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The internal friction associated with bainitic transformation, and bainitic transformation in a Cu–Zn–Al shape memory alloy

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Abstract. The internal friction in bainitic transformation in a Cu–Zn–Al alloy has been studied. It has been found that a Q^{-1} peak associated with bainitic transformation on the curve of Q^{-1} against T occurs at about 245 °C for the quenched specimen during heating ($\dot{T} = 1\text{ }^{\circ}\text{C min}^{-1}$). The frequency variation accompanying the peak is similar to that of martensitic transformation. The peak temperature is independent of frequency with T constant. If T is kept constant at an adequate temperature, an isothermal Q^{-1} peak appears on the curve of Q^{-1} against time. The internal friction in bainitic transformation is strain amplitude dependent. The Q^{-1} peak associated with bainitic transformation was attributed to the motion of the interface dislocations between bainite and parent phases under vibrating stress. The bainitic transformation has also been discussed. It was considered that bainitic nucleation is related to anti-domain boundaries, and its growth is controlled indirectly by diffusion.

1. Introduction

Bainitic transformation of the metastable ordered β phase in Cu–Zn and Cu–Zn–Al alloys will occur during isothermal aging in the mesothermal region (Flewitt and Towner 1967, Cornelis and Wayman 1974, Kennon *et al* 1982, Wu and Wayman 1986, Takezawa and Sato 1986). Some characteristics of the bainitic transformation process, such as the surface relief, the long-period stacking structure, the orientation relationship between bainite plates and the matrix and habit plane, are similar to those of martensitic transformation. However, other parameters, such as the incubation period, the change in composition and the isothermal change in the amount of the bainite which fits a Johnson–Mehl type of curve, support a diffusion-controlled transformation. Therefore the mechanism of bainitic transformation still remains controversial.

Internal friction (IF) has been used extensively in the investigation of materials as a means of research because it depends on the microstructure. The IF in martensitic transformation in Cu–Zn–Al alloys has been reported in many previous papers (Dejonghe *et al* 1977, Bojarski *et al* 1983, Van Humbeeck and Delaey 1983, Koshimizu and Benoit 1982, Morin *et al* 1985), but only a few of these were about the IF in bainitic transformation. The investigation into the IF in bainitic transformation not only leads to understanding of the physical phenomena during the transformation but also helps to determine the mechanism of bainitic transformation. In the work of Zhang *et al* (1986)

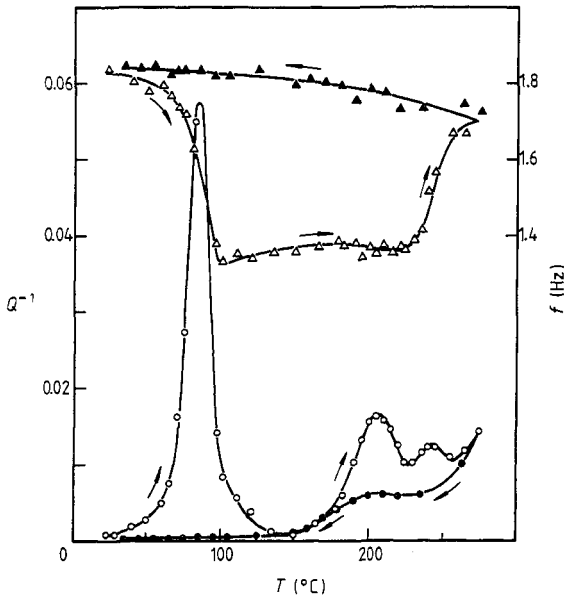


Figure 1. Curves of Q^{-1} (circles) and f (triangles) against T for step-quenched samples under the continuous heating and cooling ($\dot{T} = 1^\circ\text{C min}^{-1}$) conditions.

a Q^{-1} peak was observed on the curve of Q^{-1} against time for a Cu–Zn–Al alloy after it had been heated at 750°C , cooled rapidly to a temperature between 220 and 320°C and held at that temperature; Zhang *et al* attributed the peak to the bainitic nucleation within the incubation period, but no bainite was observed. In the present work, using the characteristic that the transformation crystallography between parent phase and martensite is reversible during the thermoelastic martensitic transformation, the martensitic structure was obtained; first the specimen was quenched and then the parent phases could be produced by reverse transformation during heating. The IF in bainitic transformation was observed by heating the specimens to the temperature range in which bainitic transformation occurred. The IF behaviour was analysed, and the mechanism of bainitic transformation discussed.

