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INTERNAL FRICTION IN SOME HIGH-DAMPING ALLOYS

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Résumé - On a décrit les caractéristiques d'amortissement de deux matériaux marchands à amortissement élevé: un alliage à base de Mn-Cu et un alliage de Zn-Al. Un element important de l'amortissement de l'alliage à base de Mn-Cu est fonction de l'amplitude mais n'est que faiblement fonction de la fréquence. Au contraire, dans le cas de l'alliage de Zn-Al, l'amortissement n'est pas fonction de l'amplitude et est fonction de la fréquence. On a effectué des essais dans les éventails de température et d'amplitude de déformation par vibrations qu'on rencontrera probablement lorsqu'on utilisera ces alliages. On a examiné les mécanismes d'amortissement se produisant dans ces deux alliages.

Abstract - The damping characteristics of two commercial, high-damping materials, a Mn-Cu based alloy and a Zn-Al alloy, have been characterized. A major component of the damping in the Mn-Cu based alloy is amplitude-dependent and only weakly frequency-dependent. In contrast, the damping in the Zn-Al alloy is amplitude-independent and frequency-dependent. Tests have been carried out over the ranges of temperature and vibrational strain amplitude likely to be encountered in the applications of these alloys. Damping mechanisms in the two alloys are also discussed.

I - INTRODUCTION

The study of internal friction has played a vital role in establishing many of the properties of crystalline defects, including their configuration, movement and interaction [1-4]. Since internal friction is the capacity of a material to covert the mechanical energy of vibrations into heat that is dissipated in the material, the property can be exploited in practical applications. For example, HIDALLOYS (HIgh Damping ALLOYS), find applications in structures where vibrations and noise are unwanted [5].

In this paper, we outline the characterization of the internal friction or damping properties of two HIDALLOYS in which the mechanisms responsible for the elevated damping levels are very different. The first has the trade name SONOSTON [6]. It is an Mn-Cu based alloy developed by Stone Manganese Marine Limited [7] as a "quieter" propeller material for submarines. In addition to good mechanical and corrosion properties, shaft vibrations and other noise are to a large extent dissipated in the material of the propeller, rather than being "broadcast" acoustically through the sea, revealing the position of the source. The second HIDALLOY is a die-cast Zn-Al based alloy, specifically Zn-27 wt% Al, designated ZA27 by the producer, Noranda Limited [8]. This alloy has high as-cast strength, hardness and wear resistance, as well as other favourable physical properties. These properties make it an attractive alternative to aluminium, brass, bronze or iron for the designer of structures and machine parts that can be die-cast. Furthermore, under certain restricted service conditions, ZA27 can probably be classified as a HIDALLOY. This enhances its attractiveness in the majority of applications, particularly those in powered vehicles, such as automobiles and aircraft, where the reduction of vibration and noise is one of the primary objectives of the designer.

The purpose of this paper is to show how a few, well-selected tests with just two of the most popular techniques available in many internal friction laboratories can give an overall picture of the most important damping features of a given HIDALLOY. This approach involves low-frequency measurements with a pendulum device and high-frequency measurements by a piezoelectric, ultrasonic, composite oscillator technique (PUCOT). Of course, such an approach does not eliminate the need to carry out exhaustive tests at the frequencies to be encountered by the HIDALLOY in service, nor does it eliminate the need to evaluate the performance of the HIDALLOY in the field. It does, however, as an initial survey, reveal many of the phenomenological attributes of the damping mechanism, or mechanisms, involved, and allows the investigator to predict behaviour at intermediate frequencies and plan a more complete characterization of the damping over the whole frequency range of interest.

