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An investigation of the internal friction of manganese-copper alloys

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AN INVESTIGATION OF THE INTERNAL FRICTION OF MANGANESE-COPPER ALLOYS

BY

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A

THESIS

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Arrangement of Ke Pendulum Apparatus (Photograph, courtesy of U. S. Bureau of Mines)

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INTRODUCTION

Internal friction is defined as the ability of a vibrating solid to convert its mechanical energy of vibration into heat, even when completely isolated from its surroundings. (1) The most familiar manifestation of internal friction is the damping of a freely vibrating body, such as a torsional pendulum. Another example would be the increased width of the resonance peak observed when a nonelastic body is forced to vibrate over a spectrum of frequencies.(2) Internal friction manifests itself in numerous ways, and we will here be concerned with the first example cited and the potency of data gained in studying the decay of torsional vibration.

During the past ten years internal friction has become an increasingly prominent research topic among physicists, metallurgists, and engineers. To the engineer internal friction manifests itself as high damping in alloys, which he can machine into mechanical components having the ability to abate unwanted and destructive modes of vibration. In turn, the metallurgist endeavors to selectively heat treat, age, or alloy various metallic elements and thus produce alloys bearing efficient damping mechanisms. In conjunction with this vast research program, the physicist looks to internal friction for information about the basic structure of solid matter and the laws that govern its dynamic behavior.

Interest in internal friction has been shown at the Bureau of Mines in Rolla with regard to the damping capacity of manganese-copper alloys.

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(1) Nowick, A.S., Progress in Metal Physics
Vol. 4, p. 1, 1953.

(2) Zener, C.M., Elasticity and Anelasticity of Metals
p. 64, 1952.

Extensive investigations by the Bureau of Mines have brought to light the valuable qualities of this alloy as an engineering material, and at the same time have presented data revealing the structural nature of the alloy in various states. A need was felt for information that could be obtained by a study of the behavior of manganese-copper alloys in torsional vibration at very low stress levels. Emphasis was placed on the variation of internal friction and dynamic rigidity with temperature. Thus an investigation was proposed which entailed the following:

1. Design and construction of a Ke type pendulum for measurements under vacuum or inert atmospheres and elevated temperatures. Adaptation of that instrument to the measurement of internal friction and dynamic rigidity of manganese-copper alloys under conditions of varying temperature and reduced pressure.

2. Design and construction of equipment for heat treating manganese-copper wires in the solid solution range, and the development of a technique for rapidly quenching the wire specimens without bending them. Use of this equipment to prepare straight and unoxidized wire specimens (13 inches long by 1/32-inch in diameter) of two compositions (85 per cent manganese-15 per cent copper and 75 per cent manganese-25 per cent copper), as quenched from the γ-solid solution region, in an attempt to retain the solid solution structure at room temperature.

3. Measurement of the internal friction and dynamic rigidity of these specimens as a function of temperature, at low stress levels and low frequencies.

4. Development of aging techniques for annealing these specimens to produce α-manganese precipitation.

5. Investigation of the effect of the precipitated α-manganese on the internal friction and dynamic rigidity of these alloys.

6. Correlation of the data thus obtained to establish a mechanism for the vibration damping encountered in these alloys.

REVIEW OF LITERATURE

T'ing Sui Ke(1) developed a very sensitive torsional pendulum for measuring the internal friction of aluminum wires at low stress levels. His equipment incorporated a built-in furnace which afforded considerable temperature latitude for the measurements. This is a very desirable feature when using internal friction measurements to study diffusion phenomena, because with a knowledge of the temperature shift of an internal friction peak one can calculate the heat of activation for the process.(2)

Ke was able to measure internal friction down to a magnitude of Q^{-1}(3) equal to 0.001 and as high as Q^{-1} equal to 0.11. He designed the inertia member to give a period of vibration of about twenty seconds, and then made all amplitude and frequency measurements visually. The inertia member was immersed in thick machine oil to dampen lateral motion.

With this equipment Ke investigated the internal friction of polycrystalline aluminum(4), and observed a relaxation peak at about 300° C. He then measured the internal friction for a single crystal specimen, and found no peak in this region. Since the essential difference in the two specimens was the presence of a labyrinth of grain boundaries in the polycrystalline specimens, he concluded that the peak was caused by relaxation across these grain boundaries.

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(1) Ke, T. S., and Ross, Marc, An Apparatus for Measurement of Extremely High Internal Friction, Rev. Sci. Inst., Vol. 20, No. 11, pp. 795-799, Nov. 1949.
(2) Nowick, A. S., Progress in Metal Physics, Vol. 4, p. 32, 1953.
(3) Q^{-1} is defined on page 20.
(4) Ke, T. S., Experimental Evidence of the Viscous Behavior of Grain Boundaries in Metals, Phys. Rev., Vol. 71, No. 8, pp. 533-546, April 1947.

Zener(1) explained the mechanism in this manner: the energy dissipated is proportional to the product of the relative displacement of adjacent grains and the shear stress producing the displacement. At low temperatures the displacement during a half cycle of vibration is negligible, because the grain boundary viscosity is high. At high temperatures the shear stress is completely relaxed at all times, because the viscosity is low. But, there exists an optimum temperature range where neither quantity is negligible, and thus the energy dissipated is appreciable.

Investigation at the Bureau of Mines(2) has shown that the internal friction of solution treated manganese-copper alloys varies with composition. The alloys were quenched from the γ -solid solution phase, and it was found that those having less than 77 per cent manganese had very low internal friction, while above this value the internal friction increased very rapidly with increasing manganese content. When these alloys were aged for two hours at 450° C., to precipitate α-manganese, it was found that the previous internal friction curve appeared to be inverted. That is, the alloys bearing less than 70 per cent manganese had very high (practically constant) internal friction, whereas above this value the curve decreased with increasing manganese content. The solution-treated alloys, at room temperature, were tetragonal down to 78 per cent manganese content. Below this value they had a cubic structure. Aging the alloys precipitates α -manganese,

(1) Zener, C. M., op. cit., p. 150.
(2) Rowland, J. A., Armantrout, C. E., and Walsh, D. F., Casting and Fabrication of High-Damping Manganese-Copper Alloys, Report of Investigations No. 5127, April 1955.

and also produces tetragonality in the cubic specimens. It was felt that the high internal friction is associated with the tetragonal structure.

Siefert and Worrell(1) have found high internal friction in a manganese-copper (88 per cent manganese) alloy. They quenched specimens from the γ-solid solution phase, and then measured their internal friction at room temperature. They assumed that the resultant structure of the quenched specimens was characteristic of the solid solution phase. Their data also showed that a manganese-copper alloy (88 per cent manganese), as quenched from the gamma solid solution, had high internal friction. Subsequent aging of the specimens (below the gamma phase region for repeated seventy-two hour periods at 625° C.) resulted in reduction of the internal friction at room temperature. Simultaneous metallographic studies revealed that a specimen quenched from the gamma phase was highly twinned, but with aging this twinning gradually disappeared. They were thus led to the conclusion that the twinned structure must be responsible for the internal friction, and have suggested a mechanism that Zener(2) has explained in a manner similar to that for the peak in Ke's polycrystalline aluminum: the energy dissipated is proportional to the product of the twin boundary movement and the stress producing the movement. In the low temperature range relatively little displacement of a twin boundary occurs during a half cycle of vibration due to the slow motion of twin boundaries. At high temperatures the motion is so fluid that the shear stresses are relaxed at all times. But, again there is a temperature range of high internal

(1) Siefert, A. S., and Worrell, F. T., J. Appl. Phys., Vol. 22, No. 10, pp. 1257-1259, 1951.
(2) Zener, op. cit., pp. 160-161.

friction where both the twin boundary displacement and shear stresses are appreciable. Worrell(1) found that the peak for the manganese-copper (88 per cent manganese) alloy occurred at minus five degrees centigrade with a magnitude of Q^{-1} equal to 0.0065. This dropped off to a value of Q^{-1} equal to 0.0023 at 25° C.

The explanation of the mechanisms for grain boundary relaxation and twin boundary relaxation are similar in that: (1) they require a friction force to exist for approximately one period of vibration; (2) this force must do irreversible work at the expense of vibrational energy; (3) the magnitude of the force decreases with increasing temperature.

Basinski and Christian(2) have made Debye-Sherrer diffraction patterns in the gamma phase field of manganese copper which show the structure to be face centered cubic. They also found that quenched specimens bearing more than 82 per cent manganese are face centered tetragonal at room temperature. Alloys of less than 82 per cent manganese become tetragonal on cooling below room temperature. The transformation is diffusionless (martensitic), and produces the highly twinned structure seen in the tetragonal specimens. The twin bands lie on (110) planes, and it is believed that the twinning is produced by two shears on these planes at sixty degrees to each other. The heavy twinning is a consequence of atomic movements in the cubic lattice essential for alleviating high residual stresses on cooling.

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(1) Worrell, F. T., Twinning in Tetragonal Alloys of Copper and Manganese, J. Appl. Phys., Vol. 19, pp. 929-933, 1948.
(2) Basinski, Z. S., and Christian, J. W., The Cubic Tetragonal Transformation in Manganese-Copper Alloys, J. Inst. Metals, Vol. 80, pp. 659-666, 1952.

EQUIPMENT AND PROCEDURE

The general design of the pendulum follows that described by Ke(1), and hereafter will be referred to as the Ke pendulum. A few additional features were incorporated in order to adapt the machine to manganese-copper alloys and to make it more versatile. With a few modifications, the Ke pendulum may be used to measure several characteristics of a wire specimen in torsional vibration: internal friction, modulus of rigidity, the relative phase of stress and strain, stress relaxation at constant strain, and strain relaxation at constant stress. A tube furnace was incorporated to allow the measurements to be made at different temperatures. The equipment used in this project had the added advantage of allowing the operator to obtain data at reduced pressures or in an inert atmosphere. The latter was deemed necessary in order to age the specimens without removing them from the pendulum.

