile strength and hardness. Furthermore, corrosion resistance of nickel-aluminum bronze ranks from worse to better in the following order: aged, quenched, normalized, hot-extruded and annealed. However, with the exposure time of corrosion test increasing, the difference of average corrosion rate between those nickel-aluminum bronzes turns small.

Key words: nickel-aluminum bronze; heat treatment; microstructure; mechanical property; corrosion resistance

1 Introduction

Nickel-aluminum bronze is a series of copper-based alloy with additions of aluminum, nickel and iron. Combined with high strength, it shows good resistance to corrosion and wear, which makes it one of the most versatile engineering materials[1−3]. It is widely used as engineering parts, such as various worm-gears, gears, bearings, dies, valves and propellers[4−7]. In recent years, microstructure and corrosion behavior of cast nickel-aluminum bronze have been investigated. It has been reported that nickel-aluminum bronze has a microstructure consisting of Cu-rich solid solution or α phase, several intermetallic phases collectively referred to κ phase, and some β' phase[8−11]. Some researchers have investigated the seawater corrosion of nickel-aluminum bronze. They conclude that nickel-aluminum bronze is susceptible to dealloying corrosion in the cast condition due to the presence of β' phase, which is anodic with respect to the α matrix[12−13]. Until now, little work has dealt with the correlation of phase transformation with different heat treatments, such as quenching, normalizing, aging and annealing. Moreover, their effect on the mechanical properties and corrosion resistance of nickel-aluminum bronze is still not clear. Therefore, the purpose of this study is to investigate the effect of heat treatment on the microstructure and properties of a hot-extruded nickel-aluminum bronze.

2 Experimental

Nickel-aluminum bronze was prepared by melting pure aluminum, iron, nickel, manganese and copper, modifying elements Ti and B, then cast into iron molds to obtain rods, which were subsequently hot extruded. The chemical composition of the experimental material was 9.6% Al, 4.1% Fe, 4.2% Ni, 1.2% Mn (mass fraction), and balance Cu. The heat treatments provided to the specimens are summarized in Table 1.

Microstructure of the experimental material was analyzed by scanning electron microscopy(SEM). The specimens were mechanically polished and etched with

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the solution of 5 g $FeCl_3$+5 mL HCl+100 mL H_2O. Tensile test was carried out at room temperature with a tensile rate of 1.5 mm/min. Tensile fracture morphology was also observed by SEM. Hardness was measured by Brinell hardness tester with a load of 750 kN and a holding time of 30 s.

Table 1 Heat treatments provided to samples of hot-extruded nickel-aluminum bronze

Heat treatment	Temperature/℃	Time/h	Cooling method
Quenching	900	1	Water cooling
Normalizing	900	1	Air cooling
Aging (after quenching)	400	1	Air cooling
Annealing	750	1	Furnace cooling

Salt spray test was conducted according to the GB/T 10125—1997 standard. The NaCl concentration of the salt solution was 50 g/L. The specimens were placed in a testing chamber with the exposed faces upwards, and the unexposed faces protected by rubberized fabric. The periods of test were 48, 96, 168, 240 and 480 h respectively. After the exposure, the specimens were washed with clean running water to remove any salt deposits from their surfaces, and then dried. The corrosion products were removed from the specimens with 50%HCl solution, according to the GB/T 16545—1996 standard. The specimens were then weighed in order to evaluate the mass loss due to corrosion exposure.

3 Results and discussion

3.1 Microstructures

Microstructures of the experimental material under different conditions are shown in Fig.1. The microstructure of the hot-extruded sample consisted of α