2. Experimental procedure

The tested alloy was prepared from electrolytic copper (99.9 wt%), pure zinc (99.99 wt%) and industrial purity aluminium (99.7 wt%), melted under inert-gas protection, then poured into an ingot of diameter 60 mm and length 500 mm. Specimens of 0.95 mm diameter for the IF measurement were obtained through hot rolling and cold drawing of the ingot. The composition of the tested alloy is Cu–25.75 wt% Zn–4.32 wt% Al. The specimens were subjected to step quenching, heating at 850°C for 20 min, then quenched in an oil bath at 130°C for 3 min and finally quenched in water at room temperature. The microstructure showed martensite.

The IF measurements were made under continuous heating and cooling ($\dot{T} = 1^\circ\text{C min}^{-1}$) conditions and under isothermal conditions at 215°C . Three frequencies were used: 1.8, 1.0 and 0.6 Hz (at room temperature). The specimens were under a constant stress of 1 MPa during the measurements.

A vacuum Kê pendulum was used for the IF measurements. The length of the even-temperature region is 280 mm at 300°C and over this region the temperature variations were less than $\pm 1^\circ\text{C}$. The length of the tested specimens was 120 mm.

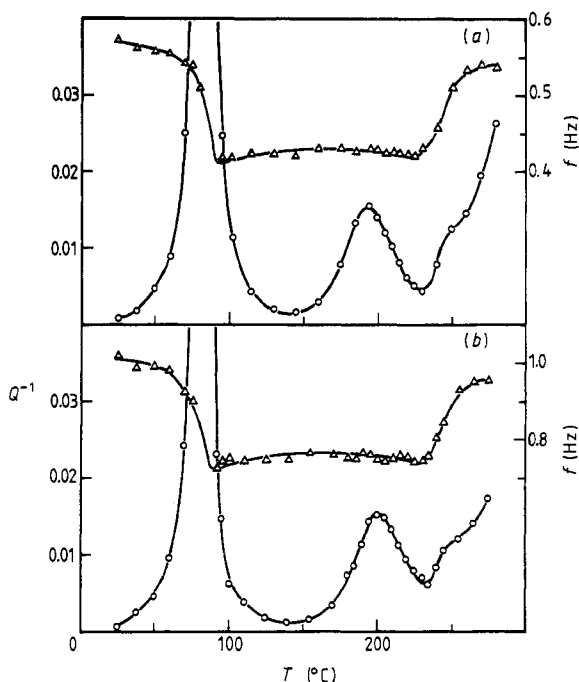


Figure 2. Curves of Q^{-1} (circles) and f (triangles) against T measured on heating at different frequencies.

3. Results

3.1. The internal friction during heating and cooling

Figure 1 gives the IF and frequency curves of a step-quenched specimen during heating. Three peaks can be observed in the curve of Q^{-1} against T in the range from room temperature to 280 °C. These peaks are located at about 85, 210 and 245 °C ($f \approx 1.8$ Hz). The 85 and 245 °C peaks are accompanied by similar sudden changes in frequency and also by evident zero drift. During cooling, the 245 and the 85 °C peaks disappear, the 210 °C peak decreases and the frequency f increases in the normal way. Figure 2 gives the IF and frequency curves of the specimens at different measurement frequencies. It can be observed that the peak temperatures of the 85 and 245 °C peaks do not change and the 210 °C peak temperature varies with change in frequency. When $f \approx 0.6$ Hz, the peak temperature of the 210 °C peak shifts to near 190 °C. It has been shown that the 210 °C peak is a relaxation peak. Its activation energy was measured to be 26 kcal mol⁻¹. The 85 and 245 °C peaks are IF peaks caused by two different processes. The 85 °C peak which is associated with the process of reverse martensitic transformation is a typical Q^{-1} peak due to a reverse martensitic transformation and the 245 °C peak which is associated with bainitic transformation is also caused by phase transformation.

