JOURNAL OF MATERIALS SCIENCE 31 (1996) 5333–5338

Grain refinement and microstructural effects on mechanical and tribological behaviours of Ti and B modified aluminium bronze

YUANYUAN LI, T. L. NGAI*
Second Department of Mechanical Engineering, South China University of Technology, Guangzhou, People's Republic of China

Microstructural effects on mechanical and tribological behaviours have been studied for a series of aluminium bronzes with different microstructures. ASTM 1045 and 52100 steels were used as the counterparts in the friction and wear tests. Experimental data show that the coefficients of friction, wear rate and mechanical properties strongly depend on the volume fraction of α-phase present in the alloy and, to a lesser extent, on the average α-grain size. The minimum coefficients of friction and the wear rate correspond to a yield strength of 370 N mm^{-2} and a bulk hardness of HB 168. Except for extreme low average α-grain size (corresponding to low volume fraction), both the coefficients of friction and the wear rate show linear relations with the reciprocal of the yield strength of the alloy, but not to the reciprocal of the hardness as expected. Based on these results, a design principle for high strength wear-resistant aluminium bronze has been developed.

1. Introduction

Aluminium bronze is a widely used nonferrous engineering material. It contains 5 to 12 wt % of Al as the primary alloying element. The addition of iron, nickel and manganese modified its properties and provided a series of commercial alloys which rank among the best acid-resistant high strength alloys. It is tough, resists abrasion and metal-to-metal wear. It reduces friction, galling and seizing when mated against dissimilar metals. As an excellent wear-resistant engineering material, it has found many applications as engineering parts working under high stress, such as various worm-gears, gears, bearings, and bushes, etc. [1].

In the last two decades, many authors have paid attention to the investigation of the tribological behaviour of aluminium bronze. Since the late 70s, Sullivan's research group [2–6] studied the wear of aluminium bronze on steel under boundary lubricating conditions. They studied the roles of aluminium diffusion, transfer and segregation in the wearing process. They also studied the effects of additives, the mechanisms of boundary film formation and the mechanisms of oxidation wear. They set up a theoretical wear model for boundary lubrication. Reid and Schey [7, 8] investigated the effects of adhesion and hardness on the friction of aluminium bronze. They concluded that there is no correlation between the coefficient of friction and the bulk hardness. Harder materials do not imply lower friction. Metal transfer and adhesion are not necessarily lower either. A greater increase in surface hardness or a higher strain-hardening rate do not imply either lower friction or lower adhesion. An increase in hardness during sliding would lead to an increase in friction only if the mating pairs are metallurgically compatible. A difference in compatibility rather than an increase in hardness would govern the magnitude of the friction between mating pairs. Until now, authors in most of the literature studied the effects of external factors such as lubricating media and working environment on the tribological behaviour of bronze. However, little work has dealt with the effects of the basic characteristics of the alloy itself, such as composition, microstructure, volume fraction ratio of the relatively soft phase to the relatively hard phase, and average grain size. These factors are important in engineering material design. The present authors try to use both metallurgical and tribological viewpoints to investigate the inherent relations between the basic characteristics of the alloy and its tribological behaviour, and then set up a guiding principle for the designation of high strength and wear-resistant aluminium bronze with an optimal composition and microstructure.

2. Experimental procedures

2.1. Casting

Aluminium bronze alloys were prepared by melting high purity aluminium (99.95 wt %), high grade commercial iron (99.7%), nickel (99.5%), manganese (99.5%), copper (99.8%) and other modifying elements

*Dr T. Leo Ngai is also a part-time Research Fellow in the Materials Research Center, City Polytechnic of Hong Kong, Hong Kong.

0022–2461

in a graphite crucible, then casting into iron moulds to obtain worm-gears with an outer diameter of 456 mm and a thickness of 60 mm (for elevator tractor use). The composition range of the alloys prepared were (in wt %) : 8–13% Al, 2–5% Fe, 1–3% Ni, 0.5–3% Mn, with Cu making up the balance. Ti and B were added as modifying elements. By varying the amount of modifying agents and controlling the chemical compositions within the above range, and varying the processes of melting and casting, a series of alloys with various average α-grain sizes and different volume fraction ratios of relatively soft α-phase to relatively hard β'- and κ-phases were obtained to meet the test requirements. The relative proportions of α- and β'-phases in the alloys depend greatly on the aluminium contents. The higher the aluminium content the alloy contains the higher the volume fraction of β'-phase.