The Pendulum

The major portion of the pendulum (Fig. 1) is suspended in a tubular vacuum chamber, and the lower end of the pendulum extends into a cylindrical tank at the bottom of the tube. An inertia member is attached to the lower end of the pendulum, and is free to oscillate in the tank. The pendulum support at the top of the tube consists of a pin vise welded to a 1/8-inch stainless steel rod that is soldered into a brass fixture at the end of the tube. This fixture, rod and pin vise, form a solid support that is not subject to measurable strain at the stress levels used in this investigation. The maximum error possible,

(1) Ke, T. S., Phys., Rev. 71, 533 1947
Rev. Sci. Inst., 20, 795 1949

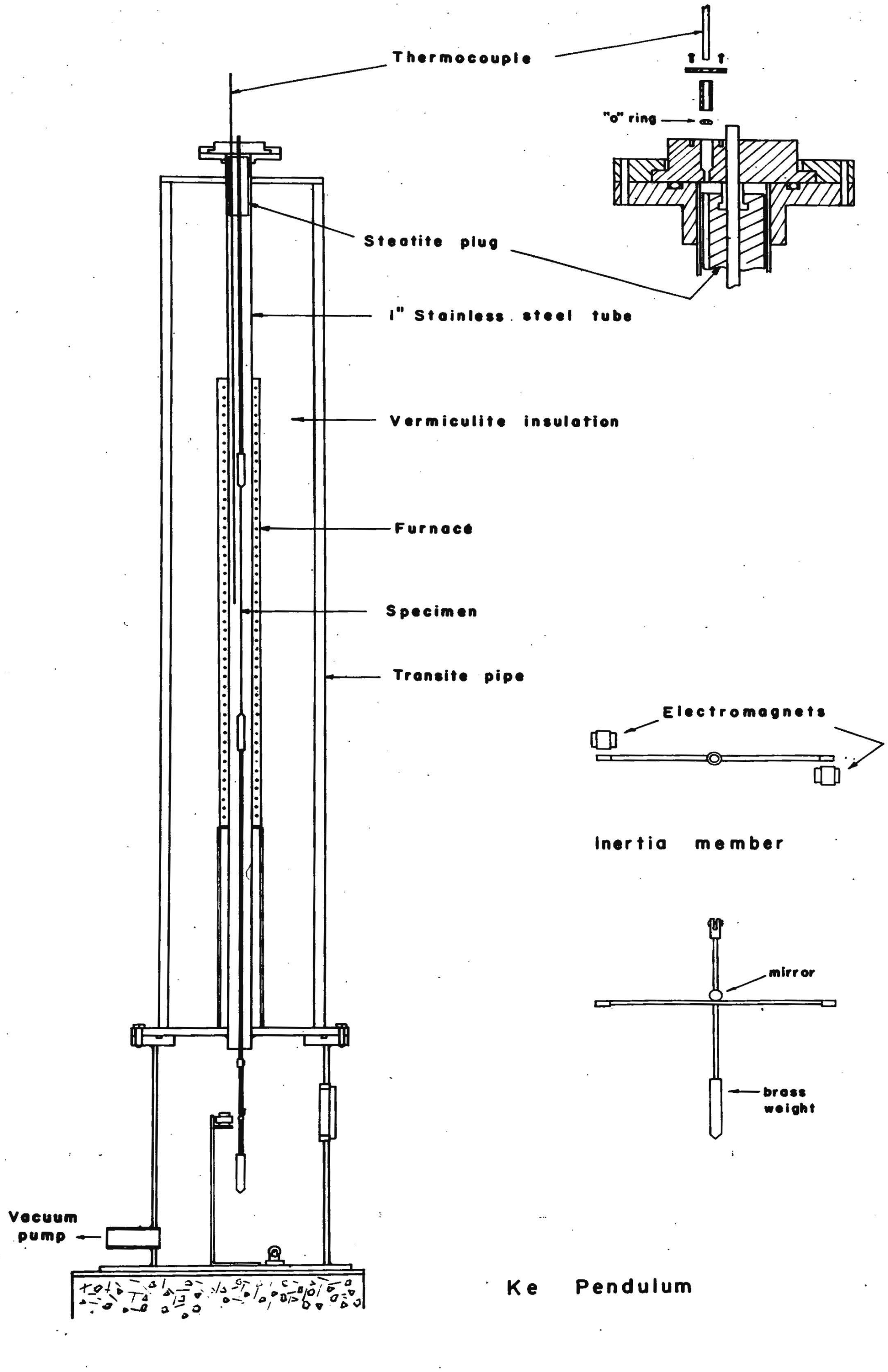

Fig. 1 Ke Pendulum

due to strain in the support, was calculated to be 0.3 per cent. A 1/32-inch wire specimen is fastened to the upper pin vise, another pin vise and rod assembly are attached to the lower end of the wire specimen, and this assembly extends into the tank below where the inertia member is fastened.

The inertia member consists of a vertical piece of 1/8-inch rod having a cylindrical brass weight soldered to its lower end and a six inch cross-bar fastened to its center. The cross-bar accounts for the greatest percentage of the moment of inertia of the inertia member, and its design determines the natural frequency of the pendulum. A frequency of about five cycles per second was obtained by making the cross-bar of thin sheets of brass rolled into almost cylindrical shape and bearing short lengths of a small iron nail at either end. A simple coupling, similar to that on the leg of a drafting compass, was devised for attaching the inertia member to the pendulum suspension. The inertia member weighs about forty grams, and maintains a tensile stress of about 117 pounds per square inch on the specimen.

The oscillation of the inertia member is initiated by means of two small electromagnets mounted on adjustable stands and placed near the pieces of iron. These magnets are excited by a multitap battery connected through a micro switch. The magnitude of the initial displacement can be controlled by the proximity of the magnets to the pieces of iron or by the magnitude of the voltage applied to them. The micro switch is used to enable the operator to minimize the life of the magnetic field set up by the electromagnets. In this way the inertia member can be set into motion by impulsive forces, and the field is too short duration to produce lateral displacement of the inertia member.

Ke suggested and employed the use of oil as a damping medium for lateral oscillation. This was tried by immersing the brass weight of the inertia member into a vial of vacuum pump oil. Many shapes for the immersed portion of the weight were tried in an attempt to minimize the damping of torsional vibration and maximize the damping of lateral vibration. In all cases the torsional damping was significant and undesirable, even when the end of the weight was fashioned into a needle-like shape and only 1/8-inch immersed in the oil. Therefore, this technique was abandoned in favor of using impulse type forces to displace the inertia member. As a result, it was possible to measure internal friction as low as Q^{-1} equal to 0.21×10^{-3}, whereas, the lowest value reported by Ke was about 1×10^{-3}. With a little practice this technique was perfected quite satisfactorily.

The housing of the pendulum is made in two sections. The lower section consists of a steel tank eight inches in diameter and is bolted to a massive concrete block. The tank has a window in front which allows a beam of light to be reflected off the mirror on the inertia member. It also enables the operator to inspect the positioning of the inertia member. A small three volt light was mounted inside the tank for this purpose. The upper portion of the housing consists of a circular steel plate, 1/2-inch thick, supporting the tube furnace, and a 6-inch O.D. transite pipe which houses the furnace and "Vermiculite" insulation. The upper part of the housing is suspended by cable from the ceiling, and is counterbalanced by a lead weight. The two portions of the housing are bolted together, and made vacuum tight by means of a large "O-ring."

A brass fixture at the top of the tube was designed to provide a solid support for the pendulum, to contain a sliding vacuum seal for a 1/8-inch rod-shaped thermocouple, and to permit 360 degree rotation of the entire pendulum. Thus the thermocouple could be moved to any desired depth in the tube furnace, and the pendulum suspension rotated without breaking the vacuum.

The pendulum was assembled in a horizontal position in a wooden jig. This made it easier to fasten the specimen wire in the pin vises with the proper gauge length, and reduced the danger of bending the wire. When thus assembled (except for the inertia member), the jig was moved to a vertical position and the pendulum suspension lifted free. The suspension was then let down into the tube furnace from the top, and the inertia member attached from the bottom. This entire assembly was then carefully lowered onto the tank and bolted into place.

Heating Methods

The specimen was heated by means of a tube furnace mounted around the center portion of the stainless steel tube. The furnace consists of three Fisher furnace units (4 inch, 8 inch, and 12 inch). These were wired in a parallel fashion, incorporating a variable resistor and a replaceable fixed resistor to provide control of the temperature gradient along the tube furnace. For temperatures less than 220° C., the gradient was held to ±1° C., and it did not exceed 2° C. at higher temperatures.

The power to the furnace was regulated by an on-off technique through a Brown Potentiometer Controller. Voltage from a line regulator was stepped down through a Variac, and the desired value then applied to the furnace.

The temperature within the stainless steel tube in the region of the specimen was measured by means of an iron-constantan thermocouple. By means of a switching arrangement only one thermocouple was needed to measure temperature and to activate the controller. The furnace serves to heat the specimens to the desired temperatures for internal friction measurements, and also to age the specimens at higher temperatures without having to remove them from the apparatus.

Vacuum Technique

A fore pump was connected to the system, through a pipe in the steel tank, and kept running as long as the system was closed. The pressure was measured by means of a thermocouple type vacuum gauge which was mounted between the fore pump and the tank. The movable parts of the system were made vacuum tight by means of "O-rings" lightly greased with Apiezon "T" grease. A half inch glass plate was sealed to the opening in the front of the tank by means of a gasket cut from rubber sheet and coated with shellac dissolved in methyl alcohol. This proved to be the best vacuum seal in the system.

A pressure of 150 microns was selected as the maximum pressure for the measurements, and all runs were made at or below this level. This rather arbitrary value was selected because of the ease with which it could be maintained, and because work by Cottell et al.(1), indicates that little is gained by working at a lower pressure. That is, 150 microns is sufficiently low to minimize air damping.

(1) Cottell, G.A., Entwistle, K.M., and Thompson, F.C., The Measurement of the Damping Capacity of Metals in Torsional Vibration, p. 398, 1947.

