The Effects of Static Strain on the Damping Capacity of High Damping Alloys

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Influences of static strain on the damping capacity in Mn-based M2052 and Fe–6Al alloys were studied with the forced flexural oscillation method by using a dynamic mechanical analyzer (DMA). The static surface strain was applied on the 3-point bending specimens in the range of $10^{-3}$–$2 \times 10^{-5}$. The damping capacity of the M2052 alloy showed a continuous increase, but that of the Fe–6Al alloy showed a continuous decrease with increasing static strain in the range below $1 \times 10^{-3}$. The variation of the damping capacity with increasing static strain was fitted with an exponential function, and the exponential index turned out to be 0.25 and $-0.5$ for the M2052 and Fe–6Al alloys, respectively. Static strains in the vicinity of $1 \times 10^{-4}$ caused the formation of a damping peak, which accelerated the increase of the damping capacity in the M2052 alloy, but softened the decrease of the damping capacity in the Fe–6Al alloy. A significant reduction of the damping capacity appeared at static strains above $1 \times 10^{-4}$ in both high damping alloys.

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1. Introduction

Material damping, on its own or accompanied with active damping measures, is becoming the prominent method to control vibration and noise in vehicles and instruments. In contrast to the viscoelastic materials, such as rubbers and plastics, high damping alloys illustrate adequate damping capacities, as well as superior stiffness, strength and durability. Because of the highly nonlinear nature of high damping alloys, the damping capacity varies with many environmental factors, e.g., temperature, strain amplitude, frequency and static preload, which usually change extensively in practical service conditions. Therefore, the characterization of the damping behavior under the practical application environments becomes indispensable for supplying adequate information of high damping alloys to the mechanical designers.

In a previous work, a contour map format for the damping capacity was proposed to show the effects of both the strain amplitude and the frequency, based on the measurement of the resonant peaks of the centrally excited high damping alloy beams. With this centrally excited beam method, the damping behavior of high damping alloys can be characterized for oscillations in the strain amplitude range of $1 \times 10^{-6}$–$1 \times 10^{-3}$ and the frequency range of 50–4000 Hz, simultaneously. However, very few experimental result have been reported on the effect of the static preload on the dynamic properties of damping materials which is commonly encountered in practical applications of high damping alloys.

A general theory was developed to predict the combined linear dynamic and nonlinear static behavior for viscoelastic materials, based on the experimental results of the dynamic and static properties measured separately. Based on this theory, the damping capacity of the viscoelastic materials was calculated to decrease with the application of the static preload. However, it seems impossible to determine the nonlinear static behavior of damping alloys accurately, because the elastic strain range of the alloys is much smaller than that of the ordinary viscoelastic materials. Since the natural frequencies and the vibration mode of a resonant beam specimen may change when static preload is appended through some attachments, it is reasonable to choose the forced oscillation experiment to measure the effects of the static preload. We used the oscillation frequencies much less than the natural frequencies of the tested specimens to ignore the influence of the static preload on the vibration mode of the specimens. The flexural deformation mode in the dynamic mechanical analyzer (DMA) was used in the present work, and a static strain was traced during the temperature or frequency sweeping measurement of the damping capacity of some high damping alloys.

2. Experimental Procedure

The M2052 alloy and the Fe–6Al alloy ingots of 20 Kg with compositions of Mn–22.1Cu–5.24Ni–1.93Fe and Fe–5.87Al–0.002C (mass%), respectively, were prepared by induction-melting, using industrially pure metals in an argon atmosphere. $1 \times 10 \times 60 \times 3$ mm$^3$ beam samples were produced by forging and rolling the cylindrical ingots. The M2052 alloy was solid solution treated at 1173 K for $3.6 \times 10^3$ s, and continuously cooled to room temperature in $3.6 \times 10^3$ s in the argon-replaced quartz-capsules. On the other hand, the Fe–6Al alloy was held in an argon atmosphere at 1123 K for $3.6 \times 10^3$ s and then water quenched.