2.2. Characterization

All samples were taken from the flanges of cast worm-gears. Samples were prepared by normal metallographic process for the investigation of phases. The volume fraction of different phases and the average grain sizes were determined by standard quantitative metallographic analysis. Scanning electron microscopy (SEM) and electron microprobe (EPMA) were used to analyse the topographical features, microstructure, and microconstituents of worn surfaces and debris. X-ray diffraction was used for phase identification.

2.3. Mechanical and tribological behaviours

A pin-on-disc frictionmeter was used for the coefficient of lubricated friction measurements. Disc samples were made of aluminium bronze alloys. Pin samples were made of quenched ASTM 1045 steel with a hardness of HRC 48. The nominal specific pressure used in the test was 7.486 MPa, and the linear sliding velocity was 3.989 $m\,s^{-1}$. The lubricant used was WA elevator lubrication oil.

A cylinder-on-ring wear test machine was used for measuring the wear volume and the wear rate. Cylinder samples were made of aluminium bronze and ring samples were made of quenched ASTM 1045 steel with a hardness of HRC 48. The test load was 686 N, and the linear sliding velocity was 0.886 $m\,s^{-1}$. The lubricant used was WA elevator lubrication oil.

A block-on-ring frictionmeter was used for measuring the coefficient of non-lubricant friction. Block samples were made of aluminium bronze and ring samples were made of quenched ASTM 52100 steel with a hardness of HRC 62. The test load was 98 N and the sliding linear velocity was 0.396 $m\,s^{-1}$.

The duration for the friction and wear measurements was 1 h.

Chinese mechanical testing standards were employed for the mechanical property measurements such as bulk hardness, microhardness and yield strength. Experimental data reported in this study were average values taken from at least three separate measurements.

3. Results and discussion

3.1. Microstructure

Cook *et al.* [9] investigated the phase relationship in a 5% Ni and 5% Fe aluminium bronze. For aluminium content less than approximately 10%, β is the first phase formed during cooling from the liquid state, followed by precipitation of α-phase and the formation of κ-phases. Based on their phase morphologies, Weill-Couly and Arnaud [10] reported four forms of κ-phase in Ni–Al bronze with a nominal composition of 9.5% Al, 5% Fe, 5% Ni and copper for the remainder. Culpan and Rose [11] confirmed Weill-Couly and Arnaud's findings with SEM and energy dispersive spectroscopy (EDS). Recently Ridley's research group [12, 13] studied these phases in details. They classified κ-phases based on their chemistry and crystallography rather than on morphology alone. According to these authors, the κ_I-phase forms only in alloys with higher iron contents (relative to Ni). It is a metastable, cored, dendritic-shaped precipitate with a composition which varies from an iron-rich solid solution to Fe_3Al, and the phase relationships are extremely complex in this composition region. The κ_{II}-phase is also dendritic in shape with a composition based on Fe_3Al and DO_3 structure. The κ_{III}-phase is a product of eutectoid decomposition, having a lamellar or globular shape, with a composition based on NiAl and has a B2 structure. The κ_{IV}-phase is a relatively small, equiaxed precipitate in the α-phase. Its composition is based on Fe_3Al and a DO_3 structure. A typical metallographic structure of the as-cast alloy in this study is shown in Fig. 1. Light areas are α-matrix, dark regions are the so called "retained β" or β'-phase and fine dots dispersed in the matrix are intermetallic κ-phases. The α-matrix is a relatively soft (Hv = 200–274) Cu-based substitutional solid solution of face-centred cubic structure with a lattice parameter $a \approx 0.3666$ nm. The β-phase is a Cu_3Al-based solid solution with a body-centred cubic structure and stable only above 565 °C. The dark β'-phase between the α-matrix in Fig. 1 is the supercooled β-phase resulting from the interrupted eutectoid transformation. The β'-phase is essentially hard martensite with a microhardness of Hv = 290–407. The κ-phases found in the present study are relatively hard and brittle Fe_3Al-based solid solutions: κ_{II} is in rosette form and κ_{IV} is a fine precipitation within the α-grains. Their microconstituent is approximately 10.10% Al, 65.58% Fe, 5.79% Ni, 2.71% Mn and 15.82% Cu.

