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A Study of Impact Toughness of Fe-Cr-*X* Damping Alloys

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A study was carried out on the impact toughness of Fe-Cr-*X* damping alloys. Two measures proved to be effective in improving impact toughness. One was to lower carbon plus nitrogen content to an ultra-low level. This method is suitable for single-phase ferrite alloy. The other is to use dual-phase damping alloys. The presence of martensite in Fe-Cr-*X* alloys can enhance impact toughness remarkably, but lower damping capacity drastically. This shows the importance of achieving balance between mechanical properties and damping capacity by properly controlling martensite volume fraction in dual-phase alloys.

Keywords
dual-phase damping alloy; impact toughness

1. Introduction

THE most fruitful period in both the fundamental research and commercial exploitation of high damping alloys (HIDALLOYS) came at the end of the 1970s and continued through the 1980s. In the 1990s, investigation and practical application of structural damping, i.e., internal friction of materials, will be accelerated due to rekindled interest in materials with an actual or potential high damping capacity. By far the most important products are Fe-Cr-*X* HIDALLOYS of single-phase ferrite such as Silentalloy[1] and Vacrosil-010.[2] (Silentalloy is a registered tradename of the Toshiba Co., Japan,[3] and Vacrosil is a registered tradename of the Vacuumschmelzer GMBH Germany.) The extensive studies of Fe-Cr-*X* HIDALLOYS were spurred by their unparalleled advantages, which may be summarized as (1) possessing higher strength, (2) being able to maintain higher damping capacity at a wide range of temperatures and vibration stress amplitudes, and (3) being insensitive to vibration frequency.[4] However, the use of Fe-Cr-*X* HIDALLOYS in structural components is still in its infancy. One of the main reasons is that their impact toughness is generally so low that they cannot be trusted to provide safe performance in applications where elevated damping levels must be accompanied by good mechanical properties. Therefore, improvement of the impact toughness of Fe-Cr-*X* HIDALLOYS is of the utmost significance in developing high damping structural materials. The aim of this article is to try to solve this problem.

2. Materials Preparation and Experimental Methods

The chemical compositions of testing materials are listed in Table 1. Steel C2 and steel D1 were melted in a vacuum induction furnace with a capacity of 21 kg. The ingots were then subjected to forging and hot rolling. Steel S3 was prepared using a 2700-kg arc furnace. After forging, the ingot was hot rolled into plate 6 and 12 mm in thickness, respectively. Semifinished specimens for mechanical property testing and damping capacity measurement were machined from as-hot-rolled plate and ground to final size after heat treatment. Metallographic observation revealed that steels C2 and S3 are composed of single-phase ferrite, and steel D1 consists of dual phases of ferrite and martensite when air cooled. According to these results, high solution temperatures were chosen for the two single-phase alloys, followed by cooling in air. After heat treatment, steels C2 and S3 had large grain sizes (ASTM No. 1 to ~3) and consequently high damping capacity. For the dual-phase alloy, a tempering temperature as high as 800 °C was selected to reduce internal stress induced by the austenite to martensite transformation as the specimens were air cooled from a temperature of 975 °C.

Tension tests were performed using an Instron machine with specimens of 25 mm gage length and 5 mm diameter at a constant strain rate of 3.3×10^{-4} s^{-1}. Charpy V-notch impact toughness testing was carried out on a JB-30A type of tester. Damping capacity was measured by stimulating the specimen ($3 \times 8 \times 150$ mm^3) by an ear phone, on which a constant voltage amplitude (15 V) was exerted over a range of frequencies about the resonant frequency. The maximum vibration strain amplitude, ε_m, in the specimen was estimated to be on the order of 5.0×10^{-6}.[5] If Δf_A is the full width of the resonance curve at half maximum amplitude, at resonant frequency, f_r, the damping capacity, Q^{-1}, is given by:

$$Q^{-1} = \frac{\Delta f_A}{\sqrt{3} f_r} \quad [1]$$

3. Experimental Results and Discussion

3.1 *Single-Phase Damping Alloys*

Mechanical properties and damping capacity for C2 and S3 steel are presented in Table 2, which shows that C2 steel possesses a better combination of mechanical properties and damping capacity than S3 steel. The distinct difference is in impact toughness, particularly at low temperature (0 °C). Even though S3 has higher strength than C2, its superiority in strength is almost completely negated by its poor impact toughness.

