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Development and characterization of a MnCu-based high damping alloy plate

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Abstract. From the viewpoint of engineering application, the Mn-Cu based alloy plates are prepared to characterize both the mechanical properties as well as the damping capacity by employing the tensile test and dynamic mechanical analysis (DMA), respectively. The microstructure of MnCu alloy were determined by optical microscopy, while the tensile fracture morphology was observed by using a scanning electron microscopy. It is verified that the mechanical properties are similar to that of A3 steel while the vibration noise across the MnCu alloy plate cut about 5-15dB off during all the experiment frequency range from 20 to 300 Hz when the alloy backing plates are applied under a turbine electric generator. The internal friction characteristic of the alloy is disclosed to be dynamic hysteresis closely related to the vibration frequency, as well as to be static hysteresis that depending on strain amplitudes. With whatever vibration frequencies or strain amplitudes, the damping capacity ($\tan \delta$) of the alloy plate still shows satisfactory engineering application value higher than 0.02 at ambient temperature range around room temperature.

1. Introduction

Mn-Cu Alloys have been known for a long time as high damping capacity and high mechanical strength materials. It can absorb vibrational energy significantly to decrease noise and vibration. The damping capacity is contributed by twin boundary damping peak, phase-transformation damping peak, and the antiferromagnetic damping capacity of transformed *fct* phase [1]. M2052 alloy (Mn-20Cu-5Ni-2Fe, at. %) is a representative Mn-Cu based alloy showing superior temperature stability of damping capacity [2,3]. In order to obtain the high damping capacity at room temperature, an aging treatment is necessary in the range of 623K-823K to raise the martensitic phase transformation temperature [4]. The martensitic transformation (*fcc* - *fct*) is preceded by decomposition of original γ -solid solution complying with the spinodal mechanism [5-7]. And the twin damping peak is of dynamic hysteresis associated with the movement of {011} twin boundaries in the *fct* γ -Mn phase [8].

It is known that the application of the damping alloy is closely related with the temperature, amplitude and frequency, therefore, the damping properties are measured only for specific conditions [9, 10]. The mechanical spectroscopy can be used not only to evaluate the damping properties, but also is a tool for the study of phase transitions. Damping behavior related to different temperatures in Mn-Cu alloys exhibits clearly when low vibration frequencies (0.1-10Hz) are applied in the dynamic mechanical analyzer (DMA) measurement in most researches [11]. There are rare researches concerning higher frequencies. However, in the sense of engineering application, a broad and higher twin-boundary damping peak is expected for the high damping Mn-Cu alloy in higher frequency. In this study, the mechanical properties and the damping characteristics with a series of frequencies were investigated from the viewpoint of practical application.



2. Experimental

The damping alloy (Mn-20Cu-5Ni-2Fe at. %) was prepared by induction-melting the pure metals in argon atmosphere. The ingot was forged and rolled to plate of 20mm thick. After solid solution treatment at 900°C with a staged heating for 2h in vacuum (0.1bar), the plates are oil-quenched, and then are further aged at 435°C in a N₂ atmosphere (0.4Pa) for 6h.

The tensile tests were conducted to test the mechanical properties at the speed of 2 mm / min at 298 K, and the yield stress of the specimens was determined as the flow stress was at 0.2% plastic strain. All specimens for metallographic observation were etched after mechanical polishing by using a mixed solution of alcohol, phosphoric and glycerol with the ratio of 2:1:1. DM6000 model Leica optical microscopy was employed to observe the metallographic microstructure. The fracture morphology of tensile specimens was observed by a scanning electron microscopy (Phenom World Phenom Desktop Scanning Electron Microscope).

