# Internal Friction of Oxygen-Bearing Copper (2nd Report)

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## Synopsis

The internal friction of annealed copper specimens containing oxygen showed a maximum on increasing the strain amplitude. The position of the maximum changed with the heat-treatment of the specimen; the lower the temperature of annealing, the further towards the lower amplitude is displaced the maximum. It was supposed that the shift of the maximum to lower amplitude was owing to the lower solubility of the impurities at lower temperature. An interpretation was tried by using the dislocation theory of A. Granato and K. Lücke. The theory could explain the existence of a maximum in the internal friction-amplitude curve and the shift of the maximum to lower amplitude in purer specimens.

## I. Experimental

In our previous paper(1) (1st Report of this series), it was related that the internal friction of a well-annealed specimen of oxygen-bearing copper had a maximum in the internal friction strain amplitude curve, and the position of the maximum changed with the heat-treatment of the specimen. In order to clear this relation further the following study was done. The specimen signed to No. 4 was prepared by melting electrolytic copper with some amount of powder of cuprous oxide and by casting it in a horizontal iron mold immersed in cold water. The cast specimen free from any working was annealed at 200° for 2 hrs, and the internal friction was measured with its amplitude dependence. The result was shown in Fig. 4 in the previous paper and is again given in Fig. 1 in this paper.

The specimen was then subjected to heat-treatments at various temperatures in succession, and after each annealing the internal friction was measured. The results are shown in **Fig. 1** and **Fig. 2**, from which it is clearly seen that when the temperature of

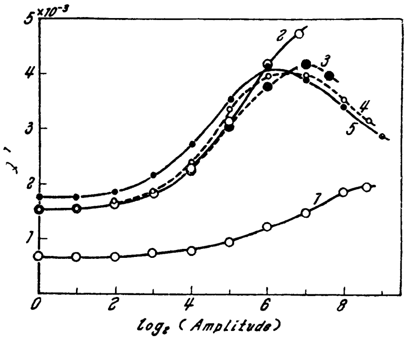


Fig. 1

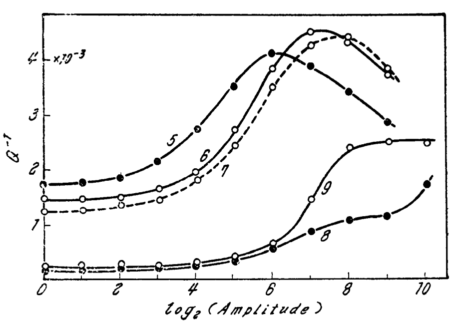


Fig. 2

Fig. 1 and Fig. 2 Internal friction/amplitude curve of the specimen No. 4
(1) as cast
(2) after annealing at 900° for 5 hrs.
(3) after annealing at 900° for 3 hrs and reannealing at 700° for 4 hrs.
(4) after reannealing at 600° for 2 hrs.
(5) after reannealing at 600° for 4 hrs.
(6) after reannealing at 900° for 4 hrs.
(7) after reannealing at 1000° for 4 hrs.
(8) after reannealing in hydrogen atmoshere.
(9) 6 days after the reannealing in hydrogen atmospere.

(1) S. Imoto, G. Mima, J. Japan Inst. Metals, **21**(1957), 267.

the heat-treatment was lowered, the position of the maximum was shifted to the lower amplitude, and when the temperature of the heat-treatment was raised, the position was shifted to the higher amplitude. The same result had been seen with specimen No. 5 partly and less distinctly. At last the specimen was held at 800° for 7 hrs in hydrogen atmosphere. The result is also shown in Fig. 2 (8). The internal friction was decreased and the maximum disappeared. After standing it for 6 days at room temperature, the internal friction was measured to be as shown in Fig. 2 (9). It remained low at low amplitudes, but was increased at higher amplitudes.