II - PREVIOUS WORK

a) SONOSTON. The high damping capacity exhibited by certain alloys of the Mn-Cu system has been known for a long time. Many studies of internal friction, elastic modulus changes, X-ray diffraction, neutron diffraction and metallography [9-21] have established that the high-damping state is associated with a metastable, antiferromagnetic, tetragonal structure, which appears after aging the alloy in a temperature range corresponding to a miscibility gap [15,18,21] in the phase diagram. Most of these studies have been on high Mn ($\geq$ 60 wt%) binary Mn-Cu alloys. Little detailed work on the high-damping characteristics of the alloys that have found practical applications has been reported. Most authors have attributed the high damping in Mn-Cu based alloys to the movement of twin-domain interfaces. More recently, we have presented experimental evidence that the antiferromagnetism of SONOSTON plays an important role in the damping mechanism [22]. Both the amplitude-dependent and amplitude-independent components of the damping behave in a manner closely analogous to their counterparts in ferromagnetic alloys [2-4] at low frequencies and near-ambient temperatures. We are not aware of any previous studies of SONOSTON at PUCOT frequencies.

b) ZA27. It has been known for some time that certain zinc-aluminium alloys fall into the category of HIDALLOYS at frequencies of about 1 Hz and temperatures from ambient to about 100°C [23]. Again, little work has been reported on the damping characteristics of zinc-aluminium foundry alloys. However, Otani et al. [24] demonstrated a systematic difference in the damping observed in samples of Zn-27 wt% Al taken from the interior or from the surface of a casting. In addition, they observed only a weak dependence of the damping on frequency in the range from 20 to 100 Hz.

III - MATERIALS AND TECHNIQUES

Typical compositions of the HIDALLOYS used in this study are given in Table 1. Samples DR-1 and DR-4 were cut from the thick end and thin end, respectively, of a propeller blade provided by the Defence Research Establishment Atlantic, Halifax, Canada. Although the overall compositions of these samples were similar, the compositions of the dendrites and interdendritic regions were substantially different [25], reflecting the different cooling rates, in the two regions of the blade after casting. The ZA27 samples were cut from the gauge section of large, die-cast, tensile-testing samples of the usual dog-bone configuration. These samples were provided by Noranda Limited, Pointe-Claire, Quebec, Canada.

TABLE 1 COMPOSITIONS OF THE ALLOYS

Designation	Alloy	Elements (wt%)						
		Mn	Cu	Al	Fe	Ni	C	Si
DR-1, DR-4	SONOSTON	55.2	38.3	4.36	3.16	1.42	0.095	0.07
		Al	Cu	Mg	Fe	Pb	Cd	Sn
ZA27	Zinc-Aluminium Die-Cast	25-28 (Balance is Zn)	2.0-2.5	0.01-0.02	0.10	0.004	0.003	0.002

Samples were machined from the as-received, as-cast, materials into small, rectangular prisms, typically 50 mm x 2.5 mm x 1.0 mm for testing in a low-frequency flexure pendulum, and 60 mm x 3 mm x 3 mm for PUCOT measurements. The flexure pendulum used in this study has been described elsewhere [26].

Our PUCOT apparatus is of conventional design [27,28] and uses an identical pair of -18.5^{o} X-cut, quartz crystals, with a fundamental, longitudinal resonant frequency of 40 kHz, as the driver and gauge crystal. Once again, our electronic system is designed so that damping can be measured in free decay (using a digital oscilloscope), in closed-loop drive, or from the half-width of resonance curves. The length of each sample tested in the PUCOT apparatus was carefully cut down from the 60 mm mentioned above so that it matched the required resonant frequency of about 40 kHz.