A dynamical mechanical analyzer (DMA, model Q800, TA instrument Co. Ltd.) was used to measure the temperature dependent damping behavior in a Dual Cantilever mode. The damping capacity was characterized by $\tan\delta$, where δ is the phase lag between stress and strain when the specimen is subjected to cyclic loading. Samples with dimensions of $1 \times 10 \times 60 \text{ mm}^3$ were spark cut from the plate. After carefully polished, they were heated from -120°C to 350°C at a heating rate of 0.083 K/s. Vibration frequencies of 0.1, 1, 10 and 50Hz, and the strain amplitudes of 5×10^{-5} , 1×10^{-4} , and 2×10^{-4} were applied, respectively. Damping capacity ($\tan\delta$) and storage modulus (E) were measured simultaneously as a function of temperature.

In order to further characterize the damping performance of the plate products, an experiment set was established to measure the vibration noise reduction through the backing plate with a dimension of $800 \times 400 \times 18 \text{ mm}$, as shown in the Figure 1. The vibration come from a turbine electric generator, and the A3 steel plate and MnCu alloy backing plate with the same dimension were placed between the vibration source and the foundation bed for a better comparison, and the vibration signals of below and above the backing plate were collected by sensors 1, 3 and 2, 4 respectively, and then the damping efficiency of different plates was obtained and shown in the display.

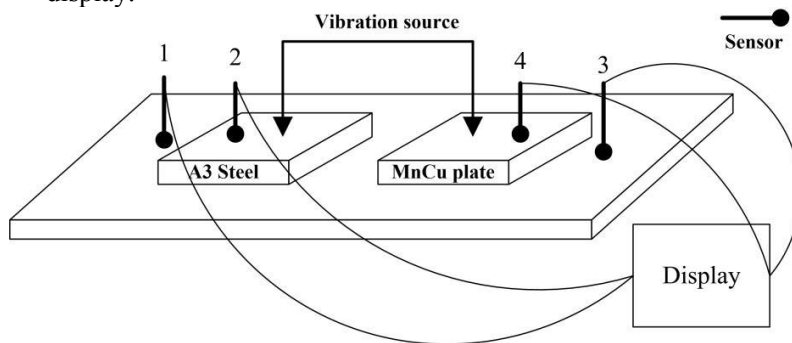


Figure 1. Application of MnCu backing plate under a turbine electric generator, and schematic of the vibration measurement set.

3. Results and discussion

3.1. Mechanical properties

Figure 2 represents the true stress- true strain curve ($S - \epsilon$) of the MnCu alloy plate, where the yield strength, tensile strength and the elongation can be identified as about 210 MPa, 486 MPa and 37%, respectively, which is similar to that of A3 steel. The hardening index n can be calculated by the curve as about 0.42, which is much higher than that of annealed low carbon steel (about 0.26). It means the Mn-Cu alloy has a uniform strain distribution, and has more excellent formability than annealed low carbon does.

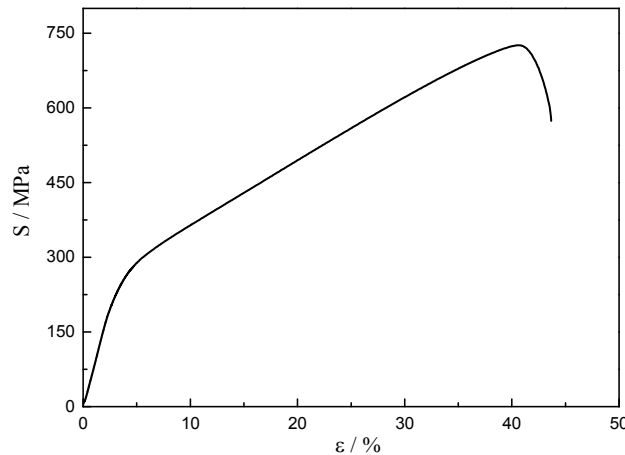


Figure 2. The true stress- true strain curve of MnCu alloy along with rolling direction.

3.2. Fracture morphology

The morphology of the tensile fracture was shown in Figure 3, indicating typical ductile fracture. The circular tensile specimen shows an obvious necking characteristic, and slip bands lying along the circumferential surface can be seen in the necking area, as shown in Fig.3a. Figure 3b shows the morphology of transient break region along the peripheral outside edge where is characterized by the elongated fan-shaped dimples. Figure 3c shows the center of the tensile fracture, it can be seen that there are many different sizes and depths of circular equiaxial dimples.