Recording Devices

The torsional vibration of a specimen was observed as horizontal oscillations of a point of light on a lucite screen. The point of light was formed by a beam from an arc lamp, reflected off the mirror on the inertia member, and focused on the screen. The movement of this light spot was recorded by a thirty-five millimeter flowing-film camera. Simultaneous with each run, timing marks were recorded on the side of the film at six second intervals. With these timing marks the frequency of oscillation was determined. A data card giving the length of the light lever arm, timing mark frequency, temperature, pressure, specimen number, and number of the run, was placed over the screen and photographed prior to each run. The film speed could be varied to suit each specimen. After the film was processed, it was placed in a microfilm reader where the frequency was determined and the amplitude of vibration measured and recorded. This is the same equipment used by Jensen(1) and described in his article on a "Torsion Pendulum."

Heat Treating Equipment

In order to prepare specimens having the γ -solid solution structure at room temperature, it was necessary to design and construct equipment (Fig. 2) for heating the specimen to about 900° C., holding it there for a period of time, and then rapidly quenching it. The equipment was to satisfy the following requirements:

1. Heat a fourteen inch length of 1/32-inch manganese-copper wire evenly to temperatures around 900° C. (The solid solution region is shown in Fig. 3);

(1) Jensen, J.W., Rev. Sci. Inst., Vol. 23, p. 399, Aug. 1952.

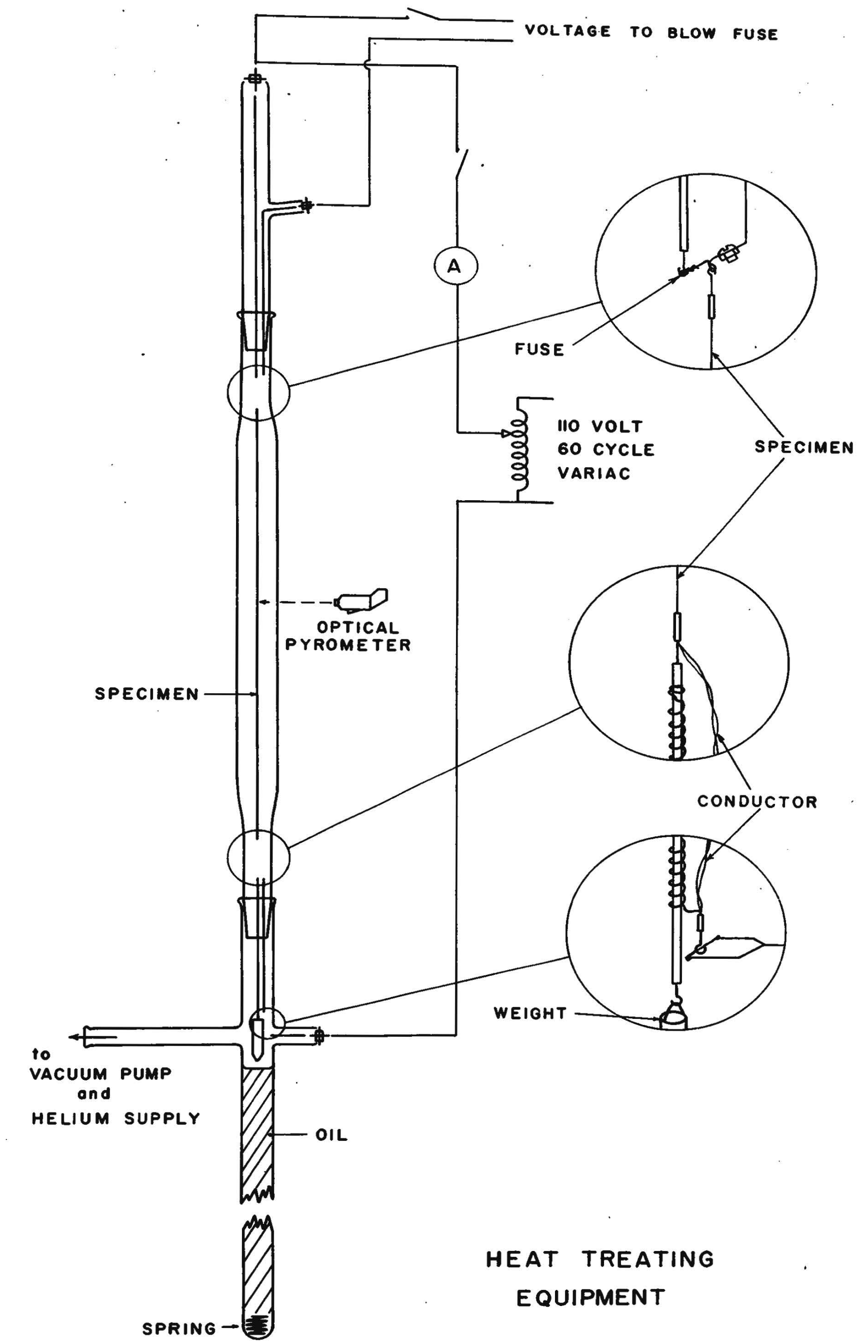

Fig. 2 Heat-treating equipment

2. Maintain the wire at constant temperature for the heat-treating period and then rapidly quench it to room temperature;

3. Produce a straight wire with a nonoxidized surface. The extra inch of wire was desired for X-ray studies.

A heat-treating tank was made from three sections of glass tubing which were joined by ground glass joints. The assembled tank was mounted in a vertical position, and the bottom section filled two-thirds full with vacuum pump oil. Just above the oil level two outlets were provided; one leading to a glass manifold, and the other providing an electrical outlet. Through the manifold the system could be evacuated, dried helium let in, and the positive gauge pressure of the helium read on a mercury manometer.

The specimen wire was suspended in the middle tube by means of a hook hung from a silver wire fuse in the top section of the tank. A spring and hook arrangement at the lower end of the specimen completed the electric circuit through the bottom outlet. A small lead weight was attached to the bottom of the specimen in order to straighten it as it was heated. The spring maintained constant electrical contact, while the wire straightened due to heating.

Voltage from a 110 volt A.C. Variac was applied across the specimen, and the resulting temperature regulated by controlling the Variac. About thirteen amperes were required to heat a specimen to 900° C. An auxiliary circuit was employed to blow the silver wire fuse at the desired instant. Thus, with this arrangement the specimen could be heated to the solid solution region, straightened in the process of heating, held at temperature for the desired length of time, then quenched by dropping it into the oil below. The wire was dropped by first shutting off the Variac, then using the auxiliary circuit to blow the silver fuse that supported the specimen. A steel spring at the bottom of the tank absorbed the shock of the falling weight.

To prevent oxidation of the specimen during the heat treatment, the tank was filled with an inert atmosphere of helium. The commercial "Grade A" helium used contained a small but undesirable amount of moisture, and therefore it was necessary to dry the helium. It was also thought that the helium might contain traces of oxygen. Thus the helium was prepared for use by passing it first through a drying tower, and then reduced by passing it through a tube furnace packed with titanium shavings heated to 750° C.

While the specimen wire was being heated, its temperature was measured by means of an optical pyrometer to assure treatment in the solid solution region. To facilitate this measurement, the central portion of the heat-treating tank was encased in a black metal shield about eight inches in diameter and having a vertical opening in front. The room was darkened and the optical pyrometer sighted through this opening. It was found that the specimen could be evenly heated except for about a half inch at either end of the wire. This was expected since the ends of the wire were fastened in small brass crimp joints. A fifteen inch piece of wire had to be assembled to obtain fourteen inches of usable specimen wire.

Preparation of Specimens

Coils of 1/32-inch manganese-copper wire were supplied by the Physical Metallurgy Section of the Bureau of Mines. In the process of drawing, the wire underwent 90 per cent reduction in area representing considerable cold working. The wire was inspected under a microscope and fifteen inch lengths selected that had no severe flaws. These were cleaned with carbon tetrachloride, and then heat treated and quenched from the solid solution. The straightened solution-treated wire was then carefully removed from the tank of oil and again cleaned with carbon tetrachloride. With all precautions taken there were still cases where a very thin layer of oxide would appear on the solution treated wire. This was carefully removed by lightly polishing the wire with number 4/0 emery paper. The ends of the fifteen inch wire were cut off and saved for X-ray analysis. Debye-Scherrer diffraction patterns were made to determine the axial ratio of the lattice structure and to detect the presence of any alpha manganese.

