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A Review of Influencing Factors of Damping Properties of High Manganese Steel

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Abstract

High manganese steel has wide prospects in industry due to their excellent mechanical and damping properties. The quenching structures of high manganese steel are ε-martensite, γ-austenite and α'-martensite. Researches show that the damping properties of high manganese steel are related to these microstructures. Besides, there are many ways to improve the damping property of damping alloys. This paper reviews the damping mechanism and the influences of the addition of alloying elements, heat treatment, pre-deformation and other factors on their damping performance, hoping to provide methods and ideas for the study of damping properties of high manganese steel.

Keywords

High Manganese Steel, Damping Properties, Alloying Elements, Heat Treatment, Deformation

1. Introduction

As industrialization progresses, the vibration and noise of objects cannot be ignored. There are three main ways to control vibration, 1) a massive and rigid structure to reduce vibration, 2) structures can be detuned to avoid resonance conditions or 3) damp vibration [1]. Excellent damping performance can be achieved by using damping structures composed of specific materials such as U-shaped damping structures [2]. The damping effects, no matter how it is realized, cannot be separated from the development of damping materials. Damping material is the material that converts mechanical energy into heat energy and dissipates it, which is mainly represented by rubber and damping alloy. With the deepening of research, scholars even developed a composite material of graphene and manganese steel. By adding 1 wt% graphene to high manganese steel, scholars can obtain a new Fe-Mn based damping alloy with excellent damping performance [3]. The high manganese steel has been widely applied in the typical metal damping alloys due to lower costs, remarkable mechanical properties and excellent damping capacities under high strain amplitude. Now the researches on damping mechanism of high manganese steel are still in progress, and there are many factors affecting damping performance. Here is a rough exploration of the damping mechanism and influencing factors.

2. Research on Damping Mechanism

The researches on damping mechanism and damping sources of Fe-Mn damping alloy are generally on the interaction between microstructure and dislocation movement on microscale [4]. According to Lee's experimental analysis, the damping source of damping alloy can be summarized as the movement of four interfaces: γ-ε phase interface, ε-martensite variable interface, γ-austenite's stacking fault and ε-martensite's stacking fault [5]. It had been found that the damping property of Fe-17Mn alloy is proportional to the content of ε-martensite, so ε-martensite is considered as the main damping source of Fe-Mn alloy [6]. Shin also found that higher ε phase will achieve higher damping performance [7]. Jun studied the contribution of damping sources to the damping properties of Fe-17Mn alloy at low strain amplitude [8] as shown in **Table 1**. The data show that the movement of γ/ε interface barely has influence on the damping property, while ε-martensite has great effects on the damping property. Besides, γ-austenite has contribution to damping performance when there's little ε-martensite in it. So here is a guess that the damping sources may be some microstructures within like stacking faults. It moves in these phases and take effects when subjected to external action.

Based on this conclusion, Wen *et al.* [9] have deeply studied the damping mechanism of high manganese steel. He thinks that there will be a lot of ε-martensite and stacking fault in high manganese steel after processing and heat treatment, the partial dislocations at the interface of martensite and stacking

Table 1. Effect of damping sources on damping performance of Fe-17Mn [8].

F_ε (%)	$\Delta\delta_\gamma$	$\Delta\delta_\varepsilon$	$\Delta\delta_{\gamma/\varepsilon}$	$\Delta\delta_\gamma$ (%)	$\Delta\delta_\varepsilon$ (%)	$\Delta\delta_{\gamma/\varepsilon}$ (%)
0	0.173	0	0	100	0	0
1	0.171	0.003	0.007	95.5	1.6	3.9
7	0.162	0.014	0.010	87.1	7.5	5.4
17	0.143	0.036	0.012	74.9	18.8	6.3
52	0.082	0.107	0.009	41.7	53.8	4.5
83	0.029	0.172	0.004	14.1	83.9	2.0
93	0.012	0.193	0.001	5.8	93,7	0.5

fault are the damping sources of Fe-Mn alloy, and the damping mechanism of Fe-Mn damping alloy is deduced by means of Granato-Lucke (G-L) dislocation model. The solute atoms are distributed in the direction of partial dislocation length, as shown in **Figure 1**. When the strain amplitude is low, the dislocation arcs out from each pinning point, and the dislocation line is dragged by the viscous force formed by the impurity atoms pinning. So, the mechanical energy is partly absorbed by the movement of the dislocation line. At same temperature and frequency, the damping performance is definite and belongs to viscoelastic damping. When the strain amplitude is high, the pinning point cannot pin the dislocation line, and the dislocation cannot be nailed. The damping performance is not dependent on the frequency under this circumstance, but on the strain amplitude, the length and the number of the valid dislocation line. The high damping mechanism caused by stacking fault and Shockley partial dislocation debonding at γ/ε interface is consistent with G-L dislocation debonding model.

