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Effects of grain size and microstructures on the internal friction and Young's modulus of a high-strength steel HT-80

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Effects of grain size and microstructure on internal friction and Young's modulus were investigated using a high-strength steel HT-80. The mechanism of the internal friction in the steel was discussed. The internal friction largely increased with decreasing grain size of specimens. This was attributed to the viscous flow at or in the vicinity of grain boundaries or phase boundaries. The internal friction of specimens with ferrite–pearlite structure was larger than that of specimens with sorbite structure at larger grain sizes, but the former was smaller than the latter at smaller grain sizes and larger strain amplitudes. These results suggested that the magneto-mechanical hysteresis loss also contributed to the internal friction of the steel, because the migration of the magnetic domain wall in the ferrite matrix was more difficult for the ferrite–pearlite structure. Internal friction also increased with increasing strain amplitudes. Young's modulus was large in both fine-grained and coarse-grained specimens for sorbite and ferrite–pearlite structures. This was related to the carbon concentration in the ferrite matrix.

1. Introduction

It has been reported that the internal friction of the material exerts a significant influence on performance, fatigue life or noise level of components in automobiles, machine tools and other mechanical installations in which mechanical vibrations are important [1–3]. Thus, engineering materials such as structural steels are often required to possess high damping capacity (large internal friction) in addition to high strength and ductility [1].

To prevent or to reduce mechanical vibrations or resonance of structural components, improvements in design have been made [3, 4], and sandwich structures composed of metallic materials [5, 6], or polymer sheets [4] with high damping capacity and steel plates, are considered to be applicable to the structural components which suffer from mechanical vibrations. However, when the application of these techniques to such components is economically or structurally difficult, it is necessary to improve the inherent damping capacity of structural materials.

The effects of cold work, alloying elements and heat treatments on internal friction have been investigated on carbon steels [2, 7–10] and several kinds of stainless steels [11–13]. But there are few reports on the relation between materials properties and internal friction in high-strength steels [2, 7].

In this study, the effects of grain size and microstructure on internal friction and Young's modulus were investigated using a commercial high-strength steel HT-80. The mechanism of internal friction of the steel was also examined.

2. Experimental procedure

A commercial high-strength steel HT-80 (a Si–Mn killed steel) was used in this study (Table I). As-received steel slabs 20 mm thick, quenched and tempered, having a sorbite structure with grain diameter of about 27 μm were used. Specimens of 140 mm length, 20 mm width and 15 mm thickness were cut out from the slabs in a lengthwise direction identical to the rolling direction of the slabs. These specimens were air- or furnace-cooled after solution heating to produce a sorbite or ferrite–pearlite structure. Table II shows details of the heat treatments, and the resulting microstructures and grain size of specimens. Specimens of the smallest grain size (about 7.9 μm) were obtained by thermal cycling four times between 1073 and 573 K after solution treatment composed of solution heating for 7.2 ksec at 1473 K and subsequent air-cooling [14], as shown in Fig. 1. The grain sizes of specimens were obtained by the statistical methods shown in [15]. These specimens were finally air- or furnace-cooled to room temperature to produce a sorbite or pearlite structure.

Fig. 2 shows typical microstructures of heat-treated specimens. Small carbide (cementite) particles are visible in air-cooled specimens. (Fig. 2a, c, e) and the as-received specimen (Fig. 2g). Furnace-cooled specimens (Fig. 2b, d, f) have a ferrite–pearlite structure, but small carbide particles are also observed in the specimen of the smallest grain size (Fig. 2b). The amount of carbides is somewhat large in the fine-grained and coarse-grained specimens (Fig. 2a, b, e, f).