IV - DAMPING AT ROOM TEMPERATURE

a) SONOSTON. The damping of SONOSTON at room temperature and pendulum frequencies increases with strain amplitude, ε, over the range $10^{-6} \leq \varepsilon \leq 2 \times 10^{-4}$, and shows signs of a peak as a function of strain amplitude at $\varepsilon > 10^{-4}$ [22]. Figure 1 shows damping as a function of strain amplitude for SONOSTON at PUCOT frequencies. These curves show that the damping is independent of strain amplitude over the range from $10^{-7} < \varepsilon < 10^{-5}$ and amplitude-dependent for $\varepsilon \geq 4 \times 10^{-5}$. They also show a softening of Young's modulus in the amplitude-dependent range and a marked difference in damping between the thick end (DR-1) and the thin end (DR-4) of the propeller. From Figure 1 it can be concluded that the cooling rates present during casting did not leave the material in the optimum high damping state. Indeed, a further heat treatment of 2 h at 700 K increases the overall damping considerably. From a comparison of the low-frequency results and PUCOT data, it can be concluded that the damping consists of two components at room temperature: an amplitude-independent component and an amplitude-dependent component. The amplitude-dependent component dominates at pendulum frequencies, while both components are comparable in magnitude at 40 kHz and $\varepsilon \sim 2 \times 10^{-4}$.

As shown in Figure 2, the softening of Young's modulus in the amplitude-dependent damping range leads to the classical hysteresis and jump-phenomenon in the resonance curves. This is accompanied by harmonic generation described in a separate paper [29].

b) ZA27. Figures 3(a), 3(b) and 4 show data measured in the flexure pendulum at room temperature. From these results the following conclusions can be drawn:

i) there is a significant variation in damping from sample to sample consistent with structure (porosity) variations in the die-casts.
ii) the damping is lower in samples aged for one week at 95°C after die-casting.
iii) the variation of damping with frequency and sample thickness shows that there is a significant component of thermoelastic damping, as expected in a high-zinc-content alloy [1].
iv) the damping is amplitude-independent over the range $10^{-6} \leq \varepsilon \leq 10^{-4}$, as shown by the set of resonance curves in Figure 4.

Damping as a function of strain amplitude at room temperature is compared for pendulum and PUCOT frequencies in the top diagram of Figure 5, which shows that the damping is amplitude-independent at both frequencies and decreases in level at the higher frequency. These results suggest the involvement of dynamic hysteresis phenomena.

V - DAMPING FROM ROOM TEMPERATURE TO 120°C

a) SONOSTON. Damping and dynamic Young's modulus curves as a function of temperature for a sample of DR-1 are shown in Figure 6. The minimum in Young's modulus marks the Néel temperature for the material. At temperatures below the minimum, the material is antiferromagnetic and the damping contains two components, an amplitude-dependent component and an amplitude-independent component. At temperatures higher than that of the minimum, the material is paramagnetic and the damping is amplitude-independent. Figure 6 also shows that the complicated peak structure at about room temperature at pendulum frequencies, is shifted to higher temperatures at the PUCOT frequency and is truncated around the Néel temperature. An unexpected feature of these results is the very large increase in the overall peak height with frequency. It should also be noted that an appropriate heat treatment can further increase the damping level at both frequencies.

b) ZA27. The lower portion of Figure 5 shows damping as a function of temperature for ZA27 at 4 Hz and 40 kHz. When allowance is made for the thermoelastic component at low frequencies, these curves can be interpreted as the low-temperature flank of a peak shifted to higher temperatures at higher frequencies. With this interpretation, an estimate of the activation enthalpy of the process can be made. The result is 107 kJ/mol, which is the same value as that obtained by Murphy et al. [30] for the activation enthalpy of creep in ZA27. It is also close to the value of 109 kJ/mol obtained by Nuttall [23] from the low-frequency internal friction of the Zn-Al eutectoid alloy (Zn-22 wt% Al). These results suggest that the mechanism involves the movement of grain boundaries in the material, related to superplasticity.