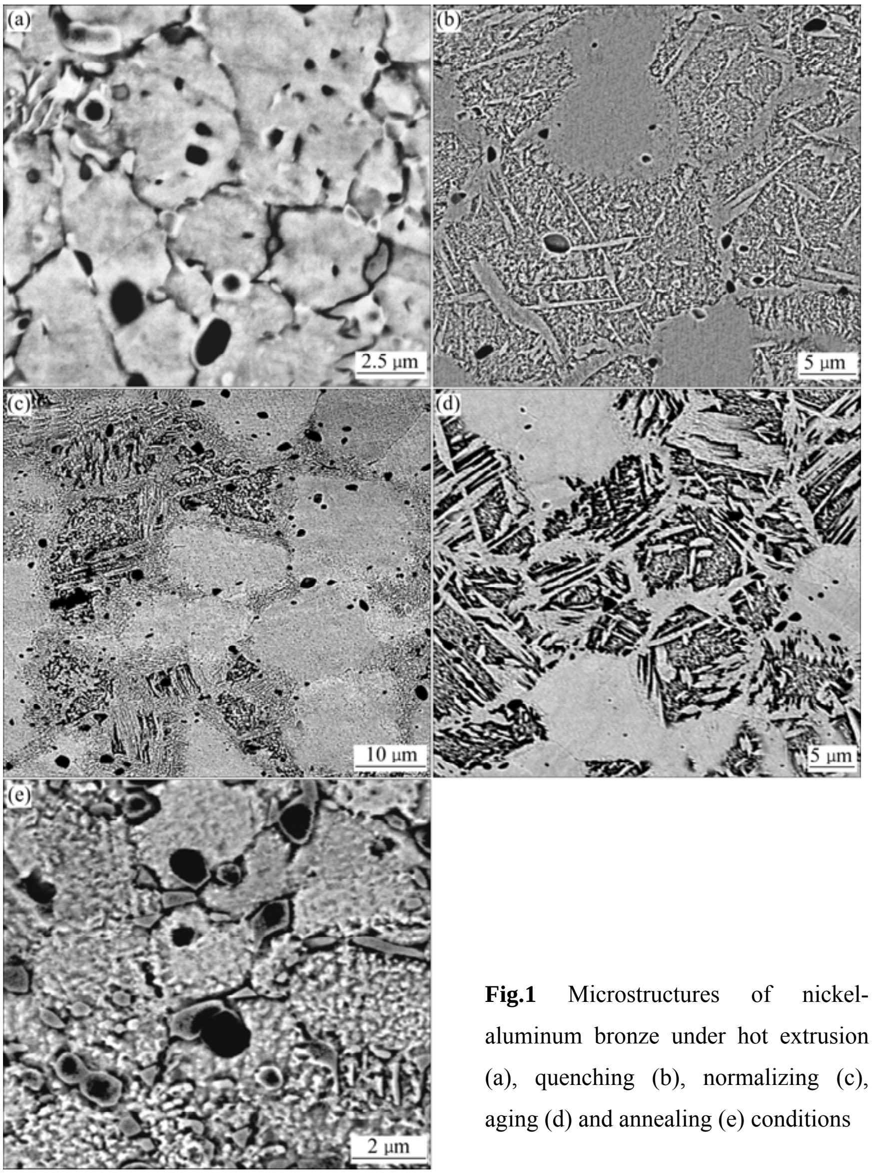

Fig.1 Microstructures of nickel-aluminum bronze under hot extrusion (a), quenching (b), normalizing (c), aging (d) and annealing (e) conditions

matrix, κ phase and a small volume fraction of β' phase. After annealing, β' phase transformed into $\alpha+\kappa$ phases, so β' phase disappeared and only α and κ phases could be observed. When normalized from 900 ℃, some of β phase transformed into β' phase, and the other transformed into lamellar α and κ phases, which distributed along the boundaries of a grain. Martensitic transformation occurred during quenching, although the microstructure of the quenched samples still consisted of α, β' and κ phases, the volume fraction of β' phase increased due to the dissolution of α and κ phases in comparison with the as-extruded material. When the quenched sample was aged, fine κ phase was precipitated from the as-quenched microstructure of β' phase. Therefore, the aged microstructure was also composed of α, β' and κ phases. However, κ phase precipitated during aging was finer than that precipitated during other processes.

3.2 Mechanical properties

Table 2 lists the ultimate tensile strength(UTS), total elongation(TE) and Brinell hardness(HB) of hot-extruded and heat-treated samples. The corresponding tensile fracture morphologies are shown in Fig.2.