3.2. Effects of microstructure on mechanical and tribological behaviour

A series of alloys, with average α-grain sizes ranging from 29 to 105 μm and volume fraction ratios of the relatively soft α-phase to the relatively hard β'-phase ranging from 55:44 to 93:6, and the rest, approximately 1%, made up of the finely dispersed hard κ-phases, were prepared. Our data shows that the α-phase volume fraction and the average α-grain size are closely related to the tribological behaviour of the alloy. Figs 2 and 3 elucidate the effects of the volume fraction and the average grain size of α-phase on

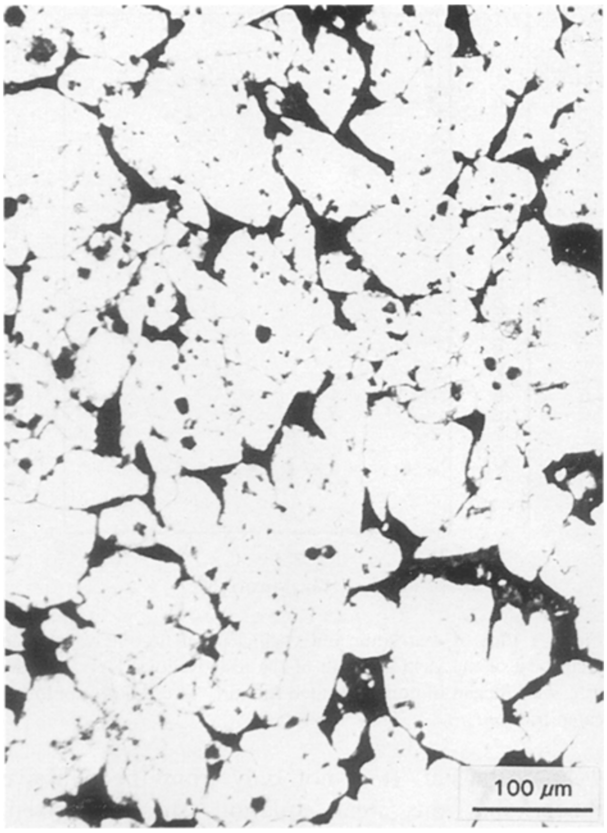
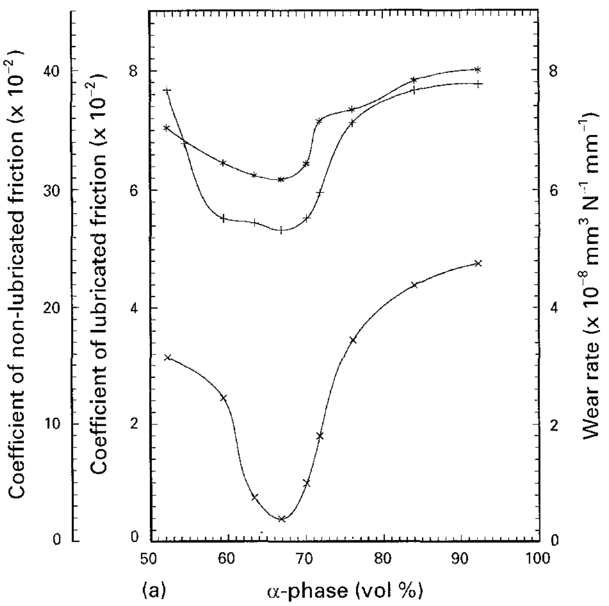


Figure 1 Typical microstructure of an aluminium bronze sample.

the coefficient of friction, wear rate and some mechanical properties of the tested alloys, respectively. These figures demonstrate that when the volume per cent of α-phase is approximately 67 or the average α-grain size is about 35 μm, the alloy would give optimal combinative mechanical properties and friction and wear behaviours when sliding against the steel counterparts.