Specimens for measurement of internal friction and

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Young's modulus were machined from the as-received and heat-treated specimens. All the specimens were finally polished with sandpaper to remove the work-hardened surface layer. The finished specimens were of 100 mm length, 10 mm width and 0.65 to 2.35 mm thickness. Internal friction measurements were made using torsional, pendulum-type equipment at various strain amplitudes. The maximum torsional strain amplitude on the specimen surface is denoted simply by 'strain amplitude' in this study. The value of internal friction (Q^{-1}) was calculated using the following equation:

$$Q^{-1} = (1/\pi N_m) \ln (A_1/A_m) \qquad (1)$$

where A_1 is the strain amplitude of the first wave in constant oscillation (immediately before free oscillation); A_m is the strain amplitude of the mth wave at free oscillation, and N_m is the number of waves between A_1 and A_m Young's modulus was obtained from measurements of resonance frequency (f_r) of each specimen by a transversal vibration method in which an electromagnetic-type apparatus (Model IFA-411, Internal Friction Co. Ltd, Tokyo) was employed. According to the characteristics of the apparatus, the value of Young's modulus (E) was calculated by the following equation:

$$E = 0.96535 \times 10^{-8} (l/a)^3 (g/b) f_r^2 \qquad (2)$$

where l is the length, a the thickness and b the width of specimens (in cm); g is the weight of specimens (g) and f_r is resonance frequency of specimens (Hz). The hardness of specimens was also measured by a Vickers hardness tester with a load of 196 N.

3. Results and discussion

3.1. Effects of microstructure and grain size on internal friction and Young's modulus

Fig. 3 shows the relation between grain size and internal friction of specimens. The internal friction increases with a decrease of grain diameter in both specimens with sorbite structure and those with a ferrite–pearlite structure. At lower strain amplitudes below 2.0×10^{-4}, the internal friction of specimens with ferrite–pearlite structure is larger than that of specimens with sorbite structure at almost the same grain size, but the former is smaller than the latter at smaller grain sizes at the strain amplitude of 10^{-3}. Fig. 4 shows the effect of microstructure on the internal friction of specimens. In specimens of almost the same grain size, the strain amplitude dependence of internal friction is a little larger in the specimen with sorbite structure than in the specimen with ferrite–pearlite structure. The internal friction of specimens increases with an increase of strain amplitude. The internal friction of the specimen with sorbite structure is larger than that of the specimen with ferrite–pearlite structure at smaller grain sizes and larger strain amplitudes.

The grain size dependence of internal friction may arise from viscous flow at or in the vicinity of grain boundaries and phase boundaries [1, 4, 16–18]. Thus the internal friction increases with increasing grain-boundary area (decrease in grain size). A viscous flow

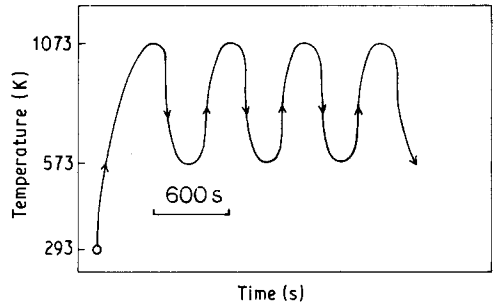

Figure 1 Schematic illustration of thermal cycling method, using air cooling or furnace cooling to 293 K to obtain fine-grained specimens.

TABLE I Chemical composition of the steel used (wt %)

Steel	C	Cr	Ni	Mo	V	Cu	Si	Mn	P	S	B
HT-80	0.11	0.49	0.82	0.30	0.04	0.16	0.25	0.97	0.016	0.006	0.001

Fe: bal.

TABLE II Grain size and microstructure of heat-treated specimens

Heat treatment	Microstructure	Grain diameter (μm)
1473 K, 7.2 ksec, AC + 4 thermal cyclings 1073–573 K, AC	Sorbite	7.9
1223 K, 1.8 ksec, AC	Sorbite	32
1373 K, 7.2 ksec, AC	Sorbite	74
1473 K, 7.2 ksec, AC	Sorbite	210
1523 K, 7.2 ksec, AC	Sorbite	340
1473 K, 7.2 ksec, AC + 4 thermal cyclings 1073–573 K, AC	Ferrite–pearlite	7.9
1223 K, 1.8 ksec, FC	Ferrite–pearlite	32
1373 K, 7.2 ksec, FC	Ferrite–pearlite	75
1473 K, 7.2 ksec, FC	Ferrite–pearlite	210
1523 K, 7.2 ksec, FC	Ferrite–pearlite	330
As-received (quenched and tempered)	Sorbite	27

AC, air-cooled; FC, furnace-cooled.

