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EROSION CHARACTERISTICS OF SURFACE HARDENED Ni–Al BRONZE

T. Kawazoe, A. Ura, M. Saito, and S. Nishikido

Surface hardness characteristics and erosion resistance of Ni–Al bronze produced by three kinds of quenching have been determined to assess their potential as surface treatments for marine propellers. Flame, high frequency, and laser processing were employed as the surface hardening treatments. Microstructures and distributions of alloying elements were examined using microscopy, computer image analysis, and EPMA. Jominy and ultrasonic erosion tests were also conducted to evaluate the depth of surface hardening and resistance to propeller cavitation erosion. The experiments revealed that Ni–Al bronze has quenching characteristics closely related to those of steel and that bronze surface hardened by flame quenching is about 1.5 times harder than as cast. It was also found that flame quenching is the most suitable technique for surface treatment of propellers.

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INTRODUCTION
Ni–Al bronze is used for marine propellers, seawater pumps, and gears because of its superior material characteristics including high corrosion fatigue strength, high corrosion resistance, and good castability.1,2 In the case of marine propellers, reducing the blade area enhances propeller efficiency but increases thrust burden per unit blade area resulting in excessive cavitation erosion of the blade; to solve this problem, a high hardness stainless steel propeller has been developed.3 In this study, on the other hand, surface modified Ni–Al bronze was investigated for their suitability in this application. There are many studies on quenching characteristics of steels, for example applying laser quenching to piston ring grooves in marine diesel engines,4 but there are few on surface hardening of copper alloys such as Ni–Al bronze.

The aim of this study is to clarify the relationship between quenching characteristics and cavitation erosion resistance of Ni–Al bronze from the metallographic point of view, taking into account application to propellers. Flame, high frequency, and laser quenchings were employed as surface hardening treatments. Microstructures and distributions of alloying elements of the test specimens were examined using microscopy and EPMA. Jominy and ultrasonic tests were also conducted to evaluate the extent of surface hardening and resistance to propeller cavitation erosion.

EXPERIMENTAL METHODS
Two Ni–Al bronze compositions were used, as follows: Cu–9.19Al–4.55Ni–5.33Fe–0.52Mn and Cu–9.10Al–4.33Ni–4.90Fe–1.75Mn. Test specimens in the as cast state had tensile strength 665 MPa, % elongation 20.8, and HB 156. Specimens for flame quenching were 220 × 50 × 65 mm; heat treatments with three kinds of cooling (water spray, forced air, and natural air) were adopted as a preliminary test after heating to 1173 K using a gas burner. Tempering treatments were carried out in the temperature range 673–773 K in order to determine the optimum temperature for residual stress relief. Jominy tests with the test specimen as shown in Fig. 1 were also conducted to examine the relation between quenching characteristics and microstructure and Mn content.

In high frequency quenching, test specimens of 100 × 50 × 20 mm were heated to 1173 K using a high frequency induction apparatus (350 kHz, maximum 150 kW) and cooled in water. In laser quenching, a CO2 laser (beam size 8 mm dia., 5 kW pulse) was traversed across the same size of test specimen as in high frequency quenching, at 200–2000 mm min−1. Manganese phosphate layers about 1 mm in thickness were applied to the surfaces of specimens as a beam absorbent, because copper alloys tend to reflect CO2 lasers. In addition, an erosion test in sea water was conducted for 2 h using a supersonic erosion apparatus to evaluate cavitation erosion resistance of the surface hardened material. The amplitude and frequency of vibration used in the test were 110 μm and 6.5 kHz, respectively.

RESULTS AND DISCUSSION
Flame quenching
Figure 2 shows the preliminary test results of flame quenchings in the atmosphere. Water spray cooling produced the hardest surface, about 1.5 times harder
than the as cast state. Figure 2 reveals that Ni–Al bronze has quenching characteristics similar to those of steels. The surface hardnesses with forced and natural air cooling are higher than that of the as cast alloy but much lower than that with water spray cooling. For reference, Table 1 gives mechanical properties after the preliminary test, in which tensile stress and 0.2% proof stress increase but elongation and Charpy impact value decrease with surface hardness. Flame quenching with water spray cooling was adopted in the main test on the basis of these results.

Figure 3 shows Jominy test results for the flame quenched material as a function of Mn content. The surface is about 1.4 times harder than the deep subsurface. By measurement of temperature with thermocouples inserted 5, 25, 45, and 65 mm from the surface, the average cooling speeds after the initial cooling were found to be 720, 380, 200, and 100 K min⁻¹ respectively. The hardness depends strongly on cooling speed and the positions deeper than 25 mm do not increase in hardness. Therefore, it is necessary to quench at cooling speeds greater than a critical value in order to promote surface hardening. As shown in Fig. 3, practical use of flame quenching is not restricted by machining and finishing requirements (about 5 mm depth) because the hardened layer is sufficiently thick. Focusing on the relation between surface hardening and Mn content, the specimen with 1.75%Mn, corresponding to the maximum allowable content in propellers, is harder than that with the usual content of 0.52%Mn. It has been reported that some alloys with both α and β phases such as Ni–Al bronze have decreasing α content and increasing β + β' content with increasing Mn. Accordingly, this test result indicates the cumulative effects of Mn content and quenching.

