# EFFECTS OF ULTRASONICS ON THE KINETICS OF PHASE TRANSFORMATIONS IN STEELS

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# ABSTRACT

## EFFECTS OF ULTRASONICS ON THE KINETICS OF PHASE TRANSFORMATIONS IN STEELS

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The effect of ultrasonic vibrations on the physical properties of materials has been extensively investigated by many research investigators. However, no previous attempts have been made to understand the effect of ultrasonic energy on the mechanisms and kinetics on phase transformations in steels. In this present investigation, attempts have been made to determine the effects of ultrasonic vibrations on the kinetics of phase transformations, carbon diffusion, hardenability, martensitic transformation temperature ($M_S$), tempering and aging phenomena of various grades of steel. Several significant effects have been observed when steels are quenched under ultrasonic vibrations. A definite increase in hardenability is a result of cavitation that is produced by the imposition of ultrasonic energy in a liquid quenching media. This produces an increase in the cooling capacity of the liquid by an increase in the rate of heat transfer through the vapor transport stage of cooling. Furthermore, there is an enhancement of carbon diffusion; either by room temperature ultrasonic quenching, or ultrasonic treatment at ambient temperature. An examination of the microstructure of the resultant transformation product showed a significant increase in the precipitation of new carbides. Further investigation indicates that only short-range diffusion is enhanced, since the growth

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of existing carbides is not induced. When specimens were quenched under ultrasonic energy above room temperature and tempered at 1000°F, the resultant martensitic morphology had been significantly affected. This is due to strain-induced carbon diffusion, thereby relieving the supersaturation of the martensite matrix.

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# CHAPTER I

## LITERATURE SEARCH

### Introduction

In the past thirty-five years, much research has been initiated to determine the effect of ultrasonic waves on the physical and mechanical properties of materials. The first systematic approach, however, was not initiated until fifteen years ago when the effect of high amplitude stress waves on the internal stress system of metal crystals was investigated.

In recent times, ultrasonics have been utilized in almost all fields of scientific and technological applications. A few of the more prominent areas are mechanical engineering, agriculture, chemistry, metallurgy, medicine and power engineering. One of the most widely-known uses of ultrasonic vibrations is flaw detection in metals and alloys. The high penetrating power of the ultrasound oscillations does not limit its uses to nondestructive testing, but has been used in determining such elastic parameters as density, viscosity, elastic modulus, elastic constants (Young's modulus, shear modulus, and Poisson Ratio).

On the other hand, chemistry and its related areas have noticed the impact of ultrasonic technology. Molecular physicists are now able to draw some conclusions about structure of substances and their intermolecular binding. Physicochemical processes such as hydrolysis and dye-making are now being developed more efficiently and economically.

Looking at ultrasonics as a physical phenomenon, it can most easily be explained as the production of bubbles in a liquid media, better known

as cavitation. These bubbles are constantly being expanded and contracted, corresponding directly to the frequency of the sound waves. During compression, the bubbles attain great compressive stresses and can actually collapse. This leads to a powerful shock wave that is very useful in breaking up or pulverizing certain solids (gpysum, granite, copper of silver); or the homogenization of colloidal dispersion solutions. As can be seen, it would be very difficult to mention all the present uses and potential possibilities for the application of ultrasonics.

## General Theory

When discussing sonics, ultrasonics or hypersonics, it is generally thought of in terms of "waves" traveling from a transmitter to a receiver. It is necessary for a media (gasses, liquid, solid) to be present when waves are traveling from one point to another. Ultrasound, or ultrasonics, is generally thought of as consisting of a frequency above that audible by the human ear ($\approx$20,000 cps) and transmitted through an elastic medium by successive displacement of adjacent atoms. The wavelength (determined from the formula $\lambda = \frac{c}{f}$ ) of the minimum frequency range for ultrasonics is dependent on the substance through which it travels; i.e., solid - $\lambda$ = 8", liquids - $\lambda$ = 2.4" and gasses - $\lambda$ = 0.63". The following table gives a summary of frequency, its uses and where it fits into the frequency spectrum:

TABLE 1

FREQUENCY SPECTRUM

| Frequency (Cycles x 1000) | Uses |
|---|---|
| 20 | Boundary between sonic and ultrasonic |
| 30 | Upper limit produced by friction |
| 50 | Testing of materials in a liquid bath |
| 60 | Practical limit for magnetastrictive transducers |
| 90 | Upper limit for tuning fork |
| 300 | Emulsion formation |
| 500 | Low limit reflectoscope |
| 1,000 | Production of oil jets |
| 6,000 | Thin limit, reflectogage |
| 500,000 | Highest ultrasonic frequency repeated at present |

Ultrasonic waves are categorized into two separate types: first, the longitudinal wave (L wave) which displaces the orbit of the transmitting medium in a direction parallel to the propagation; secondly, a shear (S wave) or transverse wave which displaces in a normal or perpendicular direction. Another method of describing waves is their effect on volume: if the volume of the material is changed they are called waves of dilatation; if they do not, they are waves of distortion.

L Waves are most widely used because they will travel in solids, liquids and gasses, and can be easily generated and detected. These waves have a high velocity of travel and very short wavelength which allows the energy beam to be focused sharply with a minimum divergence problem.

S Waves have a velocity equal to about 1/2 that of the L Wave and their wavelength is much shorter. Shear waves will not travel in liquids and solids and their beam is much more easily scattered.

The absorption of sound by solids is considerably dependent on the structure of the object. For isotropic-amorphic bodies or monocrystals,

the absorption is small and basically dependent on the coefficient of viscosity and thermal conductivity. Our concern, however, is with polycrystals. When high frequency (small wavelength ($\lambda$)) sound is considered, it is absorbed in each crystal with the coefficient of absorption proportional to the frequency squared $\lambda \approx f^2$. Very large sound absorption is observed when the crystal mean dimension is equivalent to the same order of magnitude of the wavelength ( $\lambda \approx d$). For the above case, the sound waves penetrate and scatter between the individual grains of the polycrystal, simulating light waves scattered by a turbid medium. With increased crystal size, the sound waves will be scattered only by particles which are comparatively small relative to the wavelength. Here we can consider each crystal to be subjected to a uniform pressure from the sound propagation. Due to the anisotropy and varied grain orientation, a temperature gradient arises in the vicinity of the small crystals and will cause an increase in absorption due to thermal conduction. The absorption coefficient dependence on frequency is determined by the relationship between relaxation time for thermal conduction ( $\tau_x$ ) and the period of sound (T). In polycrystals, when $\tau_x \gg T$, temperature equilization during deformation cannot occur and the resultant temperature wave will lead to damping and is proportional to the square root of the frequency ( $\alpha \approx \sqrt{f}$). Thus, it is evident that the absorption of sound in polycrystals is determined by individual crystal dimensions and sound wavelength. For low, medium and high frequencies, the absorption mechanism is dependent on thermal conductivity, diffusion scattering and the frequency squared, respectively. For very low frequencies, the Rayleigh scattering effect is predominant.

For most metals and solids the damping of longitudinal and shear sound waves is determined by:

$$\alpha = Af + Bf^4.$$

Af is a low frequency phenomenon and is caused by the presence of elastic hysteresis, while $Bf^4$ is a scattering phenomenon. When considering longitudinal elastic waves in a solid body, the propagation equation, allowing for absorption, can be written:

$$P \frac{\partial^2 \theta}{\partial t} = E_1 \frac{\partial^2 \theta}{\partial x^2} + N \frac{\partial^3 \theta}{\partial x^2 \partial t} .$$

If this equation is rewritten as a function which is proportional to $e^{iwt}$, we obtain:

$$\frac{\partial^2 \theta}{\partial t^2} = \frac{E}{P} \frac{\partial^2 \theta}{\partial x^2}$$

where Young's modulus (E) is complex and determined from the following:

$$E = E_1 + iwn = E_1 + iE_2 .$$

The ratio $\frac{E_2}{E_1}$ is the mechanical loss-angle tangent or loss factor $\varepsilon$. The coefficient $\varepsilon$ is related to the absorption coefficient by:

$$\varepsilon = \frac{\lambda \alpha}{\pi} = \frac{\alpha f}{\pi C}$$

and the inverse of E is equal to Q. Some common values of Q are shown in the following table.[1]

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[1]H. V. Fairbanks and F. J. Dewet, Iron Age, Vol. 176 (Dec. 8, 1955), pp. 139-142; Industrial Eng. Chem., Vol. 47 (1955), p. 1181.

[1]I. O. Babikov, "Ultrasonics and Its Industrial Applications," Translated from Russian (Consultants Bureau, 1960), p. 39.

TABLE 2

COMMON VALUES FOR LOSS FACTOR

| Material | cm./sec. | Q | $\frac{d}{f} \times 10^{-9}$ sec./cm. |
|---|---|---|---|
| Aluminum | 5130 | 10,000 | 0.62 |
| Tungsten-Carbon Steel | 4720 | 5,700 | 1.17 |
| Molybdenum Steel | 4700 | 8,100 | 0.83 |
| Melted Quartz | 5110 | 5,000 | 1.23 |
| Window Glass | 5140 | 910 | 6.70 |

It has been shown that when a given ultrasonic wave impinges on a boundary between two materials of different acoustical impedances, the wave is transformed into various components. A simple example would be an L wave traveling through a liquid and striking a solid at any angle other than 90°. In this case, various L and S waves of different amplitude and wavelengths are formed, resulting only in reflected L waves because S waves cannot be transmitted through liquids. It should be brought to the attention of the reader that when liquid and solid interfaces are of interest, many misleading results will be obtained unless the liquid is able to wet the solid surface to allow intimate contact. The interfaces that are common to the two media also play a very important part in the energy losses between the wave and the specimen. Some of the energy overcomes the interface boundary and passes on to the specimen while the rest is reflected back. About 88% of the energy is lost when waves are being transmitted to steel through water.

Now that the fundamental background of ultrasonic waves has been presented, how does one go about producing them? The first method is through the use of mechanical generators, or tuning fork types, but the range of waves for this method does not exceed 10,000 cycles. The second type is an arc of electric current or spark gap method to produce the ultrasonic

waves. This thermal principle is not generally used. The most widely used techniques for the production of ultrasonic waves is either by the magnetostriction effect or the piezoelectric effect. The last two methods will be discussed separately.

1. Magnetostriction Effect - Consists of a magnetized rod that will elongate or shorten under the influence of an electric field, producing an e.m.f. in the windings on the rod. If a variable e.m.f. is imposed in the windings, the rod will vibrate at this same frequency. Magnetostriction vibrators are not confined to the shape of rods, but can be made in the form of tubes or thin plates; but all are temperature dependent. The most prominent materials are iron-cobalt alloys, pure nickel and nickel alloys.
2. Piezoelectric Effect - Is the phenomenon associated with the appearance of an electrical charge at the edge of certain crystals when subject to compression or extension. Because the piezoelectric effect is reversible, under an electric field, these crystals deform and produce ultrasonic waves in the surrounding medium. The most common crystals used for this effect are quartz, Rochelle salt, tourmaline or barium titinate.

The detection of ultrasonic waves is made possible through two different phenomena when an ultrasound wave impinges on a boundary: first, the alternating pressure; and secondly, the direct pressure. The alternating pressure is commensurate with the frequency of the propagated wave and is expressed by the formula:

$$J = \frac{dc}{2} (WA^2) = \frac{Pu}{2}$$

where:

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J = intensity per centimeter squared in unit time

d = density

A = maximum amplitude of a vibrating particle

P = sound pressure

U = velocity amplitude of the individual particle.

The direct pressure, due strictly to radiation, is given by the following equation:

$$S = 1/2\ (K + 1)\ J/C$$

where K is the ratio of specific heats. This measurement gives an indication of the intensity of the ultrasonic field. The actual method for verifying the presence of ultrasonic waves was first described in the middle of the nineteenth century. Fine dust particles (lycopodium) were placed on the surface of the specimen subject to ultrasonics, and the configuration of the dust predicted the dimensions and shape of the wave.

A method which is still used today is a radiometer, a device that incorporates the principle of a torsion balance. This device is simply a supported thin mica disc and counterbalanced by a weight. The direct contact of the waves in conjunction with their unidirectional pressure causes the mica to rotate.

The method used to represent a wave (ultrasound) is through the use of an X (distance) and Y (displacement) curve. The simplest and purest ultrasonic wave can be represented by the sine wave: $X = a \cos. (wt. - \emptyset)$. It should be noted that this does not actually represent the displacement of particles, but only pictures the action. In practice, however, there is no mathematical wave expression that satisfies all the requirements of the ultrasonic wave. Therefore, the actual shape of the function must be

analyzed through other techniques such as Fourier analysis, or LaPlace transformation.

In order to thoroughly analyze the effects of ultrasonics, one must investigate the possible influence of different wave parameters on self-diffusion, diffusional and diffusionless transformations in solid metals and alloys. The length of the wave, frequency and amplitude of vibration are all significant when elastic properties and body density are to be examined. Although various methods of applying elastic vibrations of different frequency and intensity have been applied during transformations, neither theoretical or experimental evidence has been produced to show which of the ultrasonic wave parameters determine the accelerated diffusional and diffusionless transformations that have been reported. An evaluation of the elastic wave on the basis of frequency and intensity alone is inadequate, because it is impossible by this means to predetermine the conditions necessary to obtain the desired results. Analysis of possible influence exercised by different elastic wave parameters on transformations may, to an appreciable extent, facilitate both of the methods to be used for a particular component.

Let us first present the effect of elastic vibrations on self-diffusion in a homogeneous amorphous body of one pure component. In this case, the diffusion rate can only increase if a change takes place in the frequency and amplitude of the thermal vibrations of the atom, or the respective positions of the atoms (i.e., as in deformation). The propagation of elastic waves through the body is connected with periodic changes of both pressure and temperature. The temperature in the body during the compression part of the vibration increases and it decreases during the relaxation part of the cycle. This is proportional to the amplitude of the

pressure. Since the pressure varies at a finite rate, the temperature is partially equalized due to heat transfer between regions of the body with different stress levels. Thus, the temperature in the highest stressed regions, where its influence on diffusion rate is maximum, will increase to a lesser extent than if heat transfer were absent. The higher the frequency of the ultrasonic vibrations and the lower the pressure gradient, the lower the temperature equalization and thus, the higher the rate of diffusion.

Static deformation of polycrystalline bodies gives rise to a considerable increase in the rate of diffusion. This is explained by the fact that in a crystalline and more particularly, in a polycrystalline body, the stress properties are concentrated on individual shear planes, along which diffusion mainly occurs.

The concentration of stresses not only promotes diffusion transformations in metals and alloys, but also diffusionless transformations, since the formation of crystallization centers is also determined by the nature of the crystal lattice, activation energy and temperature. The degree of distortion of the lattice on individual shear planes and the distribution of centers of stress concentration throughout the grains are dependent on the composition and lattice structure of the deformed metal, and on the amount and frequency of the deformation variation. Diffusional and diffusionless transformations, as well as dislocation movement, occur mostly at points where there is the greatest distortion in the lattice. This will produce a corresponding deceleration in the rate of diffusional and diffusionless processes.

When a body is subjected to alternating deformation, the locations and degree of stress concentration are constantly changing, which prevents

the transformation process in the material from being attenuated. The transformation process is maintained when there is a cyclic variation of load. Cyclic deformation variation at infrasonic frequencies does not intensify these processes as ultrasonic frequencies of the same deformation amplitude. This is due to the strong influence of speed and gradient of deformation. A significant and, in some cases, decisive role may be played by the relation between deformation amplitude, vibration period, and speed of the transformation process.

Property changes induced by the addition of elastic waves must be studied as a function not only of the relationship between amplitude and frequency of vibrations, but also of the structure of the material.

This problem was attacked by various colleagues in their determination of sound energy absorption pertaining to dislocations. The following Table 3 was developed through internal friction methods by H. A. Van Bueran.[2] The data indicate the mechanisms responsible for a variety of dislocation behavior dependent on frequency, stress amplitude, temperature and material condition. The dislocation relaxation has been attributed to kinks in a dislocation by Seeger[3] and their subsequent migration along dislocation lines by an applied stress. The resultant anelastic strain causes the stress to lead the strain and an energy loss is observed from the stress strain hysteresis. A model for dislocation hysteresis has been presented

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[2]H. A. Van Bueran, Imperfections in Crystals (Amsterdam: North Holland Publishing Co., 1960).

[3]A. Seeger, "On the Theory of Low Temperature Internal Peak Observed in Metals," Phil. Mag., Vol. 1 (1956), p. 651.