From Figs 2a and 3a, we notice that the wear rate and the coefficients of lubricated and non-lubricated friction all show similar trends. This may be an indication that these quantities are actually interrelated. The boundary lubrication film formed between bronze and steel mitigated the effect of adhesion, so it is easy to understand that the coefficient of lubricated friction and the coefficient of non-lubricated friction show the same trend. As shown later in the next section, both the coefficients of friction and the wear rate are inversely proportional to the yield strength of the alloy, thus, it is no surprise that they show similar trends too.

Fig. 2 shows that the minima of the wear rate and the coefficients of friction are located at approximately 67 vol % of the α-phase, which coincided with the maxima of the yield strength and the tensile strength of the alloy. The best wear-resistant alloy with a low coefficient of friction can be obtained with α-phase ranging from 63 to 70 vol %. The sharp increases of the three curves in Fig. 2a for α-phase with less than 63 vol % and between 70–76 vol % are probably due to the sudden decrease of the yield strength of the alloy in these ranges. The increase in hardness would lead to the worsening of the coefficients of friction and wear rate of the alloy containing less than 63 vol % of the



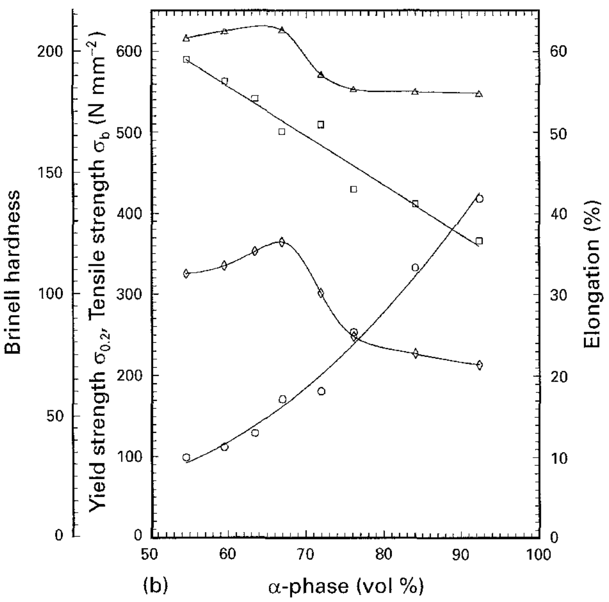


Figure 2 Variation of (a) tribological behaviour (× wear rate, * coefficient of non-lubricated friction, + coefficient of lubricated friction) and (b) mechanical properties (□ hardness, △ tensile strength, ◇ yield strength, ○ elongation) with volume per cent of the α-phase.

α-phase. The gentle increase of the three curves in Fig. 2a beyond 76 vol % of α-phase are correlated with the gentle decrease in yield strength of the alloy in the same region. Similar effects can be noticed in Fig. 3. The best wear-resistant alloy with a low coefficient of friction can also be obtained at an α-grain size ranging from 33 to 46 μm. The plateau in the Brinell hardness data and the smooth hill top exhibited by the yield strength data between the average α-grain size of 33 and 63 μm correspond to the gentle increase in wear rate and coefficients of friction data in the same range of average α-grain size. The sharp increase in hardness for average α-grain size of less than 33 μm is responsible for the rapid deterioration of the friction and wear behaviours of these alloys. The worsening of the coefficients of friction and the wear rate of these alloys for an average α-grain size less than 33 μm and beyond 63 μm are obviously related to the decrease of the yield strength of these alloys but not to the hardness.