Figure 3 shows the results measured during cooling when the specimen had been heated to a temperature which was just a little higher than the 210 °C peak temperature and before the 245 °C peak appears. It can be seen that the 210 °C peak does not change and a sharp Q^{-1} peak due to martensitic transformation appears at a lower temperature. Metallographic examination showed that the bainitic transformation did not occur and the microstructure was still the same as that of a step-quenched specimen (figure 4).

Figure 5 shows the results measured during cooling when the specimen had been heated to the temperature at which the 245 °C peak just appeared (the start of zero

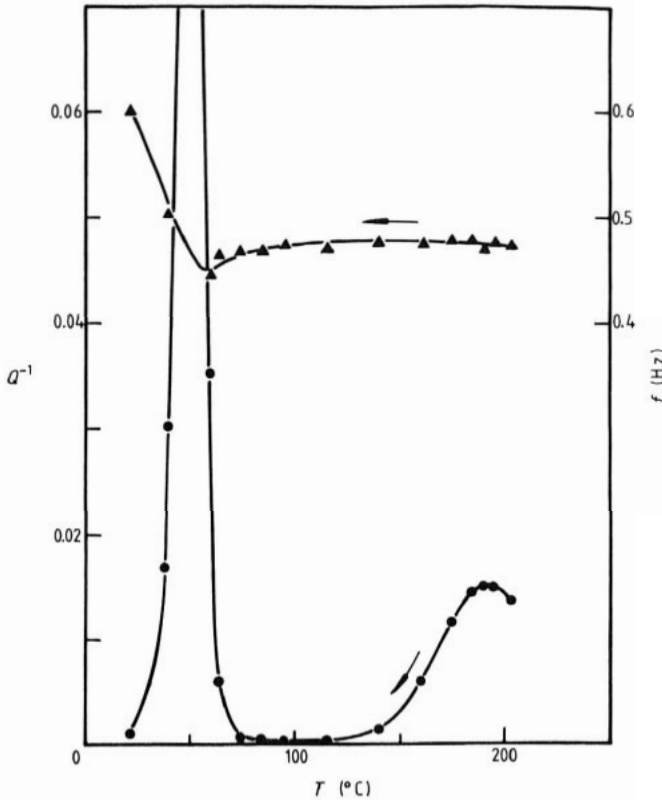


Figure 3. Curves of Q^{-1} (circles) and f (triangles) against T measured on cooling before the 245 °C peak appears.

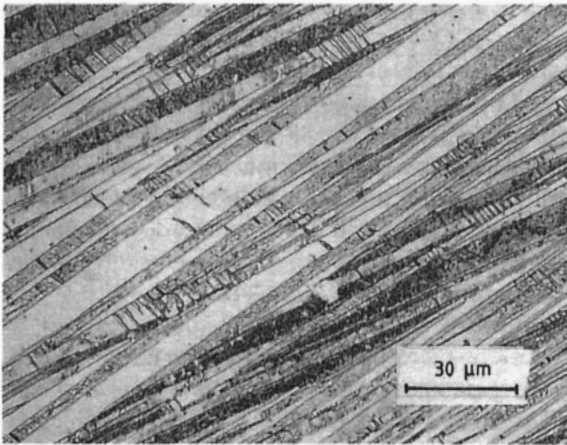


Figure 4. Optical micrograph of the sample after the IF measurement in figure 3.

drift). This time, the height of the 210 °C peak decreases and so did the height of the Q^{-1} peak due to martensitic transformation; the temperature of the martensitic transformation shifted to a lower temperature. Metallographic examination showed a mixed structure of martensite and bainite (figure 6), indicating that the bainitic transformation had occurred.

The facts mentioned above have shown that the 245 °C peak is a Q^{-1} peak due to bainitic transformation and the 210 °C peak is not.