TABLE 3

MECHANISMS OF SOUND ABSORPTION BY DISLOCATIONS

| | Region of Temperature and Frequency | Type | Frequency Dependence | Amplitude Dependence | Temperature Dependence; Energy of Activation, U | Cold-Work Dependence | Impurities Dependence | Mechanism | Inference |
|---|---|---|---|---|---|---|---|---|---|
| Dislocation relaxation | $T < 100$ K; kc-mc | Relaxation | Peak(s) | None | U (of $\tau$) 0.05-0.1 ev (Cu) | Through maximum after few percent strain | Small | Relaxation of dislocation over Peierls barrier | Peierls barrier height |
| High-temperature dislocation damping | $T > 300$ C; c-kc | Relaxation | $\sim 1/\omega$ | Undefined, small | U = 0.8-2 ev (Cu) | Large, also activation energy varies | ? | Relaxation of dislocation in internal-stress field | |
| Dislocation resonance | $T \geq 0$ C; 1-1000 mc | Damped resonance | $\sim \omega$ | None | U = 0.2-1 ev (Ge) | Very large | Impurities suppress | Resonance of dislocation in equilibrium positions | Binding energy impurity to dislocation |
| Dislocation hysteresis | $T \geq 0$ C; kc-mc | Hysteresis | None | Parabolic | U = 0.1-0.4 ev (Cu) | Very large | Impurities suppress | Breakaway of dislocation from impurity | Binding energy impurity to dislocation |
| Transient cold-work internal friction | $T \leq 200$ C; c-mc | Viscous | None | None ? | U = 0.5-1 ev annealing (Fe) | Large | ? | Rearrangement of dislocation | Diffusion of point defects |
| Deformation hysteresis | $T \leq 100$ C; c | Hysteresis of viscous | ? | Parabolic | U $\approx$0.1 ev; annealing $\approx$0.5 ev; third process present (Fe) | Large | Impurities suppress | Hysteretic dislocation motion ? | Interaction point defects and dislocations? |

by Granato-Lucke[4] for the resonance of high strain amplitudes. They observed that as the stress is increased, the dislocation segment detaches itself from lightly pinned points, but becomes restrained by more tightly pinned nodes. Upon lowering the stress, the arched segment smoothly collapses to its original position. Others have investigated the transient cold-work internal friction and deformation hysteresis which are both observed immediately after moderate cold work, but can be annealed out. This is possible by two phenomena: recovery (Norwick)[5], and/or strain aging (Granato, Hikata, Lucke).[6] The amplitude dependence of these are their main distinction; deformation hysteresis is strongly amplitude-dependent, while the latter is independent of stress amplitude.

With the help of the above-mentioned ideas and theories, much work has been performed to utilize these principles and apply them to very useful phenomena. With the information from Blaha and Langenecker[7] that states "macrosound (high amplitude ultrasonic stress waves) activates dislocation in such a way that many dislocations may now move through the crystal lattice under reduced apparent static stress," it has been shown that macrosound does noticeably influence the properties of materials. Such an example, plastic deformation with 100% reduced apparent static stress at 20,000 cps,

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[4]A. Granato and K. Lucke, "Theory of Mechanical Damping Due to Dislocations," p. 583; "Application of Dislocation Theory to Internal Friction Phenomena at High Frequencies," J. Appl. Phys., Vol. 27, (1956), p. 789.

[5]A. S. Nowick, "Internal Friction and Dynamic Modulus of Cold Worked Metals," J. Appl. Phys., Vol. 25, (1954), p. 1129.

[6]A. Granato, A. Hikata and K. Lucke, "Recovery of Damping and Modulus Changes Following Plastic Deformation," Acta. Met., Vol. 6, (1958), p. 470.

[7]B. Langenecker and F. Blaha, "Dehnung Von Zink-Kristallen Unter Ultraschal-Leinwirkung," Z. Naturwiss, Vol. 20, (Aug. 1955), p. 556.

has been performed by Nevill and Brotzen,[8] Oelschlagel and Weiss.[9] Other investigations have only noticed a small effect (Haverbeck and Weber,[10] Kristoffy,[11] Baker and Carpenter).[12] These less significant results are most likely due to the low acoustical energy density in the sample because of bad coupling with the transducer. It has been shown that the increasing strain in a crystal is not linear with respect to the increased ultrasonic energy (Caswell,[13] Chambers and Smoluchowski),[14] but there is an abrupt jump in the curve above a certain amplitude which theoretically corresponds to the unpinning of the dislocation. For a review on the comprehensive literature on the above topic, see Tryell and Elbaum.[15]

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[8]G. E. Nevill and F. Brotzen, "The Effect of Vibrations on the Static Yield Strength of Low Carbon Steel," Proc. ASTM, Vol. 57, (1957), p. 751.

[9]D. Oelschlagel and E. Weiss (in press).

[10]K. E. Haverbeck and R. R. Weber, "Influence of Vibration Energy on Metalworking Processes," (Cincinnati Milling and Grinding Machines, Inc., Interim Progress Report, April 4, 1963-Oct. 4, 1963), (Air Force Contract No. AF33(657)-10821, Oct. 1963), p. 45.

[11]I. I. Kristoffy, R. L. Kegg and R. R. Weber, "Influence of Vibration Energy on Metalworking Processes," (Cincinnati Milling and Grinding Machines, Inc., Cincinnati, Ohio, Final Report No. AFML-TR-65-211, July 1965, Contract AF33(657)-10831).

[12]G. S. Baker and S. H. Carpenter, Trans. Met. Soc. of AIME, Vol. 236, (May 1966), p. 700.

[13]H. L. Caswell, "Investigation of Low Temperature Internal Friction," J. Appl. Phys., Vol. 29, (Aug. 1958), p. 1210.

[14]R. H. Chambers and R. Smoluchowski, "Time Dependent Internal Friction in Aluminum and Magnesium Single Crystals," Phys. Rev., Vol. 117, (Feb. 1, 1960), p. 725.

[15]R. Truell and C. Elbaum, Encyclopedia of Physics, ed. by S. Flugge (Berlin: Springer-Verlag, 1962), XI, 2.

In 1957, Nevill and Brotzen found a decrease in the yield strength of low carbon steel when tensile tested in the presence of ultrasonics (15 KC/sec. to 80 KC/sec.). The decrease in yield strength was independent of frequency, temperature and prior strain, but it was proportional to vibrational amplitude. Macroscopic irradiation has caused other such phenomena which have proven very difficult to explain qualitatively: pure slip (Langenecker),[16] twinning and kinking (Langenecker)[17] in metal crystals, and the softening of high strength metals (beryllium, titanium, Steeland tungsten) by Langenecker.[18] These phenomena are theoretically explained by the "thermal zone" or weak spots in the metal due to nonhomogeneous absorption of energy waves (Langenecker),[19] or by the energy conversion at dislocation sites by a hysteresis (Granato-Lucke).[4]

Metallurgical Effects of Ultrasonic Vibrations on Ferrous Materials

The effect of ultrasonics on ferrous materials has been investigated from many different phenomenological viewpoints including various conditions under which ultrasound vibrations have been imposed upon the material.

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[16] B. Langenecker, et al., "Effects of Ultrasound on Deformation Characteristics of Structural Metals," (California: Navweps Report 8482, Naval Ordance Test Station, China Lake, 1964).

[17] B. Langenecker, W. H. Franosan, and S.R. Colberg, "Kinking in Zinc Crystals by Ultrasonic Waves," J. Inst. Metals, T.N. No. 71, Vol. 91, (1963), p. 316.

[18] B. Langenecker, "The Effect of Sonic and Ultrasonic Radiation on the Safety Factor of Rockets and Missiles," AIAA 5, Vol. 1, (January 1963), p. 80.

[19] B. Langenecker, "Effects of Ultrasonics on Deformation Characteristics of Metals," IEEE Trans. Sonics and Ultrasonics, Vol. 13, (March 1966), p. 1.

Before we discuss any effect on steels, we should first report the Effect of Ultrasonics during Heating on the Microstructure of Technically Pure Iron[20] (.04% C, .07% Mn, .03% Si, .035% S, .015% P). It has been shown microscopically that ultrasonic waves imposed during heating to 910°C cause local recrystallization. It was also observed that the grain boundary alignment is parallel to the maximum tangential stresses which was proven by internal friction techniques. Pogodin-Alekseeva[21] has shown that the rate of carburizing technically pure iron has been doubled with 21.5 Kcps.

Turning now to steels, we will first investigate the Effect of Ultrasonic Vibrations on Grain Size in Austenite and Pearlite.[22] For this investigation, a high power transducer was used with a 21 Kcps ultrasonic frequency. All the samples were treated in a salt bath to prevent decarburization of the 1045 steel. Duplicate tests were conducted for each experiment; one without ultrasonic, and the other with ultrasonic vibrations during heating, soaking and/or cooling. Upon microscopic investigation, it was evident that the ultrasonically treated samples had martensitic needles much larger than the untreated specimen. Additionally, the troostite network suggested that the ultrasonic vibration caused the austenite grain to coarsen. The hardness data after quenching revealed that the treated samples were 3-5 $R_c$ points lower. It is felt that the austenite grain growth with

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[20]Uy. E. Balalaev, Effect of Ultrasonic High-Temperature Heating on the Structure of Technically Pure Iron, translated from Metallovendenie i Termicheskaya Obrabotka Metallov, Vol. 1 (Voronezh Polytechnic Institute, January 1964), pp. 48-49.

[21]M. G. Pogodin-Alekseeva, "Metalloy, i Obrab. Metallov.," (June 1958), pp. 14-17.

[22]A. G. Vasil'yeva and T. Ye. Kobtseva, Effect of Ultrasonic Vibrations on Grain Size in Austenite and Pearlite (Baumann Technical School).

ultrasonics is due to homogenization and the formation of additional nuclei or improved carbon diffusion. Upon normalizing and quenching with ultrasound, the resultant microstructure revealed finer pearlite colonies and more isolated patches of ferrite. To differentiate between the effect of heating and soaking or quenching in ultrasonics, the latter was excluded in a subsequent experiment. From this experiment it was concluded that cooling with ultrasonics caused more coarsening of the structure.

Secondly, we will discuss the Effect of Ultrasonic Vibration on Transformation in Metals and Alloys.[23] It has been shown by Harvey[24] that ultrasonic vibration can be satisfactorily utilized to improve the cooling capacity of a liquid media as shown in Table 4. Harvey has further shown

TABLE 4

RATE OF COOLING IN VARIOUS QUENCHING MEDIA (Relative Units)

| Medium | No Stirring | Vigorous Stirring | Ultrasonically Excited |
|---|---|---|---|
| Oil | 0.25 - 0.30 | 0.80 - 1.10 | 1.65 |
| Salt Sln. | 2.0 | 5.0 | 7.5 |
| Salt Sln. at 400°F | 0.30 | 1.21 | 1.80 |

that a bath excited by ultrasonic vibrations accelerates heat transfer, thereby increasing hardness, strength and impact values. This effect is more noticeable upon quenching larger specimen (25/32" x 25/32" x 2") in

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[23] E. A. Al'ftan, Effect of Sonic and Ultrasonic Vibrations on Transformations in Metals and Alloys (review of literature).

[24] R. F. Harvey, "Sonic Quenching," Industrial Eng. Chemistry, Vol. 46, (1954), (10), p. 15A. (A much better reference is: Richard F. Harvey, Iron Age, Vol. 173, (1954), (14), p. 154, (Translator's Note).

an oil bath. When the quenching media is water and ultrasonic is imposed, the hardness was lowered and the impact values changed only slightly. A positive effect was noticed in the fact that 60%-90% more scale was detached from the specimen. Conversely, it has been shown[25] that the hardness of an SAE 8740 was increased by 6 $R_C$ points when quenched in an ultrasonically excited oil bath.

Considerable work has been done in the field of resultant transformation products after normalizing and/or austenitizing in the presence of ultrasonic vibrations. Tanaka[26] has revealed that a considerable acceleration has been observed in the diffusional transformation of a 1.2% carbon steel, along with a nonuniform grain growth phenomenon. Fairbanks and Dewez[27] showed that when annealing a .07% carbon steel in the presence of ultrasound, the result was a finer-grained and harder product. The grain size decreased as the frequency of the ultrasonic vibration was increased. Palme[28] found that at extremely high cooling rates, the ultrasonic vibration no longer influences the cooling capacity of the media, but it does induce the transformation from an unstable to a stable state which consequently softens the steel. Conversely, Gudtsov and Gavze[29,30] found no

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[25]A. Nash, Machine Shop Mag., Vol. 19, (1958), (1), p. 15.

[26]S. Tanaka, et al., Tetsu to Hagane, Vol. 37, (1951), pp. 527-532.

[27]H. V. Fairbanks and F. J. Dewez, Iron Age, Vol. 176, (1955), (6), p. 1181.

[28]L. Palme, Metaux Corrosion-Industries, Vol. 29, (1954), (243), pp. 100-104.

[29,30]N. T. Gudtsov and M. N. Gavze, "Report to the Third All-Union Conference on Physio-Chemical Analysis," (Published by USSR Academy of Sciences, 1955); Zhur. Neorg. Khimii, Vol. 1, (1956), (7), pp. 1533-1538.

effect of ultrasonic vibration (150-500 KC) on the transformation of high speed steels.

K. M. Pogodin-Alekseeva and Associates[31-33] have investigated the effect of tempering at various temperatures utilizing an ultrasonic source when producing 1,000,000 cycles/second having a specific power of 18 watts per square inch. One part of the experiment consisted of studying the tempering characteristics of U-8 steel (.76% C, .10% Cr, .10% Ni, .02% Si, .03% Mn, AISI 1078) both with and without ultrasonic energy applied during tempering. The samples studied consisted of standard impact specimens that were solution treated at 1400°F, quenched for 5 seconds in water after normalizing at 1470°F for 2 hours. The as-quenched hardness was found to be 65 Rockwell "C." In all cases, it was found that tempering with the presence of ultrasound produced higher hardnesses than tempering without ultrasound under identical conditions. Tempering for 15 minutes at 625°F produced hardnesses of 51.5 Rockwell "C" without ultrasound and 54 Rockwell "C" with ultrasound. Tempering at 660°F for 30 minutes showed 49 Rockwell "C" without any 52 Rockwell "C" with ultrasound. These results, shown in Table 5, are the mean of several measurements. This phenomenon is apparently due to age hardening and it was concluded that ultrasound promotes transformation to a more stable structure, particularly during tempering, isothermal treatment and aging, in addition to the stabilization of high alloy steels.

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[31] K. M. Pogodin-Alekseeva and G.I. Eskin, Metallov. i. Obrab. Metallov., (1956), (1), pp. 42-45. (HB Translation #4551).

[32] K. M. Pogodin-Alekseeva, Sbornik of All-Union Polytechnic Institute for Home Study, No. 13, (1956).

[33] K. M. Pogodin-Alekseeva, "Use of Ultrasound in Heat Treating Metals and Alloys," (Moscow Center of Applied Science Dissemination: 1957).

TABLE 5

HARDNESS AS A FUNCTION OF TIME AND TEMPERATURE FOR ULTRASONIC AND REGULAR TEMPERING OF A U-8 STEEL

| Tempering Temperature, °F | Time at Temperature | Hardness With Ultrasonic ($R_C$) | Hardness Without Ultrasound ($R_C$) |
|---|---|---|---|
| 625 | 15 min. | 54 | 51.5 |
| 660 | 30 min. | 52 | 49 |
| 770 | 15 min. | 54 | 48 |

Similar studies were performed by Al'ftan[34] when he used bars of AISI 1050 grade steel that were secured to a 25,000 cycle/second generator and suspended in a salt bath. Induced stresses were between 1,700 and 17,000 psi. Ultrasonically-vibrated samples were found to be from 1 to 6 Rockwell "C" units softer than samples tempered for identical times and temperatures, but without the ultrasonic vibrations. There was no difference in notch toughness for a given time and temperature for either ultrasonic or nonultrasonic specimens, but for a given hardness the nonultrasonic specimens appeared better.

When AISI 4340 grade steel was quenched from 1600°F to a tempering temperature of 630°F, an increase of 10 percent in both yield and tensile strength was found when ultrasonic vibrations were applied during tempering. The ultrasonically-tempered samples showed a finer grain structure. For this investigation, samples were attached to the ultrasonic device and suspended into the tempering bath.

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[34]E. A. Al'ftan, "Mechanical Properties of Steel Improved by Combined Heat and Ultrasonic Treatment," Izv. Vysshikh Uchenb. Zavedenii Chernaya Met., (Sept. 1960), pp. 160-166. (Brutcher Translation #5086).

Similar experiments have been conducted by Bokshtein[35] in which .57% C and .73% C steels were austenitized, water quenched and tempered in the presence of ultrasonics at 600°C and 700°C. When hardness is plotted as a function of time, there is a very sudden initial dip in the curve. This has been attributed mainly to the rapid decrease in the amount of carbide particles, or possibly to the actual softening of the matrix.

V. G. Lutsyak, D. A. Turnsunov and N. P. Kuleshova have investigated the Tempering of Carbon Steels Accelerated by Ultrasonic Vibrations.[36] These experiments consisted of austenitizing plain 0.57% C and 0.73% C steel at 1000°C. After the initial quench, the specimen was immediately tempered in a salt bath at 600°C, 650°C, and 700°C for isothermal holding periods of 6 and 30 minutes; 1, 2, 5, 10, 20, and 30 hours. It was concluded that the tempering of plain carbon steels is noticeably hastened by ultrasonic vibrations and the coalescence of carbides is accelerated by carbon diffusion.[37]

Additional work has been done by Pogodin-Alekseeva[38] when ultrasonic vibrations were applied to a 12 KhN 3A steel during low temperature tempering. This treatment caused a drop in hardness and an increase in impact properties.

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[35] S. Z. Bokshtein, "The Structure and the Mechanical Properties of Alloy Steels," (Moscow: Metallurgizdat Press, 1954). (Book in Russian).

[36] V. G. Lutsyak, D. A. Tursunov, and N. P. Kuleshova, Tempering of Carbon Steel Accelerated by Ultrasonic Vibrations, (Ukranian Research Institute for Metals, Donets Branch). (Translated from Metallovendenie i Term Obrabotka Metallov) (October 1964), No. 10, pp. 57-58.

[37] A. G. Vasil'eva and T. E. Kobzeva, Metallovedenie i Term. Orab. Met., No. 9, (Sept. 1962).

[38] K. M. Pogodin-Alekseeva, In Coll. "Modern Alloys and Their Heat Treatment," Mashgiz, (1958). (In Russian).