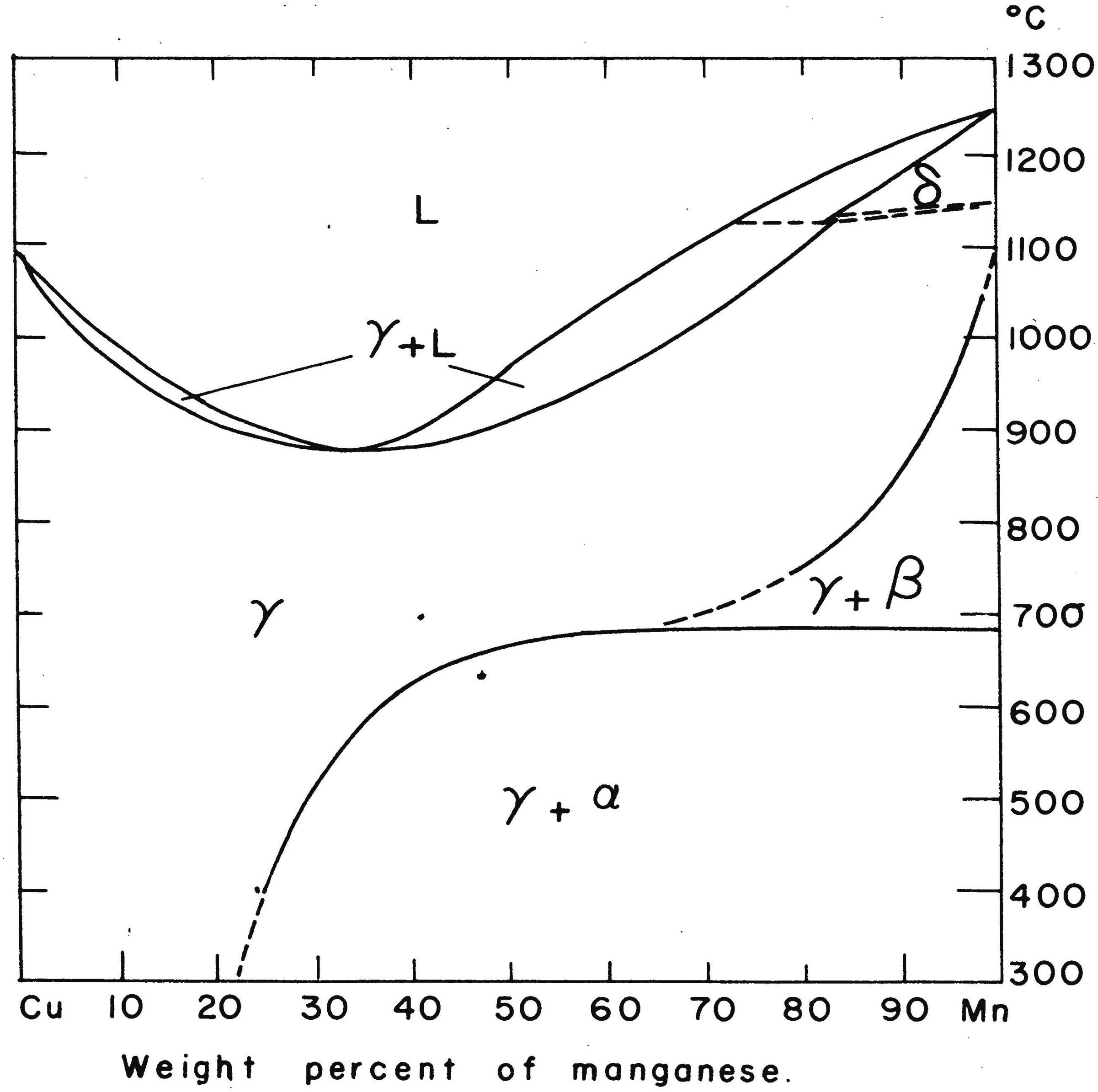

Fig. 3

PHASE DIAGRAM of MANGANESE - COPPER

INTERNAL FRICTION AND DYNAMIC RIGIDITY

Internal Friction

Internal friction was defined in the introduction as the ability of a vibrating solid to dissipate its vibrational energy. This energy dissipation is a direct consequence of the intrinsic phase relationship of stress and strain in non-elastic materials. The most direct measure of internal friction is the magnitude of the phase angle between stress and strain. This angle (or its tangent, under conditions of low internal friction) has become synonymous to the term internal friction. The angle is designated here as ϕ.

A more common experimental measure of internal friction is a quantity termed "logarithmic decrement" (δ) which is defined as the logarithm of the ratio of amplitudes in two successive vibrations

$$\delta = \ln \frac{A_n}{A_{n+1}}$$

It is related to the internal friction ϕ by

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

for small strain amplitudes(1). Q^{-1} is defined as the width of the resonance peak of a body forced to vibrate over a gamut of frequencies. This symbol is not only used in work with forced vibrations, but has also been used in reports involving free decay techniques.

The logarithmic decrement is obtained from experimental data by plotting the amplitude of vibration versus the number of vibrations on semi-log paper. For amplitude-independent internal friction a straight line is always obtained, and one simply measures the slope of the line.

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(1) Nowick, A. S., op. cit.

For amplitude-dependent internal friction, a curve results, and the slope must be measured at a given value of strain amplitude.

In order to establish a consistent basis for comparison of data, a specific strain amplitude was selected for measuring the logarithmic decrement. This became necessary when it was found that many of the runs were amplitude dependent. All of the runs were observed on a lucite screen placed sixty inches from the specimen. The oscillations were photographed, and the amplitudes were measured and recorded. These were then plotted on semi-log paper beginning at an amplitude of 4.5 inches on the screen. The slope of the curves was measured at an amplitude of 3.5 inches (corresponding to a maximum strain in the specimen of 3.8×10^{-5}), and again at the minimum value that each curve reached. These two readings gave an indication of how amplitude dependent each run was below a strain of 3.8×10^{-5}.

In order to indicate the amplitude dependency on the graphs of internal friction versus temperature, vertical bars were drawn for each run in the amplitude-dependent regions. The top of each bar represents the magnitude of the internal friction at a strain of 3.8×10^{-5}, and the length of the bar indicates the decreasing values of internal friction throughout the remainder of that particular run.

Dynamic Rigidity

The dynamic rigidity is used here to represent the ratio of the dynamic torsional stress to the torsional strain that it produces.

$$G = \frac{F}{\theta}$$

Where G is the modulus, F the stress, and θ the torsional strain.

For an elastic material the modulus is proportional to the square of the frequency, provided that the radius of the wire does not change.

The equation of motion for such a wire in torsional vibration about its longitudinal axis is

$$I \ddot{\Theta} = -G \Theta r$$

where; I is the moment of inertia about the axis.

$\ddot{\Theta}$ is the angular acceleration

G is the modulus

Θ is the angular displacement

r is the radius of the wire

From the solution of the above differential equation the frequency f of vibration is found to be

$$f = \frac{1}{2\pi} \sqrt{\frac{Gr}{I}}$$

and thus

$$f^2 \propto G$$

the square of the frequency is proportional to the modulus if the radius does not vary. The radius will change due to thermal expansion but below 300° C. the error is negligible.

This derivation is strictly valid only for an elastic body. For a nonelastic body, the forces causing damping must be included in the equation of motion. As a consequence, the modulus is proportional to the square of the frequency minus a constant (this constant is dependent upon the damping coefficient).

The curves for dynamic rigidity in this report are actually graphs of the square of the frequency, and are given in corresponding units (sec^{-2}).

In some cases there was a low amplitude (and low frequency) transverse vibration set up in the specimen along with the torsional vibration.

This motion had a component of velocity parallel to the moving film in the camera, and it changed direction (parallel to antiparallel) with each half cycle of its own vibration. This resulted in a noticeable Doppler effect on the film record of the runs. In order to avoid possible error in calculating the torsional frequency, at least 600 oscillations were counted for each run.

MEASUREMENTS AND RESULTS

Two compositions of manganese-copper (85 per cent manganese-15 per cent copper, and 75 per cent manganese-25 per cent copper) were selected for this investigation. Thirteen inch by 1/32-inch cylindrical wire specimens were prepared. These were first solution treated in the solid solution range then rapidly quenched in oil to retain the gamma solid solution structure, which is face centered cubic. Due to the martensitic transformation the 85 per cent alloy was, of necessity, face centered tetragonal at room temperature, while the 75 per cent alloy retained the cubic structure of the gamma phase.

These "as quenched" alloys were placed in the Ke pendulum and their internal friction was measured as a function of temperature at stress levels below 250 pounds per square inch. The 75 per cent alloy (Fig. 4) starts at room temperature with very low internal friction Q^{-1} equal to 0.0333×10^{-3}, and remains at about this value up to 270° C., except for a small peak at 205° C. where the Q^{-1} has increased to 0.605×10^{-3}. A complete tabulation of data is included in the appendix. The 85 per cent alloy (Fig. 5) has a much higher internal friction at room temperature (Q^{-1} lies in a range of 5.03×10^{-3} to 1×10^{-3}) which decreases to a value corresponding to the 75 per cent alloy, at 90° C. This range of internal friction for the 85 per cent manganese alloy compares with the corresponding region of the internal friction peak that Worrell(1) reported for an 88 per cent alloy. This comparison is indicative of an agreement in magnitude for the internal friction, but not necessarily the mechanism involved.

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(1) Worrell, op. cit.