Model 2980 DMA was used to measure the damping capacity of the alloys by temperature and frequency sweeping, under various strain amplitude and static strain levels. Figure 1 shows the flexural deformation geometry of the specimen. The dynamic stress, $\sigma_0 \sin \omega t$ and the dynamic strain, $\varepsilon_0 \sin(\omega t - \phi)$ of the oscillated specimen were measured while applying a sinusoidal driving force, $F_0 \sin \omega t$, which was superimposed on the static force, $F_s$. The elastic modulus and the damping capacity ($\tan \phi$) were calculated based on the specimen dimensions, force and displacement signals, and the phase lag, $\phi$ between the applied sinusoidal force and...
the resultant displacement, respectively. The surface strain amplitude of the specimen was sustained at about $1.0 \times 10^{-5}$, while heating the samples from 173–473 K at a heating rate of 5 K/min, and an oscillation frequency of 1 Hz or with a frequency sweeping in the range of 0.01–20 Hz at 298 K. The static preload for the oscillated specimen was applied by the static stress-strain curve in the range of 1.0 $\times 10^{-5}$ to 2.0 $\times 10^{-4}$. Since the damping capacity of the alloys at a stress-amplitude of one-tenth the yield stress was usually used to evaluate the damping behavior of materials, the Mooney-Rivlin equation that is commonly used to describe the nonlinear elastic behavior of materials, is given by:

$$\phi(\varepsilon) = C_2 \left(1 + \varepsilon + \frac{1}{(1 + \varepsilon)^2} \right)$$

where $\sigma$, $\varepsilon$, and $\varepsilon_s$ are the static stress, strain, and strain amplitude, respectively. By assuming a linear dynamic behavior in the viscoelastic materials, the damping capacity of the M2052 alloy can be calculated using the following equation:

$$\tan \phi(\varepsilon_s) = \frac{(C_1 + C_2) F_2(\varepsilon_s)}{C_1 F_1(\varepsilon_s) + C_2 F_3(\varepsilon_s)} - \tan \phi(0)$$

where $\tan \phi(\varepsilon_s)$ and $\tan \phi(0)$ indicate the damping capacity of the materials under the application of the static strain $\varepsilon_s$ and without the static strain, respectively. And

$$F_1(\varepsilon_s) = 2 \left[2(1 + \varepsilon_s)^2 + \frac{1}{1 + \varepsilon_s} \right]$$

Equation (1) is the Mooney-Rivlin equation that is commonly used to describe the nonlinear static stress-strain relationship for extensional strains. It is expressed as

$$\sigma = 2[C_1(1 + \varepsilon) + C_2 \left(1 + \varepsilon - \frac{1}{(1 + \varepsilon)^2} \right)]$$

where $\sigma$, $\varepsilon$, and $\varepsilon_s$ are the static stress, strain, and strain amplitude, respectively. $C_1$ and $C_2$ are the elastic constants. By assuming a linear dynamic behavior in the viscoelastic materials, the damping capacity of the M2052 alloy is calculated using the following equation:

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where $\tan \phi(\varepsilon_s)$ and $\tan \phi(0)$ indicate the damping capacity of the materials under the application of the static strain $\varepsilon_s$ and without the static strain, respectively. And

$$F_1(\varepsilon_s) = 2 \left[2(1 + \varepsilon_s)^2 + \frac{1}{1 + \varepsilon_s} \right]$$

Figure 2 shows the temperature dependent variations of the yield's modulus and $\tan \phi$ for the M2052 and Fe–6Al alloys, respectively, under the oscillation frequency of 1 Hz, a strain amplitude of $1.0 \times 10^{-5}$, and the static strains in the range of $1.0 \times 10^{-5}$ to $2.0 \times 10^{-4}$. The M2052 alloy exhibits almost the same static strain dependence at three temperatures. The damping behavior of the Fe–6Al alloy shows a high damping peak at 298 K, which is above the phase transformation temperature of $\gamma_M$, increases with the static strain up to $1.0 \times 10^{-4}$. The damping capacity of the Fe–6Al alloy exhibits almost the same static strain dependence at three temperatures. When low oscillation frequencies (0.01–10 Hz) are applied, the damping capacities shown in both alloys are almost frequency independent, although some discrepancies in the $\tan \phi$ occur for the different frequencies. Static strains in the range of $1.0 \times 10^{-5}$ to $1.0 \times 10^{-4}$ improve the damping capacity of the M2052 alloy, but reduces that of the Fe–6Al alloy at 298 K. Meanwhile, a damping capacity peak is found to occur in both alloys at static strains around $1.0 \times 10^{-4}$, and a significant decrease of the damping capacity can be observed when the static strain is above $1.0 \times 10^{-4}$.
Fig. 2 Young’s modulus and $\tan \phi$ as a function of temperature for M2052 and Fe–6Al alloys, under different static strains ($\varepsilon_s$). The heating rate is 5 K/min, strain amplitude is $1.0 \times 10^{-3}$, and the oscillation frequency is 1 Hz.

$$F_2(\varepsilon_s) = 2 \left[ 1 + \varepsilon_s + \frac{2}{1 + \varepsilon_s^2} \right]$$

