The effect of cooling method on damping capacity of Fe-16Cr-2.5Mo alloy

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Abstract. Damping capacity and magnetic domain structure of Fe-16Cr-2.5Mo alloy at different cooling rates have been investigated in this paper. DMA (Dynamic Mechanical Analyzer) was used to test the damping capacity. MFM (Magnetic Force Microscope) was used to observe the magnetic domain structures. The results indicated that furnace cooled alloy exhibited significantly higher damping capacity than water cooled alloy. For water cooled alloy, higher internal stress resulted in labyrinth domains’ formation and pinned the domain walls from moving, so the damping capacity was poor. However in the furnace cooled alloy, lamellar domains with larger size were responsible for higher damping capacity. In addition, higher initial permeability could be obtained to favor the movement of domain walls and contributed to higher damping capacity, due to the decrease of magnetocrystalline anisotropy.

1. Introduction

With the rapid development of society, the noise and vibration problems gradually become the focus of attention, which not only affect people's daily life, also seriously restrict the further development of navigation and aerospace fields. Therefore, damping alloy reducing vibration and noise receives much concern. The Fe-Cr based damping alloy has become the better choice to reduce vibration and noise, because of strong radiation resistance, excellent mechanical, processing properties, better corrosion resistance and higher damping capacity [1-5]. The damping mechanism of Fe-Cr based alloy can be concluded as magnetic domain wall’s irreversible movement. When subjected to the external alternating vibration, the magnetic domain wall in the alloy moves inversely, forming a magnetic-mechanical static hysteresis, which leads to a hysteresis curve in the relationship between stress and strain, resulting in energy dissipation [6,7].

It was reported internal stress caused by dislocations, grain boundaries and precipitates might pin the magnetic domain walls from moving, and strongly reduce the damping capacity of the alloy [8,9]. Smith and Birchak [9,10] studied the distribution of internal stress, and analyzed the influence on the damping capacity, meanwhile made good foundation for seeking a suitable heat treatment process to reduce or eliminate internal stress, finally improve the damping capacity. Pulino-Sagradi [10] conformed that appropriate heat treatment can effectively reduce the internal stress of Fe-Cr based damping alloy, then the damping capacity can be greatly developed. Water-based magnetic fluid was generally used to analyze domain structures. However the water-based magneto-fluid method may have a complex and unmanageable operation. Recently the Magnetic Force Microscope was tried to investigate magnetic domain, samples can be observed under the magnetic force microscope, the
magnetic domain characters were intuitive and clear, however less research on magnetic domain structures of Fe-Cr based alloy were reported. The effect of annealing temperatures on damping capacity were investigated in more research [11], but the cooling method were less researched. Based on the noise reduction effect of damping alloy, the Fe-16Cr-2.5Mo alloy under operating service condition needs to be researched to obtain more theoretical data and realize its promotion and application on nuclear submarines, warships, military aircraft and other areas of national defence, because of the promoted defence capabilities, therefore, in this paper the effect of cooling method on damping capacity was reported, the magnetic force microscope was used to investigate magnetic domain structures instead of the water-based magneto-fluid method; the correlation of damping capacity and domain structures with residual stress of Fe-16Cr-2.5Mo alloy was analyzed.

2. Experimental technique

2.1. Materials

The Fe-16Cr-2.5Mo (wt. %) alloy studied in this paper was prepared by vacuum induction melting with raw materials of pure iron and 99.9% pure metals (chromium, molybdenum). The chemical composition of Fe-16Cr-2.5Mo was listed in Table 1. The ingot was forged into the plate after proper temperature diffusion annealing. Samples dimensions of 70mm × 10mm × 1.0mm were cut and then heated in vacuum at different temperatures for 1 h followed by furnace cooling (FC) and water cooling (WC), respectively. At last, these samples were ready for damping capacity test and the residual stress test.

| Element | Cr  | Mo  | C   | S   | P   | Fe     |
|---------|-----|-----|-----|-----|-----|--------|
| Fe-16Cr-2.5Mo | 15.32 | 2.47 | 0.011 | 0.011 | 0.027 | Bal    |

2.2. Performance Test

In this paper, the damping capacity was characterized by internal friction Q⁻¹, and the damping behavior (Q⁻¹) was evaluated by three-point bending vibration mode on a SDTA 861e dynamic mechanical analyzer (DMA), this test was carried out at 25°C with vibration frequency of 1 Hz and the strain amplitude in the range of 1×10⁻⁴ and 6×10⁻⁴.

Magnetic domain structures were observed by MFM (Magnetic Force Microscope), the scanning area is 60μm × 60μm and 30μm × 30μm, and the scanning height is 100nm. Samples dimensions of 10mm × 10mm × 1.0mm were used for observation, before each observation, samples were previously electrochemically polished to avoid work hardening of their surfaces.

Residual stress was tested by Xstress3000, and the metallographic structures were observed by Olympus -CK40M metallographic microscope.