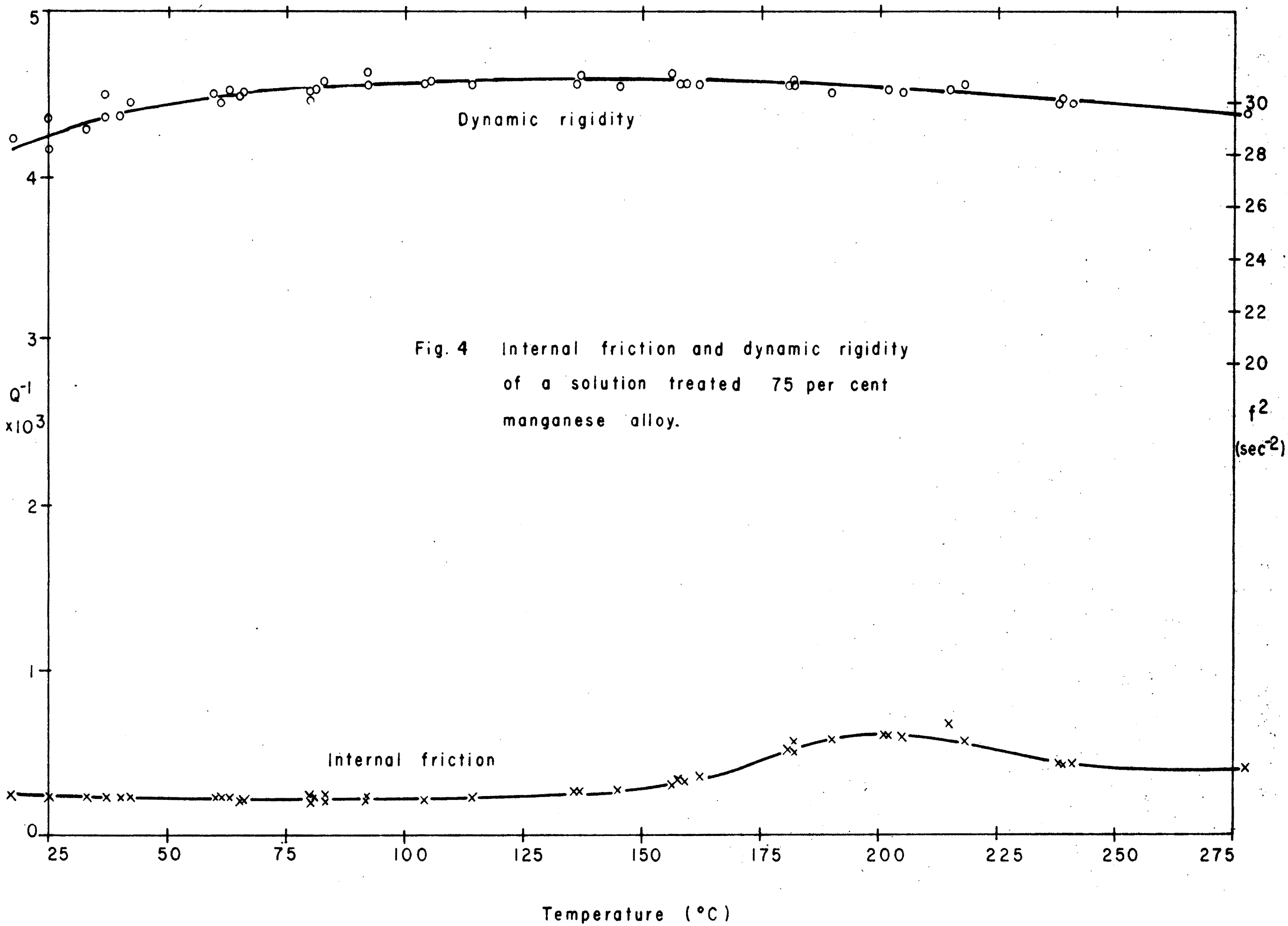

Fig. 4 Internal friction and dynamic rigidity of a solution treated 75 per cent manganese alloy.

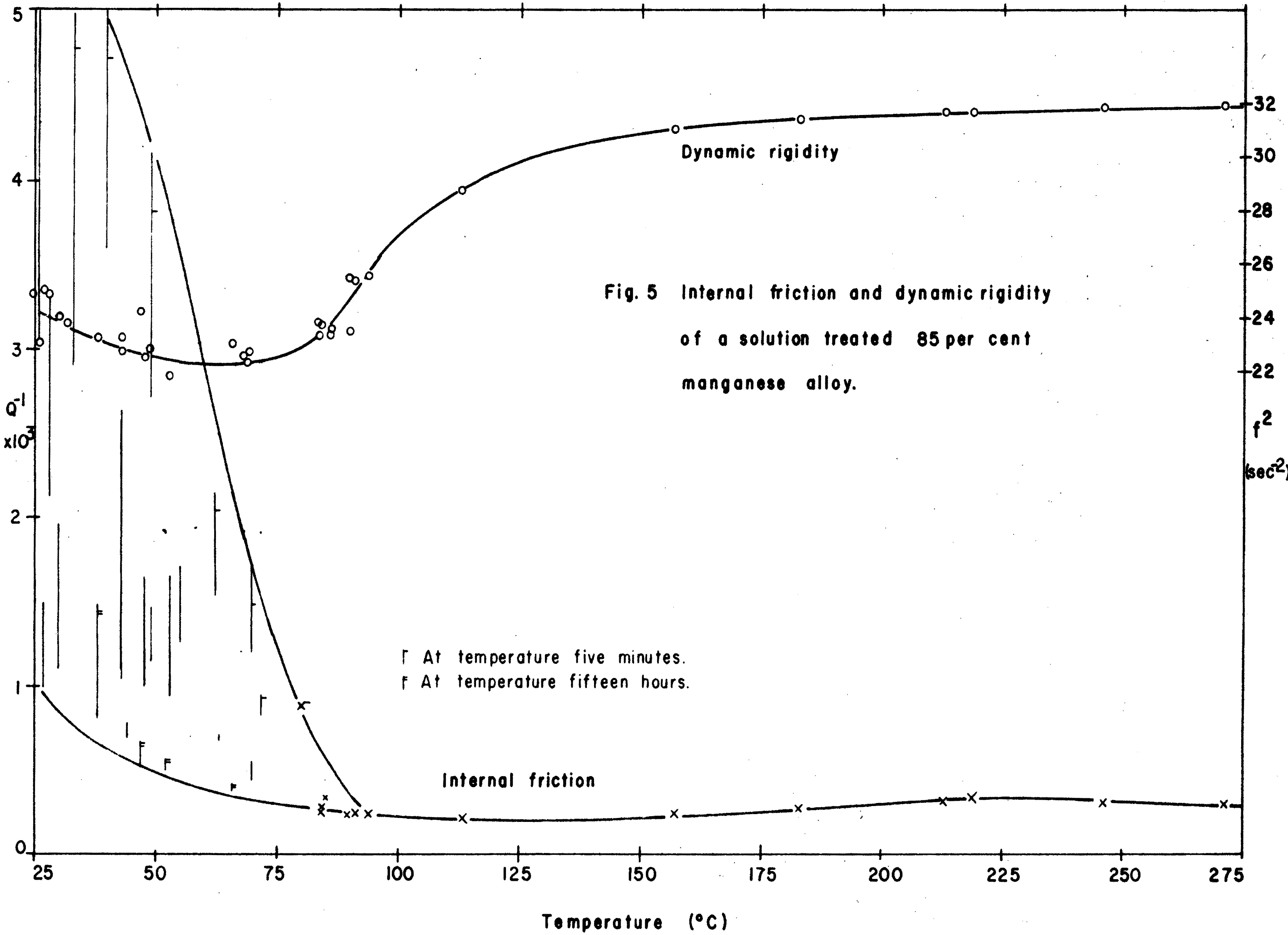

Fig. 5 Internal friction and dynamic rigidity of a solution treated 85 per cent manganese alloy.

The plot of internal friction for the 85 per cent alloy Fig. 5 indicates that the alloy has passed completely through the transformation at 90° C., which is a few degrees less than that indicated by Basinski and Christian's(1) X-ray data. In the region from room temperature to 90° C., internal friction is a decreasing function and reaches its lowest value at 90° C.

The data have also shown that below 90° C. the internal friction was very time dependent at any given temperature. That is, when the specimen was brought to some temperature and held there, then measurements made after one minute, fiften minutes, forty-five minutes, and three hours, each successive reading showed a lower value of internal friction. If after making measurements at some temperature, the specimen was heated a few degrees to a higher temperature (still less than 90° C.), the first few measurements gave higher values of internal friction than the minimum value (equilibrium value) found for the lower temperature. This sensitivity of the measurements to time decreased as the temperature approached 90° C. The greatest amount of the total decrease of internal friction at a given temperature was observed within the first fifteen minutes to an hour after reaching temperature, depending upon how far below 90° C. the measurements were made. Although the effect was smaller, the sensitivity to time at temperature was also detected for measurements made after long periods at temperature. This was especially true of measurements taken in the afternoon and then again the next morning while the specimen remained at temperature over night.

A similar sensitivity to time at temperature was observed for the dynamic rigidity. The effect was smaller and hence became unmeasurable

(1) Basinski, op. cit.

in a shorter length of time. None-the-less, the effect was quite noticeable and occurred over the same temperature region as in the internal friction measurements. The change was in the same direction as for internal friction--dynamic rigidity decreased with increasing time at temperature.

The 75 per cent alloy was aged for three minutes at 400° C. to produce -manganese precipitation (Fig. 6). Actually the precipitation probably occurred for a longer period of time, because the specimen was above 325° C. for almost eighty minutes. The writer has found, through other work at the Bureau of Mines (not published) that α-manganese can be precipitated at 325° C. This long period of time in the aging region is a consequence of slow heating and cooling rates.

The internal friction and dynamic rigidity measurements were repeated on this aged alloy. It was found that above 60° C. the internal friction was unaffected by the aging treatment. Below 60° C. both time and temperature dependent effects were observed. That is, the internal friction was high at room temperature and decreased with increasing temperature up to 60° C. At any given temperature (below 60° C.) the magnitude of the internal friction depended upon how long the specimens were held at that temperature.

The dynamic rigidity was affected over a much larger range of temperature. It was reduced about 24 percent at room temperature, and slowly increased to its original level at 160° C. Above this temperature little difference from the solution treated specimen was observed. A time dependency effect could also be detected up to this temperature.

The 85 per cent alloy was also given an aging treatment. It was held for twenty minutes at 400° C. and was in the aging region about