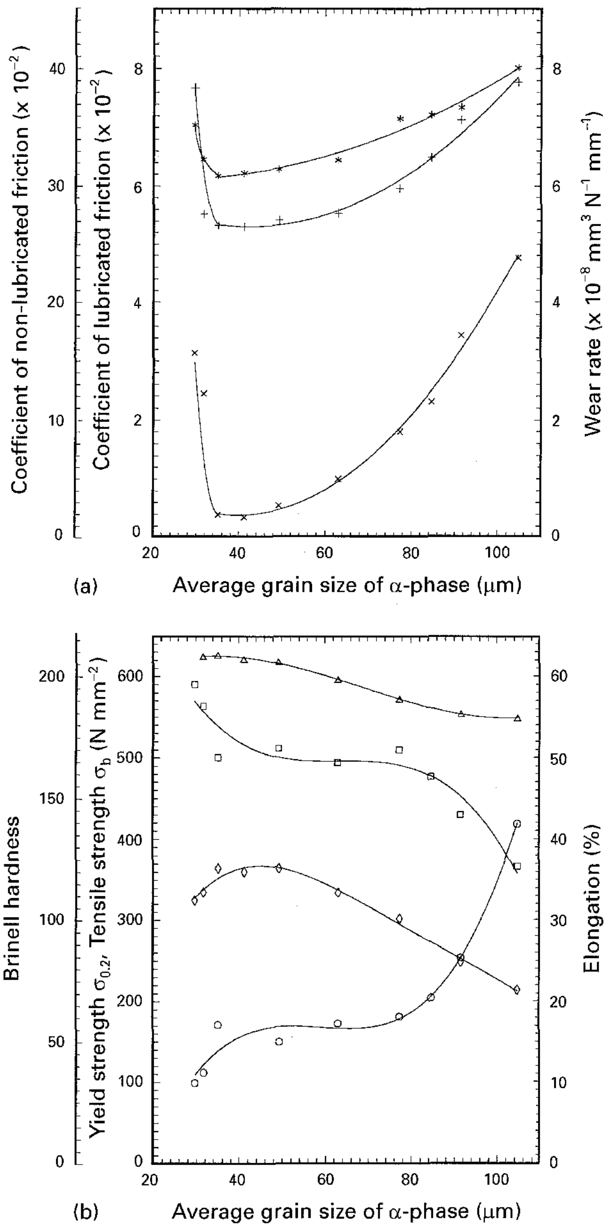


Figure 3 Variation of (a) tribological behaviour (× wear rate, ∗ coefficient of non-lubricated friction, + coefficient of lubricated friction) and (b) mechanical properties (□ hardness, △ tensile strength, ◇ yield strength, ○ elongation) with average grain size of α-phase.

3.3. Relation between mechanical properties and tribological behaviour

From Figs 2 and 3, we can notice that the minimum coefficients of friction and wear rate correspond to a yield strength of 370 N mm^{-2} and a bulk hardness of HB 168. It is clear that instead of hardness, the yield strength has a more direct implication on the friction and wear behaviours of these alloys.

A simple but useful expression for wear rate, W, which is defined as the volume of material removed per unit sliding distance, was derived by Archard [14]. He developed the adhesive theory for sliding friction by assuming that the yield pressure for the plastically deforming asperity is approximately equal to the hardness, H, of the material and that the hardness is the most important property controlling wear rate. He obtained the well known Archard wear equation $W = KL/H$, where L is the normal load and K is the wear coefficient. It is not only from the adhesive theory that this wear equation can be derived; Rabinowicz obtained the same expression for two-body abrasive wear involving plastic flow [15]. An expression resembling the Archard wear equation can also be derived for the coefficient of friction, μ, which contributes by adhesive forces, $\mu \approx s/H$, where s is the shear strength. It is well known that for metal, the indentation hardness is about three times that of the uniaxial yield stress, σ, thus $W \approx KL/(3\sigma)$ and $\mu \approx s/(3\sigma)$ [16].

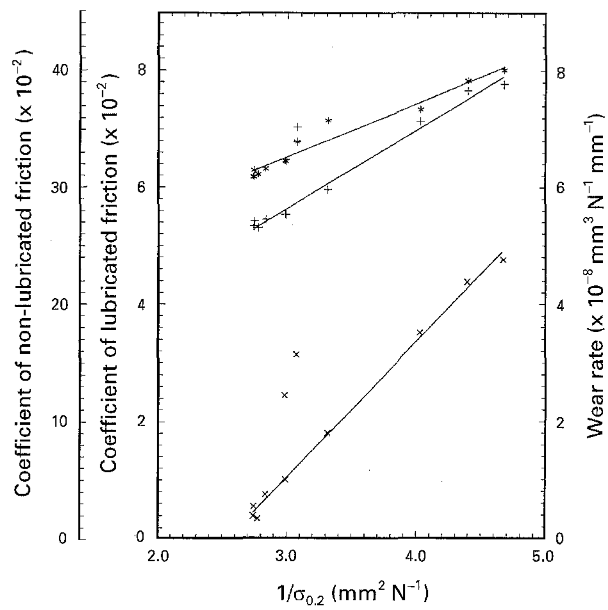


Figure 4 Plot of wear rate and coefficient of friction versus the reciprocal of the yield strength of the tested alloys. Key: × wear rate, ∗ coefficient of non-lubricated friction, + coefficient of lubricated friction.

