

AN ABSTRACT OF THE THESIS OF

Thomas Alphonsus O'Halloran, Junior for the Master of
Science in Physics

Date thesis is presented: May 14, 1954

Title: Changes of the Internal Friction in Copper After
Cold Working

Abstract approved

Investigations of the effect of cold working on the internal friction of copper have become numerous in the last few years due to the discovery that part of the internal friction is due to the motion of dislocations in the metal.

Most of the investigations so far have been done at frequencies of about 150 kilocycles per second. At these frequencies the internal friction has been found to be amplitude dependent and a function of the amount of cold work performed on the metal.

This experiment was performed at a frequency of 54 cycles per second by vibrating the reed transversely in a vacuated symmetrical transducer at room temperature.

The reed was annealed by placing it in a vacuum and passing electric current through it so that it was heated to a dull red. This was repeated and the reed was then left in the vacuum until cool.

The cold working was done by placing compressive loads of 2, 4, 6, 8 and 10 tons on two reeds of the same size. The pressure on each reed would then increase in steps of 1 ton effective load on the total surface area of each reed.

It was found that contrary to some theories, the internal friction of the reed was still amplitude dependent and a function of the amount of cold work.

The internal friction decreased upon additional cold work after the annealing. As the amount of cold work was increased, the internal friction passed through a minimum and then sharply increased.

It is proposed that the thermal currents present in

the metal at this frequency remove the free dislocations before the stress starts them oscillating under the influence of the stress. Once the dislocation has been removed it may become a bound dislocation and as such will not enter into the internal friction.

Cold working serves to increase the number of free dislocations. The thermal currents simply remove these and as a result there is a decrease in the internal friction.

The final increase is believed due to the passing of the yield point. Once this point was passed the resulting disorder and flattening of the grain structure would lead to a rapid increase in the internal friction.

CHANGES OF THE INTERNAL FRICTION IN
COPPER AFTER COLD WORKING

by

THOMAS ALPHONSUS O'HALLORAN, JUNIOR

A THESIS

submitted to


OREGON STATE COLLEGE

in partial fulfillment of
the requirements for the
degree of

MASTER OF SCIENCE


June 1954

APPROVED:




Professor of Physics


In Charge of Major



Chairman of the Department of Physics



Chairman of School Graduate Committee



Dean of Graduate School

Date thesis is presented May 14, 1954

Typed by Ruth Brown

ACKNOWLEDGEMENT

I would like to express my appreciation to Dr. J. J. Brady for suggesting the problem and for counsel during the experiment and in the preparation of the thesis.

Mr. Robert P. Merritt was always a source of help in the assembling and also in photographing the apparatus for which I am extremely grateful.

I also want to express my thanks to Mr. James Carpenter for the help extended in annealing the reed.

TABLE OF CONTENTS

	Page
INTRODUCTION	
THEORY.	4
APPARATUS	8
PREPARATION OF THE REED AND METHOD OF PROCEDURE . . .	17
RESULTS	21
BIBLIOGRAPHY.	31

FIGURES

1. Relation of the Elastic Phase Constant to the Stress and Strain	2
2. Formation and Motion of a Dislocation.	5
3. Schematic diagram of the apparatus	9
4. The apparatus as assembled for operation	10
5. The transducer with the reed mounted	12
6. Video amplifier.	14
7. Reed mounted in vise	18
8. Elastic Phase Constant vs. Amplitude for Annealed Reed	25
9. Elastic Phase Constant vs. Amplitude after 1800 psi.	26
10. Elastic Phase Constant vs. Amplitude after 3600 psi.	27
11. Elastic Phase Constant vs. Amplitude after 5400 psi.	28
12. Elastic Phase Constant vs. Cold Work.	29

TABLES

1. Data used for Figures 8, 9, 10 and 11.	30
---	----

CHANGES OF THE INTERNAL FRICTION IN COPPER AFTER COLD WORKING

INTRODUCTION

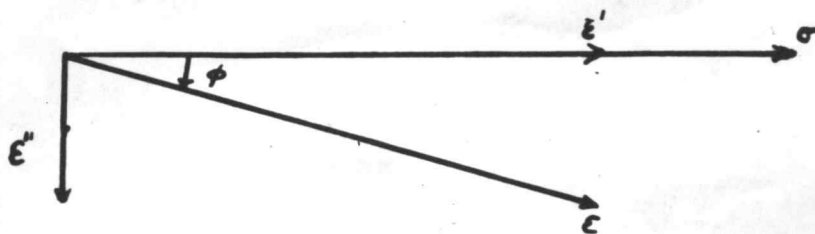
The study of internal friction is the study of the damping of a metal's motion due to the dissipation of energy by losses inside the metal. The losses arise from several causes. Under large stresses they may arise from the reorientation of the crystals themselves giving rise to a macroscopic flow of thermal currents. The losses to a smaller degree may still be due to thermal currents at lower stress amplitudes due to the differences in thermal potentials arising from the dilations caused by vibrating the metal. More modern theories show that losses may still arise from the motion of dislocations in the metal.

There are several ways of measuring the internal friction in a metal. The most common is the measurement of the decrement, Δ , which can be expressed as:

$$\Delta = \frac{\text{energy lost per cycle}}{\text{total energy}}$$

Another method of measurement is the elastic phase constant, ϕ , (5, p. 4), which is the time constant between the applied stress and the resulting strain. If the applied stress and the resulting strain were exactly in phase, there would be no energy loss and the metal would be perfectly elastic. Under an applied stress, however, the strain may be considered to be composed of two components. One is the

component which is perfectly elastic and is in phase with the applied stress and the other is perfectly inelastic and may be considered to lag the applied stress by 90° . The net resultant is a strain which lags the applied stress by some phase constant, ϕ , (Figure 1).



σ - Stress	ϵ - Total Strain
ϵ' - Elastic Strain	ϕ - Elastic Phase Constant
ϵ'' - Inelastic Strain	

Relation of the Elastic Phase Constant to the Stress and Strain

Figure 1.

The standard method for measuring the elastic phase constant is to set the specimen into oscillation by the application of a periodic driving force, the frequency of the driving force being close to a resonant frequency of the reed. The amplitude of the oscillation is then measured as a function of the frequency. The resonant frequency and the frequencies for the half power points are then found so that the reciprocal of the figure of merit, Q^{-1} can be found.

This reciprocal may be expressed as:

$$Q^{-1} = \frac{f_2 - f_1}{f_r}$$

where Q^{-1} = Reciprocal of the figure of merit.
 f_2 and f_1 = Half power frequencies.
 f_r = Resonant frequency of the reed.

If the reed is considered to be vibrating in a forced oscillation and the inelastic strain is small so that $\phi = \tan \phi$, it can then be shown, (4, p. 8), that:

$$\phi = Q^{-1} = \frac{\Delta}{\pi}$$

where ϕ = Elastic phase constant.
 Q^{-1} = Reciprocal of the figure of merit.
 Δ = Decrement.

THEORY

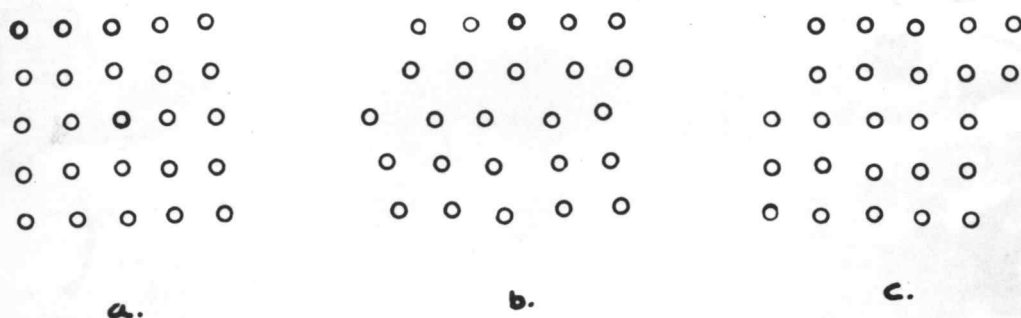
One of the first attempts to formulate a theory for the causes of internal friction was performed by Zener, (7, pp. 230-235), who attributed the internal friction losses to thermal currents arising from differences of thermal potentials in the metal. In an isotropic solid with a positive thermal expansion coefficient, a positive dilation lowers the temperature, while a negative dilation raises the temperature. The net difference in thermal potential results in the flowing of a thermal current and a dissipation of energy.

