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FACTORS EFFECTING INTERNAL DAMPING IN ALUMINUM

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The internal damping of metallic materials varies with many different environmental effects. These are the frequency, amplitude of strain or stress, and temperature. In addition, internal damping is effected by corrosion fatigue, grain size, and porosity. The damping also depends on the number of fatigue cycles. There is a functional relationship among the damping, number of cycles and applied stress. In this study, these seven different environmental factors and their effects on the damping are analysed in the case of 6061 aluminum alloy. The relationships between the damping and every single effective factor are complex and vary depending on the aluminum type.

Key words: aluminum, damping, vibration

1. Introduction

The internal damping, which basically means energy dissipation in materials under cyclic loading is an important design parameter especially for vibrating structures such as those encountered in the airplane, oil and automobile industry. Using different experimental and numerical methods, the damping has been studied in various engineering metals. Also, many different parameters have been used in those studies, because the damping varies with some environmental factors.

If a material is simple (a single crystal, pure metal, etc.) and only one or two of environmental factors are effective, the determination of the damping relations will be much easier. However, aluminum used in structures and machine parts is usually compound and subjected to many environmental factors some of which may decide about the damping level. Beside the complexity, some generalizations can be made for the damping relations in engineering applications for aluminum.

2. Factors effecting the damping

2.1. Frequency

The effects of frequency on the damping were investigated for aluminum in different studies, see Bhagat *et al.* (1989), Banhart *et al.* (1996), Basavanhally and Marangoni (1977), Gibson and Plunkett (1977), Lee and McConnell (1975), Lin and Plunkett (1989). For the first three modes, the loss factor – resonant frequency characteristics were explained for 6061 aluminum alloys by Bhagat *et al.* (1989) and are shown in Figure 1.

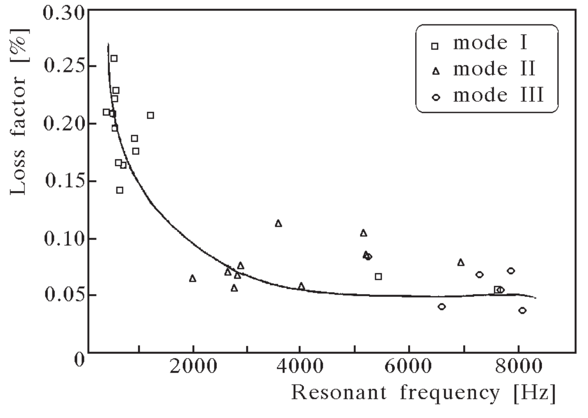

Fig. 1. Experimental data for 6061 Al cantilever beam specimens vibrating in the first three flexural modes (see Bhagat *et al.*, 1989)

In that study, the experiment was designed to measure the logarithmic decrement of freely decaying resonance oscillations in fixed-free beam specimens. A large number of resonant frequencies were found in each mode by changing the dimensions of the beam. According to Fig. 1, the loss factor in 6061 Al alloys depends on the frequency modes and the resonant frequency itself. The modal average loss factors were measured 0.00197, 0.00079, and 0.00057 for mode I, II, and III, respectively, at the fixed-free condition. Also, the loss factor occurred to be a function of frequency in two different composite aluminums, see Gibson and Plunkett (1977), Lin and Plunkett (1989). On the other hand, the obtained loss factors were nearly independent of frequency for low frequencies in aluminum foams. For high frequencies, see Banhart *et al.* (1996), Liu *et al.* (1998, 2000), the loss factor decreased with increasing frequency.

2.2. Cyclic strain amplitude

A plot of the measured loss factor versus strain amplitude is shown in Fig. 2 for 6061-T6 Al alloy along with the theoretical prediction based on a random-yielding hysteresis loop model described by Whiteman (1959), and modified to include the frequency dependence at low strain levels, see Whaley *et al.* (1984).

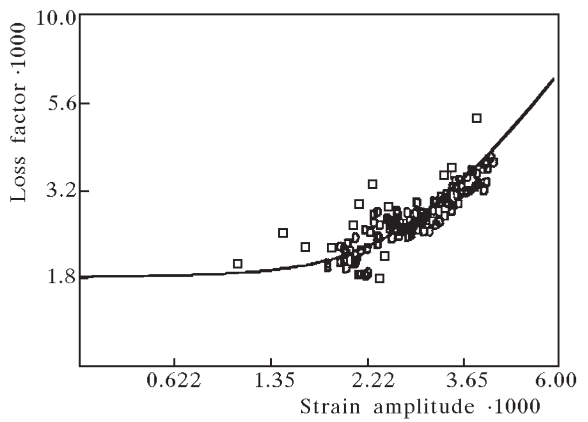

Fig. 2. Loss factor versus strain amplitude for 6061-T6 aluminum (rearranged from Whaley *et al.* (1984))