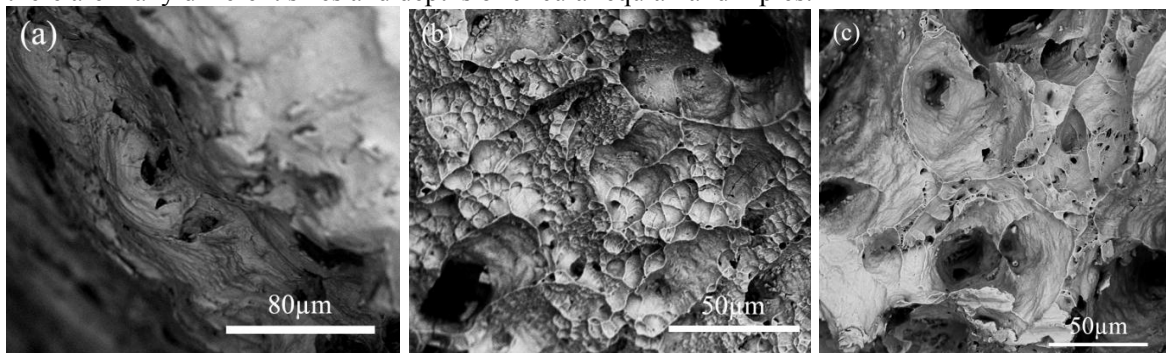


Figure 3. SEM images of tensile fracture of MnCu alloy.

3.3. Metallographic structure

Figure 4 shows the optical micrographs of the alloy plate at positions of surface, and 1/4 and 1/2 thickness, respectively. It can be seen that the grain size of most grains is about 50μm-100μm, and the average grain size varies from 76μm to 92μm and then to 100μm corresponding to the surface, and 1/4 and 1/2 thickness, respectively. The enlarged microstructure in Fig.4a shows obvious twin microstructure. It is known that there is no twin before phase transformation [12], and the strengthening effect for the nominal friction stress would be only owing to lattice friction. After phase transformation, twin will form and results in matrix strengthening and elevate the yield strength to a certain value. The followed aging treatment can significantly promote twin formation, raise twin density and increase the nominal friction stress remarkably [13].

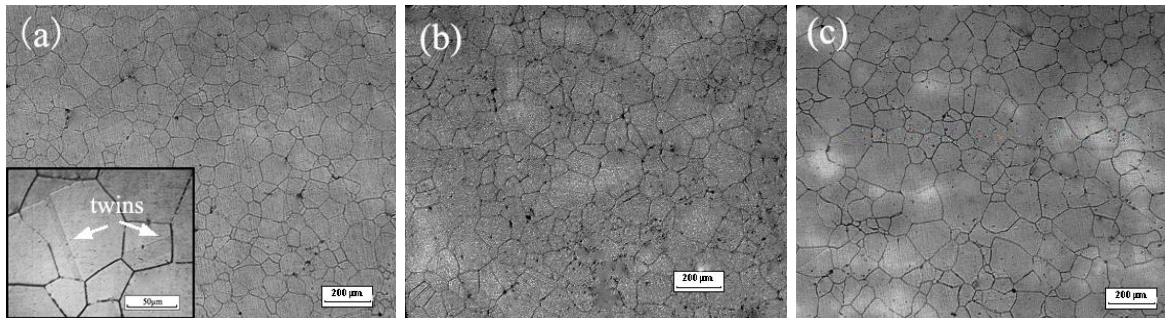


Figure 4. Optical micrographs of MnCu alloy plate at positions of (a) the surface; and (b) 1/4 and (c) 1/2 thickness.