Zener also predicted a maximum in the internal friction versus frequency curve. This is attributed to the fact that at high frequencies the thermal currents will be adiabatic while at low frequencies they will be isothermal. At the intermediate frequencies the resulting internal friction will be primarily due to these thermal currents.

In a later paper Zener (8, pp. 90-99) also showed that in addition to the thermal currents arising from the dilations of the crystals, a polycrystalline metal also offered the possibility of fluctuations in stress between the various grains. An awareness of this fact is highly essential when vibrating a polycrystalline metal such as was done in this experiment.

Until 1940, however, it was thought that at small amplitudes the internal friction was amplitude independent and Zener's theory was formulated on this basis. Read (6, p. 371), however, showed quite clearly that for strain amplitudes as small as 10^{-6} the internal friction was still amplitude dependent.

The cause of this amplitude dependence was attributed to the motion of dislocations through the metal. The motion of a dislocation is seen through the aid of Figure 2. Initially there is a perfect crystal (Figure 2a). Upon the weakening of the interatomic force one of the atoms in the crystal becomes unstable and moves to a more stable position of equilibrium (Figure 2b). The resulting motion becomes a local slip with the dislocation finally moving through the other atoms to the final array (Figure 2c).



Formation and Motion of a Dislocation

Figure 2.

It was first thought after this new theory that a general change in the nature of the internal friction could occur only at the recrystallization point where the atoms reoriented themselves as a result of the application of an applied stress or the raising of the temperature. The work of Koster as reported by Nowick (5, p. 51), however, showed surprising results. The effects of cold working on the internal friction could be virtually removed simply by allowing the metal to stand at room temperature for a week. This showed that there were two types of dislocations. One type was associated with the normal plastic properties of a metal and changed only under the application of a stress great enough for recrystallization and the other type was free in the metal changing under the application of a stress much lower than that necessary for recrystallization.

A more recent study was done by Frankl (1, p. 573) on the effects of F centers on the internal friction of rock-salt single crystals. In the "as grown" condition, after sawing and polishing, the increase of internal friction with strain amplitude was similar to the behavior of any metal. On mild x-irradiation, however, the internal friction was markedly reduced and virtually nonamplitude dependent.

The results are explained by proposing that initially the crystal contains equal numbers of positive and negative ion vacancies bound together in pairs. On trapping an

electron in a negative vacancy, the associated positive vacancy is set free and at room temperature diffuses through the crystal. It is then proposed that this positive ion vacancy interacts with the dislocation to pin it and prevent its motion. This results in a decrease in the internal friction.

All studies of lightly cold worked metals have been for reeds vibrating at frequencies in the order of kilocycles per second. It is the purpose of this experiment to examine a polycrystalline copper crystal in the audio range and to determine the effect of cold working on the internal friction.

APPARATUS

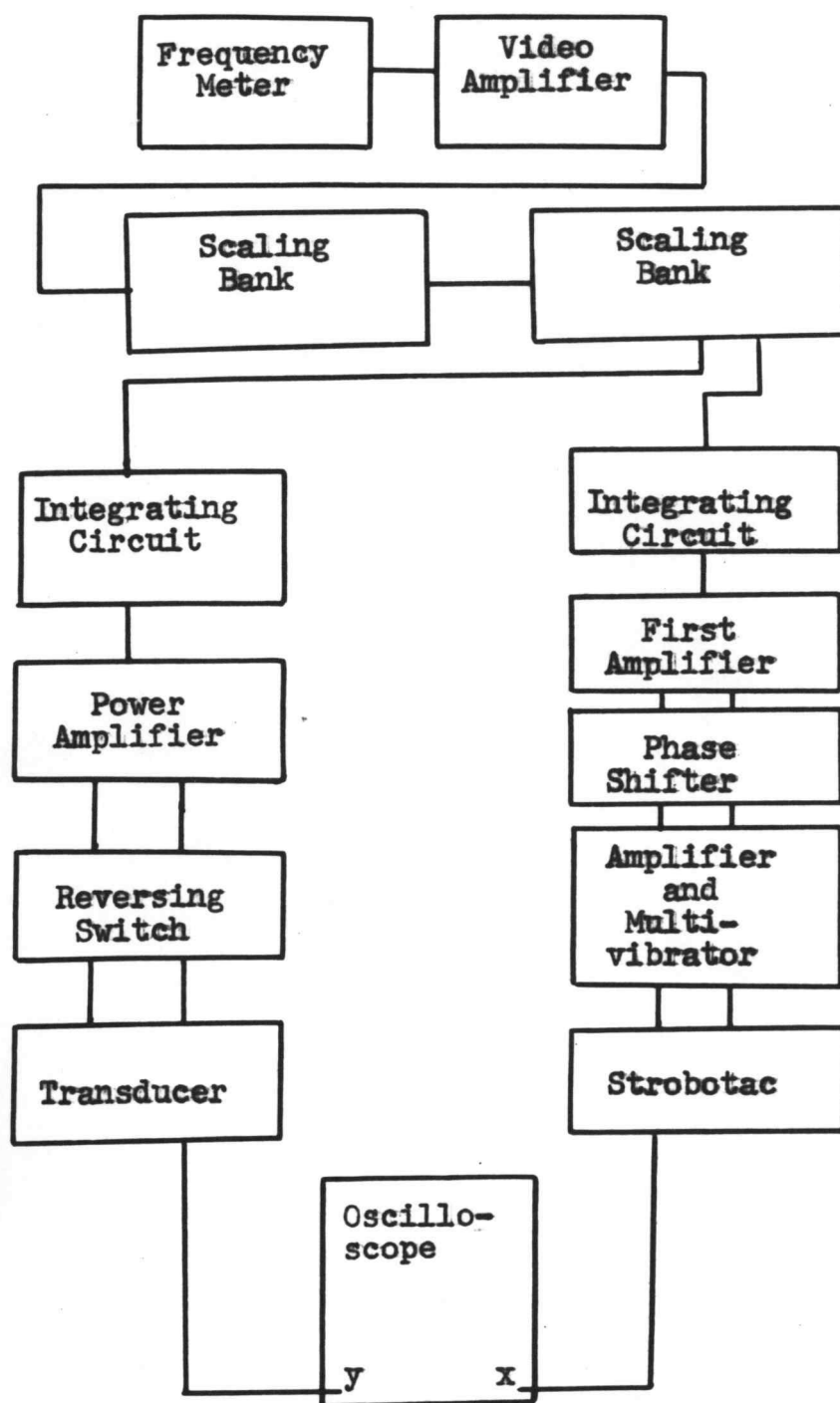
The method of measuring the internal friction used in this experiment involved the determination of the elastic phase constant for a copper reed vibrating in a vacuum. The general method was developed originally by Jewell (2, pp. 1-109).

A schematic diagram of the circuit is shown in Figure 3, while a general picture of the arrangement of the apparatus is shown in Figure 4.

The frequency meter supplies the signal which is amplified and changed to negative pulses by the video amplifier. The negative pulses then are fed into a bank of binary scalars. Each binary scalar divides the frequency by two so that any bank can be used as a source of known frequency.