In Fig. 2, the damping is independent of the strain amplitude until the critical strain level required for material damage is exceeded: if the maximum strain amplitude is over the critical strain level, which is approximately 40 to 45% of the ultimate strength S_u, the damping increases permanently, see Fig. 2. Results presented by Gibson and Plunkett (1977), Lin and Plunkett (1989) are also in good agreement with this conclusion for a 6061-T6 Al alloy specimen coated with a transverse carbon/epoxy composite material which was sinusoidally loaded in the axial direction, and a 2024-T351 0/90 scotchply Al alloy specimen which was loaded in a bending vibration test. In addition, pure aluminum was similar, compare Mason(1956). Moreover, besides the maximum strain amplitude, the damping depends on the resonant frequency for a powder metallurgically produced aluminum composite, see Fig. 3 (Göken and Riehemann, 2002). Admittedly, the damping non-linearly increases with the strain amplitude in foamed aluminum, Banhart *et al.* (1996), Liu *et al.* (1998, 2000), however the dependence is rather weak for low amplitudes.

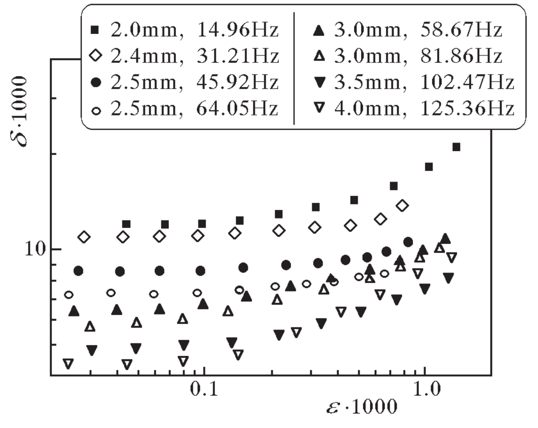

Fig. 3. Logarithmic decrement versus maximum strain (logarithmic scale) for various beam thicknesses and resonant frequencies (see Göken and Riehemann, 2002)

2.3. Porosity

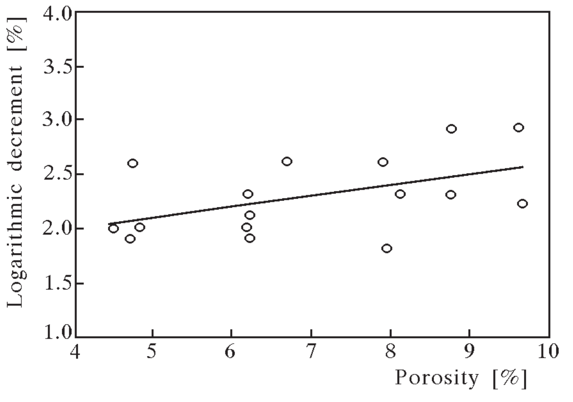

Fig. 4. Relationship between damping capacity and porosity for as-deposited 6061 Al alloy (see Zhang *et al.*, 1993)

Porosity is an important factor to be considered in the fatigue and brittle fracture problems in engineering design. It is well known that the strength of materials decreases with an increase in porosity. Higher porosity levels produce higher damping in engineering metals. Figure 4 shows a relationship between the damping capacity and porosity for 6061 Al alloy as deposited (Zhang *et al.*, 1993). Beside scattered data points, the average damping capacity increases approximately by 25% with an increase in porosity from 5% to 10%. Also, some data for foamed aluminum to describe damping-porosity relations is available by Liu *et al.* (1998, 2000).

2.4. Corrosion

Corrosion is also an effective factor for fatigue failures in aluminum. Corrosion combined with cyclic stress, called corrosion fatigue, is more destructive than either corrosion or fatigue alone. For example, the maximum cyclic stress decreases down to 110 MPa for 6061 Al alloy when a fracture occurs at 10^6 cycles in a 3.5% NaCl solution relative to that in the air (Minoshima *et al.*, 1998). In this example, the stress ratio R was one under a combined tension-torsion loading. Corrosion fatigue was studied for 2024-T3 Al alloy by Dolley *et al.* (2000) and for Al-7.5Zn-2.5Mg alloy by Dowling (1999). As shown in Fig. 5, the testing in a salt solution lowers the S-N curve for the aluminum alloy.