Other areas of investigation include aging and nitriding. Schenck and Schmidtmann[39] studied the effect of ultrasound on the physical properties of a 0.06% C, 0.018% $N_2$ steel after quenching or working. Aging was accelerated by infrasonic (8.6 cps), but not with ultrasonics. Mahoux[40,41] has studied the nitriding of steel (.35% C, .03% Ni, .03% Cu, .01% Mo, .25% Si, .25% Mn) at 930°F under the action of ultrasonics. It was observed that the hardness increased from 380 to 1033 vickers' units and increased the nitrided case from .01 mm to .35 mm. Meyer[42] found that the diffusion rate and amount of nitrogen were increased due to ultrasound, but no depth of penetration increase was noticed. Altenberg[43] concluded that ultrasonic waves could not act on diffusion through theoretical calculation. This has been confirmed[44] by the study of carburizing steel in propane, the diffusion of copper into gold cut 850°F, hydrogen into technically-pure iron, or nitriding of steel and iron in ammonia at 1020°F. However, the opposite was noticed when Pogodin-Alekseeva[45] performed an experiment on the effect of

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[39] H. Schenck and E. Schmidtmann, Arch. Eisenh., Vol. 25, (1954), (11 12), pp. 579-588.

[40] G. Mahoux, Comptes Rendus (Paris), Vol. 191, (1930), (25), pp. 1328-1330. (H.B. Translation #1647).

[41] G. Mahoux, Mecanique, Vol. 21, (1937), (275), pp. 281-287.

[42] O. Meyer, W. Eilender, and W. Schmidt, Archiv Eisenh., Vol. 6, (1932-3), (6), pp. 241-245. (H.B. Translation #1695).

[43] K. Altenburg, Z. Physik, Chemie (Leipzig), Vol. 202, (1954), (6), pp. 460-473.

[44] E. Ehringer, Dissertation (Germany: T.H. Stuttgart, 1951).

[45] G. I. Pogodin-Alekseeva, "Effect of Ultrasonic Vibrations on Diffusion in Steels and Alloys at Elevated Temperatures," Metalloved i Obrabotka-Metal, (June 1968), No. 6, pp. 14-17. (Brutcher Translation #4247).

carburizing with a solid carburizing agent, both with and without ultrasonic energy on Armco iron and 12 KhN 3A steel (0.15% C, 0.45% Mn, 0.3% Si, 0.8% Cr, 3.0% Ni, balance Fe). The samples were cylinders, 1 inch in diameter and 6-1/2 inches long. Experiments were conducted at 1830°F for 1/4 to 4 hours. Electrical power to the ultrasonic generator, when in use, was 2.4 kva. The following table shows the results. The carburizing agent

TABLE 6

TOTAL CASE DEPTH (inches) OF CARBURIZING ARMCO IRON IN ULTRASONIC ENERGY

| Carburizing Time (hours) | Armco Iron | | 12 KhN 3A Steel | |
|---|---|---|---|---|
| | Not Vibrated | Vibrated | Not Vibrated | Vibrated |
| 0.25 | 0.0047 | 0.014 | 0.0047 | 0.008 |
| 1 | 0.011 | 0.021 | 0.009 | 0.017 |
| 2 | 0.018 | 0.033 | 0.015 | 0.027 |
| 3 | 0.024 | 0.047 | 0.020 | 0.034 |
| 4 | 0.031 | 0.055 | - | - |

used was 3 parts wood charcoal and 1 part sodium carbonate (anhydrous). It is obvious that carburizing is increased by the presence of ultrasonic energy.

It was found that the effect of ultrasonic energy on carburized depth increases with the intensity of the ultrasonic vibrations. A 50% increase in intensity increased case depth from 0.033 inch to 0.045 inch in Armco iron after 2 hours at 1830°F.

Further investigation was carried out by the following associates: G. V. Zemskov, E. V. Dombrovskaya, V. T. Yarkina, L. K. Gushchin, and A. K. Parfenov, who studied the Intensitification of Nitriding by Ultrasonic

Vibration.[46] It was concluded that ultrasonic vibrations increase the depth of hardness of the nitrided layer in the process of gas nitriding of steels at 540°C to 560°C. The greatest difference was observed during the first 4 hours in which the depth of the hardened layer increased by 40%. It was also noticed that a discontinuous band of E-carbonitrides had appeared to a depth of 0.01", while more appeared in the untreated sample. The total conclusions from the previous work are as follows:

1. Direct ultrasonic vibrations of the sample produce greater case hardening in gas nitriding than in liquid nitriding.
2. Ultrasonic vibrations increase nitriding not only when applied to the sample itself, but also when the vibrations are present in the surrounding media.

This insinuates that the vibrations promote mixing, eliminate the reaction products at the surface, and activate the surface to promote additional absorption.

Other investigators, G. E. Aizentson and P. A. Malinen, have investigated the Decomposition of Residual Austenite as the Result of Ultrasonic Vibration.[47] They have shown that ultrasonic vibration with an amplitude of 20 $\mu$ and 12 $\mu$ favors the decomposition of the austenite of a Kh VG steel (0.95% C, 1.1% Mn, .24% Si, 1.22% Cr, 1.58% W) at 250°C. Additionally, the microstructure is more dispersed and the hardness is increased.

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[46] G. V. Zemskov, E. V. Dombrovskaya, V. T. Yarkina, L. K. Gushchin, and A. K. Parfenov, Intensification of Nitriding by Ultrasonic Vibration, translated from Metallovendenie i Termicheskaya Obrabotka Metallov, No. 1, (Odessa Polytechnic Institute: January 1964), pp. 52-55.

[47] G. E. Aizentson and P. A. Malinen, Decomposition of Residual Austenite as the Result of Ultrasonic Vibration, translated from Metallovedenie i Termicheskaya Obrabotka Metalov, No. 1, (Perm State University: January 1964), pp. 50-51.

This, however, is not noticed at 200°F. Other investigators[48] have shown that tempering in the presence of ultrasonic vibrations at 330°F to 410°C for 15 to 20 minutes shows a 6-8 $R_c$ increase greater than the same temper, but without ultrasound.

Another article discusses the Effect of Ultrasonic Oscillation on the Hardenability of Steel by A. G. Vasil'eva.[49] It has been reported that the hardenability of two steels (No. 45 and 30 Kh GS) had been increased, particularly when the vibration was omitted during cooling and present only during heating and soaking. It was felt that this phenomenon is attributed to a decrease in cooling rate because the heat is evolved as a result of the transformation of mechanical energy into heat energy.

The Effect of Ultrasonic Vibration on the Mechanical Properties of R18 Steel by K. M. Pogodin-Alekseeva, V. S. Bironi, and L. D. Slavin[50] has shown many interesting results. The R18 steel has the following compositions: .74% C, 17.76% W, 3.99% Cr, 1.12% V, 0.31% Si, 0.27% Mn, 0.015% S, 0.026% P, 0.18% Mo, 0.21% Ni. Through their work, the following conclusions have been made:

1. The hardness, heat resistance and rates of transformation all increase with ultrasonic vibration independent of the stage of heat treatment or its duration.

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[48]K. M. Pogodin-Alekseeva and G. I. Eskin, MiTOM, No. 1, (1956).

[49]A. G. Vasil'eva, Effect of Ultrasonic Oscillations on the Hardenability of Steel, translated from Metallovedenie i Termicheskaya Obrabotka Metallov, No. 1, (Bauman Moscow Institute of Technology: January 1964), pp. 55-56.

[50]K. M. Pogodin-Alekseeva, V. S. Bironi, and L. D. Slavin, Effect of Ultrasonic Vibration on the Mechanical Properties of R18 Steel, translated from Metallovendenie i Termicheskaya Obrabotka Metallov, No. 1, (All-Union Correspondence Polytechnic Institute: January 1964), pp. 40-44.

2. With ultrasound, the amount of carbide precipitate increases and the residual austenite decreases from 2.5% to 18%.
3. When ultrasonic vibrations are applied during tempering, the transformation product is more complete.
4. The micro-hardness increase is associated with the sub-microscopic carbide precipitate from the martensite caused by the ultrasonic vibration during tempering.

One last observation was reported by Al'ftan and Mes'kin.[51] They found no effect on the martensitic transformation of a .31% C, 23.15% Ni steel when ultrasonic energy was applied during quenching.

The Effect of Ultrasonic Vibrations on Nonferrous Materials

In addition to the extensive amount of work directed toward the field of ferrous metallurgy, similar experimentation has been performed on nonferrous materials. Blaha and Langenecker[52] investigated the stress-strain curves for polycrystalline aluminum at room temperature with various ultrasonic vibration intensities. These were similar to curves obtained at various increasing temperatures. It was suggested that ultrasonic vibrations are analogous to thermal vibrations, but since ultrasonic energy is preferentially absorbed by imperfections while thermal energy is absorbed by all atoms, ultrasonic energy application would be more effective in reducing flow stress. It was concluded that ultrasonic vibrations decrease the

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[51]E. A. Al'ftan and V. S. Mes'kin, "Investigation of the Effect of Ultrasonics on the Results of the Heat Treatment of Alloys," Fiz. Metal. Metalloved, Vol. 11, (1960), p. 533.

[52]F. Blaha and B. Langenecker, "Plastic Behavior of Metal Crystals when Exposed to Sound Waves," Bulletin of the National Institute of Sciences of India, No. 14, (March 1959).

level of the stress-strain curve by $\Delta\tau$. There was no effect of frequency on $\Delta\tau$ between 15 and 1,500,000 cycles/second. There was a marked effect of the vibrational amplitude which was treated in the following manner. Ultrasonic vibrations of P amplitude put a stress on the material. Zinc single crystals were found to have a threshold intensity ($P_1$) below which no effect was found. This is equal to the critical resolved shear stress. Above $P_1$, $\Delta\tau$ increases with intensity until it reaches $P_2$ at which equals the flow stress. At intensities above $P_2$, single crystals kink badly and polycrystals were found to fail intergranularly. To further expand on this phenomenon, Konvalov[53] has tensile tested brass (58.9% Cu, 40.0% Zn, 0.9% Pb) specimens in the presence of ultrasound. The magnetostrictive transducer had a frequency range of 30-40 Kcps and a generator output of 300 watts. The samples were cut to three various lengths: $\lambda/4$ = 27.5 mm, $\lambda/2$ = 55 mm, and $\lambda$ = 110 mm. Since the vibrating nodes carry the maximum stress amplitude, the above lengths were specified to allow these peaks to fall within the sample length while testing. The following three tables (7, 8, and 9) report the results of the test.

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[53]Ye. G. Konvalov, "Foundation of New Metalworking Techniques," Osnovy Novykh Sposiboy Metallobrabotki, (Akademiya Nauk Belorus, S.S.R.: Fiziko-Tekhnicheskiy Institut, Minsk, 1961), pp. 92-100, 150-156, 246-262, (Russian Book).

TABLE 7

TENSILE RESULTS OF TESTS ON SPECIMENS OF LENGTH $\lambda/4$ = 27.5 MM

| Specimen | Without Vibrations Load, kg | $\Delta\ell/\ell$ | Specimen | With Vibrations Load, kg | $\Delta\ell/\ell$ |
|---|---|---|---|---|---|
| 1 | 40.3 | 0.29 | 2 | 37.75 | 0.17 |
| 3 | 40.0 | 0.29 | 4 | 37.65 | 0.17 |
| 5 | 40.0 | 0.25 | 6 | 37.75 | 0.17 |
| 7 | 40.3 | 0.25 | 8 | 36.45 | 0.16 |
| 9 | 40.3 | 0.29 | 10 | 37.00 | 0.17 |
| 11 | 39.9 | 0.25 | 12 | 37.30 | 0.17 |
| 13 | 40.6 | 0.25 | 14 | 35.80 | 0.16 |
| 15 | 40.2 | 0.25 | 16 | 35.80 | 0.19 |
| 17 | 40.7 | 0.25 | 18 | 33.30 | 0.16 |
| 19 | 39.4 | 0.25 | 20 | 36.00 | 0.17 |
| Average | 40.0 | 0.26 | | 36.60 | 0.165 |

TABLE 8

TENSILE RESULTS OF TESTS ON SPECIMENS OF LENGTH $\lambda/2$ = 55 MM

| Specimen | Without Vibrations Load, kg | $\Delta\ell/\ell$ | Specimen | With Vibrations Load, kg | $\Delta\ell/\ell$ |
|---|---|---|---|---|---|
| 1 | 40.6 | 0.20 | 2 | 33.4 | 0.09 |
| 3 | 40.3 | 0.16 | 4 | 31.7 | 0.09 |
| 5 | 39.6 | 0.21 | 6 | 34.0 | 0.09 |
| 7 | 40.0 | 0.20 | 8 | 33.9 | 0.10 |
| 9 | 40.2 | 0.20 | 10 | 32.0 | 0.09 |
| 11 | 40.6 | 0.17 | 12 | 32.6 | 0.09 |
| 13 | 40.6 | 0.20 | 14 | 33.6 | 0.09 |
| 15 | 40.1 | 0.21 | 16 | 32.7 | 0.08 |
| 17 | 40.2 | 0.16 | 18 | 32.0 | 0.08 |
| 19 | 40.2 | 0.15 | 20 | 32.8 | 0.10 |
| Average | 40.2 | 0.18 | | 32.8 | 0.09 |

TABLE 9

TENSILE RESULTS OF TESTS ON SPECIMENS OF LENGTH $\lambda$ = 110 MM

| | Without Vibrations | | | With Vibrations | |
|---|---|---|---|---|---|
| Specimen | Load, kg | $\Delta\ell/\ell$ | Specimen | Load, kg | $\Delta\ell/\ell$ |
| 1 | 40.0 | 0.20 | 2 | 29.9 | 0.060 |
| 3 | 39.5 | 0.15 | 4 | 30.8 | 0.070 |
| 5 | 40.2 | 0.20 | 6 | 30.9 | 0.070 |
| 7 | 39.3 | 0.17 | 8 | 29.6 | 0.065 |
| 9 | 39.6 | 0.18 | 10 | 29.6 | 0.060 |
| Average | 39.7 | 0.18 | | 30.1 | 0.060 |

It has been concluded that the reason for the decreased load is that under vibrations, the number of "stress-reversals" becomes very rapid. In view of this, the plastic properties initially decrease due to hardening, causing microcracks and subsequently, a fatigue-type failure. A contradictory effect was noticed[54] when zinc single crystals were ultrasonically treated with 20,000 cps for 2 to 8 minutes prior to tensile testing. The increase in yield stress of specimens after ultrasonic treatment was from 2 to 17 times the original yield stress. Hardening was found to decrease with an increase in prestrain. Ultrasonically-treated samples recovered faster than conventional cold-worked samples. This has been verified[55] when both single and polycrystalline zinc were strained in a conventional manner and were annealed in oil with and without ultrasonics. The recovery of yield stress

[54]"Investigation of the Effect of Ultrasonics on the Deformation Characteristics of Metals," Interim Report #2, (U.S. Government: European Research Contracts Program, Contract Number N-62558-3436, May 1-July 31, 1963).

[55]"Investigation of the Effect of Ultrasonics on the Deformation Characteristics of Metals," Interim Report #1, (U.S. Government: European Research Contracts Program, Contract Number N-62558-3436, February 1-April 30, 1963).

at room temperature was accelerated by approximately a factor of 2, although the maximum absolute recovery was somewhat smaller for ultrasonically-treated samples. Other qualitative and quantitative studies by Langenecker, Colberg and Franosen[56] have shown pure slip, twinning, and kink band formation in otherwise unloaded single crystals of zinc, but treated with intense ultrasonic vibrations having a frequency of 25,000 cycles/second. Studies were made on single crystal wires at room temperature. The wire was grown from a high purity melt with a range of crystallographic orientations $X_o$ between 15 and 85 degrees. X-ray and photomicrograph studies indicate that this deformation is similar to conventional plastic deformation found in tension or compression tests. Ultrasonic amplitudes up to $6 \times 10^7$ dynes/cm$^2$ were applied. From 400 frame/second motion pictures of the deforming crystals, the waiting times and activation energy for the dislocations involved in the plastic deformation were obtained.

Other areas of investigation in the nonferrous field include the work done by Pogodin-Alekseeva and Eskin[57] on the effect of ultrasonic vibrations on the aging of alloy V95 (1.6% Cu, 0.1% Si, 2.0% Mg, 6.5% Zn, 0.5% Mn, 0.2% Fe, balance Al). The specimens used were discs 35/64 inches in diameter, 15/64 inches thick and were quenched directly into water from a solution treatment temperature of 880°F. They were then aged in oil, both with and without ultrasound. Two different aging temperatures were studied: 68°F and 260°F. The following table gives the results of this

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[56] B. Langenecker, S. Colberg and W. H. Franosen, "Plastic Deformation in Zinc Single Crystals by Sound Waves," Bulletin of American Physics Society, Vol. 1, p. 362.

[57] K. M. Pogodin-Alekseeva and G. I. Eskin, translated from Metallovedenie i Obrabotka Metallov, No. 1 (January 1956), pp. 42-45. (Brutcher Translation #4551).

TABLE 10

EFFECT OF ULTRASONIC ENERGY ON THE AGING CHARACTERISTICS OF V95 ALLOY

| | Without Ultrasound | | | With Ultrasound | | |
|---|---|---|---|---|---|---|
| | Aging Time | Aging Temp. | Hardness (Brinell) | Aging Time | Aging Temp. | Hardness (Brinell) |
| As Quenched (85 Brinell) | 5 hr. | 68°F | 113 | 5 hr. | 68°F | 134 |
| Start of Aging | 100 hr. | 68°F | 140 | 5 hr. | 68°F | 149 |
| As Quenched (85 Brinell) | 6 min. | 260°F | 114 | 6 min. | 260°F | 128 |
| As Quenched (85 Brinell) | 4 1/2 hr. | 260°F | 163 | 4 1/2 hr. | 260°F | 180 |
| As Quenched (85 Brinell) | 25-72 hr. | 260°F | 168 | up to 90 hr. | 260°F | 185 |
| As Quenched (85 Brinell) | 72-90 hr. | 260°F | 170-172 | 2 1/2-3 hr. | 260°F | 170-172 |

part of the experiment. It was found that aging at 260°F is greatly accelerated with ultrasonic vibrations. By using this, higher hardness is obtained than that found with natural aging.