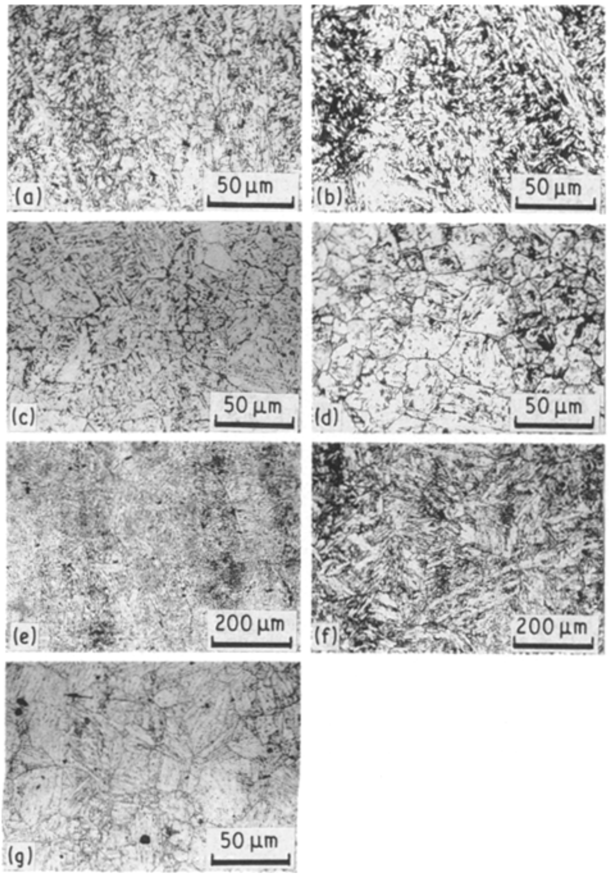

Figure 2 Optical micrographs of heat-treated specimens of HT-80 steel. d = (a) 7.9, (b) 7.9, (c) 32, (d) 32, (e) 210, (f) 210, (g) 27 μm (as-received). (a, c, e, g) sorbite structure, (b, d, f) ferrite–pearlite structure.)

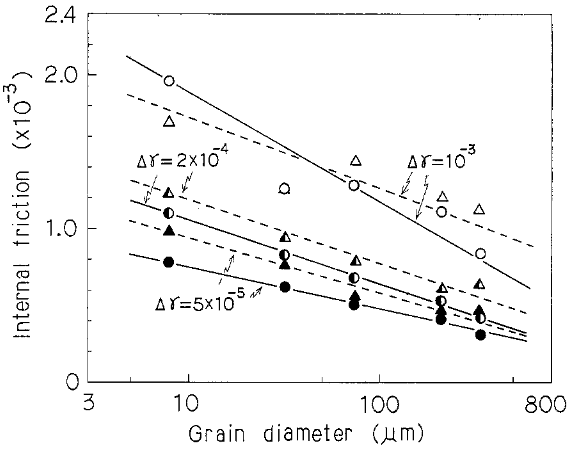

Figure 3 Relation between internal friction and grain size of specimens in HT-80 steel. Circles, sorbite; triangles, ferrite–pearlite. Frequency, 3.49 ± 0.26 Hz. $\Delta\gamma$, strain amplitude.