The circuit is divided in two. One side supplies the power to the transducer while the other side lights a strobe lamp which illuminates the reed. By using this arrangement it was possible to view the reed in any part of its vibration.

The transducer side is fed through an integrator circuit which changes the square wave pulse from the binary scalar into a sine wave. The sine wave is then fed through a reversing switch into the symmetrical transducer which



SCHEMATIC DIAGRAM OF APPARATUS
Figure 3.

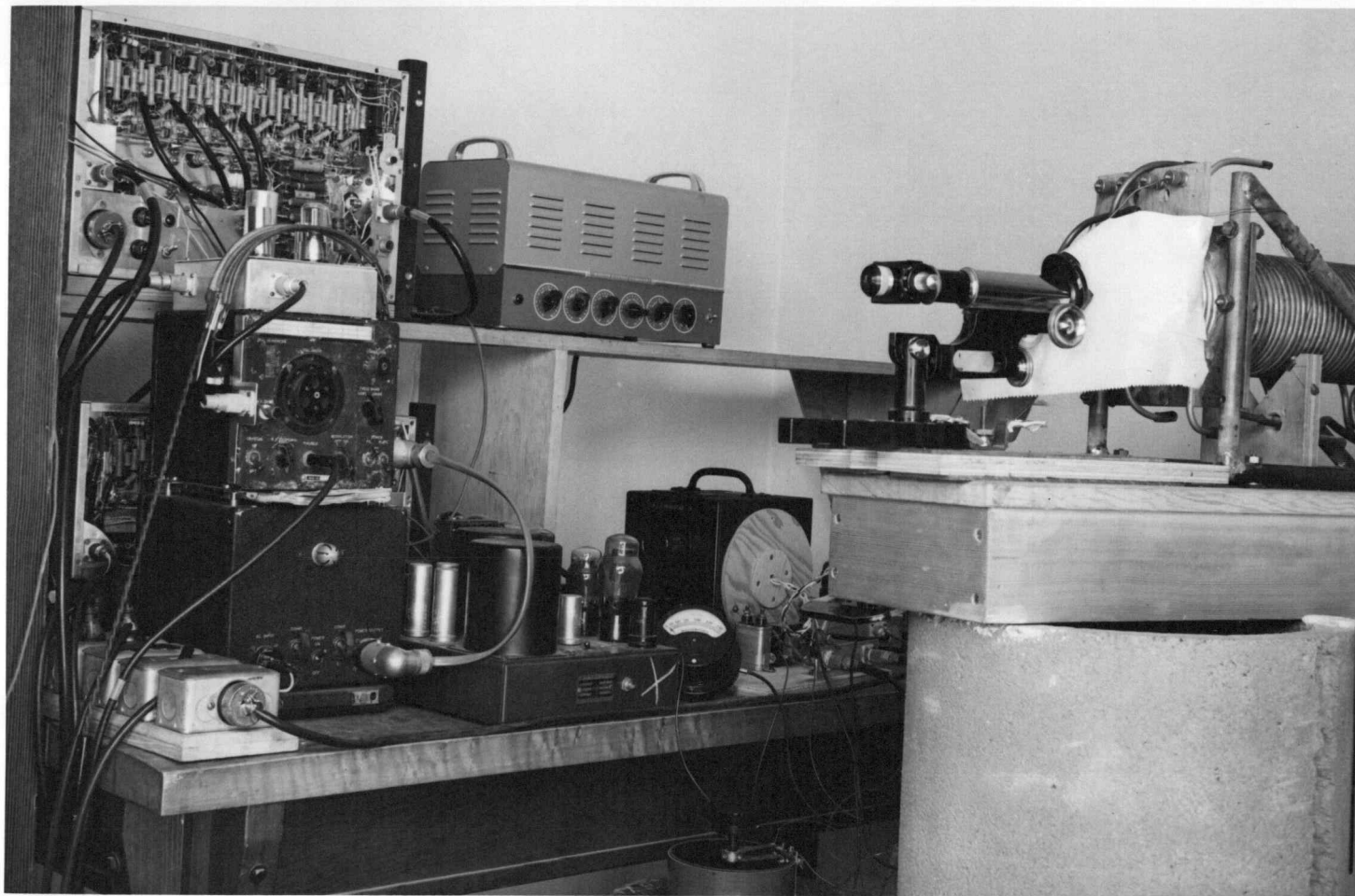


Figure 4. The apparatus as assembled for operation.

drives the reed.

The transducer (Figure 5) consists of a pair of small alnico magnets mounted above and below the end poles of a circular electromagnet. If there were no magnets, there would, on the passage of alternating current through the electromagnet, be a changing electromagnetic field between the pole faces of the electromagnets. The presence of the magnets distort the field and when the free end of the copper reed is placed between the electromagnets there is a gradient in the flux of the field along which the reed is free to move. Since the two magnets are mounted symmetrically about the electromagnet, no torques are developed in the reed.

The other half of the circuit is the stroboscope side. For reasons to be made evident later, the signal is taken off one bank more than the signal fed to the transducer. As a result of this the signal to the strobe lamp is one half the frequency of the transducer.

The signal is again fed through a set of integrators into a power amplifier to a phase shifter. The phase shifter shifted the phase of the strobe lamp so that it was possible to view the position of the reed at almost any point of its vibration. Since the phase shifter only had a maximum phase shift of approximately 150 degrees, it was necessary to have the frequency at one half the frequency