## II. Discussion

We have seen that with some specimens a maximum existed in the internal friction-amplitude curve, and with some other specimens it did not. We consider that there is no essential difference between these two behaviors of the internal friction with the increase of the amplitude of strain, that is, we infer that in the latter case the maximum is shifted towards a much higher amplitude and escapes out of our measuring range. By assuming this, the various behaviors of the internal friction with amplitude can be explained unificatively. Generally, the further towards the lower amplitude the maximum lies, the higher the internal friction at low amplitude. In our previous paper we concluded that in a specimen with higher internal friction the quantity of the impurities in a state of solution were less than that in a specimen with lower internal friction. From this, we are led to the supposition as follows. With a specimen with very little impurities in a state of solution, the internal friction at low amplitude is high and increases as the amplitude increases, reaches a maximum and thereafter decreases. As the impurities in a state of solution increase, the internal friction at low amplitude is gradually reduced and the maximum is shifted towards higher amplitudes. If the amount of impurities increases further, the internal friction is further reduced and the maximum will be forced out of our measuring range or will be disturbed by some phenomena at high amplitudes where many grains of the specimen will suffer stresses above the critical shear stress. In a specimen containing much impurities in a state of solution, the internal friction is very low and almost remains constant on increasing the amplitude. It was described in the previous paper that on the light of the supposition above mentioned the differences of behaviors of internal friction between ozygen-bearing copper and oxygen-free copper, and between a well-annealed specimen and a specimen as rapidly cast could be explained. The maximum shifting by heat-treatments is explained as well as those. The lower the temperature, the less soluble the impurities in copper, and the more impurities react with oxygen into oxide, therefore the less the impurities in a state of solution. So, the lower the temperature, the farther towards the lower amplitude the maximum is shifted. Namely, the shift of the maximum towards the lower amplitude by annealing at lower temperatures is looked upon as due to precipitation of impurities out of the state of solution.

According to the studies of the internal friction previously carried out by several researchers using single crystals of copper(2)(3), lead(4), and zinc(2)(5), the internal friction generally increases as the amplitude increases. Sometimes it remains nearly constant to a critical amplitude and at this point it abruptly increases with the amplitude. If more impurities or some alloying elements are contained in the specimen, the value of the internal friction reduces and the critical point is shifted towards higher amplitudes(4)(6). For such a phenomenon, an explanation in terms of the dislocation theory of Mott and Nabarro was successfully tried by Weertman and Salkovitz(4). But in our opinion, the shift of the critical amplitude in the case of specimens containing plenty of alloying elements does not essentially differ from the shift of the maximum in the case of specimens

(2) A. S. Nowick, Phys. Rev., **80** (1950), 249.
(3) J. S. Koehler, *Imperfections in Nearly Perfect Crystals*, 197.
(4) J. Weertman & E. I. Salkovitz, Acta Met., **3** (1955), 1.
(5) T. A. Read & E. P. T. Tyndall, J. Appl. Phys., **17** (1946), 713.
(6) S. Takahashi, J. Appl. Phys, **23** (1952), 866.