Fe-Cr-*X* HIDALLOYS containing 10 to ~15% Cr, 0 to ~5% Al, 0 to ~3% Mo, and low C + N contents usually consist of sin-

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Table 1 Chemical composition of experimental materials

Steel code	Composition, %									
	C	Si	Mn	Cr	Mo	Al	S	P	N	Ni
C2	0.004	0.29	<0.1	10-15	0-3	0-5	≤0.004	≤0.008	0.0042	...
S3	0.030	0.11	0.18	10-15	0-3	0-5	0.002	0.018	0.010	0.45
D1	0.016	0.35	<0.1	12.86	0.99	0.11	≤0.004	≤0.008	0.0109	0.95

Table 2 Mechanical properties and damping capacity for C2 and S3 steel

Steel	σ_2, MPa	σ_b, MPa	Q^{-1}	C_V, J/cm^2	
				0 °C	RT
C2	276.5	499.0	12.3×10^{-3}	240.3	>303.5
S3	320.0	440.0	10.4×10^{-3}	~6.0	~4.0

gle-phase ferrite that has a bcc crystal structure with strong ferromagnetism.[6] The high damping capacity in Fe-Cr-*X* alloys derives primarily from magnetomechanical damping.[5,7,8] Many researchers have found that magnetomechanical damping capacity is inversely proportional to coercive force, H_c, a magnetic property that is extremely sensitive to microstructure.[9] Large grain sizes, low impurity element (C, N, or O) content, or low inclusion content and low internal stress will bring about a decrease in H_c. Therefore, in practice, Fe-Cr-*X* HIDALLOYS usually are subjected to high-temperature solution treatment, followed by very slow cooling to achieve as high a damping capacity as possible. However, such treatment leads to problems in applications where impact toughness is required for safety. It is well known that the toughness of metals and alloys is intimately related to their crystal structure, chemical composition, and microstructure. Generally speaking, a fcc metal is tougher than a bcc metal, because there are more easy slip systems in the former than in the latter. That is why bcc metals usually are characterized by a sharp transition from toughness to brittleness when temperatures fall below a critical value. Refining grain size is one of the most effective means of improving toughness. It is obvious, however, that the effects of grain size on damping capacity and mechanical properties are completely different. Hence, it seems that delicate control of chemical composition is the only option to improve toughness of Fe-Cr-*X* HIDALLOYS of single-phase ferrite while maintaining their high damping capacity, in that $Q^{-1} \geq 10^{-2}$. A systematic study was undertaken by J. Lu et al.[5] of the effects of composition on the properties of Fe-Cr-*X* damping alloys. It was found that certain amounts of chromium, aluminum, and molybdenum are necessary to meet both damping capacity and strength requirements, but excessive amounts of these elements are detrimental to impact toughness. It has also been shown that the C + N content should be kept at an ultralow level because impurity elements such as carbon and nitrogen are most detrimental to impact toughness. As shown in Table 2, C2 steel with an ultra-low C + N content has much higher toughness than S3 steel with a high C + N content. The low toughness in S3 steel might simply be attributed to the synergetic effect of large grains and carbides precipitated during cooling. The synergetic effect is emphasized to indicate that alloys of pure and clean ferrite can possess high impact toughness, even with large grain sizes, as demonstrated by the results of C2 steel in the current study. Besides the beneficial effect of ultra-low C + N content in improving impact toughness, it is beneficial to damping capacity, as illustrated in Table 2.

3.2 *Dual-Phase Damping Alloys*

Figure 1 shows the variation of mechanical and damping properties with the volume fraction of martensite in D1 steel. With an increase in martensite volume fraction, V_M, impact toughness and strength are enhanced, whereas damping capacity decreases drastically in both the air-cooled (AC) and air-cooled plus tempered conditions (T).

In the air-cooled state, damping capacity decreases monotonically with the increasing V_M and levels off at $V_M > 30\%$. This occurrence might be caused by the increased dislocation density in ferrite during austenite to martensite transformation. As V_M exceeds a critical value V_c,[10] undeformed ferrite is present as discrete regions evenly spaced between martensite particles. These undeformed ferrite regions account for less than 4% of the total ferrite and quickly decrease to zero with further increases in V_M. This leads to a total loss in magnetomechanical damping from the ferrite. Tempering above the recrystallization temperature will reduce and consequently remove the severely strained plastic zones and thus will result in an increase in damping capacity.