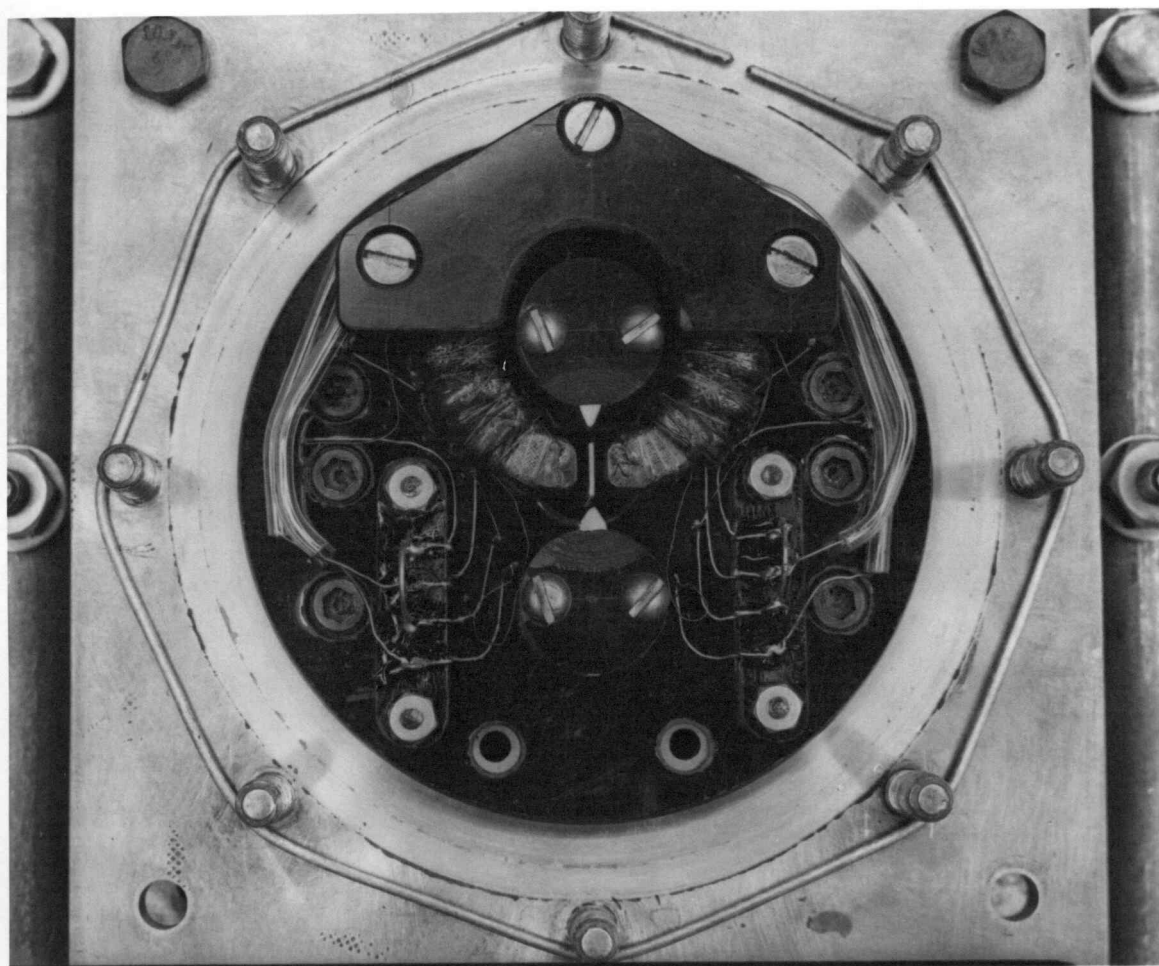


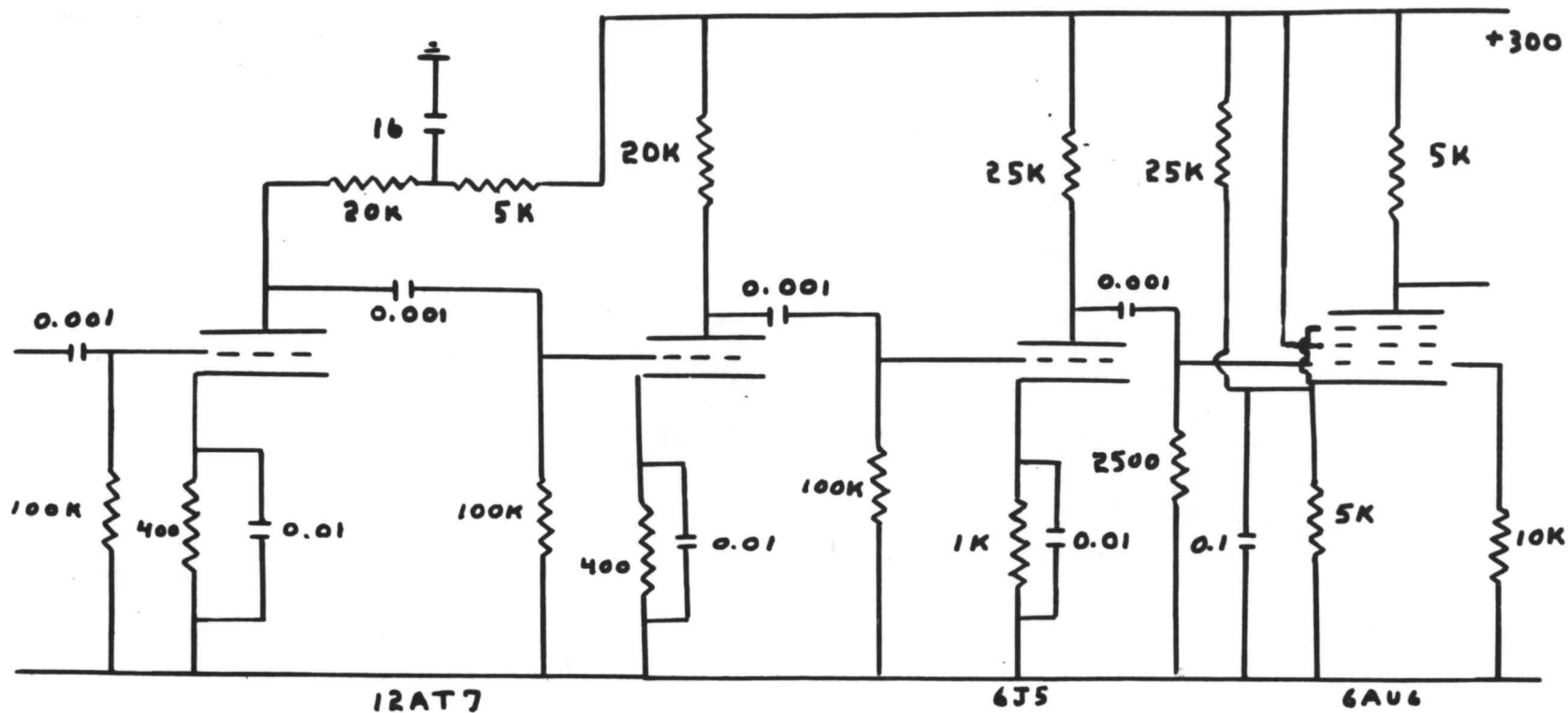
Figure 5. The transducer with the reed mounted.

of the reed in order to get a phase shift of over 300 degrees which by use of the reversing switch made possible the viewing of the reed in any position.

The output of the phase shifter was then fed into a voltage amplifier which fed a one shot multivibrator. The one shot multivibrator then delivered a 120 volt pulse to the strobatac which fired the strobe lamp.

Although the same circuit arrangement was used it was necessary to get new equipment in as much as it has been 5 years since Jewell had the equipment assembled. Instead of the army B. C. 221 frequency meter used in the previous apparatus, a navy L. M. 10 was used here. The frequency range on the lowest scale is 125 to 250 kilocycles per second. With the arrangement of the two binary scaling banks, it was then possible to get a continuous scale of frequencies from 1.9074 cycles per second to 250 kilocycles per second accurate to 5 significant places. This is extremely important in determining the elastic phase constant of the metal since the half power points are close.

Since the signal from the L. M. 10 is much lower than that from the B. C. 221, it was necessary to use an amplifier with a higher gain than before. It was more convenient to build an amplifier than to try to adapt available models. The circuit is shown in Figure 6. It has an output of approximately 90 volts and provides the negative pulses



VIDEO AMPLIFIER
Figure 6

necessary for the driving of the scaling bank. The power supply and filament current are both provided from the first scaling bank.

The power amplifier used to drive the transducer was an R.C.A. fifty watt push pull audio type amplifier with 6L6's in parallel in its output and its own power supply. It provided a good reliable signal with little distortion for a frequency as low as 10 cycles per second.

The first amplifier in the strobotac circuit was a Webster loudspeaker amplifier type 82-85. It was very poor and was the limiting factor on the low end of the frequency range. If the frequency went much below 25 cycles per second the distortion became so high that it was impossible to use the phase shifter which operates well only on the incidence of a good sine wave. Since it was necessary to have the phase shifter at one-half the frequency of the reed, it was this factor which limited the low end of the frequency range.

The rest of the circuit is the same as Jewell's and functioned very well throughout the experiment.

The oscilloscope was very handy in finding troubles. The stationary lissajou figure indicated that all was well in the circuits and was extremely handy when vibrations in the building were transmitted to the reed.

The entire transducer and reed are mounted in a vacuum.

The vacuum was approximately 1 mm. which is as Jewell points out, (2, p. 66), low enough to remove any air damping of the reed.

The end of the reed is viewed through a glass window by a microscope. Since a vertical illuminator was not available, it was decided to illuminate the reed by reflecting the light from tin foil surrounding the strobe lamp and the objective of the microscope. Although the resulting magnification was poor, this arrangement served the purpose and provided enough illumination. The poor magnification is due to the necessity of using a longer focal distance in order to place the strobe lamp beside the glass window of the transducer. With this arrangement the light was then simply scattered into the transducer.