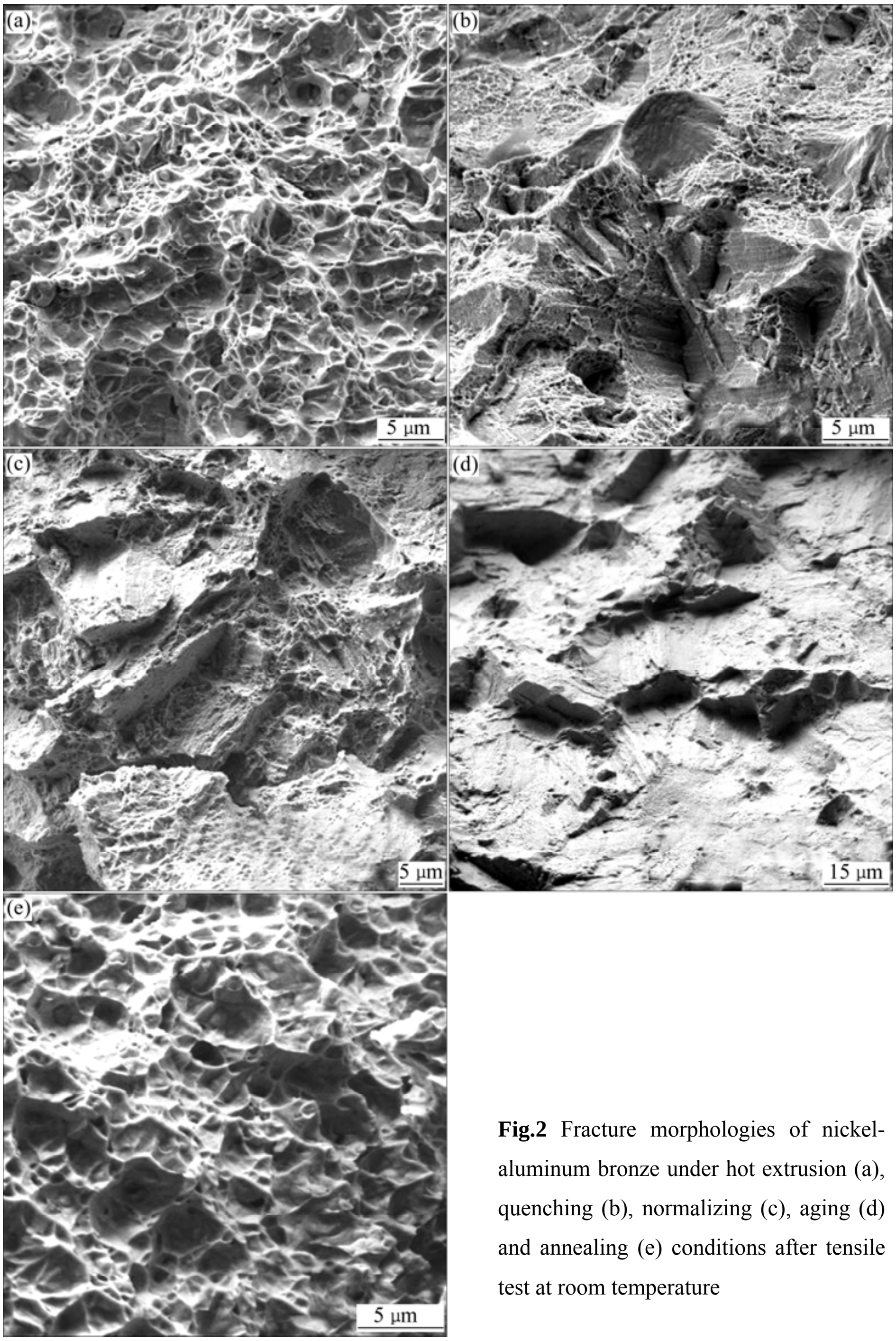

Fig.2 Fracture morphologies of nickel-aluminum bronze under hot extrusion (a), quenching (b), normalizing (c), aging (d) and annealing (e) conditions after tensile test at room temperature

Table 2 Mechanical properties of hot-extruded and heat-treated samples

Sample	UTS/MPa	TE/%	HB
Hot-extruded	761	22.7	185
Quenched	968	8.6	236
Normalized	861	15.9	193
Aged	1144	3.7	348
Annealed	697	29.7	179

Heat treatment could affect the mechanical properties through changing the microstructure of nickel-aluminum bronze. As mentioned above, the microstructure of the hot-extruded sample was composed of α, κ and β' phases, after annealing, β' phase transformed into α and κ phases. Since α phase was softer than β' phase[14−15], and annealing also caused grain growth as well as residual stress relieving, tensile strength and hardness of the annealed samples decreased while elongation increased. Compared with the hot-extruded microstructure, the normalized microstructure showed less content of soft α phase and more content of hard β' phase, so tensile strength and hardness of the samples increased while elongation decreased. Likewise, the quenched sample had more β' phase and less α phase than the normalized one, so the quenched sample had lower elongation and higher tensile strength and hardness than the normalized one. When the quenched sample was aged at 400 ℃, fine κ phase was precipitated from the as-quenched microstructure of β' phase, so tensile strength and hardness were further improved with a corresponding fall in elongation.

As shown in Fig.2, both hot-extruded and annealed specimens have fully ductile fracture morphologies with a large number of dimples. Besides the tiny ductile dimples, flat facets were also presented on the fracture surfaces of quenched and normalized specimens, and some cracks seemed to extend along grain boundaries. The aged specimens exhibited fully brittle fracture, revealing flat cleavage facets. These fracture morphologies were in accordance with the results of total elongation measurement.