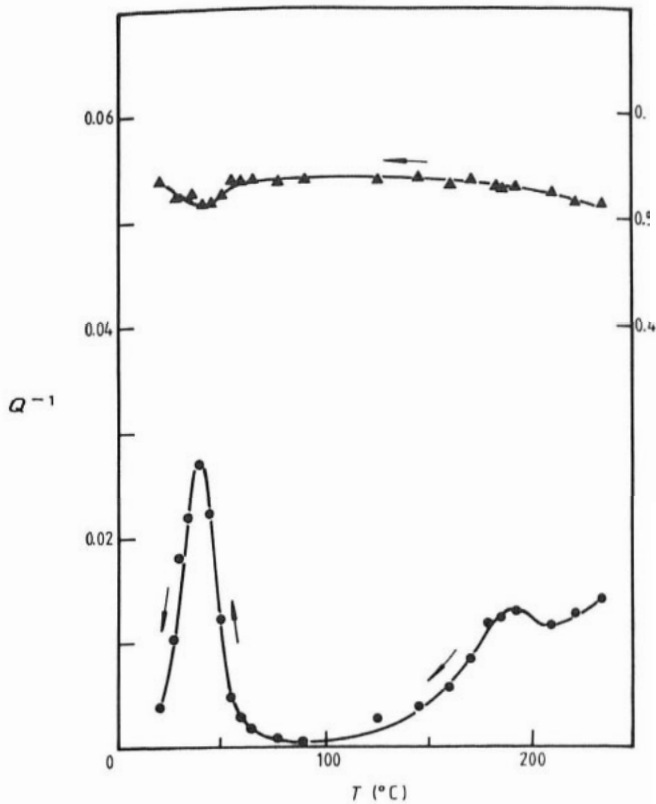


Figure 5. Curves of Q^{-1} (circles) and f (triangles) against T measured on cooling when the 245 °C peak has just appeared.

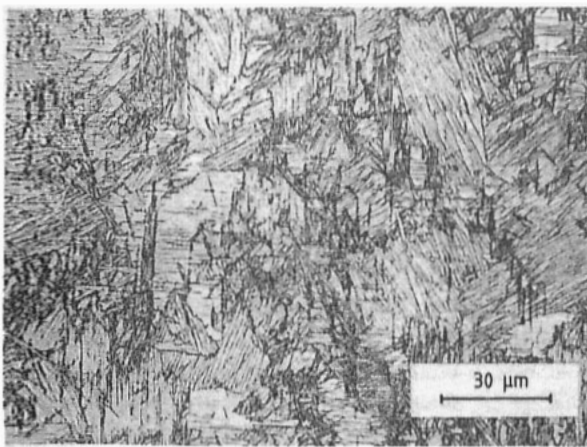


Figure 6. Optical micrograph of the sample after the IF measurement in figure 5.

3.2. The internal friction under isothermal conditions

Bainitic transformation can proceed under isothermal conditions. Figures 7 and 8 give the curves of the IF and frequency against time for step-quenched specimens during isothermal measurements at 0.6 Hz and 1.8 Hz, respectively. The isothermal temperature was held at 215 °C.

When $f \approx 0.6$ Hz (figure 7), the initial value of IF corresponds to the IF value at 215 °C in figure 2(a) and, when $f \approx 1.8$ Hz (figure 8), the initial value of IF is close to the peak

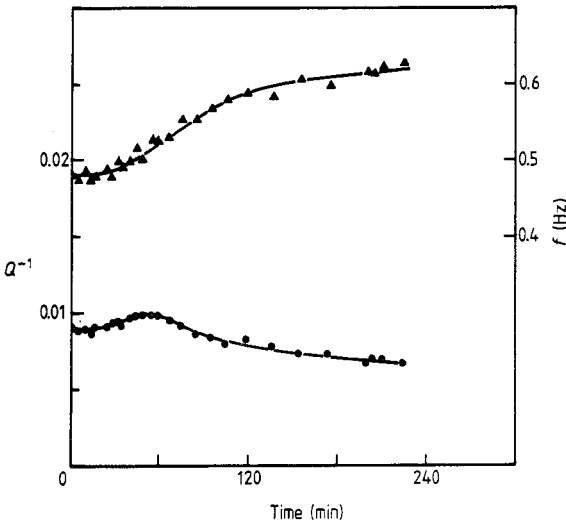


Figure 7. Q^{-1} (circles) and f (triangles) against time at 215 °C ($f \approx 0.6$ Hz).

