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Early work on dislocations and point defects at low and intermediate frequencies*

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Abstract

During the period of 1947–1951, I had the good fortune to be present in two laboratories that were carrying out pioneering work in internal friction and anelasticity. These were the laboratories of S.L. Quimby at Columbia University, where I was a graduate student, and that of Clarence Zener at the University of Chicago, where I held a postdoctoral appointment. In this article, I am happy to recall some of my impressions and experiences of that period.

1. The Quimby period (1947–49)

Professor S.L. Quimby had invented the composite oscillator, which used a piezoelectric quartz crystal to drive a specimen of interest and, thereby, permitted measurements of both elastic constants and internal friction of the specimen [1]. It covered what I will call the "intermediate" range of frequencies, from 20 to 80 kHz. A series of Quimby's students (including G. Zacharias, S. Siegel, W.F. Brown, Jr., A.W. Lawson and T.A. Read) used this device for the measurement of elastic constants and internal friction in a wide range of materials. Quimby was a meticulous experimenter and insisted on high standards in the work of his students. He did not get to be well known, primarily because he had his students publish their work without his name as co-author. Nevertheless, the totality of papers from his laboratory between 1933 and 1941 added up to a considerable contribution to the field of elasticity and internal friction.

Quimby's last student before World War II was T.A. Read, who has studied what was essentially dislocation damping in zinc and copper single crystals [2, 3]. At that time, the dislocation concept was relatively new and seemed remote from experiment. (For example, at that time, no one had actually seen dislocations under the electron microscope.) To many workers in the field of mechanical properties of materials, dislocation theory only paraphrased what was taking place in the language of the dislocation concept, but the reality of the dislocation as a distinct imperfection could be questioned. Read's work, however, seemed to provide irrefutable evidence for the presence of a mobile defect that was related to mechanical behavior. In a "pure" single crystal he found an amplitude-dependent damping that could be greatly enhanced by subjecting the crystal to loads below the yield point. Figure 1 shows an example taken from Read's work. To me, this phenomenon provided clear evidence for the presence of dislocations. I therefore chose to study these effects in greater detail.

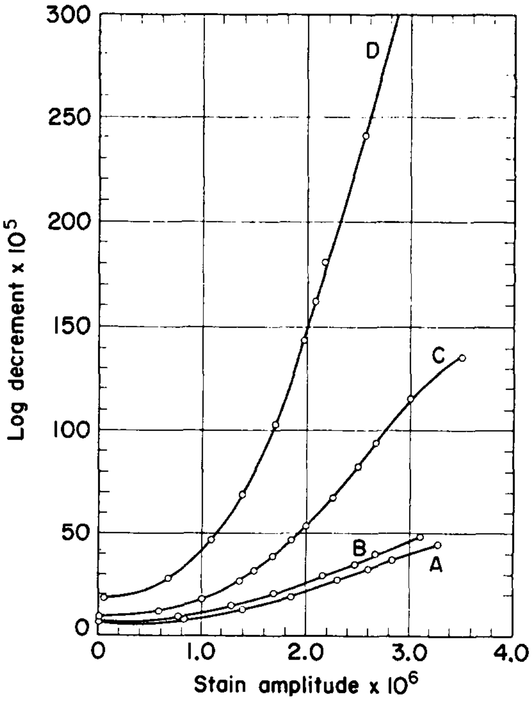

Fig. 1. Internal friction as a function of strain amplitude (at 30 kHz) for an undeformed copper crystal (curve A) and after application of stresses of 60, 120 and 150 psi, respectively (curves B, C and D). From ref. 3.

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In our work, Quimby and I studied the effects of temperature and of frequency on the amplitude-dependent damping in single crystals of copper [4]. We found that the damping was essentially frequency independent, suggesting a hysteresis or breakaway mechanism for the dislocations. These results later led Granato and Lücke to develop their well known quantitative model for breakaway [5]. The temperature dependence of the internal friction on the other hand, could be interpreted in terms of the association energy between impurities and dislocations, a concept that had been suggested by Cottrell [6] shortly before this work.

At the same time that I was carrying out these experiments, another Quimby student, T.E. Pochapsky, was measuring the compressibility of molten sodium using a novel acoustic interferometer that allowed the measurement of small velocity changes of compressional waves with high precision [7].