4. Damping capacity of the material

As for Mn-Cu based damping alloys, there exhibited the “main peak” and “sub-peak” temperature dependent damping behaviour [8]. Figure 5 shows the temperature dependence of storage modulus (E) and the damping capacity ($\tan \delta$) of the specimen cut from the MnCu alloy plate under different vibration frequencies at the strain amplitude of 5×10^{-5} . A saddle-shaped two internal friction peaks can be seen for the curve of 0.1Hz. Obviously, the lower temperature peak appeared below 273 K is the twin relaxation peak, which is owing to the formation of martensitic twins and the movement of the $\{101\}$ twin boundaries in the face-centered tetragonal (fct) phase of Mn-Cu alloys [14], while the higher one is the martensitic transformation peak, which corresponds wells to the soft mode of storage modulus during the phase transformation process from fct phase to face centered cubic (fcc) phase [15]. With the increase of vibration frequency from 0.1Hz to 1Hz and 10Hz, the peak value of $\tan \delta$ decreases from about 0.045 to about 0.027, meanwhile the higher temperature martensitic transformation peak becomes a sub-peak, whereas the position of soft mode (approximately 85 °C) remains almost unchanged. However, there are not any “main peak” and “sub-peak” and the damping peak becomes unique with increasing frequency to 50Hz. It might be attributed to the hysteresis of the movement of $\{101\}$ twin boundaries, which shift to higher temperature under higher vibration frequency, as shown in Figure 5b. As a result, the martensitic transformation peak and twin relaxation peak are coupled to form a wide damping platform and higher damping peaks near room temperature. It should be point out that although the damping capacity decreases significantly with increasing frequency from 0.1 Hz to 10 Hz near room temperature, $\tan \delta$ is still higher than 0.02 which shows satisfactory engineering application value at ambient temperature range around room temperature. More excitingly, the damping capacity increases near room temperature when the specimen is applied the higher frequency of 50Hz because of coupling mechanism. Therefore, the prepared MnCu alloy plate shows an excellent damping capacity from the viewpoint of practical application.

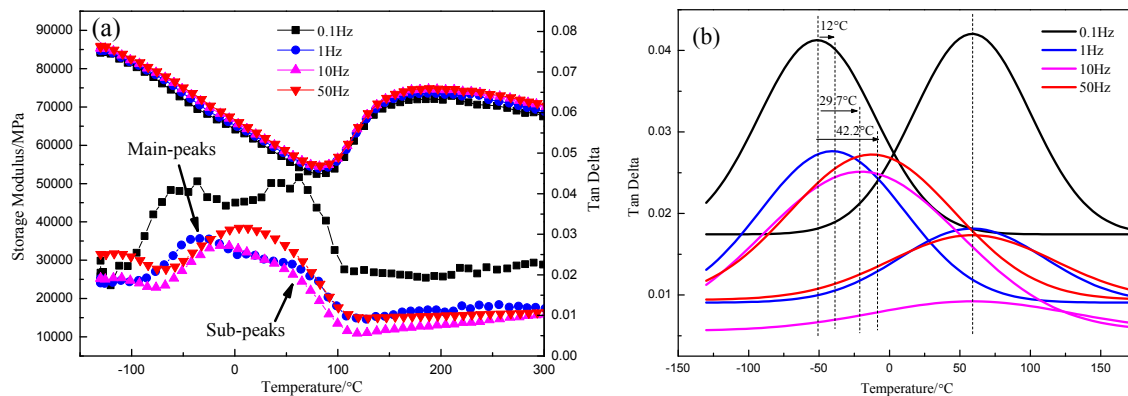


Figure 5. Internal friction and storage modulus (a) and separated peaks of damping peaks (b) for specimen at position of 1/4t thickness under different frequencies

Figure 6a shows the temperature dependent changes of damping capacity for the specimens at different positions of MnCu alloy plate. It can be seen that the main damping capacity peak decreases gradually from 0.03 to 0.025 corresponding to the specimen from the surface to the center, meanwhile sub-peak also has a small reduction. A sharper minimum peak in Young's modulus for the surface specimen while a broader peak for the 1/4t and 1/2t specimens were observed, indicating a more homogeneous Mn content in the plate surface regions [16]. Figure 6b shows the separated peaks for the specimens at different positions, it can be seen that the peak values of both twin boundary and phase transformation decreases for the specimen from surface to center, the peak position remains unchanged. It was found that the twin density shows grains size dependence, the twin formation can be promoted slightly with large grain size [12, 13]. However, in this experiment the surface position shows a smaller grain size while possesses a better damping capacity than the 1/4t and 1/2t specimens, this phenomenon is properly owing to the relatively uncompleted phase transformation in the alloy plate center .