○△ $\Delta\gamma = 10^{-3}$

◐▲ $\Delta\gamma = 2\times10^{-4}$

●▲ $\Delta\gamma = 5\times10^{-5}$

may also occur at the ferrite–pearlite phase boundaries, and the value of internal friction in specimens with ferrite–pearlite structure is larger than that in specimens with sorbite structure in most cases. In ferro-magnetic materials, magneto-mechanical hysteresis loss is one of the important mechanisms of internal friction [1, 2, 4]. Migration of the magnetic domain wall is relatively difficult in the ferrite matrix of pearlite nodules [2]. Thus the value of internal friction is smaller in specimens with ferrite–pearlite structure than in specimens with sorbite structure of the same grain size at larger strain amplitudes.

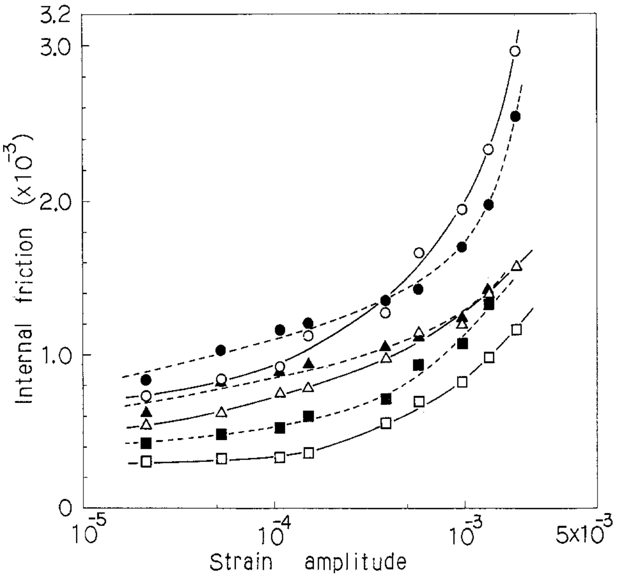

Figure 4 Effects of microstructures on the internal friction of specimens in HT-80 steel. Open symbols, sorbite; closed symbols, ferrite–pearlite. Grain diameter: circle, 7.9; triangle, 32; square, 330 μm. Frequency, 3.75 Hz.

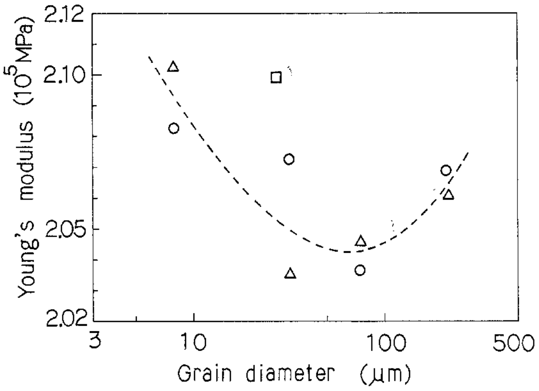

Figure 5 Relation between Young's modulus and grain size of specimens in HT-80 steel. ○, Sorbite; △, ferrite–pearlite; □, as-received.

Fig. 5 shows the relation between grain diameter and Young's modulus of specimens in HT-80 steel. Young's modulus is large in the fine-grained and coarse-grained specimens for both sorbite and ferrite–pearlite structures, and has a minimum value in the specimen of the intermediate grain size, although the scatter of experimental data is relatively large. There is little difference in the value of Young's modulus between these two microstructures. The as-received specimen has a relatively high Young's modulus. A large number of carbide particles precipitated in the fine-grained and coarse-grained specimens during heat treatment (Fig. 2). It is known that the Young's modulus of carbon steels decreases with increasing carbon content in the matrix, because of the increased interplanar spacing of the matrix phase [10]. This indicates that a decrease in carbon content due to carbide precipitation leads to an increase in the value of Young's modulus. According to Hanabusa and co-workers [19], Young's modulus of cementite is about 212 GPa and this value is very close to that of steels [20]. Therefore, the difference in Young's modulus between carbide (cementite) and matrix (ferrite) cannot explain the experimental results described above.