Fig. 4 is a plot of the coefficients of friction and wear rate versus the reciprocal of the yield strength ($\sigma_{0.2}$) of the alloy. In our data, the coefficients of friction and the wear rate do not show clear linear relationships with the reciprocal of the hardness of the material. Instead they show linear relationships with the reciprocal of the yield strength of the alloy, except for two points in the wear rate and in the coefficients of friction data. These points correspond to less than 60 vol % α-phase or an average α-grain size less than 32 μm. The reason for this is believed to be caused by the change in wear mode due to the change in alloy microstructure. In this region the relative amount or the average grain size of the α-phase in the alloy is not sufficient to hold the κ-particles in the matrix and the peeling off of these hard particles induced multi-body abrasion, as shown later in Fig. 5 in the next section.

3.4. Effect of microstructure on the wear mechanism

When the relative amount of α-phase is less than 63 vol %, the α-phase cannot provide enough inlay and protection for the hard κ-particles and therefore this leads to the tearing off of these particles. As shown in Fig. 5, deep ploughs, wedges and pea cavities can be seen, and serious abrasive wear occurred. When the relative amount of α-phase is larger than 70 vol %, the

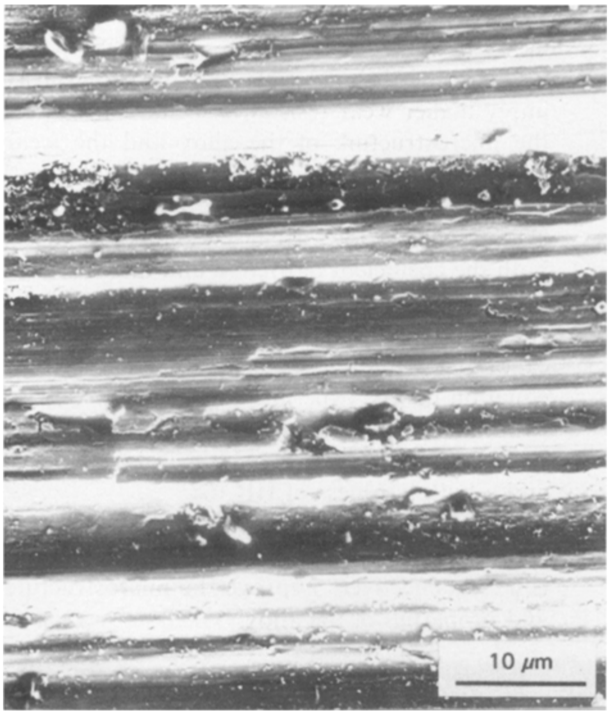


Figure 5 Wear surface of an aluminium bronze sample with 55 vol % of α-phase.

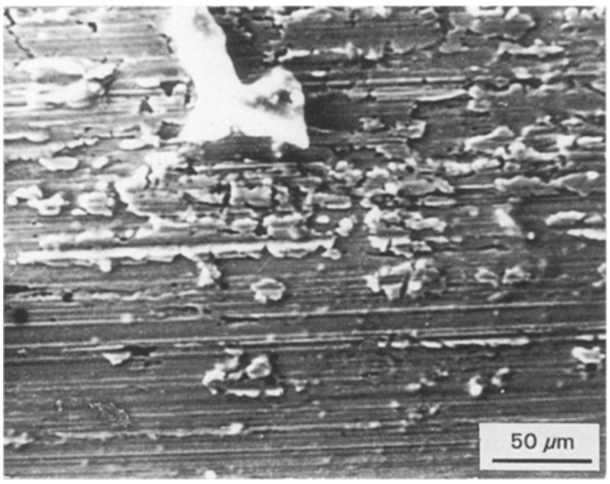


Figure 6 Wear surface of an aluminium bronze sample with 84 vol % of α-phase.

hardness and plastic deformation resistance of the alloy tend to be smaller and have a bigger tendency to adhere to the steel counterpart. As shown in Fig. 6, adhesion, ploughs and flaky wear debris can be seen, and serious adhesive wear occurred. When the microstructure is between these two features mentioned above, as shown in Fig. 7, the wear modes are mild adhesive and abrasive wears.