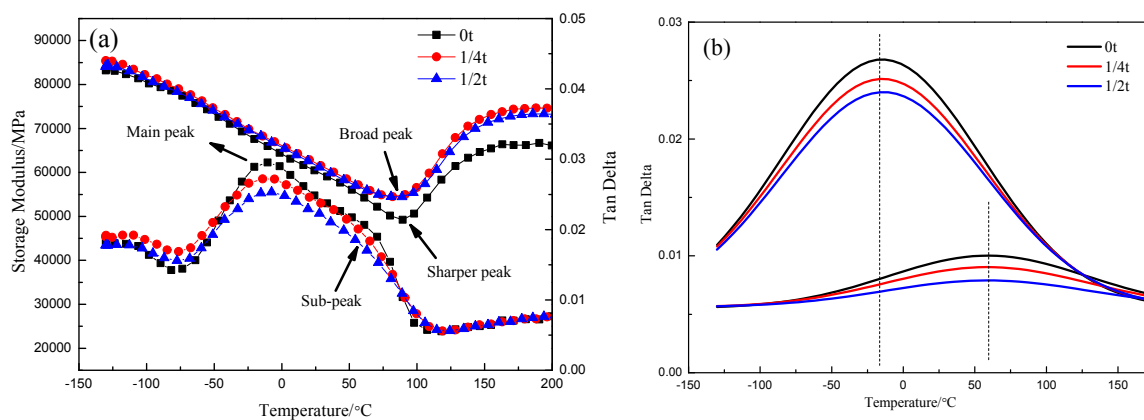


Figure 6. The temperature dependent of damping behavior for the specimens at different thickness positions of MnCu plate under frequency of 10Hz.

Figure 7 shows the temperature dependent damping capacity under different strain amplitudes with the frequency of 10Hz for the MnCu specimen at the plate surface position . It can be seen that the peak damping capacity increases from about 0.037 to 0.047 with the increase of strain amplitude from 5×10^{-5} to 2.0×10^{-4} (Figure 7a), which is determined by the damping mechanism of Mn-Cu based damping alloy. The separated peaks shown in Figure 7b indicate that both twin boundary peak and phase transformation peak increase with increasing stain amplitude. It is known that internal friction of MnCu-based alloys are featured as dynamic hysteresis which strongly depends on vibration frequency, however, this experiment discloses its internal friction is also of static hysteresis, which mechanism might be associated with stress-induced twinning or detwinning of existed twins[17].