Fig. 6 shows the relation between hardness and grain size of specimens. The hardness in both specimens with sorbite structure and those with a ferrite–pearlite structure increases with decreasing grain size, and the increase of hardness is larger at larger grain sizes. The hardness is the highest in the as-received specimen. At the same grain size the specimen with sorbite structure has higher hardness than that with a ferrite–pearlite structure because of fine dispersion of carbide particles.

3.2. Strain amplitude and frequency dependence of internal friction

Fig. 7 shows the strain amplitude dependence of internal friction in specimens with sorbite structure of the smallest grain size. The internal friction increases abruptly with increasing strain amplitude. Further, the value of internal friction is almost independent of frequency in the measurements. Fig. 8 shows the strain amplitude dependence of internal friction of the as-received steel. The internal friction of the as-received steel also increases with increasing strain amplitude, but the value of internal friction is much less in the as-received steel than in the specimen with sorbite structure of the smallest grain size. The as-received steel exhibited the smallest value and least strain amplitude dependence of internal friction in this study. Both specimens have a sorbite structure, but the as-received steel contains a large amount of carbide precipitates, as is known from the hardness values in Fig. 6. Carbide precipitates may also retard the migration of the magnetic domain wall, and may lead to a low internal friction value.

Fig. 9 shows the relation between internal friction and frequency in specimens with sorbite structure. The internal friction is almost independent of frequency at all the strain amplitudes, and is the largest in the specimen of the smallest grain size. Almost the same results were obtained in specimens with a ferrite–pearlite structure. These results indicate that the thermo-elastic mechanism which exhibits frequency dependence of internal friction [21, 22] does not contribute to the internal friction of HT-80 steel. Further, grain-boundary scattering of the elastic wave depends on minus fourth-power of grain diameter and fourth-power of frequency [22], but the experimental

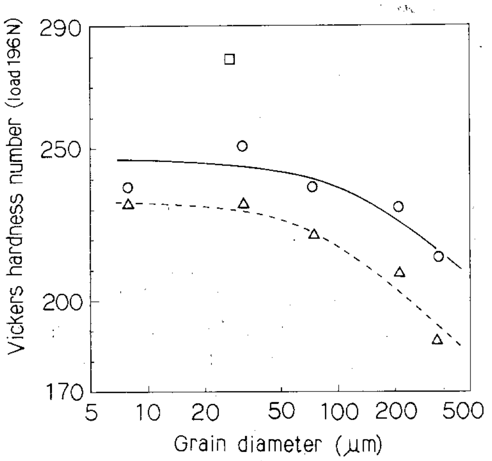

Figure 6 Relation between hardness and grain size of specimens in HT-80 steel. ○, Sorbite; △, ferrite–pearlite; □, as-received.

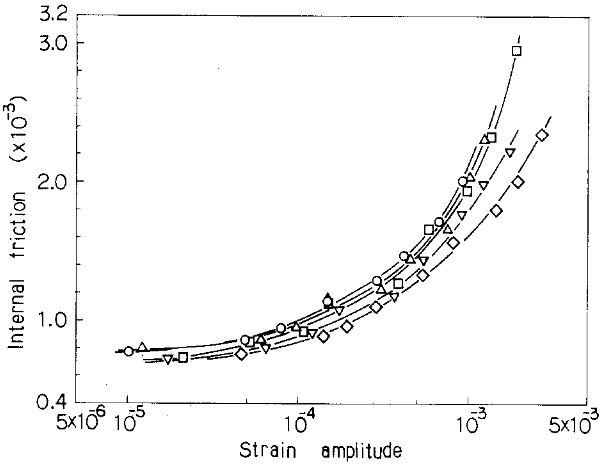

Figure 7 Strain amplitude dependence of the internal friction in specimens with sorbite structure of the smallest grain size in HT-80 steel. Frequency ○, 8.06; △, 7.12; ▽, 5.38; □, 3.75; ◇, 1.53 Hz.