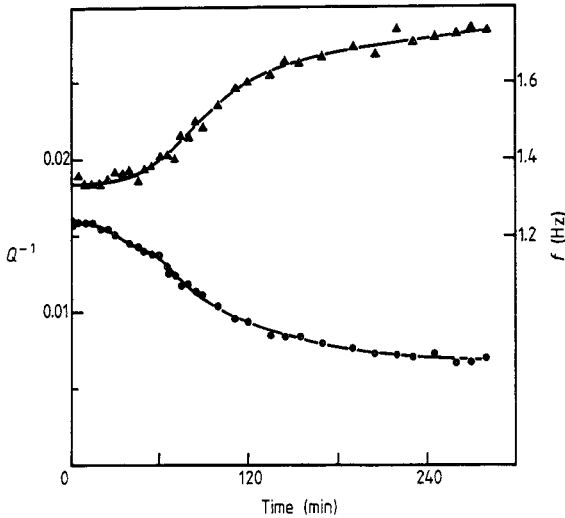


Figure 8. Q^{-1} (circles) and f (triangles) against time at 215 °C ($f \approx 1.8$ Hz).

value of the 210 °C peak in figure 1. From figures 7 and 8, an isothermal Q^{-1} peak associated with bainitic transformation on the curves of Q^{-1} against time can be observed and this peak is also accompanied by a sudden change in frequency. Meanwhile, the background, i.e. the value of the 210 °C peak, decreases on bainite precipitation. In particular, when $f \approx 1.8$ Hz, the background evidently decreases, causing the isothermal Q^{-1} peak due to bainitic transformation to become unclear. These results indicate that the value of the 210 °C peak decreases rapidly when bainite precipitates.

3.3. Amplitude dependence of the internal friction

The IF under isothermal conditions was also measured for different strain amplitudes. The curves in figure 9 show the amplitude dependence. The IF increases with increase in the amplitude. This amplitude dependence is most notable in the transformation region, is less so in the β -phase region and is smallest in the bainite + β -phase region. This result

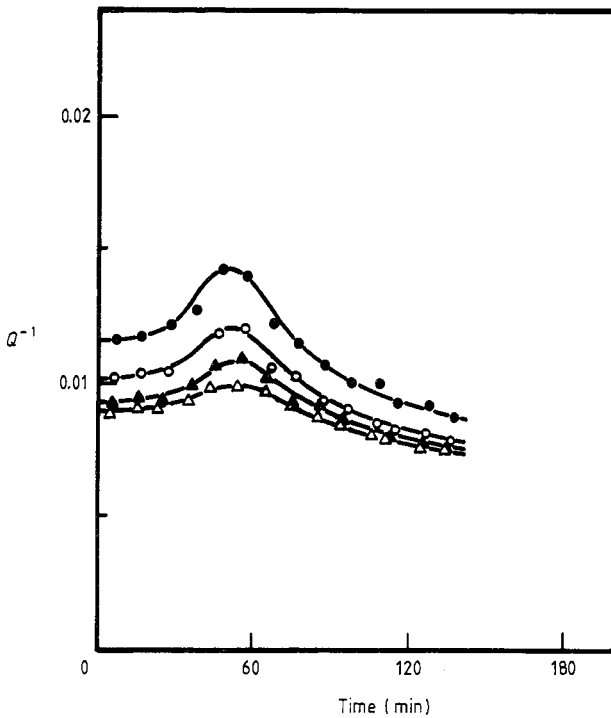


Figure 9. Strain amplitude dependence of the IF measured under isothermal (at 215 °C) conditions: ●, $\varepsilon = 1.4 \times 10^{-5}$; ○, $\varepsilon = 1.0 \times 10^{-5}$; ▲, $\varepsilon = 7.0 \times 10^{-6}$; △, $\varepsilon = 3.5 \times 10^{-6}$.

is very important, for it implies that at very small strain amplitudes the peak disappears, and this in turn implies that the IF could be due to the dislocation mobility.