The authors conclude that age hardening using ultrasonic energy is caused mostly by the vibrations and not due to any increase in temperature internally caused by the absorption of ultrasonic energy.

Similar investigation was conducted by Gorskii and Efremov[58] when ultrasonic vibrations, with a frequency of 30,000 cycles/second, a total power of 400 watts, and a specific power of 10 watts/sq. cm., were used in

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[58]F. K. Gorskii and V. I. Efremov, "Effect of Ultrasound on the Decomposition of Solid Solutions," IZV AKAD Nauk Belorussk, (3), (S.S.R.: 1953).

an aging study on Duralumin (4.5% Cu, 0.8% Mg, 0.5% Si, balance Al), immediately after water quenching. It was seen that when the samples were subject to ultrasonic treatment, maximum hardness occurred after 1 to 2 hours, while natural aging required 80 hours to reach a maximum. The hardness increased from 60 to 100 Brinell units in both cases.

The authors think that there are advantages to ultrasonic aging at room temperature, as compared to artificial aging at 212°F because the size of the precipitating particles is not affected with ultrasonic aging and thus, no decrease in hardness is expected with time.

Other investigations (Al'ftan and Mes'kin)[59] contributed to the field with their studies on the tempering characteristics of a beryllium bronze alloy. During this investigation, specimens were fastened to the ultrasonic apparatus and suspended in the tempering bath. Ultrasonic frequency of 22,500 cycles/second was used when ultrasonic energy was applied to beryllium bronze and it was concluded the tempering rate is accelerated and ductility increased.

The application of ultrasonic energy appears to increase the rate of sulfocyaniding from 200 to 700 percent at the surface and 50 percent 120 mm below the surface.

## Industrial Applications of Ultrasonic Vibrations

The use of ultrasonic vibrations in all industrial fields has become widely used in recent times. Probably the first to develop a successful

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[59]E. A. Al'ftan and V. S. Mes'kin, "Investigation of the Effects of Ultrasonics on the Results of the Heat Treatment of Alloys," Fiz. Metal. Metalloved, Vol. 11, (1960), p. 533.

extrusion process was Tarpley and Kartluke.[60] At approximately the same time, intensive work was being conducted in Russia,[61,62] Great Britain, and the U. S. Naval Ordinance Test Station in California.[63,64] Over the years, the major oversight in designing a metal-working device is intimate and efficient contact between the deformation zone and the ultrasound. A good example of the above is through the work done by Jones, DePrisco, Maropis, and Thomas.[65] The study showed that significant increases in flow rates (or decrease in extrusion forces) occur when ultrasonic vibrations are added to the extrusion force during the extrusion of lead, aluminum and during the extrusion cladding of aluminum tubes.

The die, ram, and container were ultrasonically excited at 20,000 cycles/second during ultrasonic trials. With constant extrusion force, direct extrusion of lead proceeded 13 to 88 percent faster with ultrasonic excitation. Ultrasonically exciting the extrusion force increased aluminum cladding rate by 100 percent at a temperature range of 930°F to 1020°F.

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[60] W. B. Tarpley and H. Kartluke, "Ultrasonic Tube Drawing: Niobium, Zircaloy-2, and Copper," (West Chester, Pa.: Aeroprojects, Inc., AEC Report No. NYO-10008 Contract AT (30-1)-1836, 1961).

[61] E. A. Neppiras, "Ultrasonic Machining and Forming," Ultrasonics, (Oct.-Dec. 1964), p. 167.

[62] I. Woloshyn, "Recent Industrial Applications of Ultrasonics," Ultrasonics, (April-June 1964), p. 71.

[63] A. T. Robinson, "The Application of Ultrasonic Energy to Metal Wire Drawing," Wire and Wire Prod., (Dec. 1964), p. 1925.

[64] B. Langenecker, C. W. Fountain and V. O. Jones, "Ultrasonics: An Aid to Metal Forming," Metal Progress, Vol. 85, (April 1964), p. 97.

[65] J. B. Jones, C. F. DePrisco, N. Maropis, and J. B. Thomas, "Ultrasonic Energy Applied to Aluminum Extrusion Cladding of Tubes," (West Chester, Pa.: Aeroprojects, Inc., Report No. DP-418, Contract AT(07-2)-1, Nov. 1959).

The extrusion of lead was accomplished by placing billets 6 inches long x 1 1/4 inches in diameter in the container and heating to 570°F and ultrasonic energy applied with a constant force of 7500 lb. The extrusion rate was recorded over a 10-second interval. The ultrasonic vibrations were removed and extrusion proceeded using the same load and the rate. The experiment was then repeated using an extrusion force of 10,500 lb. The results are reported in the two attached tables, 11 and 12.

Similar work was conducted by Oelschlagel.[66] While being plastically deformed, single crystals of zinc were also ultrasonically vibrated with an intensity of 29 watts/cm$^2$. A softening of crystals subjected to ultrasonic treatment was found over the entire stress-strain diagram. The softening was observed to be independent of crystal orientation and increased in direct proportion to ultrasonic field intensity. The mechanism for softening could be interpreted as increased mobility of dislocations via absorption of ultrasonic energy.

Furthermore, Severdenko and Klubovich[67] utilized an ultrasonic frequency of 23,000 cps to the die head while drawing M1 grade copper wire with initial diameter 1.57 mm, and a final diversion of 1.25 mm (36.5% reduction). The amplitude of ultrasonic waves at the head end of the die was 0.012-0.020 mm. Initial trials found the wire breaking 55 mm after leaving the die. This failure was found to be due to heating of the wire by the ultrasonic vibrations. This was eliminated by damping the wire both

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[66]D. Oelschlagel, "Die Verforming von Zinkeinkristallen bei Ultraschalleinwirkung," A. Metall K., Vol. 53, (6), (1962), pp. 367-371.

[67]V. P. Severdenko and V. V. Klubovich, "Drawing of Copper Wire in an Ultrasonic Field," Doklady Akad. Nauk Belorus, (S.S.R.: Feb. 1963), (2), pp. 95-98.

TABLE 11

EFFECTS OF ULTRASONIC ENERGY APPLIED DURING DIRECT EXTRUSION OF LEAD

| Test | Vibration Applied Intermittently to | Ultrasonic Power, w | Ultrasonic Effect Compared with Non-ultrasonic Extrusion on Same Billet[a] | | | Ultrasonic Effect Compared to Control Extrusions with Nonultrasonic Applications | |
|---|---|---|---|---|---|---|---|
| | | | Effect on Ram Speed at Indicated Extrusion Force, percent | | Effect on Force at Ram Speed of 0.2 IPM, percent | Effect on Rate at Extrusion Pressure of 3.5 TSI, percent | Effect on Pressure at Ram Speed of 0.2 IPM, percent |
| | | | 7,500 lb | 10,500 lb | | | |
| 10 | Die | 200 | +47 | +76 | -8 | +227 | -25 |
| 11 | Die | 200 | +25 | +74 | -5 | +127 | -17 |
| 12 | Ram | 200 | +33 | +13 | -7 | +104 | -16 |
| 13 | Die | 500 | +88 | +80 | -15 | +141 | -20 |
| 16 | Container | 200 | +14 | +41 | -4 | +309 | -28 |

[a]Effect determined at 2-in. ram-travel position.

TABLE 12

EFFECTS OF ULTRASONIC ENERGY APPLIED DURING DIRECT EXTRUSION OF ALUMINUM BILLETS

| Test | Type of Billet | Extrusion Die | Type of Test | Ultrasonic Power, w | Temperature, C | | Peak Force, lb. | |
|---|---|---|---|---|---|---|---|---|
| | | | | | Indicated Range | Average at Peak Force | Indicated | Corrected to 525 C |
| 11 | Solid | Shear | Ultrasonic | 1200-1400 | 514-532 | 528 | 19,200 | 19,700 |
| 12 | Solid | Shear | Ultrasonic | 1200-1400 | 521-530 | 525 | 19,800 | 19,800 |
| 13 | Solid | Shear | Control | - | 526-537 | 530 | 22,200 | 23,200 |
| 14 | Laminated | Shear | Ultrasonic | 1300-1500 | 516-525 | 520 | 18,800 | 18,000 |
| 15 | Laminated | Shear | Control | - | 528-548 | 538 | 19,800 | 22,200 |
| 16 | Solid | Shear | Pulsed-ultrasonic | 1500 | 514-540 | 530 | 25,000 | 26,000 |
| 17 | Solid | Conical | Control | - | 515-529 | 523 | 24,000 | 23,600 |
| 18 | Solid | Conical | Ultrasonic | 1300-1500 | 507-528 | 518 | 23,400 | 21,900 |
| 19 | Solid | Conical | Pulsed-ultrasonic | 1500 | 520-538 | 524 | 23,400 | 23,200 |
| 20 | Laminated | Conical | Control | - | 510-527 | 520 | 24,500 | 23,500 |
| 21 | Laminated | Conical | Ultrasonic | 1300-1500 | 510-527 | 519 | 23,500 | 22,300 |

before and after the die. It was found that the ultrasonic vibrations melted the wire in the die if the drawing force is removed.

It was found that by using a drawing rate of from 0 to 1.67 ft./min., a force of 20 kg was required with ultrasonic energy applied to the die, while a force of 40 kg was required without the ultrasonic energy. After drawing, the tensile strength of samples drawn with ultrasonic energy applied to the die was about 15 percent less than conventionally-drawn wire. The elongation of the ultrasonically-drawn wire was 15 percent higher. The increase in ductility was accompanied by a lower hardness.

Another approach for the use of ultrasound in the forming industry was presented by Peacock.[68] The dimpling of A-110AT titanium sheet and 7075-T6 aluminum sheet was accomplished at room temperature with results as good as those obtained with heated dies. Dimpling of the aluminum sheet was done at 14,000 cycles/second, a static pressure of 50 psi, and a stroke of 0.008 inch. For the titanium alloy, vibrations from 10,000 to 14,000 cycles/second with strokes of 0.007 inch, and a static pressure of 500 psi was used. These specimens were microscopically examined after deformation and the only obvious conclusion was that the ultrasonically-treated samples were more uniform. Additional work on forming with ultrasound has been investigated.[69]

The mechanisms of ultrasonics have not been confined to only the metal-working aspects of industry, but many other fields are influenced by

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[68] J. Peacock, "Forming Goes Ultrasonic," American Machinist, Vol. 105, (24), (Nov. 1961), pp. 83-85.

[69] F. Blaha and B. Langenecker, "Dehnung Von Zink - Kristallen unter Untraschalleinwirkung," Z. Naturwiss, Vol. 20, (Aug. 1955), p. 556.

these technological advancements. These include ultrasonic soldering,[70] drilling,[71] welding,[72] and fatigue testing.[73] Whitehurst[74] has shown where sonic testing has led to the direct calculations of dynamic properties of concrete, such as compressive stress, flexure strength, creep characteristics, uniformity, and cracking. Rozenberg, Kazantsev, Makarov, and Yaknimovich[75] have shown the value of ultrasonic vibrations in the cutting process of super-hard materials (tungsten, titanium carbide, diamonds, rubies, sapphires, and corundum) which is very similar to a grinding operation. Similarly, very brittle material (glass, germanium, silicon, and quartz) are cut by ultrasound by a form of abrasion. A more detailed explanation and fundamental approach of the above processes is given by Nomoto,[76] Neppiras,[77] and Dikushin and Barke.[78]

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[70]F. Thomas and E. Simon, Electronics, Vol. 21, (London: 1948), p. 90.

[71]E. A. Neppiras, J. Sci. Instr., Vol. 30, (1953), p. 72.

[72]T. W. Black, Tool Engr., Vol. 39, (12), (1957), p. 111.

[73]E. A. Neppiras, Brit. J. Appl. Phys., Vol. 11, (1960), p. 143.

[74]Neppiras, ibid.

[75]Roaenberg, Kazantsev, Markarov, and Yaknimovich, translated from Russian, (New York, New York: Consultants Bureau, 1964).

[76]A. Nomoto, "Ultrasonic Machining by Low Power Vibration," J. Acoust. Soc. Am., Vol. 26, (6), (1954), p. 1018.

[77]E. A. Neppiras, "Report on Ultrasonic Machining," Metalwork. Prod., Vol. 100 (27-31), (1956), pp. 33-34.

[78]V. I. Dikushin and V. N. Barke, "Ultrasonic Erosion and Its Relation to Vibrational Parameters of the Tool," Stanki i Instr., No. 5:10, (1958).

The improvement of various processes has been noticed when ultrasonic irradiation is induced during the solidification of molten metal.[79] Vibrations in excess of 20,000 cps have improved diffusion[80] by more uniform mixing of metals that do not readily form alloys. Similarly, degassing[81] has been made more efficient because the cavitation process causes the suspended particles to accumulate more readily, reach a critical size, and subsequently float to the top. In addition, ingot structure has been improved[82] and solidification has been accelerated. The vibrating action causes more nucleation sites for crystallization and disrupts the crystal growth. Through this, grain sizes of 1/3 to 1/4 the round size have been produced.

Although much work has been done in the field of ultrasonics and its uses are presently being employed in many areas, man is on the threshold of far greater advancements in all fields of science, technology, and industry. It appears from the literature review that considerable research activities must be initiated to determine the effects of ultrasonic vibrations on the properties of materials. In this present investigation, attempts have been made to investigate the effects of ultrasonic vibrations on the kinetics of phase transformations.

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[79] D. H. Lane, J. W. Cunningham and W. A. Tiller, Trans. Met. Soc. A.I.M.E., Vol. 218, (Dec. 1960).

[80] K. N. Dologopolov, V. M. Fridman and N. M. Karaveen, Dokl. AKAD Nauk, Vol. 93, (S.S.R.: 1953), (2).

[81] N. T. Gudstov and M. N. Gavze, "Ultrasound and Its Use in Physicochemical Analysis," (U.S.S.R.: Academy of Sciences, 1955).

[82] K. M. Pogodin-Alekseeva, "Use of Ultrasound in Metallurgy," Collection of Papers from the Union Correspondence Polytechnic Institute, No. 13, (1955).

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# CHAPTER II

## EXPERIMENTAL PROCEDURE AND RESULTS

It can be concluded from the review of the literature presented in the preceding section, that considerable research activities must be initiated to understand the effects of ultrasonic energy on material properties. Although many Russian and German investigators have observed some changes in the resultant transformations due to the imposition of ultrasonic energy during heat treatment, the actual mechanism is not thoroughly understood. In this country, not much experimental work has been conducted on the effects of ultrasonic vibrations on material properties. In this present investigation, attempts have been made to analyze the effects of ultrasonics on material properties. The following attempts have been made to investigate the effects of ultrasonics on the kinetics of phase transformations, carbon diffusion, hardenability, Martensitic transformation temperature ($M_s$), tempering and aging phenomena. Several different grades of steel were used in the above investigation.

### Transformation Products Obtained Under Ultrasonic and Regular Quenching

In this investigation, the effects of quenching under ultrasonic energy on the resultant transformation product of various grades of steel were examined.

The initial portion of the investigation consisted of comparing the microstructures of duplicate samples of AISI 1018, 1041, 1050, 1085 and 4140 grade steels after austenitizing and quenching with and without

ultrasonic energy. These two different quenches will be denoted as "ultrasonic quench" and "regular quench". The as-quenched samples were then treated for various times at 70°F in ultrasonically vibrated water. Austenitizing commenced in a high temperature atuomatic controlled furnace and sample temperatures were ascertained by placing a chromel-alumel thermocouple in close proximity of the samples. The quench tank used was an ultrasonic cleaning tank with internal dimensions of 12 inches x 12 inches x 11 inches deep. Eight and one-half inches of water was used, resulting in a quench media volume of 1224 cubic inches. A coarse mesh basket was constructed in such a manner that samples placed in the basket were quenched at the geometric center of the bath. Ultrasonic energy was applied to the bath by transducers which are an integral part of the tank. The ultrasonic energy was supplied by a generator with an average power output of 500 watts and a fixed frequency of 23,000 cycles per second.

The chemical analysis of the various grades of steel used is given in Table 13.

The samples [1 inch x 1 inch x 0.5 inch] were taken from 0.5 inch transverse tests cut from 6 inch x 6 inch billets hot rolled from 23 inch x 25 inch big end up, hot topped ingots. In order to minimize the possibility of chemical segregation, the tests were cut from locations corresponding to the bottom portion of the ingots and from the mid-radius positions of the billet. Companion samples of a given steel grade were austenitized (solution treated) side by side in the high temperature furnace at the selected temperature for thirty minutes. They were then quenched alternately with and without ultrasonic energy. For each steel grade and austenitizing temperature, four samples were quenched

with and without an ultrasonic energy. Three of the quenched companion samples were then returned to the quench bath for ultrasonic treatment at 70°F. Companion samples were removed from the bath after 5, 10 and 15 minutes of treatment. In addition to the 5, 10 and 15 minute ultrasonic treatments, companion samples of 1018 grade, austenitized at 1700°F, were given treatments of 30 and 141 minutes. Samples were then carefully cut in half on a standard cutoff wheel exposing a 1 inch x 0.5 inch face showing the longitudinal rolling direction. The cut faces were then prepared, polished and etched in 2.0 percent nital solution for microexamination and photomicrographs at 500X. For the set of 1018 grade samples austenitized at 1700°F before quenching, hardness determinations (Rockwell "A") were taken at 16 places across the cut face using standard procedures. Care was taken so that no hardness readings were taken within 1/16 inch from the sample edge. Hardness determinations were also made on 1041 grade samples austenitized at 1750°F and 1050 grade samples austenitized at 1700°F and 1900°F in the same manner except the Rockwell "C" scale was used. Sample identification, austenitizing temperatures, kind of quench, length of ultrasonic treatment and average hardness for the various grades studied are given in Tables 14 through 18. Photomicrographs of the various samples are shown in Figures 1 through 20. In order to reduce the effect of the more rapid cooling rate found with the ultrasonic quench, 1/8 inch thick samples of 1018 and 1050 grade steel were austenitized and quenched using regular and ultrasonic quenching on duplicate samples. Photomicrographs of these samples are shown in Figures 21-22.