In the present work, the dual-phase damping alloy studied does not have good damping capacity even though it was tempered at 800 °C. This is perhaps due to the existence of a large fraction of martensite. The presence of a large fraction of tempered martensite disturbs the regular pattern of ferromagnetic domains in ferrite and results in an increase in coercive force, H_c, and consequently causes damping capacity to decrease sharply as expressed by:[11]

$$Q_t^{-1} = Q_{f0}^{-1} \frac{1 - V_M}{1 + BV_M} \quad (V_M \leq 25\%) \qquad [2]$$

where Q_{f0}^{-1} is damping capacity of pure ferrite, $(1 - V_M)$ is the effective volume fraction of ferrite; and B is a coefficient related to the magnitude of disturbing stress resulted from the tempered martensite.

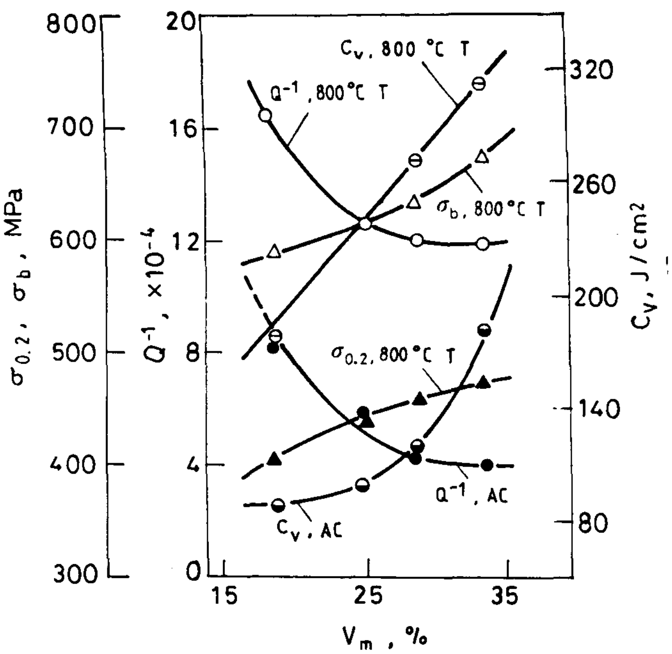

Fig. 1 Effect of martensite volume fraction on mechanical properties and damping capacity.

Another explanation of low damping capacity in D2 steel might be that the quenching temperature is not high enough so that the ferrite grains could grow as large as those in C2 and S3 steel.

In the air-cooled plus tempered condition, impact toughness of dual-phase damping alloys almost increases linearly with increasing V_M, as shown in Fig. 1. At present, it is hard to provide a distinct and definite explanation of the mechanisms of improving impact toughness by martensite. It seems that two mechanisms may be in effect. First, the effective grain size of the alloy is reduced because of the presence of tiny islands of martensite, and therefore, crack propagation might be effectively suppressed by these fine martensite colonies. Second, the purge of impurity elements such as carbon and nitrogen from the ferritic matrix will be accomplished more thoroughly if martensite plays the role of a scavenger. The combined result of the two possible effects of martensite is the improvement in impact toughness of dual-phase damping alloys.

The peak position of damping capacity in Fe-Cr-*X* dual-phase damping alloys may be shifted, as predicted by the Smith-Birchak theory,[8] to a higher vibration strain amplitude because of the presence of tempered martensite. This phenomenon should be considered in applications of Fe-Cr-*X* dual-phase damping alloys because they can provide a complete range of maximum or potential damping capacity only at a larger vibration stress amplitude.

4. Conclusions

Low C + N content in ferrite is effective in improving impact toughness of Fe-Cr-*X* single-phase ferritic HIDALLOYS in the sense that $Q^{-1} \geq 10^{-2}$. Fe-Cr-*X* dual-phase damping alloys can possess excellent impact toughness, but their damping capacity is lowered drastically by the martensite. Therefore, further investigation is needed to find the optimum volume fraction of tempered martensite and the satisfactory balance between damping capacity and mechanical properties.

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