From these experimental data, some special relationships between the mechanical properties and the friction and wear behaviours can be observed. The higher the strength, the lower the coefficient of friction and the wear rate. Hardness and plasticity have more complex effects on the coefficients of friction and wear rate. When adhesive wear is significant, increasing the hardness and lowering the plasticity would be advantageous in reducing the coefficients of friction and the wear rate. However, when abrasive wear is significant,

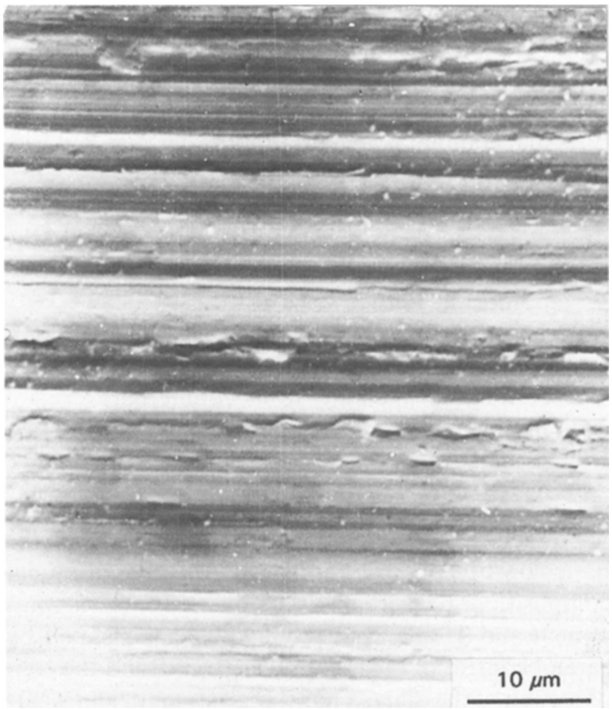


Figure 7 Wear surface of an aluminium bronze sample with 67 vol % of α-phase.

increasing the hardness and lowering the plasticity would give an opposite result. Thus, the wear of materials, to a certain extent, depends upon hardness. From Figs 2 and 3, it is not difficult to observe that the effects of the mechanical properties on the friction and wear behaviours are closely related to the microstructure of the alloy.

4. Design principle for high strength wear-resistant aluminium bronze

Figs 2 and 3 show that when the microstructure of the bronze is out of the optimal range, the coefficients of friction and wear rate would increase rapidly. As a result, premature work failure might occur in work pieces made of this material. In order to avoid this from happening, correct design and control of the microstructure of the alloy is very important in addition to external factors such as load, speed, lubrication and working environments, etc.

Fig. 1 shows a fine dispersion of hard particles (κ-phases) on the relatively soft matrix (α-phase). Experience told us that this is the ideal microstructural feature that would give excellent wear-resistant properties for multi-phase materials. The fine and hard particles can limit the junction growth and thus reduce the friction and wear that are caused by adhesion. Also, if these hard particles are harder than their counterparts, they can provide excellent abrasion resistance. Of course, the matrix should provide enough inlay to hold them in place to avoid them peeling off and causing multi-body abrasion.

From the above experimental results, the present authors preliminarily conclude a design principle for high strength wear-resistant aluminium bronze.

1. Controlling the relative volume fraction of soft α-phase to hard β′- and κ-phases at a ratio of approximately 67:33 or the average α-grain size of approximately 33 to 46 μm to obtain the optimal combinative mechanical properties and friction and wear behaviours of the bronze.
2. Solution strengthening, dispersion strengthening and grain refining of the α-phase to increase the strength and the resistance to plastic deformation of the alloy.
3. Adding a proper amount of anti-friction component or particles to increase the ability to resist adhesion of the alloy to its counterpart.
4. Eliminating or minimizing the gas cavities, shrinkages and inclusions to increase resistance to fatigue wear of the alloy.