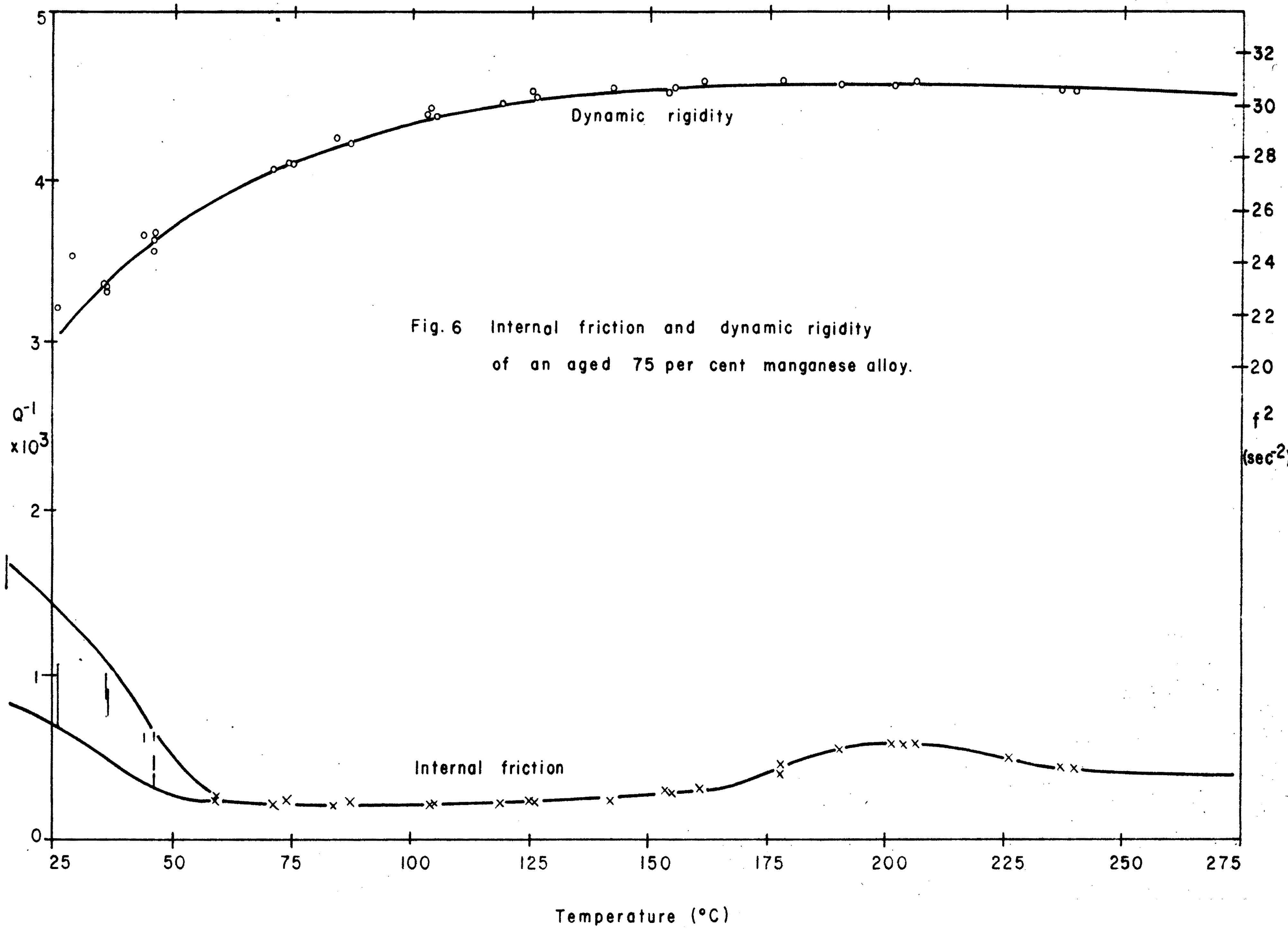

Fig. 6 Internal friction and dynamic rigidity of an aged 75 per cent manganese alloy.

ninety minutes. This treatment produced an over-all increase in the internal friction (Fig. 7) up to a temperature of 130° C. Above this temperature no significant change in the internal friction was observed. The same time-at-temperature sensitivity was found in the internal friction and dynamic rigidity of this alloy as for the 75 per cent alloy.

After investigation of the first 85 per cent alloy was begun, it was found that the measurement of its heat-treating temperature could have been in error, so the technique for measuring the temperature with an optical pyrometer was improved by enclosing the heat treating equipment in a black metal shield and observing the hot wire through a slot in the shield. When the temperature was measured in this manner, with the room darkened, it was found that the wire was not as hot as previously thought. This meant that the first 85 per cent alloy to be investigated may have been heat treated too near the β-manganese region, and as a result might have β-manganese in it. When the internal friction curve was plotted for this specimen, it was found to have a rather high peak at 215° C. Photomicrographs were made of a section of the wire which revealed that β-manganese was present in this specimen. Subsequently, the improved technique for measuring the temperature was adopted, resulting in almost complete disappearance of the peak in new specimens.

The curves for internal friction and dynamic rigidity were plotted with data obtained from repeated heating cycles between 20° C. and 270° C. The dynamic rigidity and internal friction changes all seemed to be reversible in this range when due regard was given to the time-at-temperature sensitivity. The only exception noted was for the first measurements made after mounting a new specimen. The internal friction

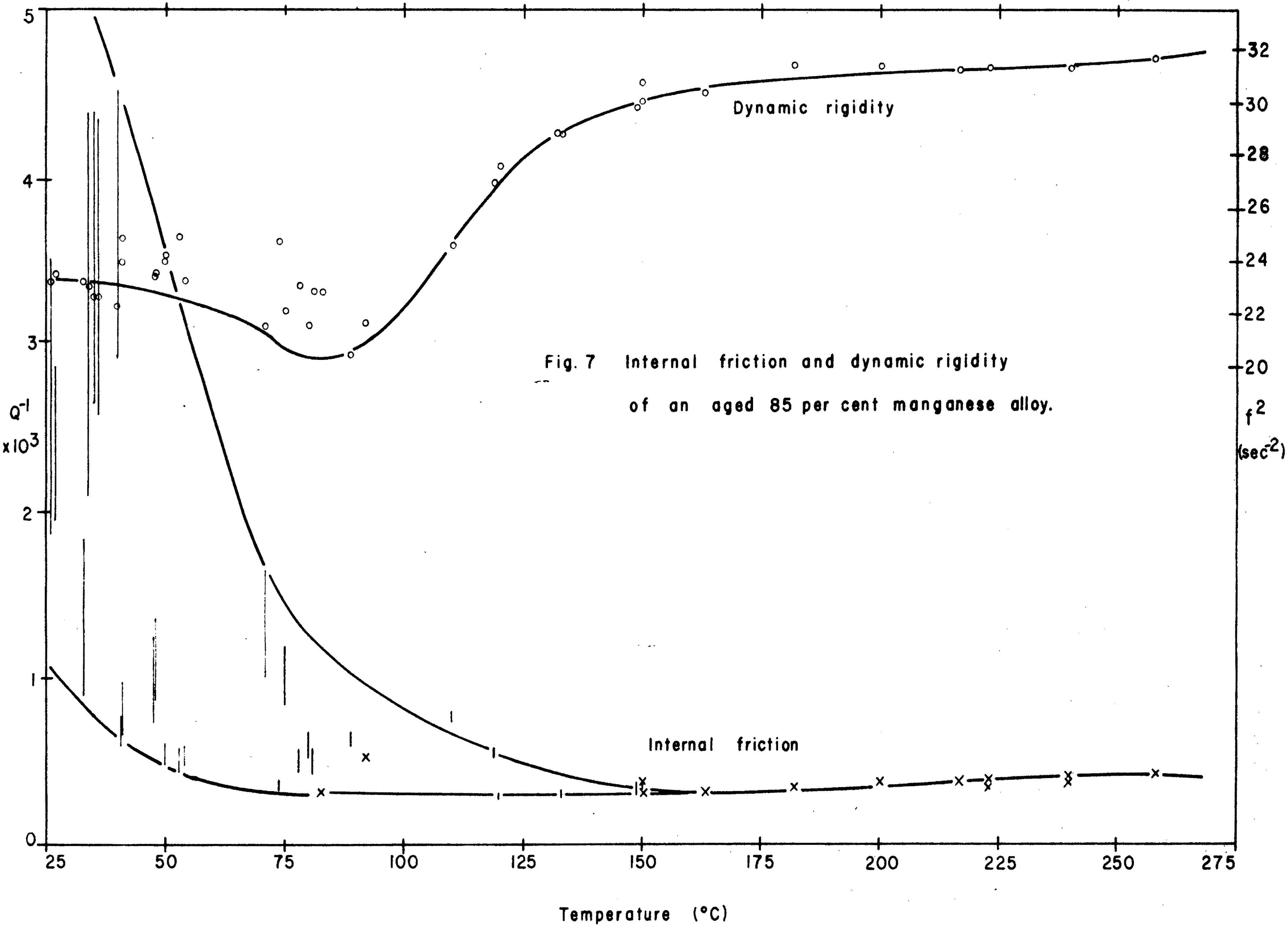

Fig. 7 Internal friction and dynamic rigidity of an aged 85 per cent manganese alloy.