poor in impurities in a state of solution. These are the two extremes in the behaviors of the internal friction with the amount of impurities. Therefore any theory which can explain the former phenomena must also explain the latter. But we could not find a theory which explains the existence of the maximum and the shift of it till the appearance of the theory of Granato and Lücke(7). In outline the theory is as follows. A pure single crystal contains a network of dislocations, and for large enough concentrations of impurity atoms the length of loop is further pinned down by the impurity particles through the Cottrell mechanism. Let the network length be denoted by $L_N$ and the length determined by the impurities which pin down the dislocations $L_C$. For zero applied stress the length $L_N$ is pinned down by the impurity atoms as qualitatively shown in **Fig.3** (a). For a small stress, the loops ($L_C$) bow out (Fig. 3 (b)), and continue to bow out until the breakaway from an impurity atom occurs, which instantly brings about the catastrophic breakaway and all the impurities between the two strongly pinned down network points are releasad from the dislocation loop (Fig. 3 (c)). Upon further increase in the stress the loop length ($L_N$) bows out. Now the stress is decreased, the long loops ($L_N$) collapse elastically along a path determined by the long loop length, thus the path of unloading part is not the same as that of the loading part, giving a hysteresis loop. The solid line in **Fig.4** shows the stress-dislocation strain curve that results for the model shown in Fig. 3. The path $ABCDE$ is the loading part and $FDA$ is the unloading part. The dotted curve is that which would result if not all of the loops have the same length. This hysteresis is the cause of the internal friction in kilocycle range. Granato and Lücke have calculated this hysteresis loss using an approximation which was valid only for the early stages of the breakaway process, and successfully explained the shift of the critical amplitude with the amount of impurities. It is readily seen from Fig. 4, the hysteresis loss per square of the strain amplitude increases with the strain amplitude, but at much larger strain amplitude it has reduced values, that is, the internal friction has a maximum in the relation to the strain amplitude. Along Granato and Lücke's theory we calculated the internal friction as the function of strain amplitude over its wide range in the case of $L_N/L_C=11$ and $L_N/L_C=51$. The result is shown in **Fig.5**. There is shown that the curve has a maximum and the maximum is at lower amplitude in the case of $L_N/L_C=11$ than in the case of $L_N/L_C=51$. If the impurities in a state of solution are increased, the loop length $L_C$ between the impurity atoms will be shorter, therefore $L_N/L_C$ is increased. So the maximum is shifted towards higher amplitude. In this way, our experimental results can be qualitatively explained through this theory. On the absolute values of the internal friction at the maximum and its strain amplitude, the theory can give the values which agree with the observed results, using sufficiently reasonable constants. A disagreement between the theory and the observed results is that the breadth of the peak observed is too wide as compared with that deduced from the theory. One of the causes

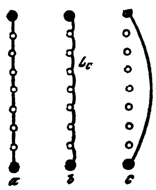

Fig. 3 Schematically drawn successive motions of a dislocation by an increasing stress.

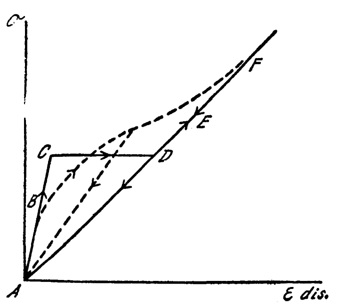

Fig. 4 Stress dislocation strain curve obtained with the model shown in Fig. 3.

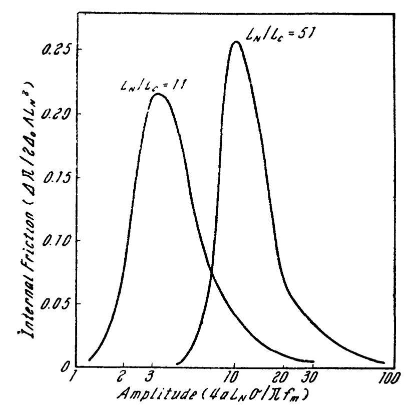

Fig. 5 Internal friction-strains amplitude curve calculated by the theory of Granato and Lücke.

(7) A. Granato & K. Lücke, J. Appl. Phys., **27**(1956), 583.

of this discrepancy may be owing to the distribution of the loop length ($L_N$) in the actual case, which was assumed to be single in the theory.

## III. Summary

If we temporarily name the specimen of higher internal friction as soft, and that of low one as hard as done in the previous paper, our results are summarized as follows:

(1) A specimen which contains more impurities in a state of solution is harder, and vice versa.

(2) Generally the internal friction increases as the amplitude of strain increases, reaches a maximum and thereafter decreases.

(3) The softer the specimen, at the lower amplitude is the maximum.

(4) If the specimen is hard enough, the maximum escapes out of our measuring range and will be disturbed by some other effects caused by a large stress even if the measuring range is extended.

(5) These results are explained through the dislocation theory of Granato and Lücke.