4. Discussion

4.1. Internal friction of bainitic transformation

The process of martensitic transformation is accompanied by the soft-mode phenomenon in some alloys. For Cu-Zn-Al alloys the elastic constant $C' = (C_{11} - C_{12})/2$ will decrease during the transformation and the modulus will show a minimum. In the present study, the frequency minima in figures 1-3 deviate from the centres of the Q^{-1} peaks associated with martensitic and reverse martensitic transformation because of the larger modulus of martensite. This result is in agreement with that of Wang *et al* (1981) in the investigation of the IF of martensitic transformation in Au-Cd alloy. Clapp (1973) has developed a localised soft-mode theory and considered that strain induces elastic instability in a particular region. Guenin *et al* (1982) applied the theory to the $\beta \rightarrow 9R$ transformation. In the study of Zhang *et al* (1986), it was also shown that the bainitic transformation in Cu-Zn-Al alloys is associated with the soft mode.

As pointed out in § 3, the dependence of the IF on the strain amplitude can imply a relationship with dislocation motion. This dependence follows the Granato-Lücke (1956) theory of dislocation breakaway (figure 10). According to the observed amplitude dependence in figures 9 and 10 and the localised soft-mode theory, our results can be interpreted as due to the motion of interface dislocations. We consider that the elastic constant $C' \rightarrow 0$ occurs only in the parts of the specimen just undergoing transformation. Because C' decreases, the dislocations at the β -bainite interfaces are able to move under

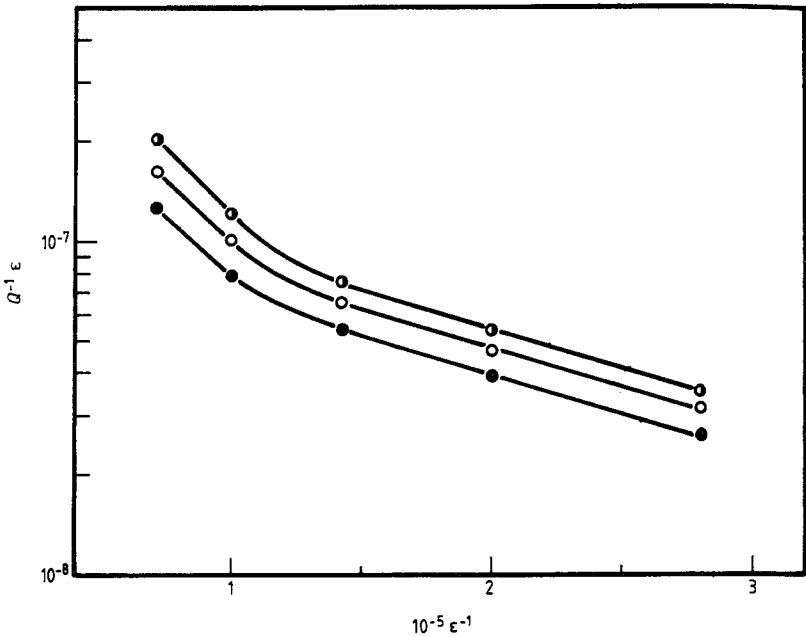


Figure 10. Granato-Lücke plot for peak height (●), β background (○) and β + bainite background (●).

the action of a small vibrating stress and are in turn responsible for the IF.

The IF martensitic transformation is related to the mobility of two types of interface: β -martensite and martensite-martensite (Dejonghe *et al* 1976). For the IF in bainitic transformation, however, only one type of interface, β -bainite, is dominant. In addition, the growth of bainite is controlled by diffusion (which is explained in the following), and thus the motion of the interface dislocations suffers a resistance due to diffusing atoms. For these two reasons, the Q^{-1} peak value for the bainitic transformation is smaller than that for the martensitic transformation.