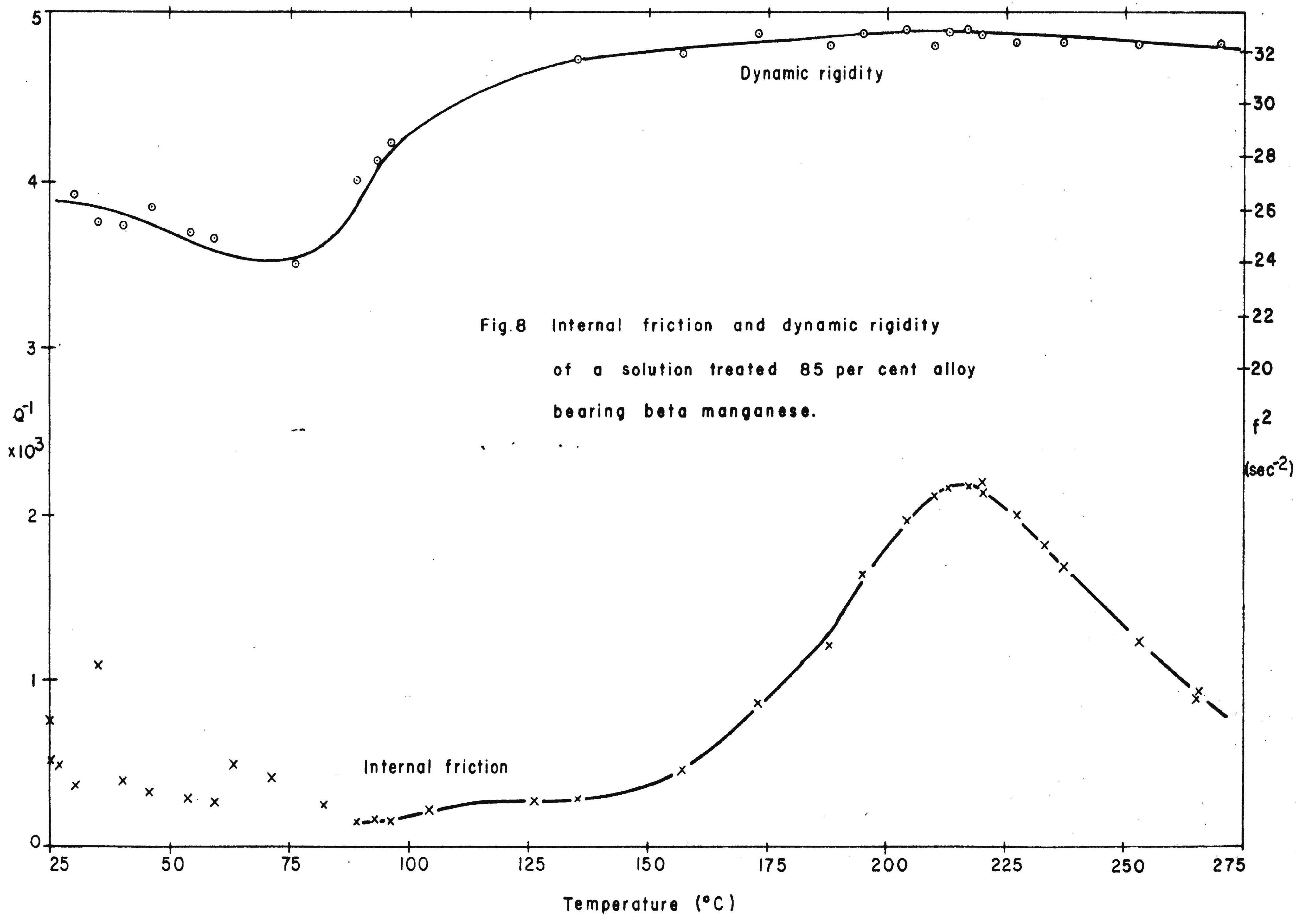

Fig.8 Internal friction and dynamic rigidity of a solution treated 85 per cent alloy bearing beta manganese.

for a new specimen is usually lower (for temperatures less than 90° C.) than what one might expect, while the dynamic rigidity does not seem to be affected. This decrease in internal friction is probably due to unavoidable cold working of the wire while removing any oxide and in mounting it in the pin vises.

Ke's(1) work on the viscous behavior of grain boundaries in polycrystalline aluminum, has been cited several times in literature, because of its completeness and confirmation of the theoretical predictions for anelastic effects. As he pointed out, much of the ease in interpreting his data depended upon the linearity of these effects on applied stress and prior strain. This required that the internal friction and dynamic rigidity be independent of strain amplitude. This was not the case in the work with manganese copper. Although the experiments were conducted at strains less than 4.9×10^{-5} (measurements were made at and below a strain of 3.8×10^{-5}), the internal friction was, in most cases, amplitude dependent. The dynamic rigidity did not seem to be affected.

CONCLUSIONS

The results of measurements made in this investigation show that the Ke pendulum is a sensitive instrument adaptable to studying the internal friction and dynamic rigidity of manganese copper. The upper limit of the temperature range used in studying these characteristics was not determined by the equipment, but rather by the phase changes in the alloy being investigated. For this reason, manganese-copper alloys were not studied above 270° C. for fear of initiating α-manganese precipitation.

It was a decided advantage to be able to age the specimens repeatedly, without intermittent handling, because this removed any chance of cold working them. The low internal friction on the first heating cycle of the specimens was apparently produced by unavoidable cold working while mounting the wires.

It was found that the vibrations of the specimens could be satisfactorily initiated by impulse forces, thus minimizing unwanted lateral vibrations, without the use of a damping medium. This facilitated measurement of lower values of internal friction than previously reported in Ke's work. The graphs in this report indicate that this added sensitivity was essential for detecting the internal friction attributed to β-manganese.

An internal friction peak was discovered at 215° C. (in an 85 per cent manganese alloy), which was apparently produced by the presence of β-manganese. Improving the solution-treating technique to reduce the chances of having β-manganese precipitate on quenching, resulted in marked reduction of this peak. All specimens prepared by the improved method still showed increased internal friction around 200° C. This seems to indicate that it is extremely difficult to prepare a specimen (containing more than 60 per cent manganese) having the gamma solid solution structure at room temperature, without precipitating beta manganese. It also shows that the internal friction measurements are a sensitive means of detecting the presence of β-manganese.

Comparison of the internal friction and dynamic rigidity curves of the aged specimens, with their corresponding curves for the solution treated condition, shows that the presence of α-manganese increases the internal friction in the region around room temperature, and also shifts this region to higher temperatures. It was found that in these regions the magnitude of internal friction depends upon the time spent at temperature and also on the amplitude of vibration. This indicates that the room temperature internal friction of an 85 per cent manganese alloy is not caused by simple anelastic (amplitude independent) effects. This is contrary to the work of Worrell(1) who suggested that this internal friction is due to anelastic behavior, referred to as a relaxation across twin boundaries.

Reference has not been found in the literature concerning the sensitivity of the internal friction and dynamic rigidity of manganese-copper alloys to time at temperature. It may be that previous investigations were carried out at too high stress levels for this to be observed. This investigation has shown that this effect is of prime importance if one is to predict the magnitude of internal friction or dynamic rigidity at low stresses in the tetragonal region.

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(1) Worrell, F.T., op. cit.

Although this investigation has not established a mechanism for the vibration damping in manganese-copper alloys, it has indicated several characteristics relevant to the behavior of the alloys, which may be of aid in future work.

An extension of this investigation would make it possible to obtain valuable information about the mechanisms of internal friction in manganese copper. The internal friction attributed to beta manganese was found to be amplitude independent, which suggests that an anelastic effect may be involved. Further work, using a change in frequency of vibration, could be done to determine the heat of activation for the relaxation process. Varied heat treatment and quenching techniques could be used to investigate the limits of the beta manganese peak.

Continued work on the effects of alpha-manganese precipitate may give more information about the range through which the transformation point (tetragonal to cubic) can be moved by aging. This could also lead to a more complete understanding of the sensitivity of the alloy to time at temperature (at low stresses), and thus help to correlate this effect with high stress work.

SUMMARY

A torsional pendulum for studying the internal friction and dynamic rigidity of 1/32-inch wires has been designed and constructed after the successful work of T'ing Sui Ke. It was built into a vacuum chamber to minimize the effects of air damping upon the measurements. The characteristics of two compositions of manganese-copper alloys (85 per cent manganese-15 per cent copper, and 75 per cent manganese-25 per cent copper) were investigated with this pendulum.

Heat-treating equipment was designed and built in order to prepare straight and clean wires of manganese copper having the γ-solid solution structure at room temperature. This required heating the wires to about 900° C. and then rapidly quenching them to retain the solid solution structure.

The internal friction and dynamic rigidity of these "as-quenched" alloys were measured, and then they were aged to determine the effect of the presence of α-manganese on these quantities. The aging was performed while the specimens remained mounted in the apparatus.

It was shown that only the 85 per cent alloy has appreciable internal friction at room temperature, and that this decreases with increasing temperature up to 90° C. where it then coincides with that of the 75 per cent alloy. Aging increases the room temperature internal friction of both alloys, and it is still temperature dependent decreasing with increasing temperature. The aging process raises the temperature at which the 85 per cent alloy reaches its minimum of internal friction to about 160° C. The minimum for the aged 75 per cent alloy occurs at about 60° C.

In the regions from room temperature to where the internal friction reaches its minimum, the measurements were found to be time dependent. That is, measurements made while a specimen was held at constant temperature showed decreasing internal friction with increasing time. In the same regions the internal friction was found to be amplitude dependent. The magnitude of this amplitude dependency also was dependent upon the time at temperature, and decreased with increasing time.

It was found that if β-manganese is precipitated in the quenched alloy it will have an internal friction peak around 200° C. Aging to produce α-manganese did not effect the internal friction in this region.

When the internal friction at room temperature was high, the dynamic rigidity was low. It increased with decreasing internal friction and reached a maximum at a higher temperature than the internal friction reached its minimum. Aging shifts the maximum to a higher temperature. The dynamic rigidity was seemingly unaffected by the presence of β-manganese.

APPENDIX

Specimen: 75 per cent manganese - 25 per cent copper

Heat treatment: Held at 882°C for three minutes (required 12.5 amp. at 38.5 volts a.c.) then quenched in oil.

Diameter: 0.03125 in.

<u>Data from Ke pendulum runs:</u> (see Fig. 4)

Light lever arm- 60 in. Timing mark intervals- 6 sec.

Pressure- less than 150 microns.

Temp. °C	Time at temp.	f^2 sec^{-2}	$Q^{-1} \times 10^3$ max. min.	Temp. °C	Time at temp.	f^2 sec^{-2}	$Q^{-1} \times 10^3$ max. min.
60	1hr	30.4	0.23	25	45'	29.1	0.23
37	3'	30.4	0.23	40	5'	29.5	0.23
37	0.5hr	29.5	0.23	42		29.9	0.23
34	1.3hr	29.0	0.23	42	24hr	30.0	0.23
45	3'	30.0	0.23	66	5'	30.4	0.22
46	2.5hr	29.5	0.23	65	1hr	30.4	0.22
60	3'	30.3	0.23	80	3'	30.1	0.22
61	1.5hr	30.0	0.24	83	1hr	30.8	0.22
63	18hr	30.5	0.22	104	3'	30.7	0.22
80	5'	30.5	0.24	105	1hr	30.8	0.22
81	1.5hr	30.5	0.23	145	1hr	30.6	0.26
92	10'	31.2	0.23	162	3'	30.7	0.36
92	1.5hr	30.7	0.23	184	5'	30.8	0.57
92	16hr	30.7	0.22	190	45'	30.4	0.58
114	3'	30.7	0.24	215	5'	30.5	0.68
114	1hr	30.7	0.23	218	45'	30.7	0.57
137	3'	31.0	0.27	240	3'	30.0	0.43
136	2.5hr	30.7	0.26	205	3'	30.4	0.60
158	3'	30.7	0.34	202	40'	30.5	0.61
159	1.3hr	30.7	0.33	239	5'	30.2	0.42
156	22hr	31.1	0.31	238	1.5hr	30.0	0.44
181	3'	30.7	0.52	278	3'	29.6	0.40
182	1.3hr	30.7	0.51	25	73hr	28.3	0.24
17		28.7	0.23				
25	5'	29.4	0.23				

Specimen: 85 per cent manganese - 15 per cent copper

Heat treatment: Held at 902°C for three minutes (required 12.75 amp. at 16 volts) - quenched in oil.