Following this design principle, by adjusting the basic constituents (Al, Fe, Ni, Mn, Cu) to an optimal composition, by adding Pb as an anti-friction component and Ti and B as modifying elements, and by careful control of the melting, degassing and the solidification of the alloy, a novel high strength and wear-resistant aluminium bronze has been developed in our laboratory. Details of these shall be discussed in another paper.

5. Conclusion

1. The coefficient of friction and the wear rate of aluminium bronze show a very close relationship with microstructure. They strongly depend on the volume fraction ratio of the relatively soft phase (α) to the relatively hard phases (β′ and κ), and to a lesser extent, depends on the average grain size of the α-phase. Microstructure not only determined the mechanical properties of the alloy, but also plays an important role in their friction and wear behaviours.
2. The optimal combinative mechanical properties and friction and wear behaviours can be obtained when the volume fraction ratio of α-phase to β′- and κ-phases is about 67:33, or the average grain size of the α-phase is between 33–46 μm.
3. When the relative amount of the α-phase is larger than 70 vol % or the average grain size of α-phase is larger than 63 μm, serious adhesive wear occurred. When the relative amount of α-phase is less than 60 vol % or the average grain size of the α-phase is less than 33 μm, serious abrasive wear occurred. Within these regions the coefficients of friction and wear rate of the alloy are relatively large.
4. The wear of a material depends on its bulk hardness up to a certain extent. However, higher hardness of the material does not necessarily imply higher wear resistance. It all depends on the microstructure of the alloy and the wear modes.
5. Except for extreme low average α-grain size (corresponding to low α-phase volume fraction), both the coefficient of friction and the wear rate show linear relations with the reciprocal of the yield strength of the alloys but not to the reciprocal of the hardness as expected. An Archard-type equation fits the experimental data very well.
6. Minimum coefficient of friction and wear rate correspond to a yield strength of $370\ \mathrm{N\,mm^{-2}}$ and a bulk hardness of HB 168.
7. Adding modifying components Ti and B, and controlling the melting and solidification process, can effectively improve the microstructure and properties of the alloy.

Acknowledgements

Part of this work was done in The Materials Research Center, City Polytechnic of Hong Kong. The authors gratefully acknowledge the facilities they provided.

References

1. R. J. C. DAWSON, *Eng. Mater. Design* **22** (1978) 25.
2. W. POOL and J. L. SULLIVAN, *ASLE Transactions* **22** (1979) 154.
3. *Idem, ibid.* **23** (1980) 401.
4. J. L. SULLIVAN and L. F. WONG, *Tribol. Int.* **18** (1985) 275.
5. J. L. SULLIVAN, *J. Phys. D* **19** (1986) 1999.
6. *Idem, Schmierungstechnik* **18** (1987) 41.
7. J. V. REID and J. A. SCHEY, *Wear* **104** (1985) 1.
8. *Idem, ibid.* **118** (1987) 113.
9. M. COOK, W. P. FENTIMAN and E. DAVIS, *J. Inst. Met.* **80** (1952) 419.
10. P. WEILL-COULY and D. ARNAUD, *Fonderie* **28** (1973) 123.
11. E. A. CULPAN and G. ROSE, *J. Mater. Sci.* **13** (1978) 1647.
12. F. HASAN, A. JAHANAFROOZ, G. W. LORIMER and N. RIDLEY, *Met. Trans. A* **13A** (1982) 1337.
13. A. JAHANAFROOZ, F. HASAN, G. W. LORIMER and N. RIDLEY, *ibid.* **14A** (1983) 1951.
14. J. F. ARCHARD, *J. Appl. Phys.* **24** (1953) 981.
15. E. RABINOWICZ, "Friction and Wear of Materials" (John Wiley, New York, 1965).
16. I. M. HUTCHINGS, "Tribology: Friction and Wear of Engineering Materials" (Edward Arnold, London, 1992) p. 29.

Received 31 October 1994
and accepted 13 February 1996