## Carbon Diffusion

Although it seems that cooling rate is a predominate factor in the as-quenched structure, there are also changes in the matrix due to strain induced carbon diffusion under ultrasonic vibrations. It seemed that ultrasonic treatment at ambient temperature could promote carbon diffusion in the as-quenched, supersaturated Martensitic structures. To investigate this possibility, samples 5A and 5E from the previous portion of the investigation were selected for further treatment. These samples were 1050 grade steel austenitized at 1900°F and quenched, 5A without and 5E with ultrasonic energy in the quenching media. After the samples were prepared, polished and etched in a 2.0 percent nital solution, a field in the central area of the specimen was selected and photomicrographs were taken at 1250X. These fields were marked in such a manner that they could be easily relocated. The samples were then treated at 70°F for 180 minutes under ultrasonic vibrations. After careful repolishing and reetching, the selected fields were again photographed at the same magnifications. The samples were given 330 additional minutes of ultrasonic treatment and reprepared and rephotographed. These photographs are shown in Figures 23 through 28.

## Hardenability

The cooling rate plays an important role in phase transformations in steels; therefore, an extensive program was initiated to determine the difference in cooling rate in hardenability between ultrasonic and regular quenching.

The investigation consisted of austenitizing various cube sizes of 1050 grade steel at 1900°F and quenching companion samples to 70°F

with and without ultrasonic energy. Cube sizes were 1/2, 3/4, 1, 1 1/2 and 2 inches and the chemical composition of the steel used is shown in Table 13. All of the cubes were taken from tests cut from 6 inch x 6 inch and 8 inch x 8 inch square billets that were rolled from 23 inch x 25 inch big end up, hot topped ingots. Tests were cut from locations corresponding to the bottom portion of the ingots and mid-radius positions on the tests. The same equipment used in the previous sections was used for austenitizing and quenching.

Companion cubes were austenitized at 1900°F for a time determined by the "rule of thumb," 60 minutes at the austenitizing temperature for each inch of cross-section. The cubes were then quenched alternately using a "regular quench" for one and an "ultrasonic quench" for the other. After quenching, each cube was carefully cut in half exposing a center face in the longitudinal direction. After normal sample preparation, hardness determinations were made at one-sixteenth inch intervals through the face center and perpendicular to the edge. All hardness readings were made using standard Rockwell "C" procedure. The hardness determinations made for the various cube sizes considered are shown in Tables 19 through 23 and graphically in Figures 29 through 33. A standard jominy hardenability curve was plotted for the steel using data which permits the correspondence of Hardness and cooling rates for 1050 grade steel.

The procedure is outlined in Caterpillar Engineering Specification IE38 issued by the Caterpillar Tractor Company. This jominy hardenability curve is shown as Figure 34 and the data used for plotting the curve is shown in Table 24. Also included on Figure 34 are the cooling rates at 1300°F for each jominy distance. These cooling rates were taken from ASTM Form A255-42T, which is the standard form for plotting jominy

hardenability. In addition to the hardness determinations, mentioned previously, Tables 19 through 23 also show the cooling rate at 1300°F as determined from Figure 35, which is a plot of hardness against cooling rate at 1300°F shown on Figure 34. In order to measure the actual cooling at the center of the cubes, an iron constantan thermocouple was installed at the geometric center of a one inch cube. The cube was heated until the temperature at the center was 1700°F and it was then quenched to 70°F in the same manner as the hardenability test cubes. This procedure was followed alternately using regular quench and ultrasonic quench. This was repeated several times with the ultrasonic quench being considerably faster. Table 25 shows the recorded cooling data at the center of the one inch cube during regular and ultrasonic quenches at one second intervals.

## Martensitic Transformation Temperature ($M_S$)

The significant changes in the cooling rate and the carbon diffusivity in these steels seem to indicate that the Martensitic transformation temperature ($M_S$) may be affected.

From a bar of hot rolled "4340" steel, discs were cut, 1/16" x 1 1/4", to be used for this study. This size was selected to avoid any cooling effects during ultrasonic quenching. The following experiments were performed both with and without an ultrasonic quench after austenitizing for ten minutes at 1600°F.

1. 1600°F → water (no ultrasonics)
2. 1600°F → 500°F (with and without ult.) → water
3. 1600°F → 580°F ( " " ) → water

4. 1600°F → 450°F (with and without ult.) → 1000°F → water
5. 1600°F → 580°F ( " " " ) → 1000°F → water
6. 1600°F → 700°F ( " " " ) → 1000°F → water

Each step of the above experiments was held ≈ 5 seconds. Comparative samples were mounted in the same mount, etched with Picral, and pictures were taken of the resultant transformation product and are shown in Figures 38-48.

## Tempering Characteristics

It can be seen from the previous experiment that the resultant transformation product is affected by ultrasonic quenching. It seems that the ultrasonic energy has induced the phase transformation, possibly through elastic lattice strain. It was attempted to investigate the tempering characteristics of a 1050 grade steel after quenching in ultrasonic energy.

Samples of "1050" grade steel were sectioned into one inch cubes from a one inch transverse test cut of a 6 inch x 6 inch billet, hot rolled from a big end up, hot topped ingot. Two adjacent samples were placed in the heat treating furnace, and after one hour of austenitizing at 1900°F, one sample was quenched into regular water and the other was quenched under ultrasonic energy. The samples were then quartered and Rockwell "C" hardness readings were taken on each piece corresponding to the center of the master cube. One quartered specimen of each of the two types of quench were then placed into a tempering furnace which was equipped with an inert atomsphere to prevent scaling and decarburization. The samples were tempered at 700°F, 800°F, 1000°F and 1200°F for thirty minutes. The ultrasonically quenched and regular quenched samples were

again quenched into ultrasonically agitated and regular water, respectively, after the heat treatment. Comparative hardness readings (R"c") were again taken in the same position as previously after surface grinding and the results are shown in Table 36 and Figure 55. As can be seen, the initial hardness of the ultrasonically quenched specimen is higher than the normal quenched sample. In order to be consistent, the two initial hardness values had to be normalized, that is, corrected to the same initial base (58.0 Rc). These results are shown in Table 37. Photomicrographs were taken of the following treatments - as quenched, 800°F temper and 1200°F temper and are shown in Figures 49-54.

## Aging Phenomena Under Ultrasonic Vibrations

The essential difference in the microstructures, in addition to the possibility of enhanced carbon diffusion, seems to indicate that a significant change in the microstructure should occur upon ultrasonic aging.

A piece of low carbon rimmed steel, as pickled, was obtained and cold reduced 15%. One inch x one inch coupons were cut from the original piece and hardness readings were taken on each sample. One set of samples was placed in boiling water (212°F) and extracted after various periods of time (5 min.-75 min.). Hardness readings were again immediately taken. The other set of samples was treated with ultrasonic energy at room temperature for various periods of time (15 min.-85 min.). Hardness was taken immediately after treatment. The results are plotted in Figures 56 and 57.

## Results

TABLE 36

HARDNESS AS A FUNCTION OF TEMPERING TEMPERATURE FOR ULTRASONICALLY AND REGULAR QUENCHED 1050 STEEL

1) Absolute Hardness

As Quenched (Ultrasonic) - 58.0 As Quenched (Water) - 52.5

| Temp. | Hard. (Rc) | ΔRc | Temp. | Hard. (Rc) | ΔRc |
|---|---|---|---|---|---|
| 700°F | 44.75 | 13.25 | 700°F | 42.00 | 10.50 |
| 800°F | 40.50 | 17.50 | 800°F | 38.00 | 13.50 |
| 1000°F | 34.50 | 23.50 | 1000°F | 32.20 | 20.30 |
| 1200°F | 31.25 | 31.25 | 1200°F | 27.50 | 25.00 |

TABLE 37

NORMALIZED HARDNESS AS A FUNCTION OF TEMPERING TEMPERATURE FOR ULTRASONICALLY AND REGULAR QUENCHED 1050 STEELS

2) Normalized Hardness (58 Rc)

Ultrasonic - 58.0 (Rc) Water - 58.0 (Rc)

| Temp. | Hard. (Rc) | ΔRc | Temp. | Hard. (Rc) | ΔRc |
|---|---|---|---|---|---|
| 700°F | 44.75 | 13.25 | 700°F | 47.50 | 10.50 |
| 800°F | 40.50 | 17.50 | 800°F | 43.50 | 13.50 |
| 1000°F | 34.50 | 23.50 | 1000°F | 37.70 | 20.30 |
| 1200°F | 31.25 | 31.25 | 1200°F | 33.00 | 25.00 |

## Aging Study - "1008" Steel

TABLE 38

HARDNESS AS A FUNCTION OF ROOM TEMPERATURE
ULTRASONIC AND BOILING WATER AGING OF 1008 STEEL

| Average Before Treatment (R30T) | Time at 212°F | Average After Treatment (R30T) | ΔR30T |
|---|---|---|---|
| 53.90 | 5 min. | 56.20 | 2.30 |
| 54.90 | 15 min. | 57.60 | 2.70 |
| 56.50 | 30 min. | 60.00 | 3.50 |
| 52.75 | 45 min. | 57.10 | 4.35 |
| 54.90 | 60 min. | 57.50 | 2.60 |
| 54.50 | 75 min. | 56.50 | 2.00 |

| Average Before Treatment (R30T) | Time in Room Temp. Ultrasonics | Average After Treatment (R30T) | ΔR30T |
|---|---|---|---|
| 55.50 | 15 min. | 57.50 | 2.0 |
| 55.20 | 30 min. | 57.50 | 2.3 |
| 53.20 | 45 min. | 56.50 | 3.3 |
| 54.70 | 60 min. | 57.00 | 2.3 |
| 53.70 | 75 min. | 56.25 | 2.55 |
| 55.00 | 85 min. | 57.00 | 2.00 |

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# CHAPTER III

## DISCUSSION

The experimental results indicate that ultrasonic energy has a significant effect on several physical parameters of steels. It has been shown that the cooling velocity of a sample is significantly increased due to the presence of ultrasonic energy in the quenching media. Other effects, such as strain-induced carbon diffusion, changing of the martensitic transformation temperature, and differences in the tempering characteristics, have been observed.

### Transformation Products Obtained under Ultrasonic and Regular Quenching

In our attempt to understand the effect of ultrasonic on the transformation product, metallographic investigation of the transformed volume was initiated under the conditions described in the experimental procedure section. An examination of the microstructure of the samples quenched both with and without ultrasonic energy reveals pearlite, free ferrite, and phase (X) (see Figure 2) for the sample quenched under ultrasonic vibrations in contrast to pearlite and ferrite for the sample quenched in ordinary water (Figure 1). The phase (X) cannot be resolved with an optical microscope, but appears to be a very fine pearlite phase produced by the increased cooling rate due to ultrasonic energy. There appears to be no significant difference in the hardness values for the samples that were quenched in regular water or under ultrasonic energy, 59 and 60 "$R_A$," respectively.

The similarity of microstructure in thin samples of 1018 grade steel having regular and ultrasonic quenches (Figures 7 and 8) indicates that the essential difference seen between Figures 1 and 2 was due to the difference of cooling rate between the two kinds of quench.

In order to investigate the effect of ambient temperature (70°F) ultrasonic treatment on the microstructure of 1018 grade steel that was quenched after austenitizing at 1700°F, "as-quenched" samples were immersed in the ultrasonic bath for varying lengths of time. Figures 3 and 5 show the microstructures of regular-quenched samples that were ultrasonic-treated for 15 and 30 minutes, respectively, while Figures 4 and 6 show the microstructures of ultrasonic-quenched samples with the same times of treatment. When Figures 3 and 5 are compared with Figure 1 and Figures 4 and 6 with Figure 2, it appears that there are noticeable differences in the structures for regular and ultrasonic quenching when the samples were held for different times at ambient temperature (70°F) in the ultrasonic bath. An increase in free ferrite (the white phase) is seen with 15- and 30-minute ultrasonic treatments for both kinds of quench. Since ferrite is the phase with the lowest carbon content, it seems that carbon atoms have diffused out of the matrix in order for ferrite to form. The enhanced carbon diffusion possibly is the result of strain and interactions of ultrasonic vibrations with the lattice.

We have examined the effect of ultrasonic quenching on 1018 grade steel austenitized at 1700°F before quenching. For this grade of steel, the "knee" of the isothermal transformation diagram[83] approaches the zero

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[83]"Atlas of Isothermal Transformation Diagrams," (United States Steel Corporation Research Laboratory, 1963), p. 19.

time axis, indicating that no matter how rapid the quench rate, the transformation product will be some combination of ferrite and cementite. We wanted to determine the effect of ultrasonic quenching on a steel where the "knee" of the isothermal transformation diagram is shifted a small amount along the time axis, thus permitting the formation of metastable transformation products with a rapid rate of quench. AISI 1050 grade steel was selected and appropriate samples were austenitized at 1700°F and quenched. Figures 9 and 10 show the "as-quenched" microstructures for this steel grade for regular- and ultrasonic-quenched. Both kinds of quench produced a completely martensitic microstructure with uniformly-distributed carbide particles, but the martensite in the ultrasonic-quenched sample (Figure 10) has a finer acicular structure due to the faster cooling rate characteristic of this kind of quench. Figures 11 and 12 show the microstructures of samples having the same austenitizing and quenching conditions as the samples for Figures 9 and 10, except that these were held 15 minutes at ambient temperature (70°F) under ultrasonic vibrations. These structures are similar to the "as-quenched" structures with the exception that they appear to have a greater amount of carbide particles. This means that there has been carbon diffusion from the supersaturated martensite to either existing carbide particles or to other areas where new carbide particles can be nucleated. The increase in carbon diffusion is possibly due to strain introduced by ultrasonic energy.

In order to determine the effect of austenitizing temperature on the transformation products of quenched 1050 grade steel, appropriate samples were austenitized at 1900°F and quenched. Figures 13 and 14 show these "as-quenched" microstructures. These are similar to the microstructures shown in Figures 9 and 10 which are samples quenched from 1700°F. No

significant difference was observed in regular-and ultrasonic-quenched structures quenched from the different austenitizing temperatures. The ultrasonic quench produced a finer acicular structure for both austenitizing temperatures due to the faster cooling rate.

Figures 15, 17, and 19 show the microstructures of regular-quenched samples of 1050 grade steel austenitized at 1900°F before quenching and then held for 5, 10, and 15 minutes at ambient temperature (70°F) under ultrasonic energy. Figures 16, 18, and 20 show the microstructures of companion samples quenched in ultrasonic energy. These show that the amount of carbide increases when "as-quenched" samples are treated ultrasonically. From these samples the effect of time of ultrasonic treatment on the increase of carbide particles could not be determined.

For all samples of 1050 grade steel quenched from 1700 and 1900°F austenitizing temperatures, the carbides formed during ambient temperature ultrasonic treatment tend to form in a regular pattern that might be prior austenite grain boundaries.

As was the case with 1018 grade steel, the similarity of microstructure in the thin samples of 1050 grade steel having regular and ultrasonic quenches (Figures 21 and 22) indicate that the essential difference observed between Figures 13 and 14 was due to the difference in cooling rates between the two kinds of quench.

From the above observations, it can be concluded that there is a detectable difference in morphology between "as-quenched" samples for regular and ultrasonic quenching for AISI "1018" grade steel austenitized at 1700°F. Samples quenched in ultrasonics have a phase that cannot be resolved with the optical microscope and it is not observed in samples with regular quench. The balance of the structure is pearlite and free ferrite for both

kinds of quench. There is more free ferrite if the samples are held in the ultrasonic bath at 70°F for 15 and 30 minutes when AISI 1018 grade steel samples are austenitized at 1700°F prior to quenching. This is observed in both regular-and ultrasonic-quenched samples. It appears that carbon atoms have diffused out of the matrix in order for the ferrite to form, possibly due to strain and interactions of ultrasonic vibrations with the lattice. There is no significant difference observed in the microstructures of thin samples of 1018 grade steel austenitized at 1900°F prior to either regular or ultrasonic quenching. Pearlite is undetectable when samples of AISI 1050 grade steel are quenched with or without ultrasonic energy after austenitizing to 1700 or 1900°F. The microstructures consist entirely of martensite with distributed carbide particles. Ultrasonic quench samples have a finer acicular structure due to the faster cooling rate associated with quench. There is an increase in the carbide phase observed when the samples are held for varying times in an ambient temperature ultrasonic bath when AISI 1050 grade steel samples are austenitized at either 1700 or 1900°F prior to quenching. These carbides tend to form in a regular pattern that may be prior austenite grain boundaries. It appears that carbon atoms have diffused out of the martensitic matrix in order for the carbides to form, possibly because of strain and interaction of the ultrasonic vibrations with the lattice. Again, there is no significant difference observed in the microstructures of thin samples of 1050 grade steel austenitized at 1900°F prior to either regular or ultrasonic quenching.