Stacking fault is a common interface defect in manganese steel, but the mode of action of its boundary on damping capacities remains unknown. WANG *et al.* [10] considered that stacking faults also have an effect on damping performance. The result shows that the damping capacity of Fe-19Mn alloy is consistent with the change of martensite stacking fault probability and the relative length of γ/ε boundary. So, the stacking fault in martensite has an effect on the damping property. Based on the TEM observations of γ-austenite Stacking Fault, it can be concluded that the γ-austenite stacking fault boundary has fewer contribution to the damping capacity of Fe-19Mn.

HUANG *et al.* [11] studied the relationship between ε-martensite and damping performance unexpectedly found that the damping capacity of the alloy with more martensite was smaller than that of the alloy without martensite. Combining with the SEM results, he thinks that the damping source is determined by stacking fault, accompanying with the motion of Shockley partial dislocation, which is also very consistent with G-L dislocation model. In order to study the further relationship between ε-martensite and damping capacities, Li Xing had made nanoindentation experiments on Fe-19Mn, the loss modulus of a small amount of martensite and austenite reaches several hundred MPa and mainly distributed in the region of ε-martensite, so the damping source exists in ε-martensite. With further research on ε-martensite [12] through TEM, as shown in **Figure 2**. The interface of martensitic lath is composed of partial dislocations, and there are a lot of parallel dislocations walls in ε-martensite lath. According to the theory put forward by Granato [13] [14], he thinks that the dislocation wall inside the martensitic lath is the damping source.

The results show that the damping property is not a linear relationship of single structure, and the factors that affect the damping property of high manganese steel are not only positively correlated with the number of damping sources. However, γ-austenite barely has effect on the damping property, which is different from the previous cognition. There are a lot of stacking faults in high manganese steel, which are only part of the damping source, such as in **Figure 2(b)**. One of the main reasons for the excellent damping property of high manganese steel is the dislocation wall generated by the accumulation of partial dislocations in ε-martensite. Therefore, the damping property of high manganese steel is affected not only by the number of damping sources, but also by the microstructure and defect on dislocation under different conditions.

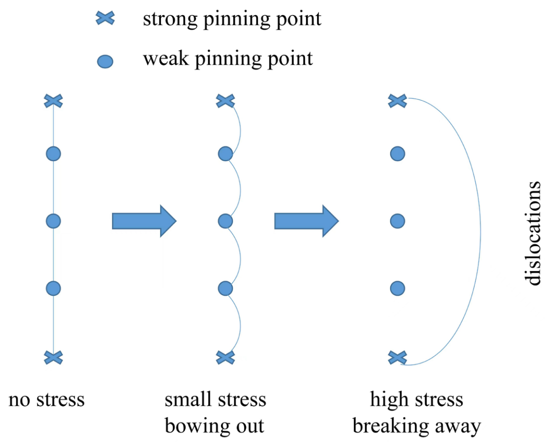

Figure 1. Damping mechanism of Fe-Mn alloy [9].

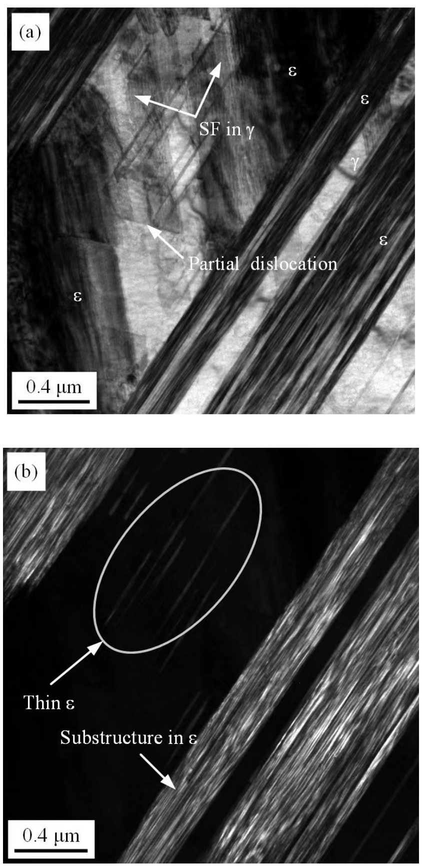

Figure 2. (a) Stacking Fault and partial dislocation in alloy; (b) Substructure in ε-martensite [12].