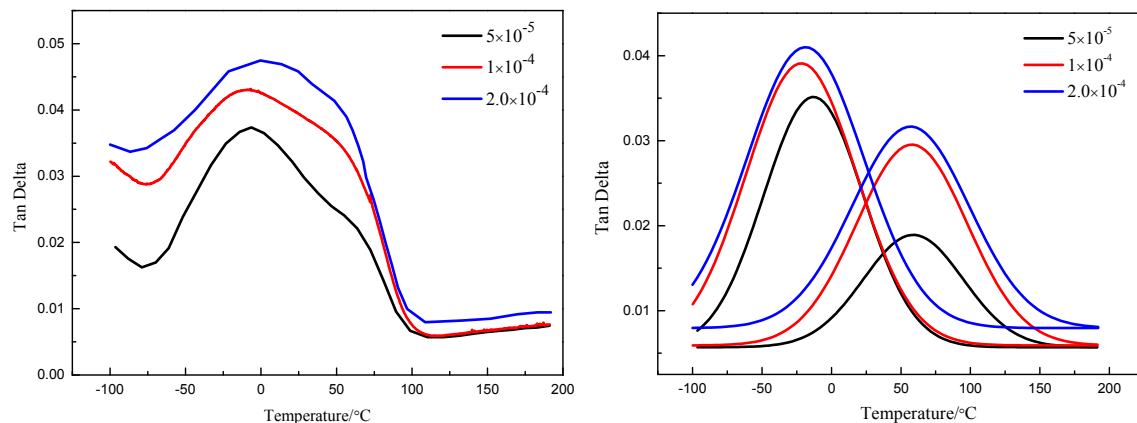


Figure 7. The temperature dependent damping capacity for the MnCu specimen under different amplitudes with the frequency of 10Hz.

Figure 8 represents the vibration measurement results when the backing plates are applied under a turbine electric generator. As shown in the figure, the vibration across the A3 steel plate show small attenuation effect, while that across the MnCu alloy plate shows a significant damping effect of about 5-15dB during all the experiment frequency range from 20 to 300 Hz. Up to now, MnCu based damping alloy has been reported to be used as screws, springs and such small workpiece, it could be expected that large MnCu alloy structural framework would be widely applied in extensive fields including naval ship, aircraft, high-speed rail, automobile and so on.

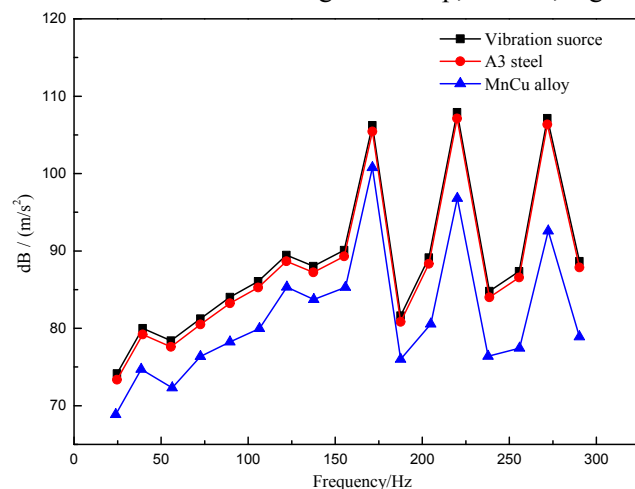


Figure 8. The comparison of vibration and noise reducing capability between A3 steel and MnCu alloy with different frequencies.

5. Conclusions

(1) The MnCu alloy plate were prepared by induction-melting and then forged and rolled to plate of 20mm thick followed by solution treatment and ageing at 435 °C. The phase transformation temperature corresponding to the position of soft mode occurs approximately at 85 °C. The yield strength, tensile strength, the elongation and the hardening index n can be indentified as about 210 MPa, 486 MPa, 37%, and 0.42, respectively. The tensile fracture morphology shows a typical characteristic of ductile fracture mechanism.

(2) The internal friction of the alloy is featured as dynamic hysteresis which strongly depends on vibration frequency. With the increase of vibration frequency from 0.1Hz to 1Hz and 10Hz, and then to 50Hz, the internal friction peaks vary from saddle-shaped to the coexistence of a main-peak

and a sub-peak and then to a broaden one, while the peak value of $\tan \delta$ decreases from about 0.045 to about 0.031

(3) The average grain size varies from 76 μm to 92 μm and then to 100 μm corresponding to the surface, and 1/4 and 1/2 thickness, while the damping capacity decreases gradually from 0.03 to 0.025 corresponding to the specimen from the surface to the center.

(4) This experiment result discloses the internal friction of the alloy is also of static hysteresis. The peak damping capacity increases from about 0.037 to 0.047 with the increase of strain amplitude from 5×10^{-5} to 2.0×10^{-4} .

(5) When the alloy backing plates are applied under a turbine electric generator, the vibration noise across the MnCu alloy shows a significant damping effect of about 5-15dB cut-off during all the experiment frequency range from 20 to 300 Hz.

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