2. The Zener period (1949–51)

With the completion of my doctoral thesis at Columbia, I moved on to the University of Chicago where Clarence Zener's group was doing exciting things in the famous west stands of the Stadium (where earlier Fermi had carried out the first self-sustaining nuclear chain reaction, thus opening up the nuclear age). Zener was a member of the Institute for the Study of Metals, probably the first interdisciplinary laboratory for materials studies, begun by Cyril S. Smith immediately after the Second World War. Smith was a metallurgist who had worked at Los Alamos during the War where he saw what benefits could be derived by bringing together chemists, physicists and metallurgists to attack difficult problems. Today in the United States, there are many Materials Research Laboratories, but the one at Chicago was far ahead of its time, and it was due to Smith's foresight. To this exciting environment, Smith brought Clarence Zener.

Zener had first developed an interest in internal friction through a study of thermoelastic heat-flow damping. By 1948, he had written his book: *Elasticity and Anelasticity of Metals* in which he defined a new field of anelasticity [8]. Previously, the term had been used loosely to refer to any type of non-elastic behavior. Zener saw the advantages of focusing on behavior involving linear, time-dependent deformation that is fully recoverable. Anelasticity has since become one of the major fields of study of mechanical behavior.

Zener had an associate, T.S. Kê, who perfected the torsion pendulum and applied it at an early stage to the study of grain-boundary relaxation. Also working with Zener was Charles Wert, who had earlier studied dislocation damping, but had become disillusioned with the poor quantitative reproducibility of such phenomena and instead had turned to a study of the Snoek effect due to interstitial solutes (C, N, O) in body-centered cubic (b.c.c.) metals (*e.g.* Fe, Nb, Ta). The torsion pendulum was used in the frequency range around 1 Hz. It was a simple device with a mirror attached to reflect the image of a slit on to a distant scale, so that the observer could determine the logarithmic decrement in free decay. It was a remarkably inexpensive piece of equipment – in fact the most expensive part was the temperature controller for the surrounding furnace. Zener was a theoretician, but he was very proud of what was being done in his laboratory with so simple a device. In fact, when visitors came to the University of Chicago to see that University's great state-of-the-art cyclotron of that period, Zener enjoyed taking them to see the low-cost torsion pendulum and to show them that with it one could measure directly the rates of hopping of atoms in metals.

At this time, stimulated by the work they were doing on the Snoek effect, Zener and Wert published papers on the significance of the pre-exponential of the hopping rate in which they introduced the concept of the entropy of activation [9]. This concept has remained a part of the way that we think about the nature of atom migration and diffusion till today.

I came into this environment looking for something different to do and found that, a few years earlier, Zener had studied a single crystal of alpha-brass (Cu–Zn) and observed a beautiful relaxation peak, not much broader than a single Debye peak [10]. Zener had first explained it based on an assumption that the equilibrium distribution of zinc atoms was non-uniform, but he clearly was not satisfied with this explanation. In 1947, he wrote a paper suggesting that the mechanism was one of reorientation of pairs of solute atoms in the presence of stress, by analogy to the Snoek relaxation [11]. This suggested that what Zener had observed for alpha-brass was a universal property of all solid solutions.

I looked for a solid solution in which the size difference between solute and solvent would be greater than that for brass, and chose the silver–zinc system. Subsequently, I demonstrated that such a Zener relaxation did indeed occur for these alloys, with a specific peak height quite a bit larger than for brass (see Fig. 2). Also, the fact that the variation of peak height with concentration obeyed nearly a square law rather than a linear one supported Zener's model. (Later work by Berry on more dilute Ag–Cu alloys confirmed the square law very well.) Nevertheless, because of the high solute concentrations (up to 30%), the concept of reorientation of simple pairs seemed inappropriate and was better generalized to a concept of stress-induced ordering [12].

