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INTERNAL FRICTION IN SONOSTON - A HIGH DAMPING Mn/Cu-BASED ALLOY FOR MARINE PROPELLER APPLICATIONS

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Résumé - On compare les changements dûs au frottement interne et au module de Young, dans l'éventail de température de 10 à 600°C, sur des échantillons coulés en laboratoire à partir du SONOSTON, un alliage binaire de Mn-Cu, et les échantillons prélevés d'une pale d'hélice de SONOSTON. L'état de frottement interne élevé, à la température ambiante, du SONOSTON dépend fortement de l'amplitude et les résultats obtenus sont semblables à ceux observés chez les alliages ferromagnétiques. On observe, chez le SONOSTON, un pic de relaxation ainsi que chez l'alliage binaire de Mn/Cu à ~ 400°C. Le pic de relaxation de 400°C est probablement une relaxation du type Zener mettant en jeu un arrangement ordonné régulier des atomes de Mn dû aux contraintes.

Abstract - Internal friction and Young's modulus changes over the range 10 to 600°C in laboratory cast samples of SONOSTON, a binary Mn-Cu alloy and samples cut from a 200-kg propeller blade cast from SONOSTON are compared. The high-damping state at room temperature in SONOSTON is very amplitude dependent, and the results are similar to those observed in ferromagnetic high-damping alloys. Besides the high-damping peak close to room temperature, there is a major relaxation peak in SONOSTON and in the binary Mn/Cu alloy at ~ 400°C. The 400°C peak is probably a Zener-type relaxation involving the stress-induced ordering of Mn atoms.

I - INTRODUCTION

Alloys based on the Mn-Cu system are of technological interest because, after certain thermomechanical treatments, they exhibit a very high internal friction (IF) or damping capacity [1,2]. A particular alloy of the system containing ~ 52 wt.% Mn, ~ 38 wt.% Cu, and minor additions of Fe, Ni and Al to improve strength, corrosion resistance to seawater and castability, has been developed for naval propellers. Propellers cast from SONOSTON, the trade name given to the alloy developed by Stone Manganese Limited [3,4], are in service with several navies, while high-damping alloys of a similar composition are referred to as AURORA alloys [5] in the USSR.

Studies of IF [6-8], elastic modulus changes [7,9], X-ray diffraction [10-12], neutron diffraction [13-15], optical metallography [10,16] and electron microscopy [17,18] have established that the high-damping state is associated with an antiferromagnetic tetragonal structure, which appears after aging the alloy in a temperature range corresponding to a miscibility gap [12,15,18] in the phase diagram. Most of these studies have focussed their attention on high Mn ($\geq$ 60 wt.%) binary Mn-Cu alloys. Surprisingly little work has been published on the alloys that have found practical applications. Also, the nature of the dissipation mechanism responsible for the high-damping capacity is still uncertain. Most authors attribute the damping to the movement of twin-domain interfaces, with the implication that the presence of a similarly twinned structure in the absence of antiferromagnetism would give rise to a similar high-damping phenomenon. This is not the case. Even though the same martensitic reaction that yields the twin-domain structure in Mn-Cu alloys is responsible for the twinned structures in In-Tl and Au-Cd alloys, the highly amplitude dependent, high-damping peak has only been observed in the antiferromagnetic Mn-Cu alloys [19].

The purpose of this paper is to report studies of IF and Young's modulus changes in samples of laboratory cast SONOSTON, and to compare the results with those obtained on a binary Mn-Cu alloy and samples cut from a 200-kg naval propeller blade cast from SONOSTON.

II - MATERIALS AND TECHNIQUE

Compositions of the alloys used in this study are listed in Table I. Samples A and B were cut from ingots cast at the Physical Metallurgy Research Laboratory (PMRL) of Energy, Mines and Resources, Canada, and C was cut from a propeller blade provided by Defence Research Establishment Atlantic, Halifax. The foundry characteristics and mechanical properties of the materials are detailed elsewhere [20,21]. Samples in the form of small, rectangular prisms, typically 50 mm x 2.5 mm x 1.3 mm, were tested in a low-frequency flexure pendulum [22]. To accommodate the large zero-point drift that frequently occurs during the initial heating of commercial alloys, particularly samples in the "as-machined" state, the average gap between the pendulum and the transducer was continuously monitored and adjusted, when necessary, using a computer-controlled stepping motor.