4.2. 210 °C peak

Ghilarducci and Ahlers (1983) have studied the IF behaviour of β -Cu-Zn-Al alloys. They observed a relaxation peak at about 200 °C ($f \approx 1.9$ Hz) for the alloys in ordered β -phase crystals and found that, in fact, the peak is present after any heat treatment. The activation energy is 25 kcal mol⁻¹. In the present study, when the 210 °C peak appears, the specimen is just in the ordered β -phase structure state. The activation energy was measured to be 26 kcal mol⁻¹. The 210 °C peak in our work is considered to be the same as the peak observed by Ghilarducci and Ahlers at about 200 °C. We have previously discussed the peak in the investigation of the IF in a Cu-Zn-Al alloy under equilibrium conditions (Zhao *et al* 1988) and attributed the peak to the movement of point defects around anti-domain boundaries under a vibrating stress in the ordered β phase.

4.3. Bainitic transformation

4.3.1. *Bainitic nucleation.* As shown in figures 7 and 8, the IF value of the 210 °C peak decreased when bainite is precipitated. Here, the amount of the bainite precipitating is

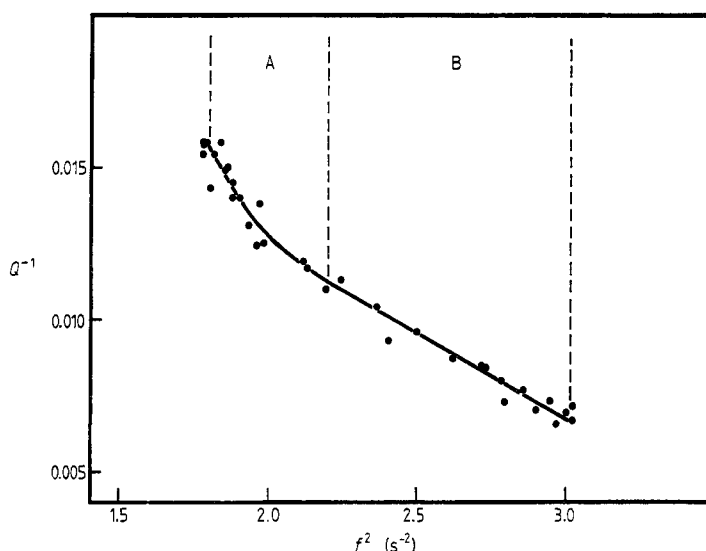


Figure 11. Variation in Q^{-1} with f^2 at 215 °C.

represented approximately by the amount of the variation in the square of the frequency, i.e. f^2 . From figure 8, the variation in Q^{-1} against f^2 was obtained (figure 11). The curve in figure 11 may be divided into two parts: A and B. The increase in f^2 in region A shows the early formation of the bainite and the increase in f^2 in region B shows the later formation. In region A, the IF (i.e. the 210 °C peak) decreases rapidly with the increase in f^2 . If we subtracted the increment caused by the bainitic transformation, this decrease would be more marked. In region B, the decrease in the IF becomes weaker compared with that in region A, and shows a linear relation with f^2 . The linear variation in Q^{-1} with f^2 indicates that the decrease in the 210 °C peak in region B is mainly due to the reduction in the volume of parent phases caused by bainitic transformation. However, besides the volume effect, there should be another reason for the strong decrease in the IF in region A (the stage of early formation of bainite). This implies that the bainitic precipitation is related to defects which give rise to the 210 °C peak. Probably, bainitic nucleation is mainly at sites where defects are present.

It has been indicated by Zhao *et al* (1988) that the anti-domain boundaries are responsible for the 210 °C peak. It is known that the atoms on the two sides of the anti-domain boundary have the same orientations but different energies. It is easy for there to be a variation in composition and a higher energy at the boundaries. So, the anti-domain boundaries should be advantageous to the bainitic transformation. The incubation period could be associated with the adjustment in composition. In our work, there are undoubtedly other types of defect, such as inclusions, α rods and grain boundaries; these can also promote the nucleation (Takezawa and Sato 1986).