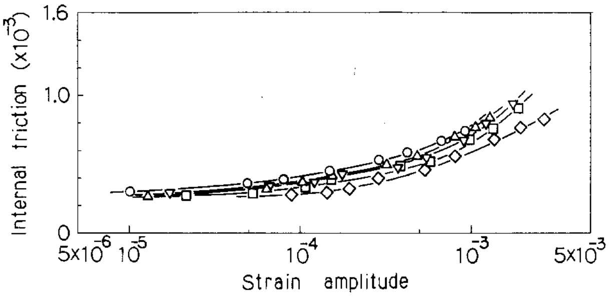

Figure 8 Strain-amplitude dependence of the internal friction of the as-received HT-80 steel. Frequency ○, 8.06; △, 6.96; ▽, 5.38; □, 3.75; ◇, 1.53 Hz.

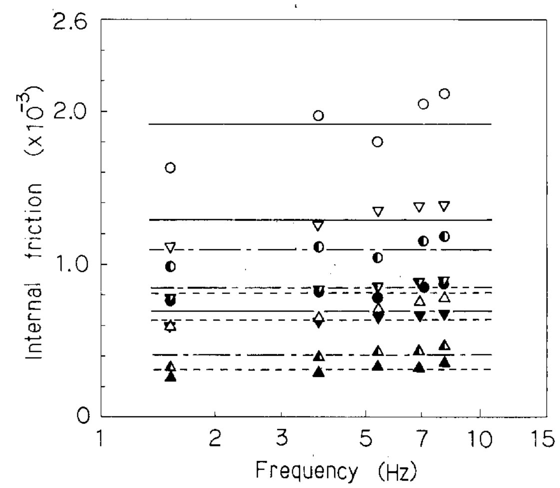

Figure 9 Relation between internal friction and frequency of specimens with sorbite structure in HT-80 steel. Grain diameter ○, 7.9; ▽, 32; △, 27 Strain amplitude, (——) 10^{-3}; (— — —) 2×10^{-4}; (----) 5×10^{-5}.

○▽△ $\Delta\gamma = 10^{-3}$

◐▼◭ $\Delta\gamma = 2\times10^{-4}$

●▼▲ $\Delta\gamma = 5\times10^{-5}$

results in this study are very different from these dependences.

The experimental results in this study showed that a decrease in grain size leads to an increase in internal friction. Both internal friction and Young's modulus were large in the specimen of the smallest grain size for sorbite and ferrite–pearlite structures. The fine-grained, high-strength steels will find more applications in service, because these steels generally have high yield strength and ductility.

4. Conclusions

The effects of grain size and microstructure on internal friction and Young's modulus were investigated using a high-strength steel HT-80. The results obtained are summarized as follows:

1. In both sorbite and ferrite–pearlite structures, the internal friction increased with decreasing grain size. In specimens of the same grain size, the ferrite–pearlite structure exhibited the larger value of internal friction than the sorbite structure. The as-received (quenched and tempered) steel showed the smallest value of internal friction.
2. The internal friction increased with increasing strain amplitude in both specimens with sorbite structure and in those with ferrite–pearlite structure, but the as-received steel exhibited the least strain amplitude dependence of internal friction. The internal friction in HT-80 steel was almost independent of frequency.
3. The mechanisms of internal friction in HT-80 steel were the viscous flow at or in the vicinity of grain boundaries and phase boundaries, and the magnetomechanical hysteresis loss in the migration of the magnetic domain wall. Grain-size dependence of internal friction was explained by the former mechanism, but the difference in internal friction values between sorbite structure and ferrite–pearlite structure could be explained by both mechanisms.
4. Young's modulus was large in both fine-grained and coarse-grained specimens for sorbite and ferrite–pearlite structures. This was because the carbon concentration in the ferrite matrix decreased owing to carbide precipitation during heat treatment.
5. It was found that the fine-grained, high-strength steels had large values of internal friction (damping capacity) and Young's modulus in addition to high yield strength and ductility.

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