III - INTERNAL FRICTION AT ROOM TEMPERATURE

Samples of the laboratory cast materials, A and B, were tested in three conditions: (1) air cooled after 2 h at 450°C, (2) cooled at 0.2°C/min after 2 h at 850°C, and (3) water quenched after 2 h at 850°C. Surprisingly, only the propeller itself, sample C, gave the expected high damping. As shown in Figure 1, samples of A could be obtained in the high damping state after a fresh heat treatment at 450°C, but the damping was not stable and gradually aged away at room temperature (RT). In contrast, the high damping in the propeller material was suppressed by a water quench from 850°C. Subsequent aging in the range 400 to 450°C gave rise to even higher damping than in the "as-cast" condition, but the damping decayed away to approximately the original level of the "as-cast" condition with aging for about 1 month at RT.

Previous studies of the high-damping state in Mn-Cu alloys have revealed small segments of a peak of damping as a function of amplitude at RT [6]. In this study, in some samples of C, most of the peak fell into the window of strain amplitudes observed, as shown in Figure 2. Such a peak is typical of unpinning phenomena and of the damping observed in ferromagnetic alloys in the absence of a saturating magnetic field or a static bias stress. It was established that the damping has the following properties: (i) it is substantially reduced by a static tensile bias stress, (ii) it is altered by prolonged vibration at a particular amplitude, and (iii) it shows a marked hysteresis when measured over a closed loop of increasing and decreasing amplitudes. All of these results can be understood, at least qualitatively, if the mechanism involved is the interaction of antiferromagnetic domain boundaries with pinning points that have some mobility at RT. We suspect that higher levels of C and Si in solution in the laboratory cast samples are responsible for the pinning of the domains that leads to the relatively rapid aging away of the high damping at RT.

IV - INTERNAL FRICTION FROM ROOM TEMPERATURE TO 600°C

The IF spectra of the SONOSTON samples, A and C, are almost identical at low strain amplitudes $< 10^{-5}$. A typical example is shown in Figure 3. It has three main features: (i) a peak at or below RT, (ii) a shoulder at ~ 250°C, and (iii) a well-defined peak at ~ 400°C. The corresponding curve for the changes in Young's modulus shows a minimum at ~ 60°C - the Néel temperature - and a broad anomalous peak over the range from about 100°C to 350°C. Similar anomalous behaviour of the elastic modulus has been reported in other antiferromagnetic Mn-based alloys [23,24]. The spectrum of the binary alloy, B, is somewhat different, as shown in Figure 4. Initial heating of this material in state 1 revealed the major peak at ~ 400°C, as in SONOSTON, and a well-defined peak at ~ 250°C. At temperatures lower than the 250°C peak, the damping is low and featureless, while the Young's modulus passes through a broad minimum from about 130°C to 190°C. Further observations of the IF in the temperature range from RT to 600°C showed that in the SONOSTON samples, the IF was amplitude dependent below the Néel temperature and essentially amplitude independent above it.

We attribute the low-temperature, amplitude-dependent peak that is responsible for the high-damping properties of SONOSTON to the stress-induced movement of antiferromagnetic domain boundaries. The peak at ~ 400°C has been reported previously [8], with the speculation that it is a Zener relaxation. From the shift of the peak with frequency over the narrow range of 2 to 6 Hz, we find that the relaxation enthalpy, H_R, and the pre-exponential factor, τ_o, are given by

$$H_R = (1.82^{+0.18}_{-0.11})\ \text{eV} \quad \text{and} \quad \tau_o = 10^{-(15^{+1.3}_{-1.1})}\ \text{s}$$

and the peak is only ~ 15% broader than a single-time-of-relaxation peak. H_R is close to, but slightly lower than, the diffusion enthalpy of the faster diffuser Mn, and the value of τ_o is in keeping with the D_o value obtained by more standard diffusion techniques [25]. Increasing the concentration of vacancies by heat treating at 850°C, followed by water quenching, shifts the peak to lower temperatures, as expected for a Zener relaxation.