This was a period of considerable excitement over the vacancy mechanism of diffusion. The calculations of Huntington and Seitz [13] in 1942 had shown that

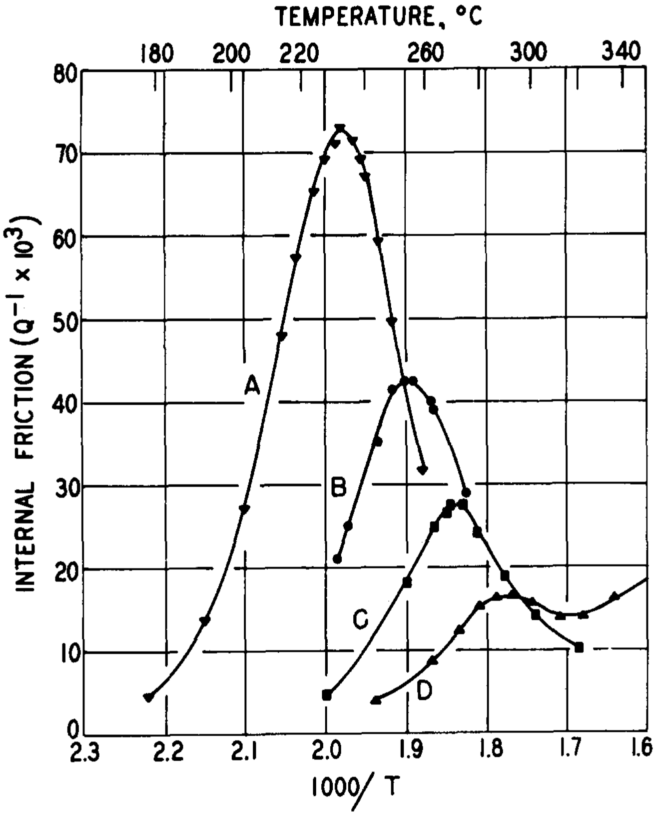

Fig. 2. The Zener relaxation in a series of Ag–Zn solid solutions. Curves A to D, respectively, are for 30, 24, 19 and 16 at.% Zn (frequency, 0.7 Hz). From ref. 12.

a direct exchange of two neighboring atoms in a close-packed metal like copper would require far more energy than the observed activation energy for self-diffusion, but that diffusion by vacancy migration gave reasonable numbers. Subsequently, the famous Kirkendall diffusion experiment [14] showed that in chemical diffusion, both atoms in a solid solution do not migrate at the same rate, suggesting a vacancy mechanism. Meanwhile, Zener had reexamined the question of atomic interchange mechanisms by demonstrating that a ring of four atoms has a much lower potential energy barrier than that of a ring of two (as involved in direct interchange). He suggested that such "ring diffusion" be seriously considered as an alternative to the vacancy mechanism [15]. It seemed to me that the Zener relaxation offered a unique opportunity to test the vacancy mechanism, *viz.*, by introducing a greater-than-equilibrium concentration of vacancies through quenching from high temperatures. It was also clear, however, that internal friction methods could not provide the way to carry out the experiment, since non-equilibrium vacancies would anneal out too rapidly in the course of an internal friction experiment. Instead, quasi-static experiments (*e.g.* elastic after-effect) would be better, since they allow measurements to be carried out at lower temperatures where the annealing would be slower. Accordingly, I quenched Ag–Zn alloys and then carried out elastic after-effect measurements. The striking result was that the Zener relaxation was now observed with relaxation rate approximately 10^4 times faster (for the given temperature) than under equilibrium conditions [16]. Further, with the passage of time, the relaxation time increased indicating that vacancies were annealing out. The experiment was a clear demonstration of enhanced atomic mobility through quenching, a result that could only be explained by a defect mechanism of diffusion. Zener was a bit disappointed in this refutation of his ring mechanism, but expressed satisfaction that the result was obtained in his laboratory.

Zener's creative mind was always moving into new directions. In his final year at Chicago he turned his attention to magnetism and generated a number of highly original papers. In 1951 he left Chicago to become Associate Director of Research at the Westinghouse Research Laboratories thus bringing to a close this wonderful era of anelasticity and internal friction at Chicago.

3. Final remarks

From the many aspects of work in the two laboratories that I have described, I would like to emphasize the following in closing. The crystal lattice defects that are so firmly established today, particularly dislocations and vacancies, were once doubted and even disputed. It is gratifying to me that the study of internal friction and anelasticity played a key role in establishing the existence of these defects and in helping to better understand their roles, respectively, in plastic deformation and in atomic mobility.

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