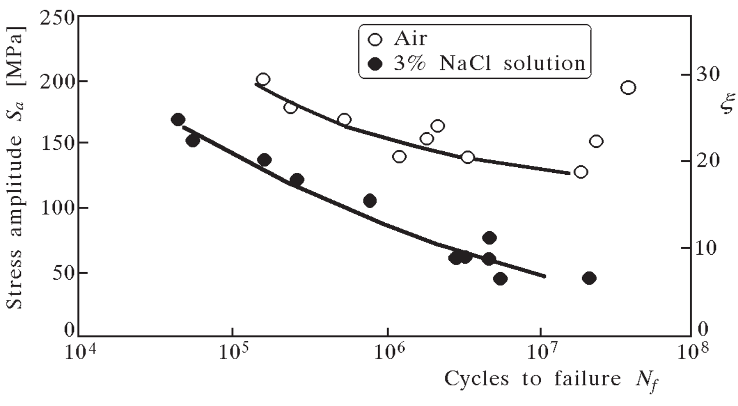

Fig. 5. Effect of salt solution similar to seawater on bending fatigue behavior of Al-7.5Zn-2.5Mg alloy (see Dowling, 1999, p. 385)

2.5. Grain size

The fine-grained microstructure of 6061 Al alloys may also play an important role in increasing the fatigue life (Carlson *et al.*, 1998). The dissipated energy depends on the magnitude of the shear stress and inelastic shear strain, and is also proportional to the grain boundary area per unit volume. In other words, energy dissipation is inversely proportional to the grain size. For example, the loss factor is 0.7 for 32 μm grains and 0.8 for 22 μm grains in as-spray-deposited 6061 aluminum alloys within the same strain amplitude range, i.e. from ± 340 to ± 60 micro-strain (Zhang *et al.*, 1993).

2.6. Temperature

For metals and crystalline ceramics, creep deformation occurs above a temperature that is generally within the range of 30 to 60% of its absolute melting temperature (Dowling, 1999). Therefore, the effects of temperature on the damping are very low and negligible in aluminum and its alloys at ambient temperatures. However, temperature is usually the most important single factor that effects on the damping in polymers (Nasif *et al.*, 1985).

The behaviour of the internal damping in 2618-T6 Al, 7075-T7351 Al, and rapidly solidified Al-Fe-Mo-Si/Al alloys was analyzed by Shenglong *et al.* (1998). The loss factor versus temperature characteristics were explained experimentally.

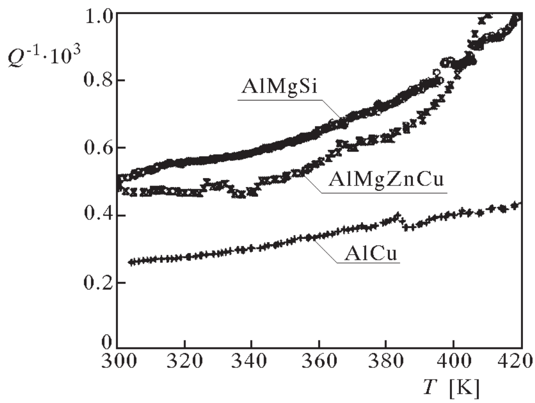

Fig. 6. Damping in three commercial aluminum alloys; 1 – 2017 Al, 2 – 7022 Al, and 3 – 6082 Al (see Xie *et al.*, 1998)

The loss factor remains constant below and around 150°C for 2618-T6 Al and 7075-T7351 Al alloys. Above approximately 150°C, the loss factor increases with increasing temperature. In addition, the effects of the frequency on the damping-temperature characteristics were investigated in same study. The damping is unambigously frequency-dependent above 50°C, with the lowest frequency resulting in the highest loss factor found by the torsion pendulum method. Similar relations were observed in foamed aluminum and bulk pure aluminum by Wei *et al.* (2002b), and for some aluminum composites by

Wei *et al.* (2002a). The damping, temperature, and frequency relations were studied there. Beside the frequency, some density or porosity effects on the damping-temperature relations were introduced by Gui *et al.* (2000). Finally, Fig. 6 shows the loss factor measured in the free-free bar apparatus at approximately 3 kHz as a function of temperature in three investigated aluminum alloys (Xie *et al.*, 1998). One observes that 2017 Al alloy presents a lower damping than 6082 Al alloy and 7022 Al alloy. The damping increases moderately with increasing temperature. In 6082 Al and 7022 Al alloys, the damping level is almost two times higher than in 2017 Al alloy. In same study, the effects of the strain amplitude and heat treatment on the damping-temperature characteristics were analysed. For example, Fig. 7 shows the damping of a 6082 Al alloy 1 hour solution-treated at 813 K and quenched into cold water. A strong damping-amplitude effect is observed for strain amplitudes higher than 10^{-3} in the low frequency range.