PREPARATION OF THE REED AND METHOD OF PROCEDURE

The reed was cut from a sheet of copper selected for flatness and then draw filed to size. Although no special attempt was made to reduce the amount of stress induced in the reed by its preparation, this process was done as carefully as possible to keep the induced stresses to a minimum. When mounted in the vise, (Figure 7), the dimensions of the reed were 9.25 cm. x 0.65 cm. x .015 cm.

The annealing of the reed presented several problems since it was desired to have as small an increase in the impurity content as possible. At first the annealing was attempted in a small oven with a natural gas atmosphere. It was found, however, that no matter how carefully this was done there was a large amount of impurities deposited on the reed.

The final arrangement that was settled upon was the mounting of the reed in the shadow caster used for the electron microscope. The system was closed and the air pressure reduced to approximately 50 microns. A voltage was applied across the reed and upon the passage of about 60 amperes, the reed turned to a dull red. This was done for approximately 30 seconds. The reed was then allowed to cool for about 3 hours. On the reed finally used this process was repeated to insure annealing. The reed was not clamped, but

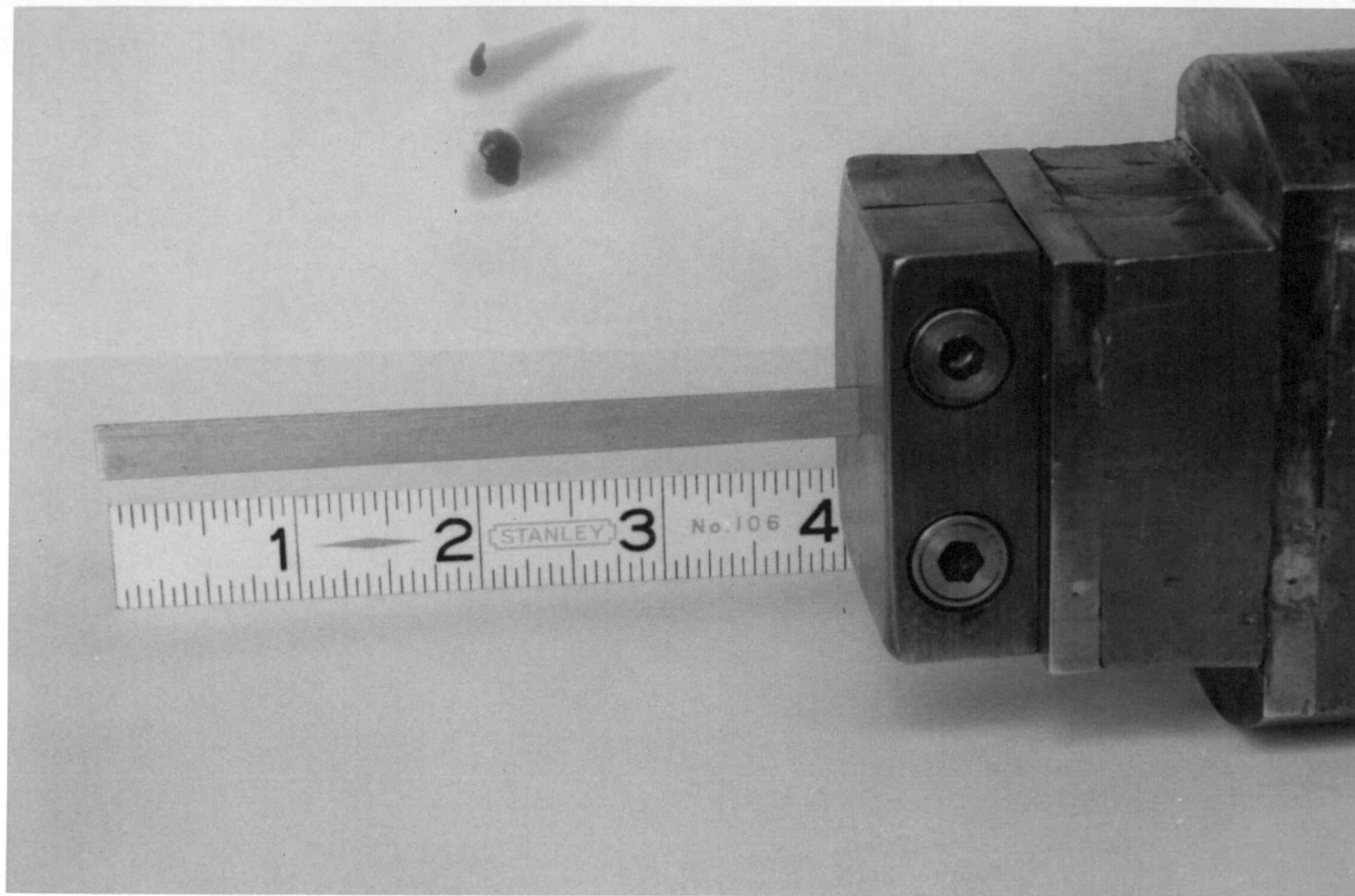


Figure 7. Reed mounted in vise.

merely laid on two supports.

Proper annealing is quite important as pointed out by Lawson (3, p. 335). He reports that if the annealed reed was dropped only one quarter of an inch, the internal friction was increased substantially. For this reason once the reed was annealed great care was used in handling it.

The first method of taking data was to drive the reed at a given energy and then record the amplitude versus frequency. The amplitudes recorded in all cases were between the two end positions of the reed in its vibration. These positions were ascertained by turning the phase shifter until the reed was seen to go through a maximum by noting the reversal of its direction of movement. Once this position was fixed, the amplitude was recorded and the reversing switch thrown to place the reed at its other end position with respect to the strobe light.

It was found upon plotting this data, recording the half-power points and then determining the elastic phase constant that this method was not accurate enough. It was then decided that the only proper method was to actually find the resonant frequencies and then find the half-power points.

This method proved to be extremely time consuming, but it enabled one to get very consistent data. It took approximately 2 hours to get each point on the final curves. When

an error did arise it was necessary to start over and re-check the data. It was found possible to do this without any noticeable change as long as it was done within the first 10 hours. If, however, the reed was allowed to stand for approximately 36 hours, it was found that the internal friction had changed.

The cold working was performed by a hydraulic press. The reeds were placed between two bars and the press placed forces in steps of 2 tons on the reeds.

Since it was not desirable to cold work the reed in such large steps and the dial on the press was calibrated in two ton increments, two reeds of the same size were placed between the supporting bars so that the effective force acting on the reed used in this experiment increased in steps of 1 ton.

For the particular dimensions of the reed used, this amounted to increases in pressure of 1800 pounds per square inch with each application. The reeds were carefully placed about the center line of the line of action of the hydraulic ram and the clearance between the supporting bars checked visually.

RESULTS

The plotting of the elastic phase constant versus amplitude for the annealed reed, (Figure 8), shows a marked amplitude dependence. Succeeding curves for increasing amounts of cold working, (Figures 9-10), show decreasing values of the internal friction along with a slightly smaller amount of amplitude dependence. The final amount of cold working applied, 5400 pounds per square inch, (Figure 11), shows increased values of the elastic phase constant along with an increased amplitude dependence. The final results are included in Figure 12 which is for an amplitude of 400 units or 0.944 mm.

The results are quite different from other investigations of internal friction versus cold working (3, pp. 330-335). They show a decrease instead of an increase of the internal friction with cold working, the internal friction going through a minimum and then rising.

The essential difference is that the vibrations here were in a transverse direction rather than the usual longitudinal direction and the frequency here was approximately 54 cycles per second rather than the previous frequencies of 150 kilocycles per second. With the decrease in frequency and a transverse vibration, the thermal currents present in a reed will become a larger part of the internal

friction.