3. Effect of Alloy Elements on the Damping Properties

Alloy elements directly participate in the formation of the alloy. They can directly affect the solidification structure, so it has a greater impact on the structure and properties. The main transformation in manganese steel is austenite transformation and martensite transformation. The main influences on damping property are related to martensite, so the austenite's stacking fault energy (SFE) can reflect the trend of microstructure's transformation to some extent. It is found that some elements can decrease the stacking fault energy of austenite, and lower SFE is beneficial to the formation of more ε-martensite, the damping property of Fe-Mn alloy is positively correlated with the content of ε-martensite. Therefore, the effect of different elements on microstructure and properties are different.

3.1. Effect of Non-Metallic Alloy Elements on the Damping Properties

Adding nonmetal to alloys can often have a different effect. As an important component of high manganese steel, element C can promote the formation of austenite in high manganese steel. Curtze, S *et al.* [15] proved that C element increases stacking fault energy of high manganese steel by thermodynamic modeling, it enhances the stability of austenite and reduces the volume fraction of ε-martensite and the quantities of Shockley partial dislocations. Besides, the radius of C atom is smaller than that of Fe and Mn, so C atoms tend to converge to the stacking fault zone, which limits the movement of Shockley partial dislocations and eventually deteriorates the damping property of Fe-Mn alloy. Murasov [16] found that C had little effect on the inherent internal friction of the γ phase but inhibited the movement of the damping during relaxation. The experimental results show that even a small amount of C can sharply reduce the damping connected with the boundary motion of γ-ε interface and widen the stacking fault by the movement of partial dislocations. To study the influences of C element in high manganese steel, WANG [17] controlled C element to 0.0017% in Fe-19Mn and try to find out the effect of C element on microstructure and properties, the results show that the strength of ε-martensite is lower due to the lack of carbon solute strengthening, and the dislocation movement can be inhibited more effectively because the hardness of α'-martensite is higher than that of ε-martensite. As one of the austenite forming elements, a right amount of element C can regulate microstructures more easily. Therefore, in order to obtain better damping property of high manganese steel, the content of C element should be strictly calculated.

The N element in alloys is also difficult to control because of its low solubility in molten steel. Choi [18] found that it had little effect on the damping property with nitriding and solid solution at 520˚C on the surface of the cold-rolled sample, but it could improve the mechanical properties. As an alloying element, it's the other way around. LEE [19] found that the increase of element N content would contribute to the decrease of ε-martensite and γ-austenite in the alloy. In addition, the addition of N reduces the stacking fault energy, which is beneficial to increasing the content of ε-martensite and the number of stacking fault in γ-austenite. So, the damping capacity barely changes. In contrast, it was found in Blizun's studies that N can improve the damping property of quenched Fe-14Mn and decrease the damping property of Fe-16.5Mn alloy [20]. Although the influence of N in Fe-Mn alloy is complex, we can use the characteristic of decreasing SFE to apply it properly.

Si, as a common alloying element, can also reduce the stacking fault energy of high manganese steel. However, researchers have found that the ε-martensite cross-distributed in the alloy on account of the addition of Si, hindering the movement of the damping source through pinning the dislocation [21]. In addition, Si has a much smaller atomic radius than Fe and Mn, large lattice distortion and vacancy will be formed in the alloy, thus pinning partial dislocation will move and damping property will be deteriorated. As Si is one of the austenite forming elements, the stacking fault energy of Fe-19Mn alloy is reduced, the γ/ε phase transformation is promoted with the increasing of ε-martensite content and refined ε-martensite lath. Therefore, a small amount of Si can improve the damping capacities, and the damping performance will be obviously deteriorated when the content of Si exceeds 1%. Huang [22] has also proved that Si decreases the stacking fault energy, increases the stacking fault probability and the number of Shockley partial dislocations in Fe-Mn alloy so as to a poor damping performance. In view of engineering application, the content of Si in Fe-Mn alloy also should be strictly controlled.

3.2. Effect of Metal Alloy Elements on the Damping Properties

According to thermodynamic calculation, manganese, as the main alloying element of high manganese steel, can greatly reduce the stacking fault energy of the alloy, which is beneficial to form ε phase, and the atomic radius of manganese element is close to that of iron element. In theory, the higher the manganese content, the better the damping performance. However, GE Xing [23] carried out experiments on high manganese steel with different manganese content, and found that although α'-martensite was produced at 17Mn and ε-martensite content was lower than 19Mn and higher than 15Mn, its damping property was the best.