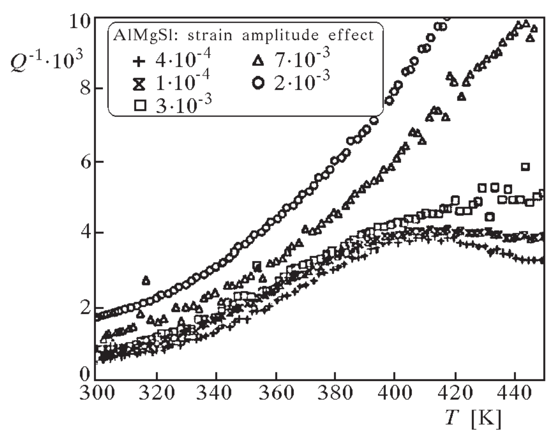

Fig. 7. Strain amplitude effect on damping-temperature relation for 6082 Al alloy 1 hour solution-treated at 813 K and quenched into cold water (see Xie *et al.*, 1998)

2.7. Number of fatigue cycle

The micro-mechanical theory of crack initiation was applied to aluminum single crystals, and hysteresis loops were analyzed under high-cycle fatigue in three-dimensional elasto-plastic deformation by Lin *et al.* (2000). It was found that the shape of hysteresis loops and the number of fatigue cycles were affected by the distribution of the initial stress. In Pedersen and Tvergaard (2000), a numerical cell model analysis was used to study fatigue damage in aluminum reinforced by aligned short SiC fibres. The matrix material was represented by a cyclic plasticity model in low cycle fatigue. An increased fiber aspect ratio gave a stiffer material response with the corresponding narrower hysteresis loop. Using a 355 stainless steel/2024-T8 Al alloy composite, a constant damping coefficient was computed for specimens subjected to different stress amplitudes that covered a range of the cyclic life in axial fatigue tests (Varschavsky and Tamayo, 1969).

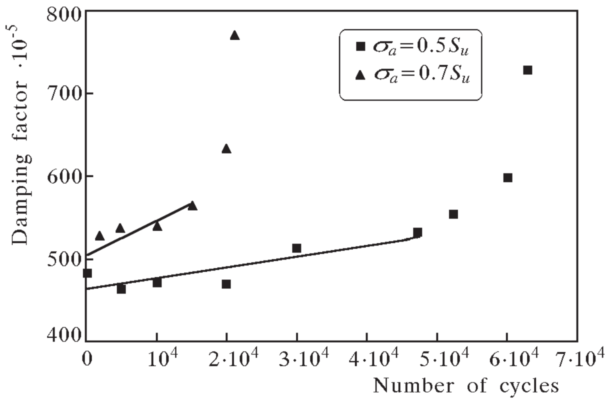

Fig. 8. Measured damping factors for 6061-T6511 Al alloy under bending vibration load

Using a technique of damping monitoring, characteristics of the damping versus number of cycles were studied in 6061-T6511 Al alloys (Colakoglu and Jerina, 2003). The measured damping factor versus the number of fatigue cycle and linear curve-fit of the measured results (solid lines) up to crack initiation are shown in Fig. 8 for the first vibration mode. The damping factor increases with the number of fatigue cycles as expected. The increase is small up to fatigue crack initiation, and a significant increase is seen in energy dissipation after crack initiation that occurs after 4.5×10^4 cycles for $\sigma = 0.5S_u$, and 1.5×10^4 cycles for $\sigma = 0.7S_u$, see Fig. 8.

3. Conclusion

Apart from mechanical properties and testing techniques, the internal damping in aluminum depends on many different environmental factors. Seven of them have been explained in this paper with the survey of previous studies taken into account. The damping occurs to change with different factors. The changes may vary in different conditions. Sometimes these factors are negligible, but usually their effect on the damping is of major design concern in vibrating structures.

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Czynniki wpływające na poziom tłumienia wewnętrznego w aluminium

Streszczenie

Tłumienie wewnętrzne w materiałach metalicznych zmienia się w zależności od wpływu wielu czynników środowiskowych. Czynnikami tymi mogą być częstość i amplituda przykładanego naprężenia i odkształcenia oraz temperatura. Ponadto na tłumienie wewnętrzne wpływa zmęczenie korozyjne, rozmiar ziarna i porowatość materiału. Tłumienie zależy również od liczby zrealizowanych cykli zmęczeniowych. Istnieje funkcyjna relacja pomiędzy wartością współczynnika tłumienia a liczbą cykli i stanem naprężenia. W pracy zaprezentowano siedem różnych czynników środowiskowych decydujących o poziomie tłumienia wewnętrznego na przykładzie stopu aluminium 6061. Zależności pomiędzy współczynnikiem tłumienia a każdym z tych czynników z osobna okazały się dość skomplikowane i wrażliwe na typ badanego aluminium.

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