The maximum value of the internal friction due to thermal currents is predicted by Zener (7, p. 233) to occur at a frequency which may be expressed as:

$$f = \frac{\pi}{2} D d^{-2}$$

where d is the width of the reed in the plane of vibration and D is the thermal diffusion constant which may be expressed as:

$$D = \frac{\text{thermal conductivity}}{(\text{specific heat})(\text{density})} \quad (5, \text{ p. 61})$$

Substituting in the values for the reed used it is found that this maximum will occur at 82.2 cycles per second. Since the reed is polycrystalline this maximum point will be lower, but without a knowledge of the mean grain diameter it is not possible to compute this lower frequency.

Nowick (5, p. 59) has proposed that at low frequencies a relatively free dislocation may be pulled away from its barrier by thermal activation without having to wait for the applied stress to free it. Once the dislocation is freed in this manner it would have no tendency to enter into the stress vibration, but could adhere to an impurity and become a bound dislocation.

It is proposed that the internal friction at this frequency is composed of two types; that due to thermal currents and that due to the motion of dislocations.

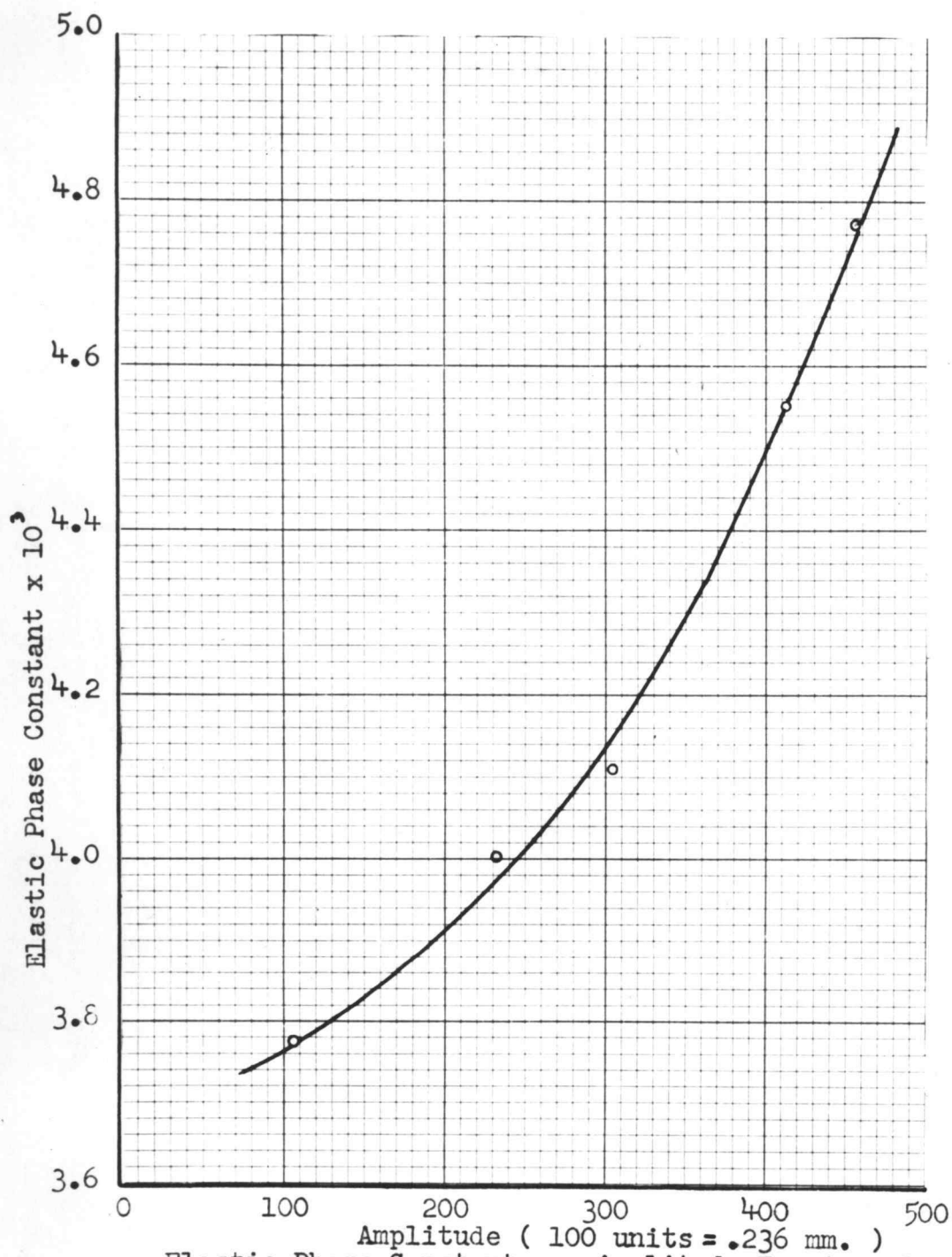
In the annealed reed the dislocations are relatively well fixed and so the thermal currents do not free them. Under the application of a stress, however, the dislocations are made more unstable and the thermal currents free some of them which can then become fixed. As a result fewer are moved by the stress and so the internal friction is decreased.

This continues approaching a minimum until the yield point of the metal is reached. At this point there will be a sudden increase in the internal friction due to the flattening of the crystal sizes as mentioned by Zener (9, p. 583) in his experiments for higher frequencies where the temperature was increased past the recrystallization point.

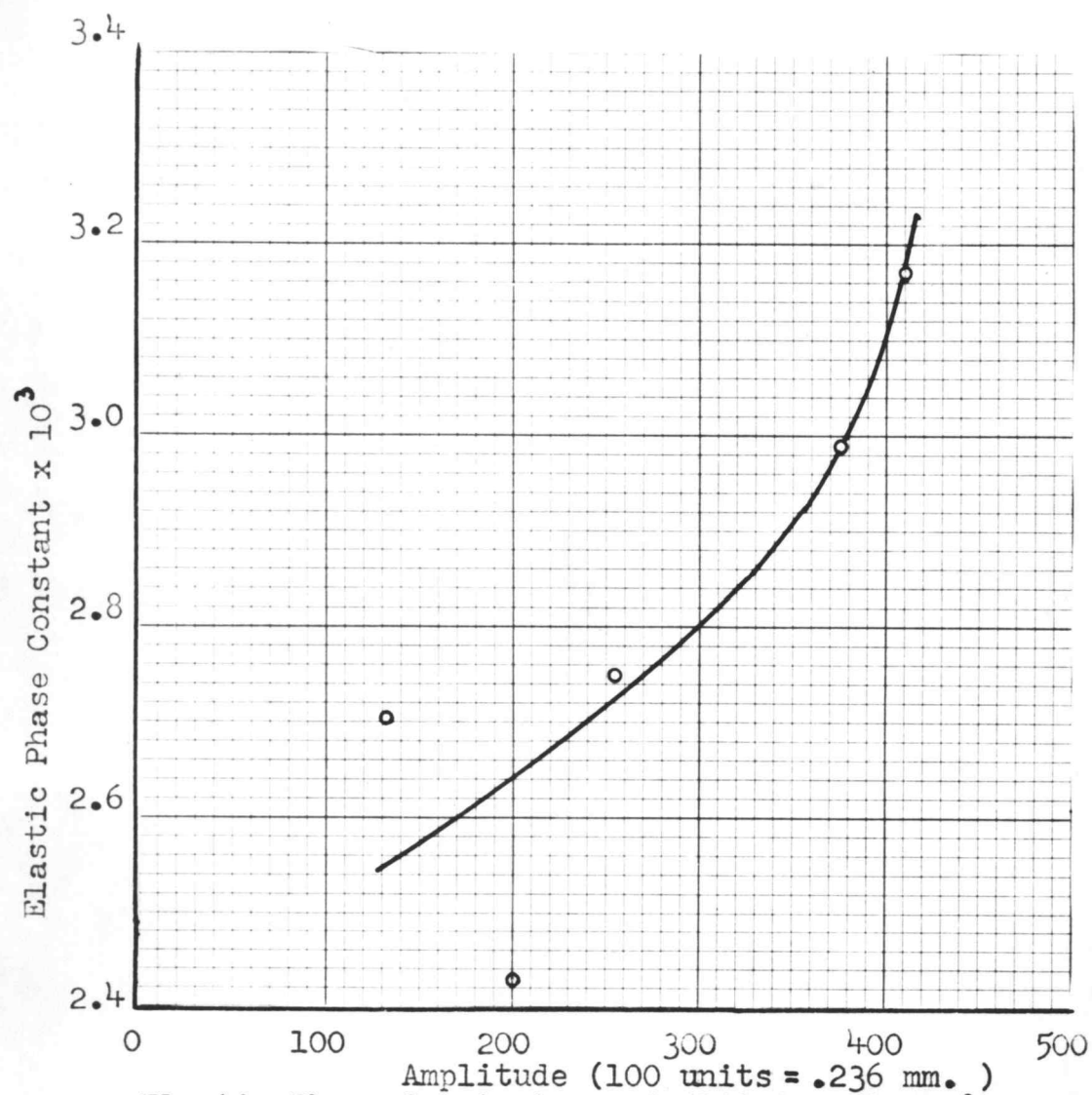
The curves obtained support this idea with a decrease in the internal friction until a pressure of 5400 pounds per square inch was applied. There was then a sudden increase in the internal friction. The yield point for annealed copper is 5000 pounds per square inch (4, p. 421) and so the final increase is explained.