4.3.2. Bainitic growth. When a small amount of bainite has precipitated, the Q^{-1} peak due to the martensitic transformation appears at a lower temperature on the curve during cooling (figure 5). If a large amount of bainite has precipitated, no peak due to martensitic transformation appears above room temperature (figure 1) even though the parent phases still exist since the 210 °C peak is still well defined in the curve during cooling. That is to say, the temperature M_s of martensitic transformation will decrease with increase in the amount of the bainite, indicating a change in the composition of the parent phase. This fact shows that the bainitic transformation is associated with atomic

diffusion, which has been confirmed for Cu–Zn alloys in previous work (Lorimer *et al* 1975, Doig and Flewitt 1981).

However, the bainitic transformation is also associated with macroscopic deformation, surface relief and the crystallographic nature is similar to that of martensitic transformation, showing a shear characteristic on the bainitic transformation. It is well known that martensitic transformation is a type of shear process and its growth is controlled primarily by strain energy. On the basis of the experimental phenomena and the characteristics of the bainitic transformation, we consider that the bainitic transformation also proceeds as a type of shear process and its growth is also controlled by strain energy. However, for the bainitic transformation, the strain energy can be released by the diffusion of atoms and other defects. When the strain energy is released, the bainitic transformation proceeds continuously, resulting in growth under isothermal conditions. Thus, the shear process appears to be controlled by diffusion, and amount of isothermal bainitic transformation naturally agrees with the results from the equations for a diffusion-controlled transformation process.

5. Conclusions

- (i) When bainitic transformation occurs, the IF will increase for the present alloy.
- (ii) The IF peak in bainitic transformation is attributed to the motion of the dislocations at the interfaces between bainite and parent phases under a vibrating stress.
- (iii) Bainitic nucleation is related to the anti-domain boundaries, and the boundaries are the main positions of bainitic nucleation.
- (iv) Bainitic growth is a type of shear process but is controlled indirectly by diffusion.

References

- Bojarski Z, Ilczuk J, Panek T and Morawiec H 1983 *J. Physique Coll. Suppl.* 12 **44** C9 241
 Clapp P C 1973 *Phys. Status Solidi* b **57** 561
 Cornelis I and Wayman C M 1974 *Acta Metall.* **22** 301
 Dejonghe W, De Batist R and Delaey L 1976 *Scr. Metall.* **10** 1125
 Dejonghe W, Delaey L, De Batist R and Van Humbeeck J 1977 *Met. Sci.* **11** 523
 Doig P and Flewitt P E J 1981 *Proc. Int. Conf. Solid–Solid Phase Transformations (Pittsburgh, PA)*
 Flewitt P E and Towner J M 1967 *J. Inst. Met.* **95** 273
 Ghilarducci A and Ahlers M 1983 *J. Phys. F: Met. Phys.* **13** 1757
 Granato A and Lücke K 1956 *J. Appl. Phys.* **27** 583
 Guenin G *et al* 1982 *Metall. Trans. A* **13** 1127
 Kennon N F, Dunne D P and Middleton L 1982 *Metall. Trans. A* **13** 551
 Koshimizu S and Benoit W 1982 *J. Physique Coll. Suppl.* 12 **43** C4 679
 Lorimer G W, Cliff G, Aronson H I and Kinsman H R 1975 *Scr. Metall.* **9** 271
 Morin M, Vincent A and Guenin G 1985 *J. Physique Coll. Suppl.* 12 **46** C10 625
 Takezawa K and Sato S 1986 *Proc. Int. Conf. Martensitic Transformations (Nara)* p 625
 Van Humbeeck J and Delaey L 1983 *J. Physique Coll. Suppl.* 12 **44** C9 217
 Wang Y N, Shen H M, Xu Z R, Zou Y F, Zhu J S, Zhang Z F and Yang Z J 1981 *J. Physique Coll. Suppl.* 10 **42** C5 1049
 Wu M H and Wayman C M 1986 *Proc. Int. Conf. Martensitic Transformations (Nara)* p 619
 Zhang J H, Chen S C, Xu Z Y and Hsu T Y 1986 *Acta Metall. Sinica* **22** A372
 Zhao Z Q, Chen F X and Yang D Z 1988 *Mater. Sci. Prog. Sinica* **2** 29