3. Results and Discussion

3.1. Damping Capacity

Figure 1 shows the relationship between damping capacity of the Fe-16Cr-2.5Mo alloy and strain amplitude with different cooling rates. In figure 1, both the furnace cooled alloy and the water cooled alloy present a peak of Q⁻¹ in strain amplitude ranged from 1.0×10⁻⁴ to 2.0×10⁻⁴ annealed at various temperatures, and the furnace cooled alloy exhibits significantly higher damping capacity than water cooled alloy for the four annealing temperatures. According to figure 1, each peak of Q⁻¹ was correlated with different annealing temperatures followed by FC and WC in figure 2, the relationship between damping capacity of the Fe-Cr-Mo alloy and different cooling rates can be obtained. Though the samples annealed at different temperatures, all samples shows the higher damping capacity followed by furnace cooling. Both of the two display an increase with the raise temperature, then
decrease. Meanwhile the peaks of $Q^{-1}$ of the two present an obvious difference at 1100$^\circ$C, however at other temperatures, furnace cooled alloy have a slightly higher peak of $Q^{-1}$ than water cooled alloy.

![Figure 1](image1.png)

**Figure 1.** Damping capacity of Fe-16Cr-2.5Mo alloy heated at different temperatures for 1 h followed by FC and WC.

![Figure 2](image2.png)

**Figure 2.** Peak of $Q^{-1}$ at different temperatures followed by FC and WC.
3.2. **Microstructures of Fe-16Cr-2.5Mo alloy**

Figure 3 shows the microstructures of furnace cooled alloys and water cooled alloy annealed at different temperatures. At 900°C, both the two show similar grain microstructure, different cooling methods have no obvious effect on the grain size of Fe-16Cr-2.5Mo alloy. With the increase of temperature, furnace cooled alloys has relatively larger grain size than the water cooled alloy, this may partly increase the internal friction [12]. At higher temperature, the smaller grains in water cooled alloy increase the grain boundary, more grain boundary lead to the pinning effect on magnetic domains and decrease the damping capacity. Therefore, above 900°C, furnace cooled alloy has an obvious higher damping capacity than water cooled alloy.

![Figure 3. Microstructures of Fe-16Cr-2.5Mo alloy heated at different temperatures for 1 h followed by FC and WC.](image)
a: 900°C/FC; b: 900°C/WC; c: 1000°C/FC; d: 1000°C/WC; e: 1100°C/FC; f: 1100°C/WC; g: 1200°C/FC; h: 1200°C/WC.

3.3. **Residual stress of Fe-16Cr-2.5Mo alloy**

Figure 4 shows the relationship between residual stress and $Q^{-1}$ of Fe-16Cr-2.5Mo heated at different temperatures followed by furnace cooling and water cooling, respectively. Both the two show that furnace cooled alloy has significantly smaller residual stress than the water cooler alloy, although annealed at different temperatures. According to figure 4, the furnace cooled alloy has lower residual stress, however the higher residual stress in water cooled alloy may pin the magnetic domain from shifting, and decrease the $Q^{-1}$, therefore the furnace cooled alloy has higher damping capacity contrariwise the water cooled alloy.

![Figure 4.](image)
3.4. Magnetic domains of Fe-16Cr-2.5Mo alloy

Figure 5 shows the magnetic domain morphologies of the two type alloys annealed at 900°C, 1000°C, 1100°C and 1200°C, respectively. Different cooling method leads to various morphology of magnetic domains, whether the morphology or the size. The magnetic domains composed of sharp bright and dark contrast are observed by MFM, and the contrast of bright and dark for magnetic domains reflects the perpendicular anisotropy in materials. For polycrystalline, the sharper the contrast of bright and dark, the stronger the magnetocrystalline anisotropy. At 900°C, both of the magnetic domain morphology and size have unobvious difference between the two type alloys, which may correspond to the subtle difference of damping capacity between the two type alloys. With increasing temperatures, furnace cooled alloy substantially shows lamellar domains (1000°C, 1100°C), with larger size and the weaker contrast of bright and dark; Oppositely, water cooled alloy displays numerous labyrinth domains, with smaller size and the stronger contrast of bright and dark. Above 1100°C, lamellar domains in furnace cooled alloy transform into arborization domains, and labyrinth domains can be observed in water cooled alloys.

Early research shows higher residual stress in water cooled alloys promotes the emergence of labyrinth domains (the closed domains) to reduce the surface magnetic poles, and cuts down the demagnetizing energy, therefore labyrinth domains have stable structure and reduce the mobility of domain wall. Hard movement of this type domain-wall in water cooled alloy will decrease the \( Q^1 \), this may result in lower damping capacity. On the contrary, in furnace cooled alloy, the magnetic charge will not be formed due to the lower residual stress, almost no demagnetizing energy in alloy need to be consumed, thus the lamellar domains conform instead of the closed domain. This type of domain has higher demagnetizing energy than labyrinth domains which can result in easy movement of domain-wall, thus the furnace cooled alloy has higher damping capacity. In addition, compared to the labyrinth domains, lamellar domains in the furnace cooled alloy have larger size, which may contribute to the higher internal friction (\( Q^1 \)).
4. Conclusions
The damping behavior of Fe-16Cr-2.5Mo alloy annealed at various temperatures for 1 h followed by furnace cooling and water cooling were studied, respectively. For furnace cooled alloy, due to the lower residual stress, numerous lamellar domains with larger size were observed, and the easy movement of the domain-wall resulted in the higher damping capacity. Compared to the furnace cooled alloy, large amounts of labyrinth domains formed in water cooled alloy because of higher residual stress, and the poor mobility resulted in the significantly low damping capacity.

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