(4)

With this model the static strain induced changes in the damping capacity of viscoelastic materials are estimated from the nonlinearity of the static stress-strain behavior.\(^6\) Figure 4 shows the static stress-strain curves measured in the 3-point bending test for the M2052 and Fe–6Al alloys, and the calculated strain dependent $\tan \phi(\varepsilon_s)/\tan \phi(0)$ for both alloys. $C_1$ and $C_2$ for the two alloys are derived from fitting the measured stress-strain curves with eq. (1), and hence the relative changes of the damping capacity, i.e. $\tan \phi(\varepsilon_s)/\tan \phi(0)$, are calculated using eq. (2). The increasing tendency of the damping capacity in the M2052 alloy and the decreasing tendency in the Fe–6Al alloy with increasing static strain are in accordance with the experimental results, as shown in Fig. 3(b). However, there is a large difference in the static strain induced variation magnitude of damping capacity at a static strain of $1.0 \times 10^{-4}$ is below 10%, much less than the experimentally observed values. The large difference in the static strain induced variation magnitude of damping indicates that the damping behavior of high damping alloys under static strains cannot be expressed simply as a combination of the nonlinear static property and a linear dynamic property of the alloys.

The strain amplitude dependence of the damping capacity, i.e. the nonlinear damping behavior of high damping alloys, has usually been characterized with the following expression:\(^7\)

$$\tan \phi = K \varepsilon_{\text{amp}}^n$$

(5)

where $K$ is a constant and the index $n$ indicates the dependence of the damping capacity on the strain amplitude, $\varepsilon_{\text{amp}}$. To characterize the static strain dependence of the damping capacity by the index, it seems appropriate to apply eq. (5) to the static strain dependent behavior in high damping alloys. Figure 5 shows the fitted data of the experimental damping capacity results for both alloys using eq. (5), in the static strain range of $1.0 \times 10^{-5}$ to $2.0 \times 10^{-4}$. The exponential index, $n$, is found to be 0.25 and –0.5 for the M2052 and Fe–6Al alloys, respectively. This index may be used to rep-
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The static strain dependence of the damping capacity for high damping alloys. Simultaneously, the opposite static strain dependence of the damping capacity shown in the two alloys can be attributed to the different microstructures in the high damping state. As shown in Fig. 3(a), different slopes of the damping capacity with increasing static strains occur at 298 K and 223 K. A larger amount of the preferentially oriented twin boundaries may be produced by the preload strains at temperatures near the phase transformation temperature of the γMn phase. The increase of the twin boundaries in the M2052 alloy with static strains may result in the increment of the damping capacity. In contrast, the stress-induced movement of the magnetic domain boundaries by magnetostrictive coupling has been considered as the origin of the high damping capacity in ferromagnetic alloys. When preload strains or external magnetic fields are applied, the domain boundaries in the ferromagnetic alloys tend to be constrained and the magnetoelastic damping of the alloys is considerably suppressed.

As shown in Fig. 3(b), the damping peaks are observed in both alloys at static strains around $1.0 \times 10^{-4}$. The difference in the damping peaks between the experimental results and the fitted data are outlined in Fig. 5 using the exponential function. The magnitude of the damping peak difference in the Fe–6Al alloy is much higher than that in the M2052 alloy indicating the existence of some characteristic damping in the alloys, and the damping behavior contributes effectively to the overall damping capacity only at specific static strains. The most probable mechanism is the formation of some specific dislocation configurations in the statically loaded alloys. Granato and Lücke proposed a sigmoidal trend for the amplitude dependent damping behavior, based on the dislocation model. It seems that this model is also suitable for the static strain induced damping behavior in alloys when the static strain is adequate to induce the changes of dislocation configurations.

4. Conclusions

The damping behavior of the high damping alloys with static preloads is important for determining their damping effectiveness in practical applications. The damping capacity of M2052 and Fe–6Al alloys was studied by applying static strains in the range of $1.0 \times 10^{-5}$–$2.0 \times 10^{-4}$. The static strain dependence of the damping capacity in the high damping alloys was tentatively expressed by an exponential function. The exponential index was characterized to be 0.25 and −0.5 for the M2052 and Fe–6Al alloys, respectively. At static strains around $1.0 \times 10^{-4}$ there appears to be a damping peak, which overlaps with the nonlinear damping behavior with respect to the increase of the static strains. A considerable reduction in the damping capacity occurs at static strains over $1.0 \times 10^{-4}$ in the high damping alloys.

REFERENCES