VI - CONCLUSIONS

Relatively high damping is observed in as-cast or heat-treated SONOSTON samples, at high strain amplitudes and temperatures from ambient to the Néel temperature, and over a frequency range from 1 Hz to 40 kHz. At least two mechanisms are involved, one amplitude-dependent and one amplitude-independent. The amplitude-dependent phenomenon disappears at temperatures above the Néel temperature. From the peak shift of the amplitude-independent component with frequency from 4 Hz to 40 kHz, we find an activation enthalpy of 49.6 kJ/mol (0.51 eV), which is similar to the value of 51.4 kJ/mol (0.53 eV) found by Sugimoto et al. [10] for the high-damping peak in binary Mn-Cu alloys with Mn content ranging from 89 to 74 wt%. The behaviour of the amplitude-dependent damping in the antiferromagnetic phase is analogous to the amplitude-dependent damping in ferromagnetic materials, attributed to magnetostrictive movement of Bloch walls. By analogy we believe that the high damping observed at high strain amplitudes in SONOSTON is associated with the movement of antiferromagnetic domain boundaries.

The high damping observed in low-frequency bending of samples of ZA27 consists of two amplitude-independent components. One is due to thermoelasticity and the other is probably associated with the movement of grain boundaries. The material shows promise as a HIDALLOY for frequencies in the range from 1 to 100 Hz and temperatures from ambient to about 100°C.

VIII - ACKNOWLEDGEMENTS

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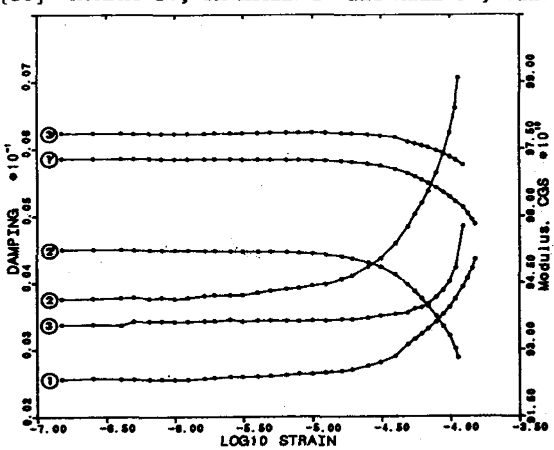

Fig. 1 PUCOT damping and dynamic Young's modulus as a function of strain amplitude. (1) as-received DR-4, (2) as-received DR-1 and (3) DR-4 after 2 h at 700 K and furnace cooling.

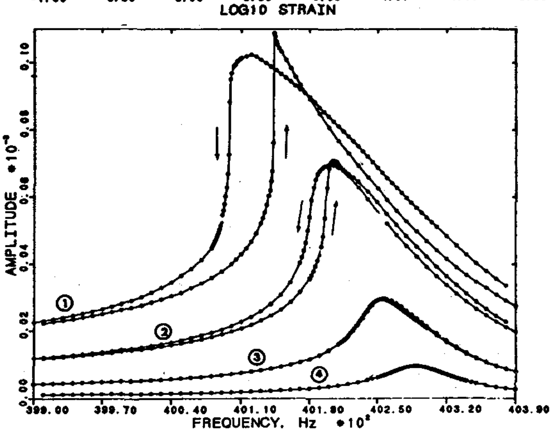

Fig. 2 Resonant frequency curves showing hysteresis and the jump phenomenon at high amplitudes in the sample corresponding to curve 3 in Figure 1.

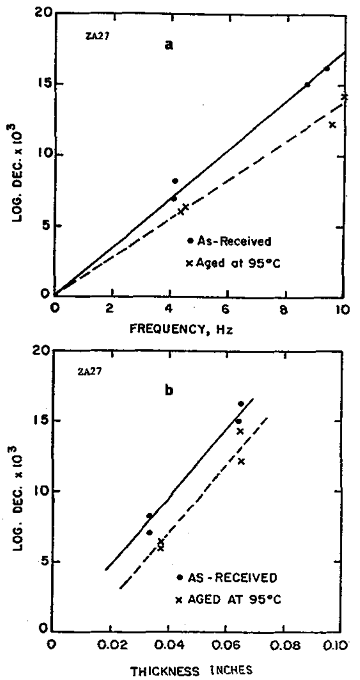

Fig. 3 Flexure pendulum results on ZA27. a) damping vs. frequency and b) damping vs. sample thickness.