There are no measurements of the internal friction of copper at these low frequencies except one reported by Jewell (2, p. 38) in his thesis. The internal friction for a corresponding amplitude and for cold work of 4800 pounds per square inch corresponds to his value within 12%. This is quite good agreement considering that the reeds were of

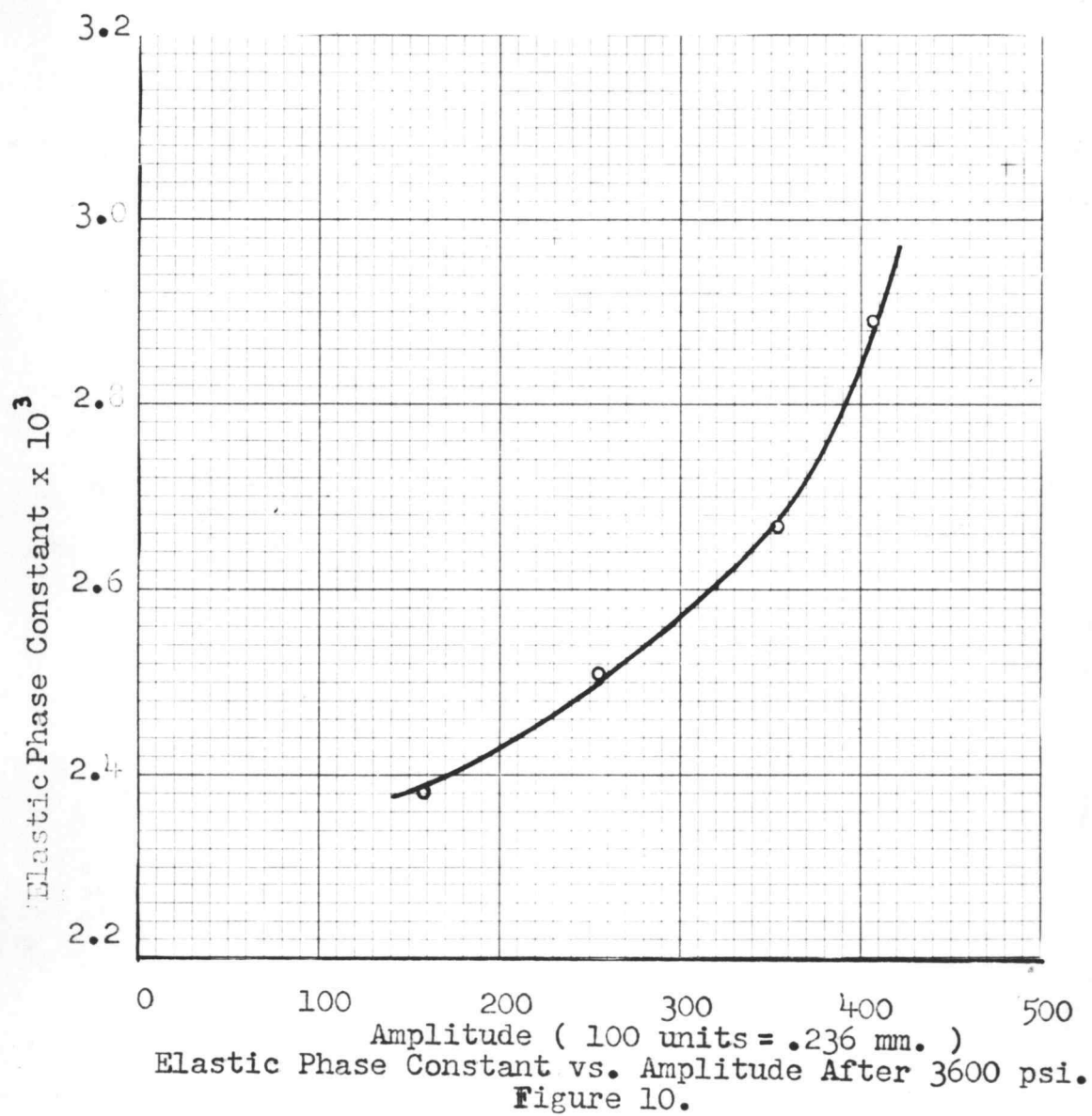
different impurity content and there is no way of telling how much cold working Jewell had done on his reed.