V - CONCLUSIONS

The high damping at RT in SONOSTON is non-linear and typical of the movement of magnetic domain boundaries. It is only observed below the Néel temperature and is attributed to the stress-induced movement of antiferromagnetic domain boundaries. The peak observed at ~ 400°C is most probably a Zener relaxation associated with the stress-induced ordering of Mn atoms.

VI - REFERENCES

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TABLE I COMPOSITIONS OF THE ALLOYS

DESIGNATION	ALLOY	ELEMENTS (wt.%)						
		Mn	Cu	Al	Fe	Ni	C	Si
A	PMRL SONOSTON	55.5	36.2	3.79	3.04	1.17	0.046	0.11
B	BINARY Mn-Cu	53.2	46.8	-	-	-	0.15	0.06
C	PROPELLER	52.4	38.3	4.36	3.16	1.42	0.095	0.07

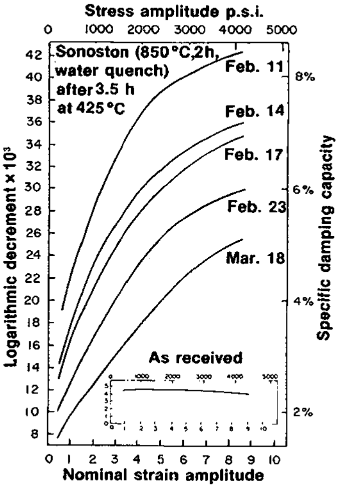

FIG. 1. Ageing at room temperature in laboratory cast SONOSTON (material A) after annealing at 425°C.

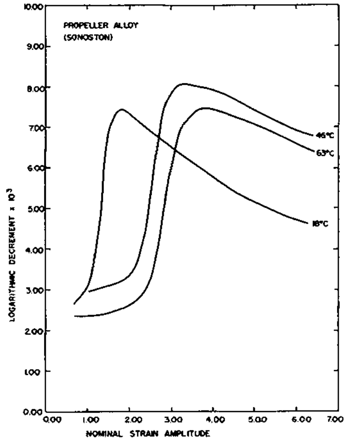

FIG. 2. IF vs. amplitude peaks on cooling the propeller material from 600°C. f ∿ 4Hz, strain amplitude = nominal amplitude x 2.0 x 10^{-6}.

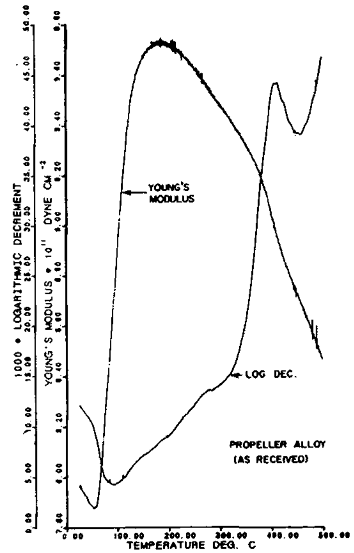

FIG. 3. IF and Young's modulus spectrum of the propeller material measured at a strain amplitude of 1.25 x 10^{-5}.

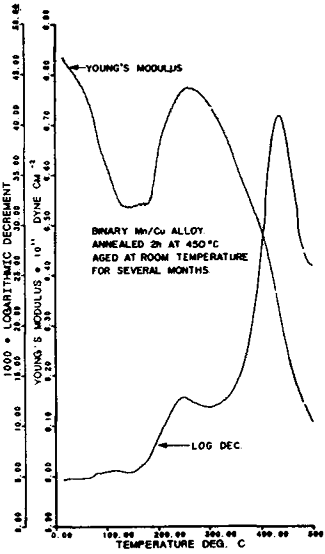

FIG. 4. IF and Young's modulus spectrum of the binary Mn/Cu alloy measured at a strain amplitude of 2.1 x 10^{-5}.