Element Cr usually improves the corrosion resistance. The poor corrosion resistance of high manganese steel is one of the factors that make it hard to use on a large scale. By thermodynamic calculation, QU Xuan [24] found that the stacking fault energy of high manganese steel could be increased by adding Cr. CHEN G [25] also found that the addition of Cr to Fe-17Mn leads to a lower content of ε-martensite, thus affecting the damping property. With the addition of Cr, a large number of dislocations pinned in the alloy decreases the damping capacity at high strain amplitudes. MENG L [26] add 8 wt% Cr to Fe-19Mn then found that SFE increased, while the volume fraction of ε-martensite decreased and the damping performance decreased before deformation due to the addition of Cr. So, the excess Cr increases the SFE and pining point of high manganese steel and decreases the volume fraction of ε phase, which results in the decrease of damping property.

Element Ni is usually used in steel to enlarge austenite phase zone and improve the stability of austenite. LI Ning *et al.* [27] added Ni to high manganese steel and found that Ni in the alloy could significantly inhibit γ-ε phase transition in Fe-Mn alloy and decrease M_S and M_F temperature. In addition, he found that with the increase of the torsion strain, the carbon element in the high manganese steel also showed a disadvantage to the damping performance of the alloy. The results indicate that the reduction of the interface area of γ/ε and the pinning effect of carbon atoms on the dislocation hinder the boundary and dislocation movement. CAO PING *et al.* [28] added 1% Ni to Fe-17Mn-5Cr alloy, it was found that the damping property and strength changed little. Therefore, the lattice changes and pinning of dislocations caused by them have little effect on the overall properties.

WANG *et al.* [29] added Co into the alloy and found that the ferromagnetic damping changed into dislocation damping with the increase of Co content. So, Co has great influence on the damping property of the alloy, but it is more complicated. When High Co content is added, the alloy system often becomes a multi-component alloy system, which is different from traditional binary alloy system. YOUNG *et al.* [30] found that Co inhibited the formation of ε-martensite, and increase the content of α'-martensite gradually. Therefore, the addition of Co is also harmful to the damping performance.

Ye WL [31] added Nb element to high manganese steel, the results show that the refinement of ε-martensite lath and the precipitation phase of Fe_2Nb are the main factors to improve the damping property of the alloy. The refinement of martensitic lath increases the number of damping-related interfaces, and the proper amount of hard Fe-Nb precipitates will increase the energy dissipation of the interface when it moves, so the damping property will be increased. A similar effect occurs when Ti and rare earth element are added [32] [33].

4. Effect of Heat Treatment on the Damping Performance

4.1. Effect of Solid Solution Treatment on Damping Performance

Different heat treatment processes have different effects on damping performance. After solution treatment, the number of defects can be reduced and the damping property can be improved, because there are a lot of defects such as vacancy and dislocation in the processed alloy. The effect of solution temperature on the damping property of Fe-21Mn alloy was studied by JEE [34]. The results show that the damping property increases with the first rise of solution temperature, and the best damping property is at 1000˚C, and then decreases with the rise of temperature, and other researchers have reached similar conclusions [35]. Girish [36] also found that the damping property of Fe-16%Mn-1%Mg-2%Si increased with the rise of temperature until it reached its peak at 1000˚C. As the temperature increases further, the damping capacity decreases, and he argues that it is the γ/ε interface, rather than the content of ε-martensite, influences the damping capacity of the alloy at this time. Despite the heat treatment at high temperature increases the number of ε-martensite but the interface area of γ/ε decreases.

4.2. Effect of Annealing on the Damping Performance

Annealing process is often used for the regulation of micro structures and performance, and has different effects on alloy tissue at different temperatures and times. HE *et al.* [37] showed that when Fe-17.5Mn is annealed at 1100˚C for 0.25 to 10 hours, the damping performance gradually increases because the α'-martensite content in the alloy decreases with the annealing time. But the α'-martensite content of Fe-16.5Mn-10.5Cr alloy is lowest at 2 h where the damping performance is the highest and comparable to the damping of Fe-17.5Mn alloy annealed at 10 h. Qian *et al.* [38] vacuum annealed Fe-17.5Mn alloy at 1100˚C to form a sandwich structure. This method uses the thermal expansion coefficient of the surface ferrite and the core, and the surface layer applies certain tensile stress to the core during the cooling process, which improves the austenitic stacking layer of the core and thus improves the damping performance. Khodaverdi *et al.* [39] had studied the evolution of microstructures during short-term deformation realization and aging. After annealing and aging, it forms fine austenite grains and thin ε-martensite strips, accompanied by some dislocation array. These microstructures are more conducive to vibration reduction.