## Carbon Diffusion

The microstructure of the same area of a regular-quenched "1050" steel sample after 180 minutes and 510 minutes of treatment at ambient

temperature under ultrasonic energy is shown in Figures 24 and 25. On the other hand, the microstructure of samples quenched in ultrasonics with the same ambient temperature treatment is shown in Figures 26, 27, and 28. The room temperature ultrasonic treatment seems to have no significant effect on the microstructure. It appears, therefore, that the diffusion of carbon has not been enhanced to form carbide clustering. However, samples with a regular and ultrasonic quench do show a fundamental difference in the as-quenched structure and the carbide particles do increase with ultrasonic treatment as shown in previous experimentation. This suggests that ultrasonic energy favors the precipitation of new carbides rather than the growth of existing carbides. This means that short-range diffusion is favored by ultrasonic energy.

The microstructure observed in the samples that have been quenched under ultrasonic vibrations is fundamentally different from the samples that have been quenched in regular water as observed in previous experiments. Room temperature ultrasonic treatment does favor the precipitation of new carbides by enhancing the carbon diffusion in both types of as-quenched structure. This implies that a short-range diffusion is favored. However, since growth of existing carbides is not induced, long-range diffusion under ultrasonic energy is small.

## Hardenability

Our results indicate that the hardenability of steels and cooling rate can both be increased by quenching under ultrasonic vibrations. An examination of cooling curves of quenched pieces reveals that the cooling rate varies with temperature, and temperature level must be defined if cooling rate is to be meaningful.

The isothermal transformation diagram for 1050 grade steel[83] shows that above 1400°F, austenite is completely stable. It, therefore, appears that the cooling history at or above 1400°F has little, if any, effect on the transformation products formed with further cooling. Pearlite can form in the temperature range from 1400°F to 980°F (980°F corresponding to the knee of the curve). It is, therefore, logical to state that the cooling rate within this temperature range is an important factor in hardenability.

The temperature range from 1400°F to 900°F has been described as the critical range, but we must note that at the 1400°F level, several minutes can pass before pearlite starts to form, while at 980°F, pearlite formation starts in less than one second. It must, therefore, be recognized that both the cooling rate and the amount of time elapsed before the start of pearlite formation vary with the temperature level within the critical range.

Several investigators have approached the problem of describing the cooling criterion that determines the relationship between cooling rate within the critical temperature range and hardenability. French,[84] through an extended series of investigations on quenching and hardening, showed that the cooling rate at 1300°F serves as a good approximation for describing hardenability in steel. His work indicated that the cooling history between 1650°F and 750°F is a function of the cooling rate at 1300°F. This range covers the entire range over which pearlite can form; thus, the cooling rate at 1300°F is useful in describing hardenability.

Other investigators have examined the cooling rate at 1000°F as a basis, but found that this did not correlate with actual hardenability as

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[84] H. J. French, "A Study of Quenching of Steels," Transactions, American Society for Steel Treating, Vol. 17, (1930), p. 798.

did the 1300°F criterion. This is because incubation time, as well as rate of pearlite formation, is involved at temperatures above 1000°F.

The cooling rate at 1300°F for correlation between cooling rate and hardenability will be the criterion used in this investigation.

The cooling rate at 1300°F has been determined[85] for each point (1/16 inch increments from the quenched end) on the standard Jominy hardenability test piece and has been found to vary from 600°F per second at 1/16 inch from the quenched end to 4°F per second in the center. These cooling rates appear at the top of A.S.T.M. Form A255-42T which is the standard form for plotting hardenability. By using these cooling rates in conjunction with a hardenability plot, we have a direct connection between hardenss and cooling rate at 1300°F for that particular steel. Figure 34 shows the theoretical hardenability curve for the 1050 grade steel used, and also includes the cooling rates at 1300°F for the Jominy points.

Figure 36 shows the cooling curves for the center of a one-inch cube of 1050 grade steel austenitized at 1700°F and quenched with a regular and ultrasonic quench; the cooling curves are shown in Figure 36. Knowing the measured cooling rate at the center of the one-inch cubes, the cooling rate at the centers of the cube sizes considered in the investigation must be calculated.

If we were to describe an ideal quench media, we would assert that it would be one which cools the surface of the quenched piece to the temperature of the quench media instantly. The actual case does not approach this ideal due mainly to surface oxides and nucleate boiling; thus, assumptions must be made before cooling rates can be calculated. The actual case can

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[85] M. A. Grossmann, "Elements of Hardenability," American Society for Metals, (1952), p. 93.

be simulated if we assume that the quench media behaves uniformly over the entire temperature range of the quench. The rate of heat loss from the surface of the quenched piece is proportional to the temperature difference between the surface of the piece and the quench media. This statement is a definition of Newton's Law of Cooling.

In order to maintain practical simplicity in the mathematical calculations for cooling rates, a constant value of thermal diffusivity must be assumed. Actually, austenite, ferrite, martensite, etc. all have different values for thermal diffusivity and each varies with the temperature level. When discussing cooling rates at internal positions, we must not only consider the diffusivity of the austenite and transformation products within the critical temperature range, but also the diffusivity at the colder areas toward the surface of the piece through which heat must be transferred. It has been suggested[85] that the use of 0.0009 $in.^2$ per second for thermal diffusivity over the entire quench range has produced the most reliable results in cooling calculations for quenching situations.

It was previously stated that the quench media is assumed to behave uniformly over the entire quench range and heat transfer from the surface of the piece to the cooling media is proportional to the instantaneous temperature difference between the surface and the quench media. It must be noted that it is heat loss, and not temperature drop, at the surface that is being considered. Temperature drop at the surface is a function of heat stored within the piece being transferred toward the colder surface. French[84] has shown that the cooling rates at the centers of common shapes follow Newton's Law of Cooling quite well. He postulated that the initial cooling at the surface is rapid and probably does not follow Newton's Law until lower temperatures are reached, after which it is obeyed closely. For

internal positions the cooling mechanism involves heat flow to the colder surface. Since low temperatures are reached at the surface before any appreciable cooling occurs at internal positions, Newton's Law of Cooling can give a good approximation of cooling in the interior of a quenched piece.

Newton's Law of Cooling is described by the equation:

$$\text{Log } Y = N_e X \qquad \text{(Equation 1)}$$

where:

$Y$ = relative temperature (dimensionless)

$X$ = relative time (dimensionless)

$N_e$ = Newton's constant (dimensionless).

Relative temperature (Y) is defined:

$$Y = \frac{t-t}{t_1-t_2} \qquad \text{(Equation 2)}$$

where:

$t$ = temperature being considered

$t_1$ = initial temperature of the piece

$t_2$ = temperature of the quench media.

The temperature of the quench media is assumed to remain constant. This is a valid assumption if the volume of the quench media is large enough. Relative time (X) is defined:

$$X = \frac{\Upsilon\theta}{r_m^2} \qquad \text{(Equation 3)}$$

where:

$\Upsilon$ = thermal diffusivity (in.$^2$ per second)

$\theta$ = real time (seconds)

$r_m$ = half thickness of the short dimension of the quenched piece (inches).

Newton's constant ($N_e$) is defined:

$$N_e = \frac{1}{2.3} \frac{Ar_m}{v} \frac{1}{m} \qquad \text{(Equation 4)}$$

where:

M = relative surface resistance (dimensionless)

A = surface area of the quenched piece ($in.^2$)

V = volume of the quenched piece ($in.^3$).

For cubes it is easy to show that $\frac{Ar_m}{v} = 3.00$; thus, equation 4 can be written:

$$N_e = \frac{3}{2.3} \frac{1}{m} . \qquad \text{(Equation 5)}$$

The data from the measured cooling at the center of the one-inch cubes given in Table 25 were converted to terms of relative temperature (Y) and relative time (X) by using equations 2 and 3. These data, along with calculated values for Log Y, are shown in Table 26 for the regular-quenched case and Table 27 for the ultrasonic-quenched case.

From equation 1, the slope of the curve Log Y vs. X is Newton's constant. Newton's constant was calculated for both the regular- and ultrasonic-quenched cases using relative time and temperature data corresponding to the critical temperature range of 1400°F to 980°F. These were found to be 1.00 for the regular quench, and 1.50 for the ultrasonic quench. With $N_e$ known and using equation 5, values for relative surface resistance (m) were determined to be 1.30 for regular quench, and 0.87 for ultrasonic quench.

By definition:

$$m = \frac{K}{hr_m} \qquad \text{(Equation 6)}$$

where:

K = thermal conductivity (BTU in./°F in.$^2$ sec.)

= 0.00044 BTU/in./°F in.$^2$ sec. for steel

h = coefficient of heat transfer from surface to quench media (BTU/°F in.$^2$ sec.).

Substituting the values for relative surface resistance (m) into equation 6 gives values for h of 0.000677 BTU/°F in.$^2$ sec. for regular quenching, and 0.00101 BTU/°F in.$^2$ sec. for ultrasonic quenching. The heat transfer coefficient (h) is unaffected by physical dimensions and shape of the piece being quenched, and is considered to be a constant depending only on the kind of quench.

Having determined h and applying equations 5 and 6, values for m and $N_e$ were determined for the different cube sizes. These are given in Table 28.

Since $N_e$ is known for each cube size and kind of quench, there are sufficient data to calculate the cooling at the cube centers. The connection between real and relative temperature and time is found in equations 2 and 3, respectively. Calculated cooling data for the different cube sizes are given in Tables 29 through 33. Using these data, the cooling rate at 1300°F (°F per sec.) was determined for each case. Applying these cooling rates to Figure 35, estimated values of hardness (Rockwell "C") were determined. Table 34 shows both measured and calculated values for hardness and cooling rate at 1300°F for each cube size and both kinds of quench. Figure 37 is a plot of cube size against cooling rate at 1300°F for both the measured and calculated cases. Note the similarity in the actual cases for cube sizes up to 1-1/2 inches. For the two-inch cube, the cooling rates approach each other for the two kinds of quench.

Scott[87] has shown that when heated objects are quenched into a liquid media, three distinct stages of cooling are encountered. The first stage, the vapor stage, starts immediately. Liquid adjacent to the surface of the quenched piece is vaporized, forming a continuous vapor film that completely blankets the piece. Cooling is dependent on heat transfer from the surface of the piece to the liquid quench media by radiation through the vapor film. The cooling achieved during this stage is relatively slow. The second stage, the vapor transport stage, starts when the continuity of the vapor film is broken and some vapor migrates into the liquid where it condenses. New liquid flows into these areas and vaporizes, extracting heat equivalent to the heat of vaporization of the quench media. This action continues violently and heat is removed from the piece at a relatively rapid rate, depending on the heat of vaporization of the quench media and the amount of liquid vaporized. This stage produces the fastest cooling rate encountered when quenching. When the temperature at the surface of the piece becomes lower than the boiling point of the quench media, the vapor film is gone and the third stage of cooling begins. This state is denoted as simple liquid cooling where heat is extracted by conduction and convection. Cooling here depends on the specific heat, thermal conductivity, and the physical agitation of the quench media. Heat loss during this stage is described reasonably well by Newton's Law of Cooling.

When quenching to obtain maximum hardness, it is desirable to uniformly cool the surface of the piece as rapidly as possible to the lower temperature ranges and the duration of the vapor stages must be kept to a

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[87]H. Scott, "The Problem Of Quenching Media for the Hardening of Steel," Transactions, American Society for Metals, (1934), p. 577.

minimum. Pilling and Lynch[88] have shown that the duration of the vapor stage in water quenching increases rapidly as the temperature of the quench water is increased above 70°F. Thus, when quenching in water, it is desirable to keep the quench bath temperature at or below 70°F.

Figures 30 through 33 show a greater depth of hardening is achieved with ultrasonic quenching for each cube size considered except the 1/2 inch cube where both kinds of quench produced full hardening throughout the cubes.

It was observed that during the quenching of the different size cubes in ultrasonically-excited water, there was no general movement of the quench media so that an increase in water temperature in the area of the quenched piece during quench was the same for both water and ultrasonic quenching. Thus, the deeper hardening achieved with the ultrasonic quench is not related to a temperature difference in the quench media in the region of the quenched cubes.

The wavelength of the ultrasonic frequency used for the ultrasonic quench is relatively large ($1.3 \times 10^6$ cm), and it is doubtful if the deeper hardening experienced with ultrasonic quenching can be explained by interaction with or penetration of the structure of the quenched piece on an atomic level.

It is, however, logical to predict deeper hardening with ultrasonic quenching if cavitation breaks down the continuous vapor film at a higher surface temperature, permitting heat to be removed by the more rapid vapor transport stage. In addition, cavitation will increase the tendency for vapor to migrate into the liquid quench media, permitting a greater amount

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[88] N. B. Pilling and T. D. Lynch, "Cooling Properties of Technical Quenching Liquids," Transactions, A.I.M.E., (1920), p. 665.

of the liquid to be vaporized in a given period of time, and as previously mentioned, this vaporization is the principal factor in the rapid heat removal of the vapor transport stage. Thus, ultrasonic energy added to the quench media not only increases the upper surface temperature for initiation of the vapor transport stage, but it also increases the rate of heat removal during this stage of the cooling. The lower limit of the vapor transport stage is fixed by the boiling point of the quench media and is probably unaffected by the ultrasonic energy.

The rate of temperature loss at any internal point in a quenched sample is a function of the difference between the heat flow from that point toward the cooling surface and the heat flow to the point from warmer areas toward the center of the piece. If the temperature loss through the critical temperature range at the point occurs while the heat transfer at the surface is within the rapid vapor transport stage, the cooling rate at the point will be fast and the corresponding hardness high. On the other hand, if the temperature loss through the critical range at the point occurs while heat transfer at the surface is in the slower simple liquid cooling stage, both the cooling rate and hardness at the point will be lower. Another factor is the amount of heat stored toward the center of the piece. For a given point and amount of heat being transferred toward the surface, greater amounts of heat stored internally will mean a higher heat transfer to the point, a decrease of the effective cooling rate, and a corresponding lower hardness.

The total amount of heat stored in the various cube sizes at 1900°F is shown in Table 35.

The greater hardenability found with ultrasonic quenching can be explained if the rate of heat transfer from the surface to the quench media

is higher for the ultrasonic case, while the temperature at a given internal point is passing through the critical range because of cavitation. The difference between the two kinds of quenching is drastic for cube sizes from 3/4 inch through 1-1/2 inches. This is shown in Figures 30, 31, and 32. Figure 33 shows that for two-inch cubes there is a less dramatic difference. At depths close to the surface there is an increase in hardening with ultrasonic quenching, but the hardenability curves approach each other at depths greater than 1/4 inch, and in fact, coincide at depths beyond 3/4 inch. In areas closer to the surface, the rate of heat removal is faster for the ultrasonic case, but so is the rate of heat flow to the point from the interior where a relatively large quantity of heat is stored. For the water-quenched case there is a slower rate of heat removed at the surface, but heat is being transferred to the point from the interior at a slower rate so that the net cooling rate through the critical range and the corresponding hardness are not greatly affected by ultrasonic quenching. By the time enough heat has been removed from the two-inch cubes so that the temperature of the central areas drops into the critical range, the surface temperature is below the boiling point of the quench water, and thus, the cooling for both kinds of quenching is governed by the slower transfer of heat at the surface which is characteristic of the simple liquid cooling mechanism. Since identical values of hardness were found in the central areas of the two-inch cubes, we can conclude that the addition of ultrasonic energy to the quench media does not affect the rate of heat flow from the surface when the simple liquid cooling mechanism is in control.

The principal difference between the effect of ultrasonic energy and cube size on hardenability of two-inch cubes, as opposed to cubes 1-1/2

inches and smaller, is the greater reservoir of heat contained in the larger cube. This can be easily seen in Table 35.

The hardenability of steel can be increased if the quench media is excited by ultrasonic energy. This results from the cavitation in the ultrasonic quench media, breaking the continuity of the vapor film that forms on the surface of the quenched piece, thus producing heat transfer from the surface to the quench media through the vapor transport stage of cooling. The cavitation also increases the heat transfer during this stage by increasing the amount of vapor which migrates into the liquid and is vaporized, thus removing additional heat. However, there is no significant increase in the heat transfer from the surface to the quenching media once the surface temperature of the specimen drops below the boiling point of the quenching media.

The increase in hardenability observed with ultrasonic quenching is greater if the mass of the specimen is small. This induces the cooling of interior sections through the critical range while heat transfer at the surface is in the vapor transport stage. If the mass of the quenched piece is large, the amount of heat stored during austenitizing will be relatively large. The hardness obtained with either regular or ultrasonic quenching will not be significantly different, for although the heat removal is greater with the ultrasonic quench, the effective cooling rate is not changed due to the increased flow of heat from the warmer, more central areas. By the time the temperature drops into the critical range, the surface temperature has dropped below the boiling point of the quench media and heat is removed by simple liquid cooling which is unaffected by ultrasonic quenching. A greater increase in hardenability can be obtained with ultrasonic quenching by using a quench media with a lower boiling point, thus increasing the

surface temperature range over which the vapor transport stage of heat transfer is effective. The imposition of ultrasonic energy into a quenching media will produce a more uniform hardenability than any type of physical agitation. The cavitation process associated with ultrasonic quenching does not have directional properties.

If the cooling history at the center of one-inch cubes is known during both regular and ultrasonic quenching, a value for Newton's constant can be determined for each case. Consequently, the cooling rate at the center of other cube sizes can be calculated. Relating these to hardness, by the criterion of cooling rate at 1300°F, produces good correlation between calculated and measured hardness values in sizes through two inches for the water-quenched, and 1-1/2 inches for the ultrasonic-quenched samples.

## Martensitic Transformation Temperature ($M_S$)

The significant increase of the cooling velocity and increase in carbon diffusion indicate a possible effect on the martensitic transformation temperature. The $M_S$ temperature for a "4340" grade steel is $\approx$ 580°F under ordinary quenching procedures. The first set of cycles (1 and 2, reported in the experimental procedure section) were designed to determine the type of transformation product obtained when the specimens were quenched below the $M_S$ temperature both with and without ultrasonic energy. A comparative study of the resultant structure will be analyzed individually:

Cycle 2 - The martensite morphology appears to be the same; however, there is more carbide precipitation when the ultrasonic quench is utilized (Figures 39 and 40).