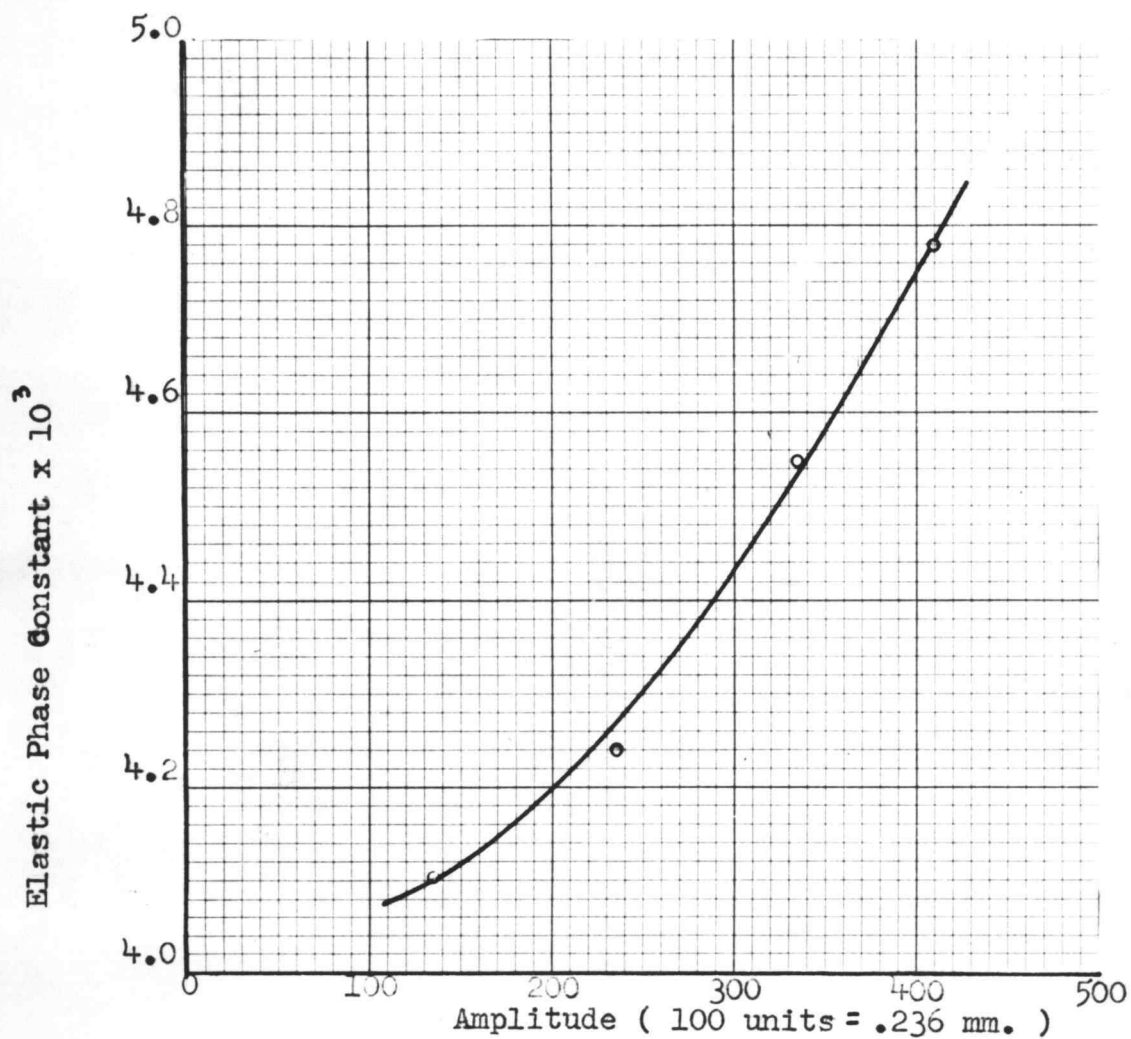


Elastic Phase Constant vs. Amplitude For Annealed Reed
Figure 8.

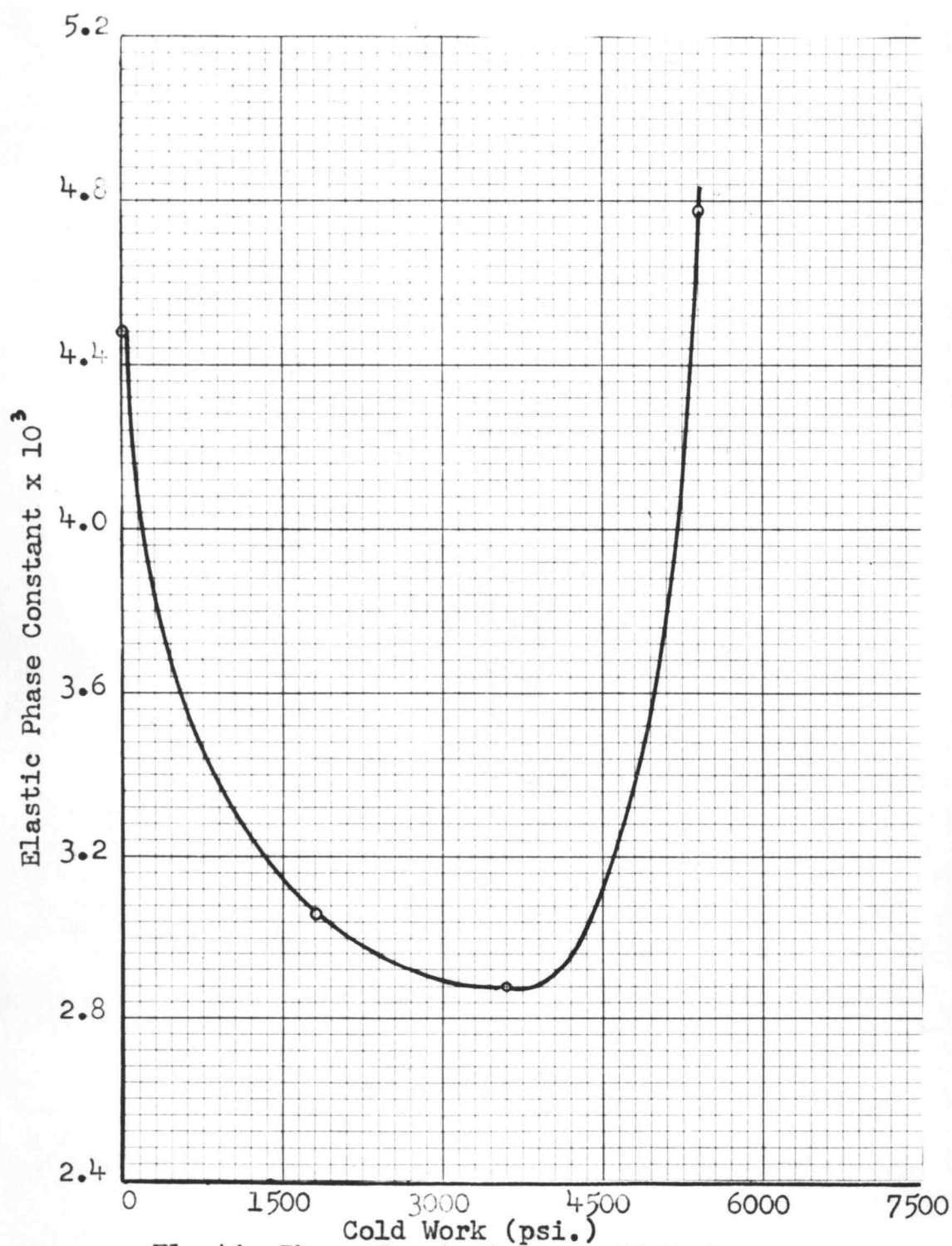


Elastic Phase Constant vs. Amplitude After 1800 psi.
Figure 9.





Elastic Phase Constant vs. Amplitude After 5400 psi.
Figure 11.



Elastic Phase Constant vs. Cold Work
Figure 12

Table 1. Data for Figures 8, 9, 10 and 11.

Amount of cold work on reed psi.	Amplitude of vibration 100 units = .236 mm.	Elastic phase constant $\phi \times 10^3$
0	104	3.78
0	244	4.00
0	302	4.12
0	407	4.57
0	455	4.79
1800	131	2.71
1800	150	2.43
1800	266	2.75
1800	375	2.99
1800	410	3.18
3600	156	2.38
3600	254	2.51
3600	331	2.67
3600	406	2.92
5400	136	4.11
5400	236	4.24
5400	336	4.55
5400	411	4.79

BIBLIOGRAPHY

1. Frankl, D. R. The internal friction of rock salt single crystals. Physical review 92: 573-579. 1953.
2. Jewell, William R. A method for measuring internal friction. Ph.D. thesis. Corvallis, Oregon state college, 1948. 109 numb. leaves.
3. Lawson, A. W. The effect of stress on internal friction in polycrystalline copper. Physical review 60:330-335. 1941.
4. Marks, Lionel S. Mechanical engineer's handbook. 4th ed. N.Y., McGraw-Hill. 1941. 2274 pp.
5. Nowick, A. S. Internal friction in metals. In Progress in metal physics, vol. 4. N.Y., Interscience 1953 pp.1-70.
6. Read, Thomas A. The internal friction of single metal crystals. Physical review 58: 371-380. 1940.
7. Zener, Clarence. Internal friction in solids I. Theory of internal friction in reeds. Physical review 52: 230-235. 1937.
8. _____ Internal friction in solids II. General theory of thermoelastic internal friction. Physical review 53: 90-99. 1938.
9. _____ Internal friction in solids IV. Relation between cold work and internal friction. Physical review 53: 582-586. 1938.