<u>Data from Ke pendulum runs:</u> (see Fig. 5)

Light lever arm- 60 in. Timing mark intervals- 6 sec.

Pressure- less than 150 microns. Diameter 0.03124 in.

Temp. °C	Time at temp.	f^2 sec^{-2}	$Q^{-1} \times 10^3$ max.	min.
27	1hr	25.0	1.48	1.00
47	15hr	24.2	0.66	0.52
70	1hr	22.5	0.53	0.44
84	15hr	23.3	0.26	
91	1hr	25.3	0.23	
157	13hr	31.0	0.23	
24		23.0	2.59	1.51
48	1.5hr	22.5	1.64	1.01
66	15hr	23.0	4.10	0.37
84	11hr	23.8	0.25	
90	11hr	25.5	0.24	
113	14hr	28.8	0.21	
213	1hr	31.6	3.26	0.30
28	4hr	23.3	3.33	2.12
43	30'	22.8	2.61	1.74
69	15hr	22.3	0.43	
84	1hr	23.7	0.26	
94	45'	25.5	0.24	
183	10hr	31.4	0.27	
219	2hr	31.7	0.32	
246	15hr	31.8	0.29	
272	15hr	31.9	0.29	
30	3hr	24.0	1.94	1.10
53	1hr	21.9	1.65	0.95
69	15hr	22.7	0.41	
86	1hr	23.4	0.27	
91	15hr	25.5	0.24	
26	3hr	23.0	3.16	1.85
38	15hr	23.2	1.46	0.81
43	30'	23.2	1.71	1.03
24	60hr	24.0	2.33	1.41
31	30'	23.8	2.02	1.33
23	12hr	22.6	9.16	4.48

Temp. °C	Time at temp.	f^2 sec^{-2}	$Q^{-1} \times 10^3$ max.	min.
31	1.5hr	23.8	1.93	1.30
44	15hr	23.8	0.68	
49	5'	22.8	1.46	1.13
55	5'	22.3	1.70	1.26
62	5'	21.3	2.15	1.55
70	5'	20.2	1.69	1.21
72	5'	19.3		
85	3'	23.5	0.31	0.35
26	10hr	24.6	7.41	3.31
33	5'	21.8	5.01	2.88
40	5'	21.5	5.01	3.60
49	5'	21.4	4.16	2.70
52	15hr	22.9	0.57	0.48
63	5'	22.5	0.70	0.65
72	5'	20.9	0.95	0.84
80	5'	19.1	0.87	
90	5'	24.8	0.25	
23	10hr	22.7	8.7	4.73
26	14hr	23.5	6.31	3.28
24	82hr	24.0	2.34	1.63
27	16hr	23.2	4.32	2.11
36	2hr	22.9	4.32	2.13
36	18hr	23.4	1.95	1.12
42	15hr	23.7	1.13	0.81
37	20hr	24.4	0.99	0.65
22	72hr	24.5	1.74	1.13
29	5'	24.2	1.72	1.29
29	4.5hr	24.6	1.39	1.03
30	19.5hr	23.8	1.18	0.78
52	22hr	22hr	0.92	0.77
72	18hr	22.3	0.46	0.44
83	2hr	22.3	0.38	

Specimen: 75 per cent manganese - 25 per cent copper

Heat treatment: Aged for ten minutes at 410°C

<u>Data from Ke pendulum runs</u>: (see Fig. 6)

Light lever arm- 60 in. Timing mark intervals- 6 sec.

Pressure- less than 150 microns.

Temp. °C	Time at temp.	f^2 sec^{-2}	$Q^{-1} \times 10^3$ max.	min.
26	74hr	22.3	1.57	0.69
36	10'	23.0	1.00	0.84
36	1hr	22.9	0.90	0.81
46	5'	24.4	0.68	0.59
46	45'	25.1	0.49	0.41
46	2hr	24.8	0.41	0.31
74	5'	27.7	0.23	
75	45'	27.7	0.23	
87	3'	28.5	0.23	
105	10'	29.5	0.22	
103	25hr	29.6	0.21	
125	3'	30.5	0.23	
126	1.5hr	30.2	0.23	
154	3'	30.4	0.30	
178	3'	30.9	0.45	
178	1hr	30.8	0.42	
203	3'	30.7	0.58	
204	1hr	30.7	0.58	
240	3'	30.5	0.44	
237	45'	30.5	0.44	

Temp. °C	Time at temp.	f^2 sec^{-2}	$Q^{-1} \times 10^3$ max.	min.
13	75hr	21.7	1.72	1.54
29	15'	24.2	0.88	
44	20'	25.0	0.64	0.58
58	10'	29.2	0.27	0.24
71	15'	27.5	0.22	0.21
84	15'	28.7	0.21	
104	15'	29.8	0.21	
121	15'	30.0	0.22	
142	15'	30.6	0.24	
155	15'	30.6	0.28	
161	15hr	30.8	0.31	
190	15'	30.7	0.55	
206	15'	30.9	0.59	
226	15'	30.9	0.59	

Specimen: 85 per cent manganese - 15 per cent copper

Heat treatment: Aged for twenty minutes at 400°C

<u>Data from Ke pendulum runs:</u> (see Fig. 7)

Light lever arm- 60 in. Timing mark intervals- 6 sec.

Pressure- less than 150 microns.

Temp. °C	Time at temp.	f^2 sec^{-2}	$Q^{-1} \times 10^3$ max.	min.
26		23.3	3.51	1.85
35	10'	22.7	4.41	2.11
34	1hr	23.1	4.40	2.11
33	16hr	23.3	1.82	0.91
41	24hr	24.0	0.98	0.67
48	20'	23.6	1.36	0.91
48	2.1hr	23.5	1.08	0.73
50	25.3hr	24.3	0.61	0.47
41	48.3hr	24.9	0.78	0.58
74	10hr	24.8	0.39	0.32
78	5'	23.1	0.57	0.43
81	5'	22.9	0.57	0.44
83	16hr	22.9	0.34	0.31
92	5'	21.7	0.52	
119	5'	27.0	0.54	
16	10hr	23.3	6.28	4.33
20	5'	23.0	5.02	3.03
36	5'	22.7	4.36	2.58
54	10hr	23.3	0.58	0.47
75	3'	22.1	1.19	0.84
110	5'	24.6	0.79	0.73
120	5'	27.6	0.30	0.28
27	48hr	23.6	2.88	1.95
132	3'	28.8	0.29	
74	10hr	33.1	0.38	0.33

Temp. °C	Time at temp.	f^2 sec^{-2}	$Q^{-1} \times 10^3$ max.	min.
163	3'	30.4	0.33	0.31
182	3'	31.4	0.36	0.28
200	3'	31.4	0.38	0.36
217	5'	31.3	0.38	0.34
223	5'	31.3	0.39	0.34
240	5'	31.3	0.41	0.35
258	5'	31.7	0.44	0.42
271	5'	30.2		
16	10hr	23.3	5.41	3.18
40	3'	22.3	4.55	2.91
71	3'	21.5	1.65	1.01
89	3'	20.5	0.67	0.59
53		25.0	0.58	0.44
80	3'	21.6	0.67	0.54
133	3'	28.8	0.34	0.31
150	3'	30.0	0.34	0.30
150	50'	30.7	0.39	0.31
149	16.5hr	29.8	0.39	0.29
177	3'	31.0	0.40	0.37
192	3'	31.3	0.41	0.38
208	3'	31.5	0.42	0.38
214	3'	31.5	0.42	0.38
218	5'	31.7	0.41	
213	20'	31.8	0.41	

Specimen: 85 per cent manganese - 15 per cent copper

Heat treatment: Inadequate solution treatment resulting in precipitation of beta manganese.

<u>Data from Ke pendulum runs:</u> (see Fig. 8)

Light lever arm- 60 in. Timing mark intervals- 6 sec.

Pressure- less than 150 microns.

Temp. °C	Time at temp.	f^2 sec^{-2}	$Q^{-1} \times 10^3$ max.	min.
45		28.4	0.29	
25		28.8	0.29	
73		23.3	0.39	
122	23'	31.8	0.24	
152	1.5hr	31.5	0.34	
214	27'	32.6	2.07	
223	45'	32.8	2.04	
25		24.8	0.51	
25		25.7	0.77	
63	25'	18.0	0.50	
71	25'	23.8	0.43	
82	23.5hr	26.0	0.26	
104	21hr	29.0	0.24	
126	2.5hr	30.2	0.29	
27		21.0	0.50	
135	1.5hr	31.7	0.31	
157	20hr	31.9	0.48	
188	10hr	32.2	1.23	
210	2hr	32.2	2.10	
238	16hr	18.8	2.12	

Temp. °C	Time at temp.	f^2 sec^{-2}	$Q^{-1} \times 10^3$ max.	min.
265	45'	32.2	0.90	
265	18hr	32.2	0.91	
253	1hr	32.2	1.22	
237	1hr	32.2	1.66	
227	45'	32.3	2.01	
220	2hr	32.6	2.11	
213	1hr	32.7	2.14	
217	1hr	32.8	2.16	
204	1hr	32.8	1.97	
195	1hr	32.7	1.64	
173	15hr	32.7	0.87	
96	45'	28.6	0.24	
93	2hr	27.9	0.24	
89	1hr	27.2	0.24	
59	2hr	25.0	0.27	
54	1hr	25.2	0.30	
46	15hr	26.2	0.33	
35	1hr	25.6	1.09	
76	1hr	24.0	0.29	
40	15hr	25.5	0.40	
30		26.7	0.37	

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