3.3 Corrosion resistance

After 48 h of salt spray test, two different kinds of regions were clearly visible on the surface of all the specimens. Fig.3 shows a typical surface morphology after salt spray corrosion test. Region 1, which suffered less serious dealloying corrosion, appeared smooth and its color was purple. Region 2 seemed to be rather rough, from which loose corrosion products had divorced. With the increase of the corrosion time, region 1 became smaller and its color turned darker, while region 2 extended and became rougher. In addition, Region 1 of the annealed specimen was not as dark as those of other specimens, and its area was the largest, indicating that it was likely to provide the best corrosion resistance compared with the other specimens.

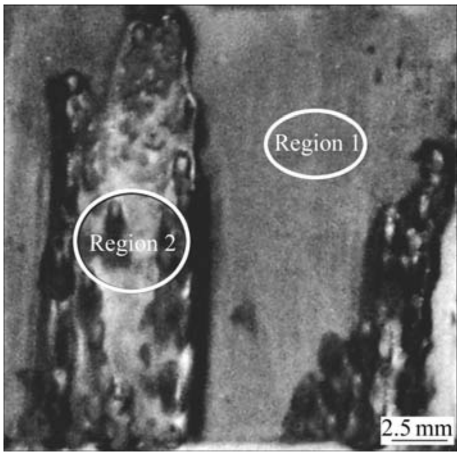

Fig.3 Optical image of surface morphology after salt spray corrosion for 240 h

The corrosion rates of nickel-aluminum bronze in the salt spray test are shown in Fig.4. In general, the average corrosion rates gradually decreased with the duration of exposure time increasing, and then tended to keep in a steady level. Meanwhile, it can be concluded that the corrosion resistance of nickel-aluminum bronze ranked from worse to better in the following order: aged, quenched, normalized, hot-extruded and annealed. Heat treatment may affect the corrosion rate by alerting the microstructure. The annealed specimens only consisted of α phase and κ phases, and their electrode potential difference was the smallest[16], besides, the grain growth reduced the number of galvanic cells and grain boundaries, so the annealed specimens offered the better corrosion resistance than the hot-extruded ones.

Compared with the hot-extruded microstructure, both normalized and quenched microstructures contained less κ phase and more β' phase, which raised the

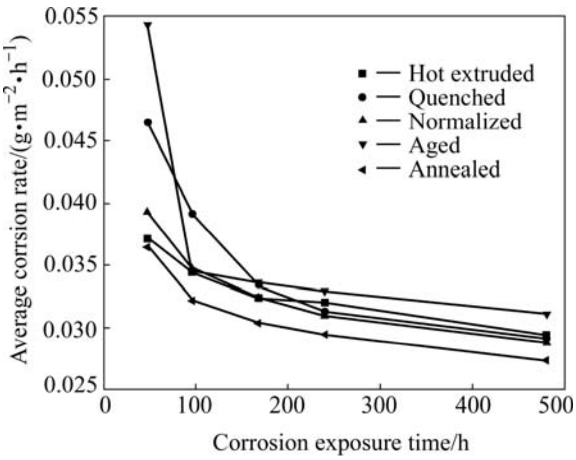

Fig.4 Change of average corrosion rate of nickel-aluminum bronze exposed to salt spray environment with exposure time

electrode potential difference of the galvanic cells, as a result, the corrosion rates increased. During aging, the precipitation of fine κ phase from the as-quenched microstructure produced many galvanic cells, so the corrosion rate of the aging specimens was the largest. However, with the exposure time of corrosion test increasing, the difference of average corrosion rate between those nickel-aluminum bronzes turned small.

4 Conclusions

1) Quenching causes all β phase transformed into β' phase, however, normalizing causes β phase transformed into β', α and κ phases. Annealing causes the transformation of β' martensite into α and κ phases, while fine κ phase is precipitated from β' phase after aging.

2) Heat treatments, in the forms of quenching, normalizing and aging, improve the tensile strength and hardness, with a corresponding fall in elongation. Annealing raises the elongation but reduces the tensile strength and hardness of the experimental materials.

3) The average corrosion rates of salt spray test gradually decreases with the duration of exposure time increasing, and then tends to keep in a steady level. The corrosion resistance of nickel-aluminum bronze ranks from worse to better in the following order: aged, quenched, normalized, hot-extruded and annealed. However, with the exposure time of corrosion test increasing, the difference of average corrosion rate between those nickel-aluminum bronzes turns small.

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