Cycle 3 - The carbide precipitation seems to be very similar in these two samples, but the martensite morphology of the ultrasonic quench is finer, smaller needled, and less defined (Figures 43 and 44).

When this part of the experimentation was completed, it seemes feasible to try to determine the amount of martensite formed on the initial quench by tempering. The samples were austenitized and quenched to the desired temperature for five seconds, followed by a 1000°F temper for five seconds and then water quenched. All the products obtained are martensite and carbide; however, the 1000°F tempering allowed much more precipitate from the metastable supersaturated martensite formed upon initial quenching.

Cycle 4 - The carbide precipitate from both types of quenching appears to be the same, but the regular-quenched specimen has a finer martensite morphology (Figures 43 and 44).

Cycle 5 - This cycle started with an initial quench (with and without ultrasound) at the approximate $M_S$ temperature for a "4340" grade steel followed by tempering at 1000°F. The morphology of these two specimens is quite different, the ultrasonically-quenched sample having a much coarser structure and no well-defined martensite needles (Figures 45 and 46).

Cycle 6 - The initial 700°F quench is well above the $M_S$ temperature, and both specimens confirm this. Neither sample shows the classical martensite and from both it can be inferred that the austenite grain size has increased (Figures 47 and 48).

The experimental results indicate a different transformation product when an ultrasonically-agitated quenching medium is used before final quenching. When the samples were isothermally treated at temperatures below the $M_S$ temperature (literature values) prior to final quenching, the sample

that was exposed to ultrasonic energy showed a greater amount of carbide precipitates. This indicates that the ultrasonic energy is additive to any thermal energy that may be imposed to increase carbide precipitation. When the samples were tempered at 1000°F after an isothermal ultrasonic hold, the former effect overwhelmed the latter, and no difference in carbide precipitation was observed. These tempered samples, however, showed a different martensitic morphology, possibly due to strain-induced carbon diffusion, thereby relieving the supersaturation of the martensite matrix.

## Tempering Characteristics

From preceding experimentation, it is evident that ultrasonic energy does affect the phase transformation. Various effects are possible:

1. If ultrasonic energy increases the strain of the lattice, the as-quenched product will have higher internal stresses and a much more brittle structure.
2. The ultrasonic energy may relieve some of the internal stress system by the formation of martensite.

When the hardness is plotted as a function of tempering temperature, the ultrasonically-quenched samples had a greater decrease in hardness ($\Delta$ H) for each tempering temperature (Figures 55 and 56).

The previous investigation has shown that quenching under ultrasonic vibrations has increased the carbon diffusion and changed the resultant transformation product. The results of the tempering characteristics further confirm these conclusions, where strain-induced carbon diffusion creates more carbide precipitation in the matrix. This is the reason that the same tempering temperature causes a greater decrease in the hardness for the sample quenched under ultrasonic energy.

## Aging Phenomena under Ultrasonic Vibrations

To further investigate the possibility of carbon diffusion, the aging characteristic of a "1008" rimmed steel was studied. From this experiment it can be seen that annealing at room temperature under ultrasonic energy accelerates a reaction which is measured by increasing hardness values. This reaction, similar to the one found in "1008" rimmed steel, involves the relocking of carbon and/or nitrogen atoms with dislocations to form a Cottrell atmosphere under increasing temperature. Boiling water (212°F) is sufficient to cause aging, with extended times causing overaging. The ultrasonic energy at room temperature seems to induce the phenomenon, but to a lesser degree (Figure 57).

It is well known that the aging phenomenon in "1008" steels is associated with the relocking of carbon and/or nitrogen atoms with available dislocations to form a Cottrell atmosphere. Ultrasonic treatment at room temperature has an effect similar to the increase in temperature to 212°F. This is observed as an increase in hardness as a function of time. This indicates that the carbon and/or nitrogen atoms do diffuse under ultrasonic treatment at room temperature.

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# CHAPTER IV

## CONCLUSIONS

It can be concluded from the preceding observations that several significant phenomena are observed in steels that are quenched under ultrasonic vibrations. The important direct effects are the increased cooling capacity of the quenching media and the enhanced carbon mobility. It is reasonable to believe that the first effect increases the hardenability of a "1050" grade steel. The cavitation that is produced by the ultrasonic energy increases the rate of heat transfer from the specimen to the quenching media through the vapor transport stage of cooling. The increase in carbon diffusion is observed from the microstructure of samples that have been quenched under ultrasonic vibrations which favors the precipitation of new carbides. This phenomenon is also observed under room temperature ultrasonic treatment. Further investigation shows that only short-range diffusion is enhanced, since the growth of existing carbides is not induced. The transformation product that is produced when samples are quenched under ultrasonic energy above room temperature seems to indicate that the ultrasonic energy is additive to any thermal energy that is imposed. This is observed as a greater amount of carbide precipitates in the microstructure of the samples quenched under ultrasonic energy. The subsequent tempering of these specimens at 1000°F resulted in a different martensitic morphology, possibly due to strain-induced carbon diffusion, thereby relieving the supersaturation of the martensite matrix.

# APPENDIX A

## Photomicrographs and Graphs

Fig. 1. 1018 Grade Steel Austenitized at 1700°F for 30 Minutes, Regular Quenched. 2% Nital Etch. X500.

Fig. 2. 1018 Grade Steel Austenitized at 1700°F for 30 Minutes, Ultrasonic Quenched. 2% Nital Etch. X500.

Fig. 3. 1018 Grade Steel Austenitized at 1700°F for 30 Minutes, Regular Quenched. 15 Minutes of Ultrasonic Treatment. 2% Nital Etch. X500.

Fig. 4. 1018 Grade Steel Austenitized at 1700°F for 30 Minutes, Ultrasonic Quenched. 15 Minutes of Ultrasonic Treatment. 2% Nital Etch. X500.

Fig. 5. 1018 Grade Steel Austenitized at 1700°F for 30 Minutes, Regular Quenched. 30 Minutes of Ultrasonic Treatment. 2% Nital Etch. X500.

Fig. 6. 1018 Grade Steel Austenitized at 1700°F for 30 Minutes, Ultrasonic Quenched. 30 Minutes of Ultrasonic Treatment. 2% Nital Etch. X500.

Fig. 7. 1018 Grade Steel Thin Sample (1/8 Inch) Austenitized at 1900°F. Regular Quenched. 2% Nital Etch. X600.

Fig. 8. 1018 Grade Steel Thin Sample (1/8 Inch) Austenitized at 1900°F. Ultrasonic Quenched. 2% Nital Etch. X600.

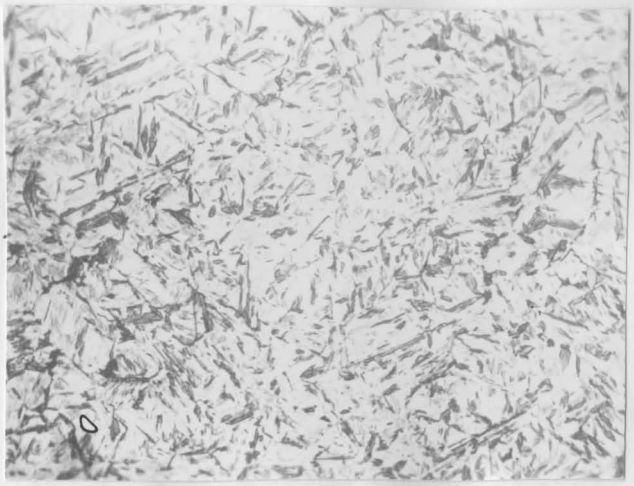


Fig. 9. 1050 Grade Steel Austenitized at 1700°F for 30 Minutes, Regular Quenched. 2% Nital Etch. X500.

Fig. 10. 1050 Grade Steel Austenitized at 1700°F for 30 Minutes, Ultrasonic Quenched. 2% Nital Etch. X500.

Fig. 11. 1050 Grade Steel Austenitized at 1700°F for 30 Minutes, Regular Quenched. 15 Minutes of Ultrasonic Treatment. 2% Nital Etch. X500.

Fig. 12. 1050 Grade Steel Austenitized at 1700°F for 30 Minutes, Ultrasonic Quenched. 15 Minutes of Ultrasonic Treatment. 2% Nital Etch. X500.

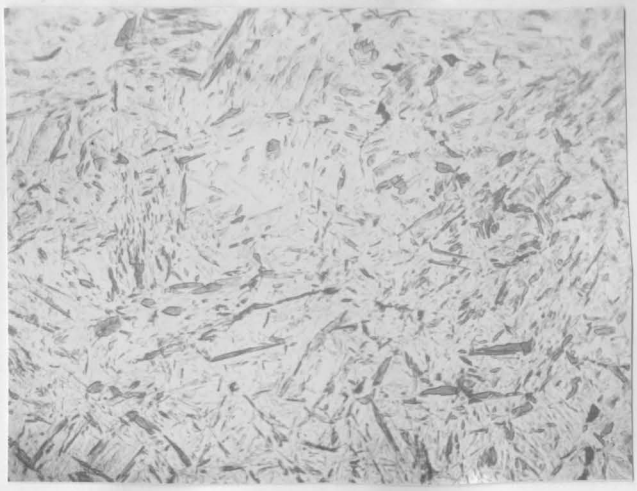


Fig. 13. 1050 Grade Steel Austenitized at 1900°F for 30 Minutes, Regular Quenched. 2% Nital Etch. X500.

Fig. 14. 1050 Grade Steel Austenitized at 1900°F for 30 Minutes, Ultrasonic Quenched. 2% Nital Etch. X500.

Fig. 15. 1050 Grade Steel Austenitized at 1900°F for 30 Minutes, Regular Quenched. 5 Minutes of Ultrasonic Treatment. 2% Nital Etch. X500.

Fig. 16. 1050 Grade Steel Austenitized at 1900°F for 30 Minutes, Ultrasonic Quenched. 5 Minutes of Ultrasonic Treatment. 2% Nital Etch. X500.

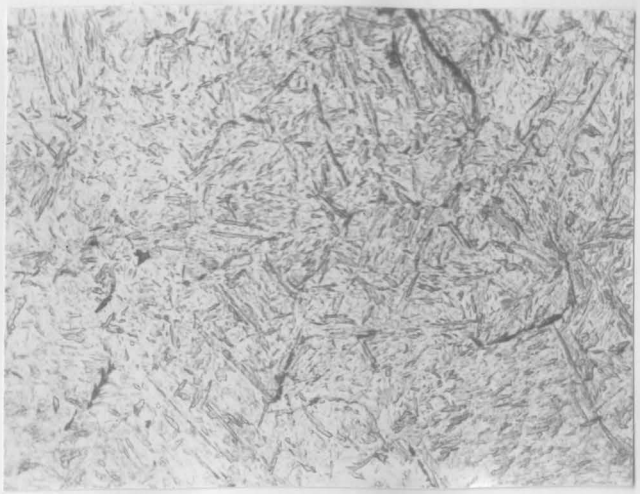


Fig. 17. 1050 Grade Steel Austenitized at 1900°F for 30 Minutes, Regular Quenched. 10 Minutes of Ultrasonic Treatment. 2% Nital Etch. X500.

Fig. 18. 1050 Grade Steel Austenitized at 1900°F for 30 Minutes, Ultrasonic Quenched. 10 Minutes of Ultrasonic Treatment. 2% Nital Etch. X500.

Fig. 19. 1050 Grade Steel Austenitized at 1900°F for 30 Minutes, Regular Quenched. 15 Minutes of Ultrasonic Treatment. 2% Nital Etch. X500.

Fig. 20. 1050 Grade Steel Austenitized at 1900°F for 30 Minutes, Ultrasonic Quenched. 15 Minutes of Ultrasonic Treatment. 2% Nital Etch. X500.

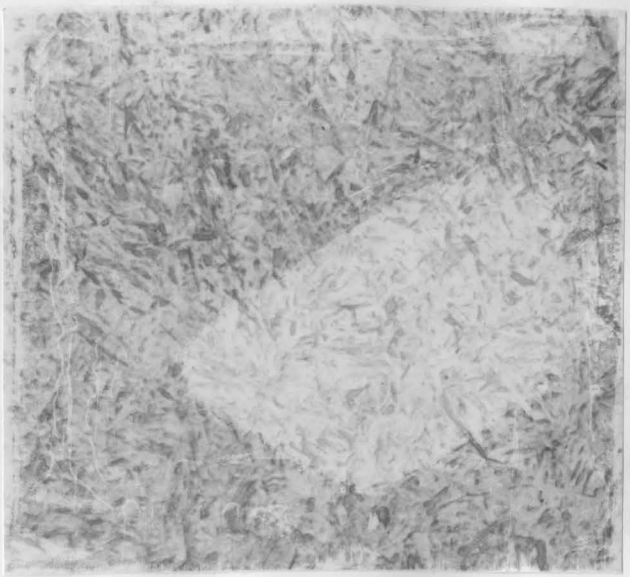


Fig. 21. 1050 Grade Steel Thin Sample (1/8 Inch) Austenitized at 1900°F. Regular Quenched. 2% Nital Etch. X600.

Fig. 22. 1050 Grade Steel Thin Sample (1/8 Inch) Austenitized at 1900°F. Ultrasonic Quenched. 2% Nital Etch. X600.

Fig. 23. 1050 Grade Steel Austenitized at 1900°F for 30 Minutes. Regular Quenched. No Ultrasonic Treatment. 2% Nital Etch. X1250.

Fig. 24. 1050 Grade Steel Austenitized at 1900°F for 30 Minutes. Regular Quenched. 180 Minutes of Ultrasonic Treatment. 2% Nital Etch. X1250.

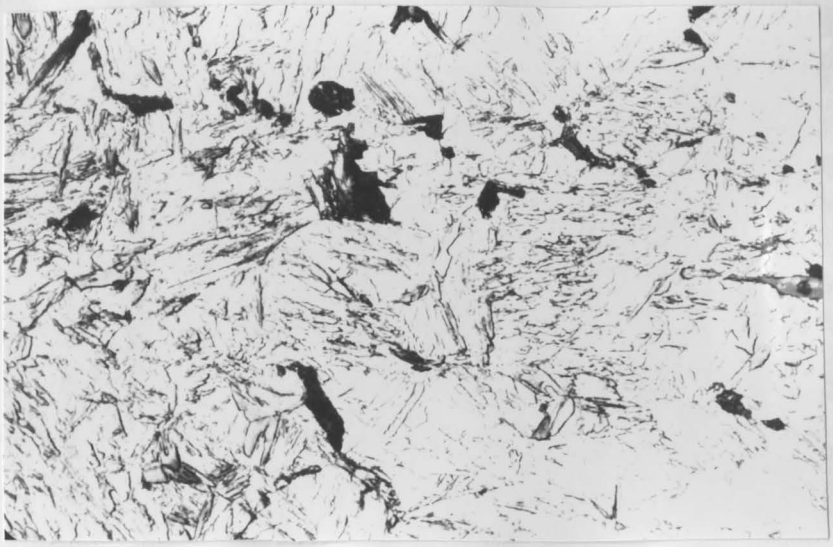


Fig. 25. 1050 Grade Steel Austenitized at 1900°F for 30 Minutes. Regular Quenched. 510 Minutes of Ultrasonic Treatment. 2% Nital Etch. X1250.

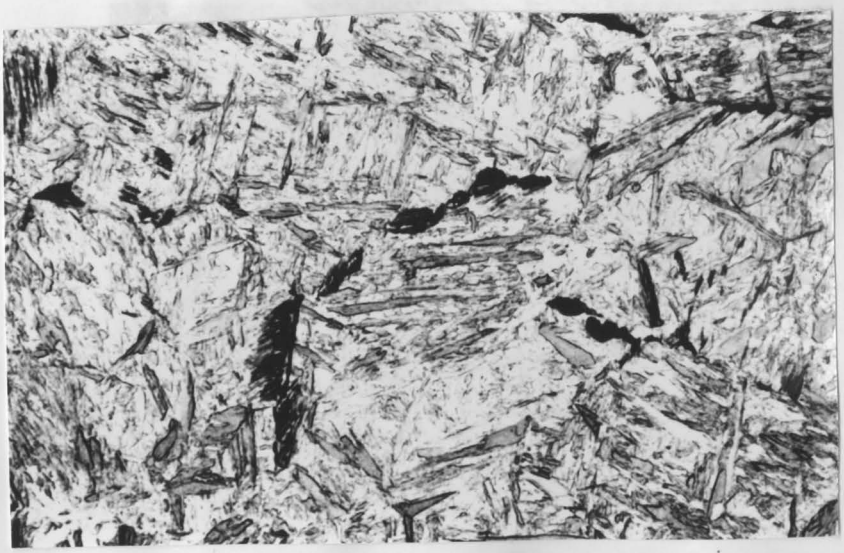


Fig. 26. 1050 Grade Steel Austenitized at 1900°F for 30 Minutes. Ultrasonic Quenched. No Ultrasonic Treatment. 2% Nital Etch. X1250.