Figure 4 shows the microstructures at the surface and at a depth of 65 mm for the flame quenched specimen. These microstructures consist of white α phase and black β + β' phase. The relation between area ratio of each phase and depth from the surface is plotted in Fig. 5 from the results of computer image analysis. In this case, α phase content increases but β + β' phase decreases as the depth increases. Measurement of Vickers microhardness as shown in Fig. 6 revealed that β content was much higher than α and the area ratio directly influenced the hardness. From the results of EPMA, it was found that β phase near the surface contains more Fe and Ni than the subsurface regions and these elements contribute to an increase of hardness.

Figure 7 shows the test results of tempering treatments in a furnace for relieving residual stress due to quenching. The hardness decreases with tempering time at a tempering temperature of 673 K and is almost constant at 723 K. On the other hand, tempering at 773 K further increases the hardness and has no stress relieving effect; in this case k phase finely distributed in the α phase (precipitation hardening) was observed by microscopy. With this material, the k phase precipitates when the temperature is greater than about 750 K. Higher temperatures produce more k phase.
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5 Phase content as determined by computer image analysis

which consists of Fe-Al and Ni-Al. Considering both the high hardness and stress relieving effect, 723 K is the optimum tempering temperature.

Laser and high frequency quenching

Figure 8 compares hardness generated by laser and high frequency quenching. Laser quenching has a tendency to increase surface hardness with decreasing feed speed, and the maximum hardness is about 1.6 times higher than the substrate at a feed speed of 400 mm min\(^{-1}\). However, the hardened layer due to laser quenching is so thin (1.5 mm) that this quenching may be conducted on the limited area of the propeller blade tip without requiring a finishing allowance. Conversely, high frequency quenching produces a rather thick hardened layer, but its surface hardness is about 80% of that resulting from laser and flame quenching. Because of the induction apparatus, it is difficult to apply this technique to large propellers with wide blade area.

Micrograph of sections of laser and high frequency quenched specimens are shown in Fig. 9a and b, respectively. The microstructure very close to the surface in Fig. 9a indicates an overall distribution of fine \(\beta\) phase produced by laser radiation which significantly increases the hardness. However at positions deeper than 1.5 mm from the surface, microstructure of \(\alpha\) phase segregated from \(\beta\) phase is observed. A characteristic of the microstructure produced by high frequency quenching (Fig. 9b), is that some \(\beta\) phase is included in \(\alpha\) phase owing to the heating effect. It can also be seen that hardness is closely related to the microstructure.

Erosion test

Erosion losses after supersonic erosion testing were: 140 mg for as cast; 53 mg for a flame heated and water spray cooled specimen; and 48 mg for a flame heated, water spray cooled, and tempered specimen. Cavitation erosion resistance is strongly related to the degree of hardening and dispersion of the hard phase. For example, the erosion loss after flame quenching and tempering was about 35% as compared to that of the as cast alloy. Also, from Fig. 10 showing surface roughness after the erosion test of 2 h in sea water, erosion damage of the flame quenched specimen can be seen to be much smaller than for the as cast. These results reveal that flame quenching contributes to the improvement of erosion resistance of Ni-Al bronze.

Application of surface hardening to propellers

When applying surface hardening treatments to actual propellers, flame quenching with water spray
cooling is thought to be most suitable as far as quenching characteristics and operational efficiency are concerned. Since cavitation erosion of propellers occurs in the region, from the blade tip to the trailing edge, which is subject to high velocity flow, it is recommended that flame quenching should be conducted on as narrow a region as possible.

Figure 11 shows the relation between hardness, blade expanded area ratio, and propeller efficiency (considering delivery results). The propeller surface hardened by flame quenching has efficiency improved by about 1.5%, resulting from a reduction in blade area of about 15% as compared to the usual propeller, which would be expected to increase ship speed by approximately 0.1 knot.

CONCLUSION
Three kinds of quench hardening of Ni-Al bronze were performed to investigate the quenching characteristics and erosion resistance, taking into account practical use in propellers. The main conclusions obtained are as follows.

1. Ni-Al bronze has quenching characteristics similar to those of steel. For example, the surface hardened by flame quenching with water spray cooling is about 1.5 times harder than as cast.

2. Hardness is closely related to microstructure. With flame quenching, hard β + β' phase is distributed in large quantities on the surface and soft α phase content increases with depth.

3. Laser quenching also produces a hard surface but the hardened layer is much thinner compared to flame quenching.

4. Flame quenching contributes to improvement of erosion resistance of Ni-Al bronze and is most suitable for applying to actual propellers. An improvement in propeller efficiency of about 1.5% can be expected.

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