4.3. Influence of Aging Treatment on Damping Performance

The phase transition during aging also affects the damping property, and the sensitivities of different alloys to aging are different. Meng L *et al.* [26] found that the aging sensitivity was related to the amount of interstitial atoms and the number of damping sources, which means, the more pinning points and denser the damping sources, the effect of aging on damping property is more obvious. Zhang J *et al.* [40] found that the damping capacity of quenching alloy increases by 176% after aging and deformation. He believed that the quantity of stacking faults and the mobility of Shockley partial dislocations in Fe-Mn-based alloys determine the damping capacity of the alloys. The segregation of atoms on stacking faults has a greater effect on the motion of some dislocations than the vacancy. Therefore, increase the number of stacking faults and reduce the number of Shockley partial dislocation pinning are efficient ways to design high damping capacities Fe-Mn alloys.

4.4. Other Factors

There are many factors that affect the structure of materials, some of which are different from the traditional heat treatment, but also have obvious effect. Li Xing [41] has carried out water cooling and air cooling respectively for Fe-19Mn. Water cooling can obtain more *ε*-martensite than air cooling. However, due to the large number of vacancy defects, the effective length of the movement of movable partial dislocation is weaken, which seriously affects the performance of damping. Na Yan [42] research the effect of the rapid solidification and found that M_S increased with the increase of cooling rate, and *ε*-martensite is formed more easily because of the joint influence of rapid solidification and heat treatment. Therefore, the volume fraction of *ε*-martensite and stacking fault rate of *γ*-austenite increase, and then the damping property increases. So, the solidification process of a certain treatment can be controlled its morphology and organization. Besides, Sum [43] also found that after several thermal cycles, the *ε*-martensite volume decreases with the increase of the *γ*-austenite volume, resulting in the decrease of the internal friction value.

5. Effect of Cold Rolling and Pre-Deformation and Cold Rolling on Damping Performance

Whether pre-deformation or cold rolling, the damping property is improved by changing the relative content of martensite and austenite and introducing dislocations. However, the recrystallization annealing of the alloy after cold rolling will change the morphology and stability of austenite, and its dislocations and defects will be relatively less. Therefore, in order to achieve the common improvement of mechanical properties and damping properties, the improvement brought by cold rolling is even greater.

The effect of different deformation on damping capacities is additionally different. The researchers studied the damping properties of the alloy under different degrees of pre-deformation. The experimental data showed that the damping properties first improved with the progress of deformation, and then reached the top at about 4% of the deformation, the damping property decreases when the deformation is further increased [44]. Wang [45] studied the damping properties of the alloy under large deformation and high strain amplitude. Firstly, the damping performance reaches the bottom when the deformation comes at 12%. Then with the progress of pre-deformation, the volume fraction of *ε* phase decreases. On the contrary the volume fraction of *γ*-austenite and *α*'-martensite increases. Besides, the *ε*-martensite phase is finer and well arranged, the *ε*-martensite lath and *γ*-austenite have higher parallelism. It is the increase of *γ*/*ε* phase interface that afford a large number of damping sources with better slip, which makes the damping property of Fe-Mn based alloy improves gradually.

Cold rolling is an effective way to improve mechanical properties. The cold rolling process changes the microstructure content, including the damping source. Kim [46] found that the volume fraction of *ε*-martensite increases with the increase of cold rolling degree. With the increase of cold rolling degree, the tensile strength increases linearly. Because of the increase of martensite volume fraction, the elongation decreases and the damping capacity increases. Girish [36] cold-rolled Fe-16% Mn-1%Mg-2%Si and believed that stacking faults in ε-martensite were the main damping source, which is very similar to the results of the latest study [12].

6. Conclusion

The damping mechanism can be well explained by G-L dislocation motion model. Alloy elements can influence the solidification structure and the form of microstructure. In the process of partial dislocation movement, the weak pinning point ensures the damping capacity at low strain amplitude, while the strong pinning point reflects the damping capacity at high strain amplitude. The main structures that affect the damping properties are ε-martensite, the movement of interface between ε-martensite and austenite and stacking faults. There is usually a large vacancy concentration in the microstructures after solid solution treatment. It is necessary to take a certain heat treatment like annealing or aging treatment. For some low ε-martensite content or large austenite grain size, a certain degree of deformation or annealing can be used to control the microstructure to improve the damping properties.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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