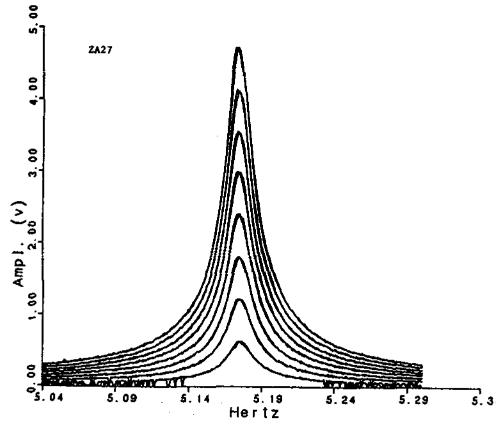

Fig. 4 A family of resonance curves measured in the flexure pendulum on ZA27. The height of the peaks increases with force amplitude, the peaks are symmetrical, with constant half-widths, and there is very little hysteresis.

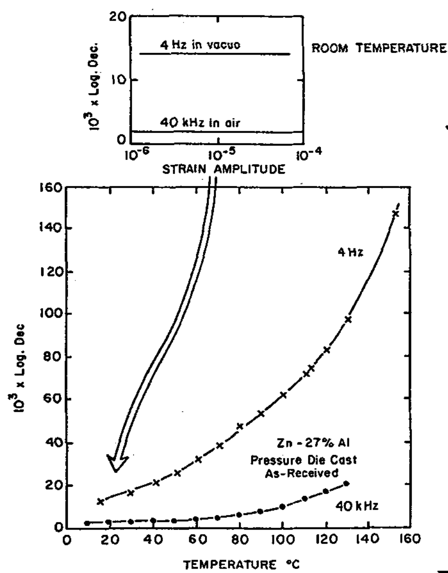

Fig. 5 Damping vs. strain amplitude (top) and damping vs. temperature (bottom) for ZA27 compared at pendulum and PUCOT frequencies.

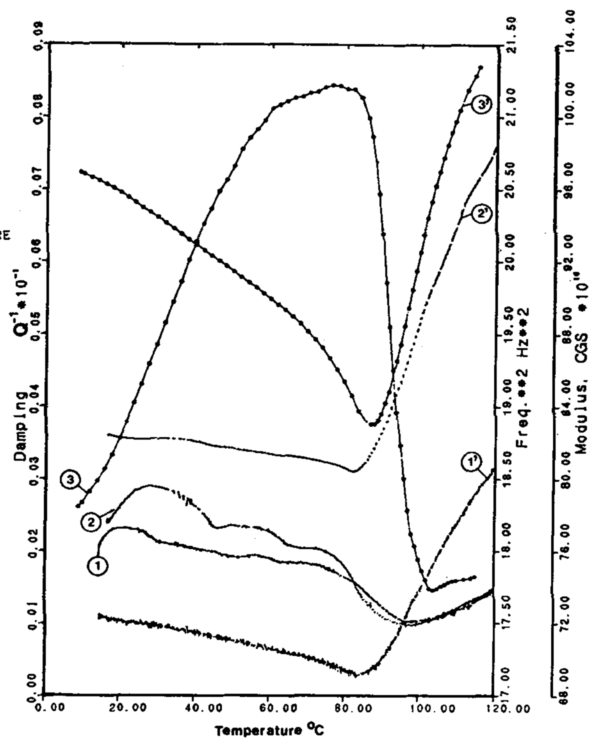

Fig. 6 Damping and Young's modulus (indicated by primes) vs. temperature ($\varepsilon = 2 \times 10^{-5}$) for DR-1. Curves 1,1' and 2,2' are pendulum results for the as-received and heat-treated conditions, respectively. Curves 3,3' are for the as-received condition at 40 kHz.