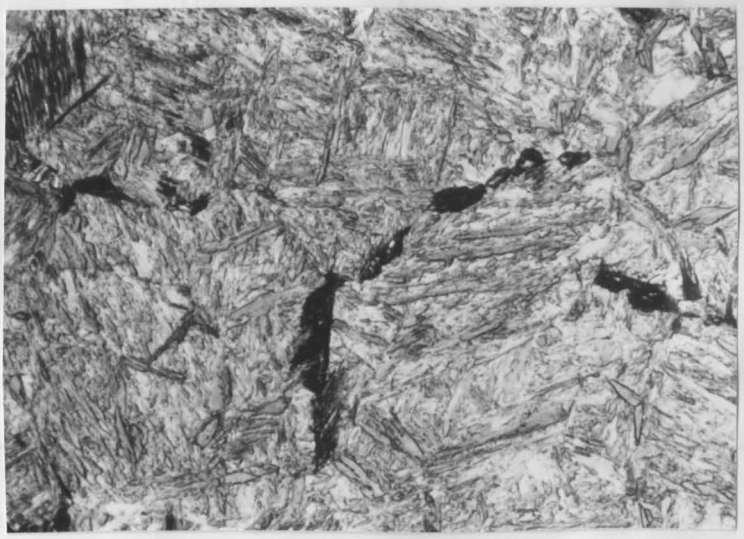
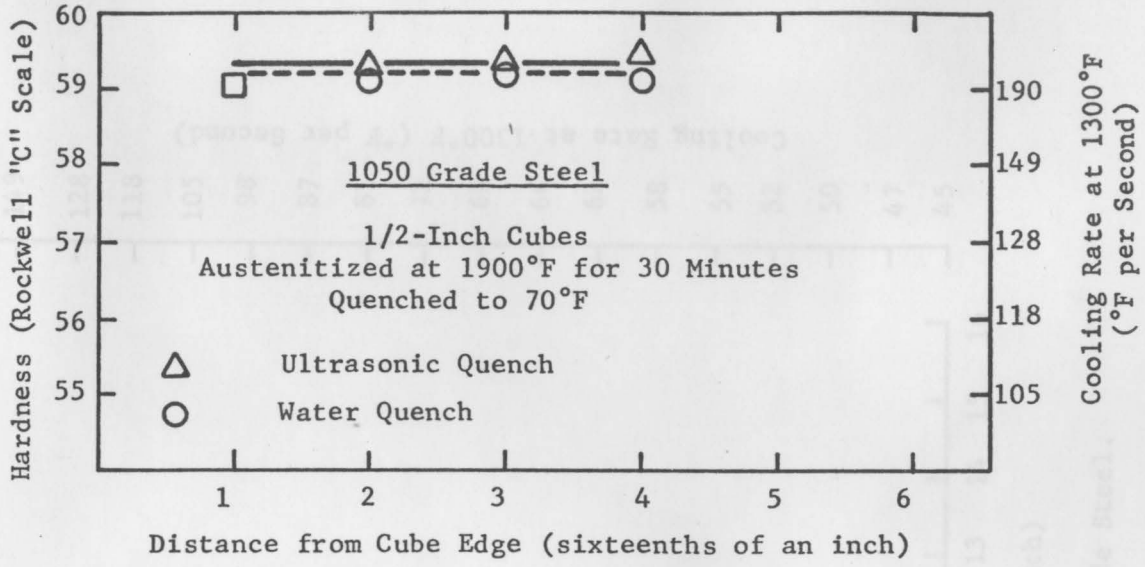


Fig. 27. 1050 Grade Steel Austenitized at 1900°F for 30 Minutes. Ultrasonic Quenched. 180 Minutes of Ultrasonic Treatment. 2% Nital Etch. X1250.

Fig. 28. 1050 Grade Steel Austenitized at 1900°F for 30 Minutes. Ultrasonic Quenched. 510 Minutes of Ultrasonic Treatment. 2% Nital Etch. X1250.



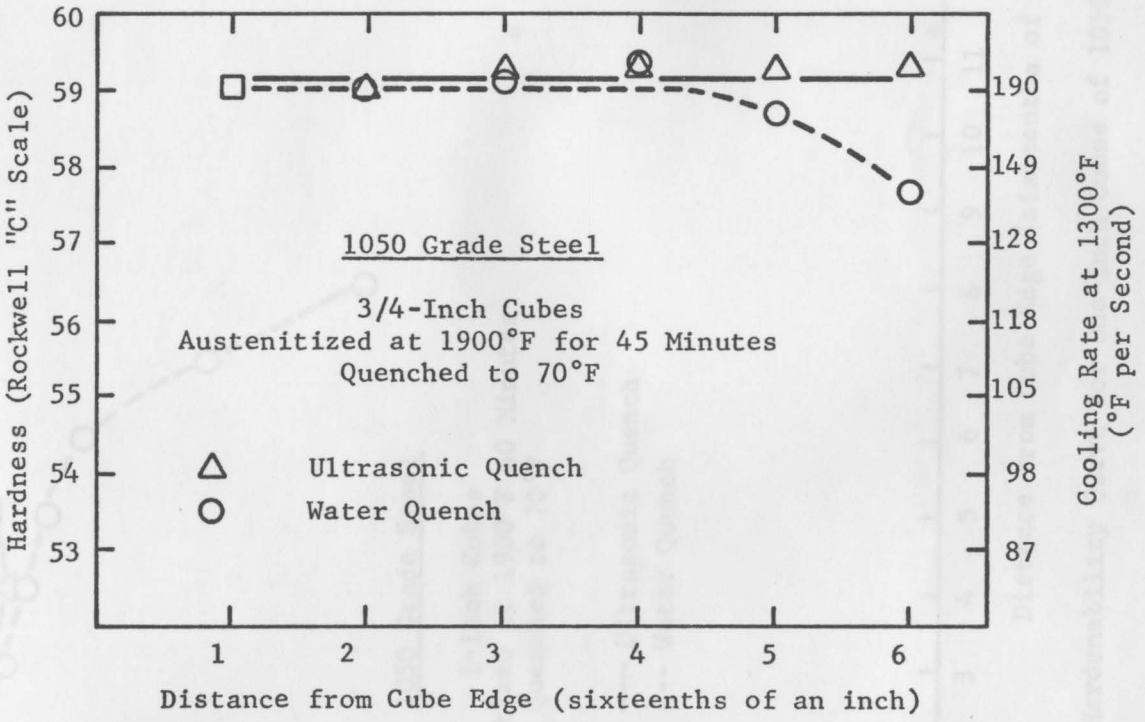




Fig. 29 and 30. Hardenability Curves for One-Half Inch and Three-Fourth Inch Cubes of 1050 Grade Steel.

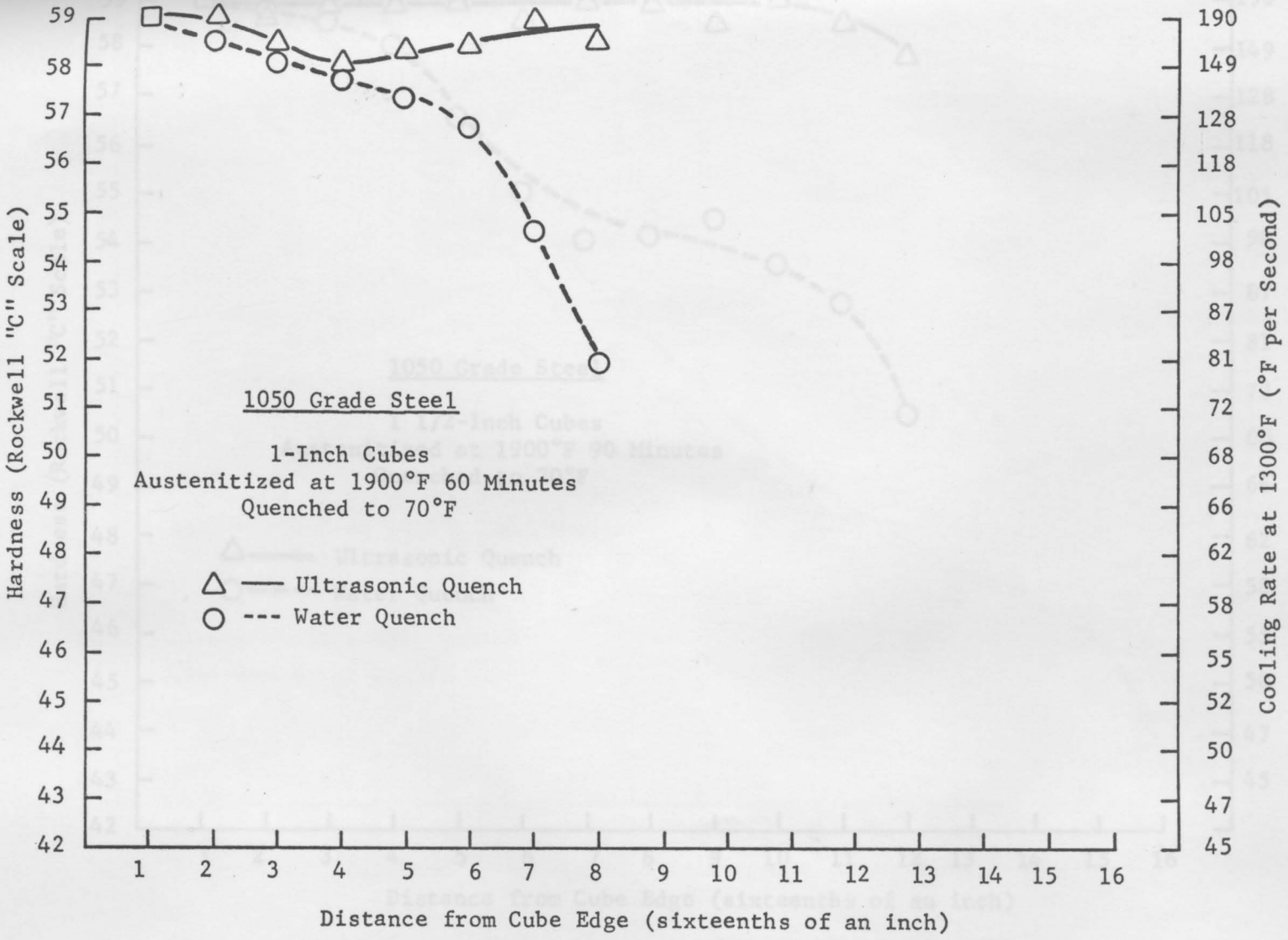



Fig. 31. Hardenability Curve for One-Inch Cubes of 1050 Grade Steel.

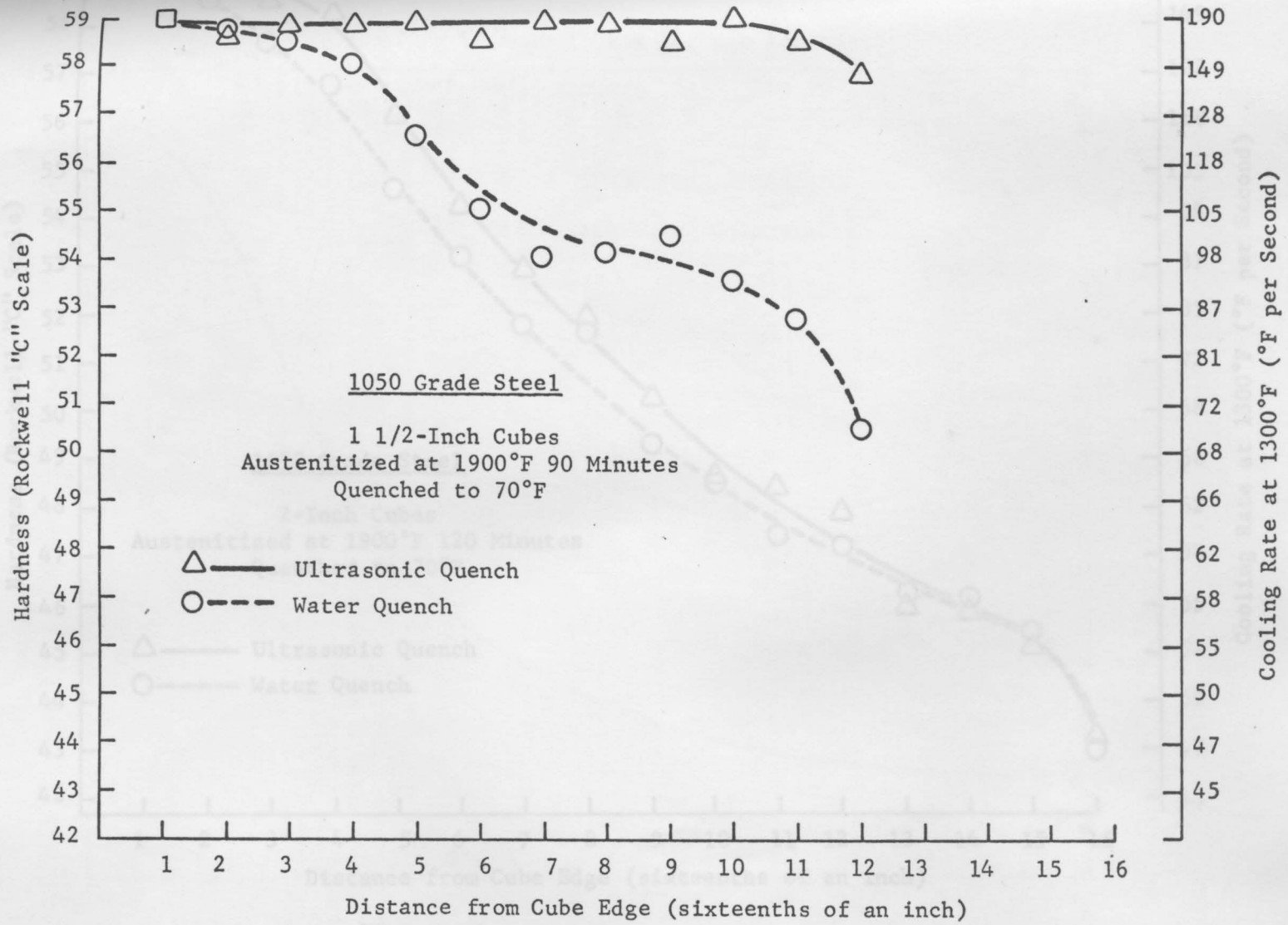



Fig. 32. Hardenability Curves for One-and-One-Half-Inch Cubes of 1050 Grade Steel.

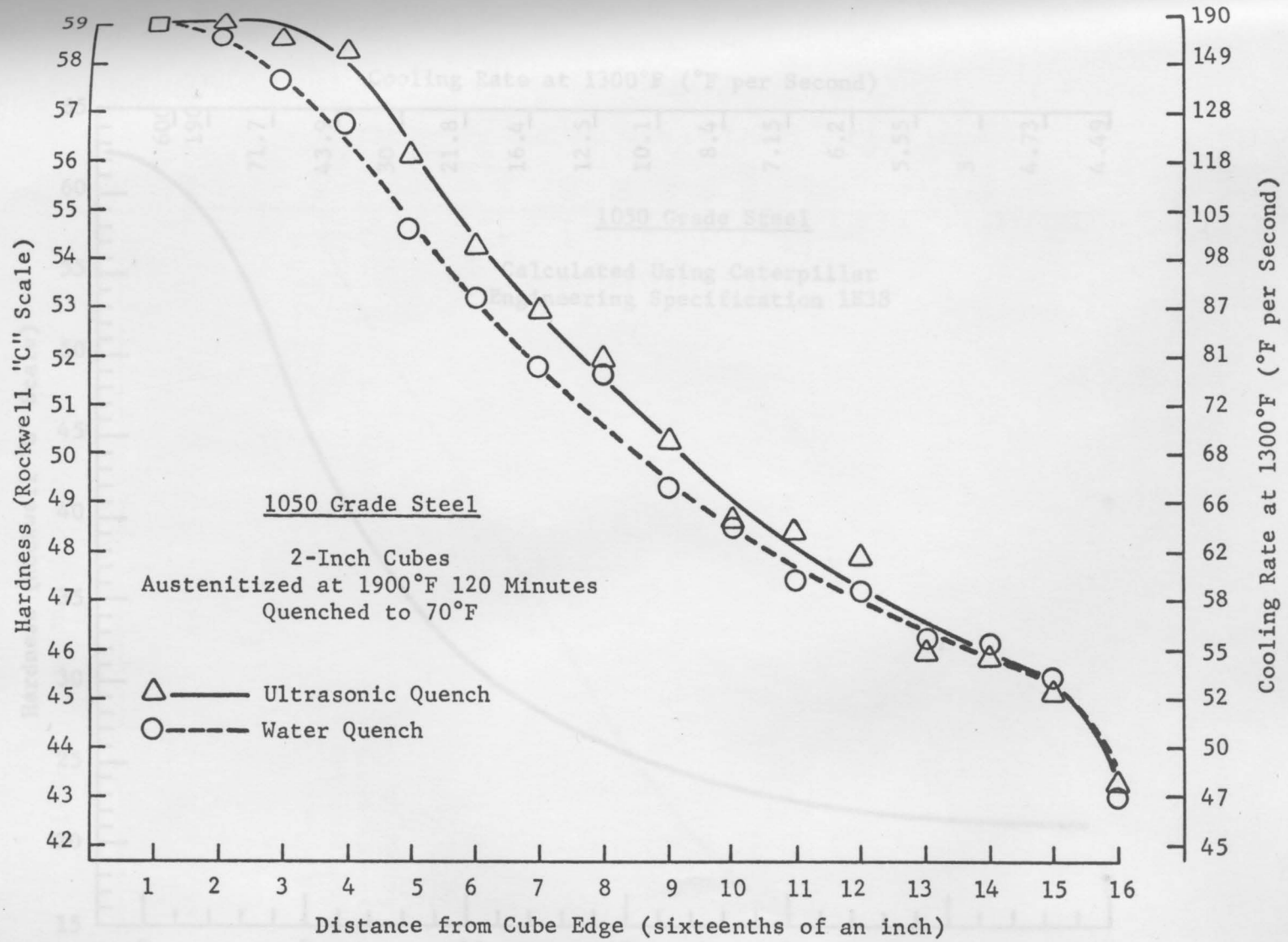



Fig. 33. Hardenability Curves for Two-Inch Cubes of 1050 Grade Steel.

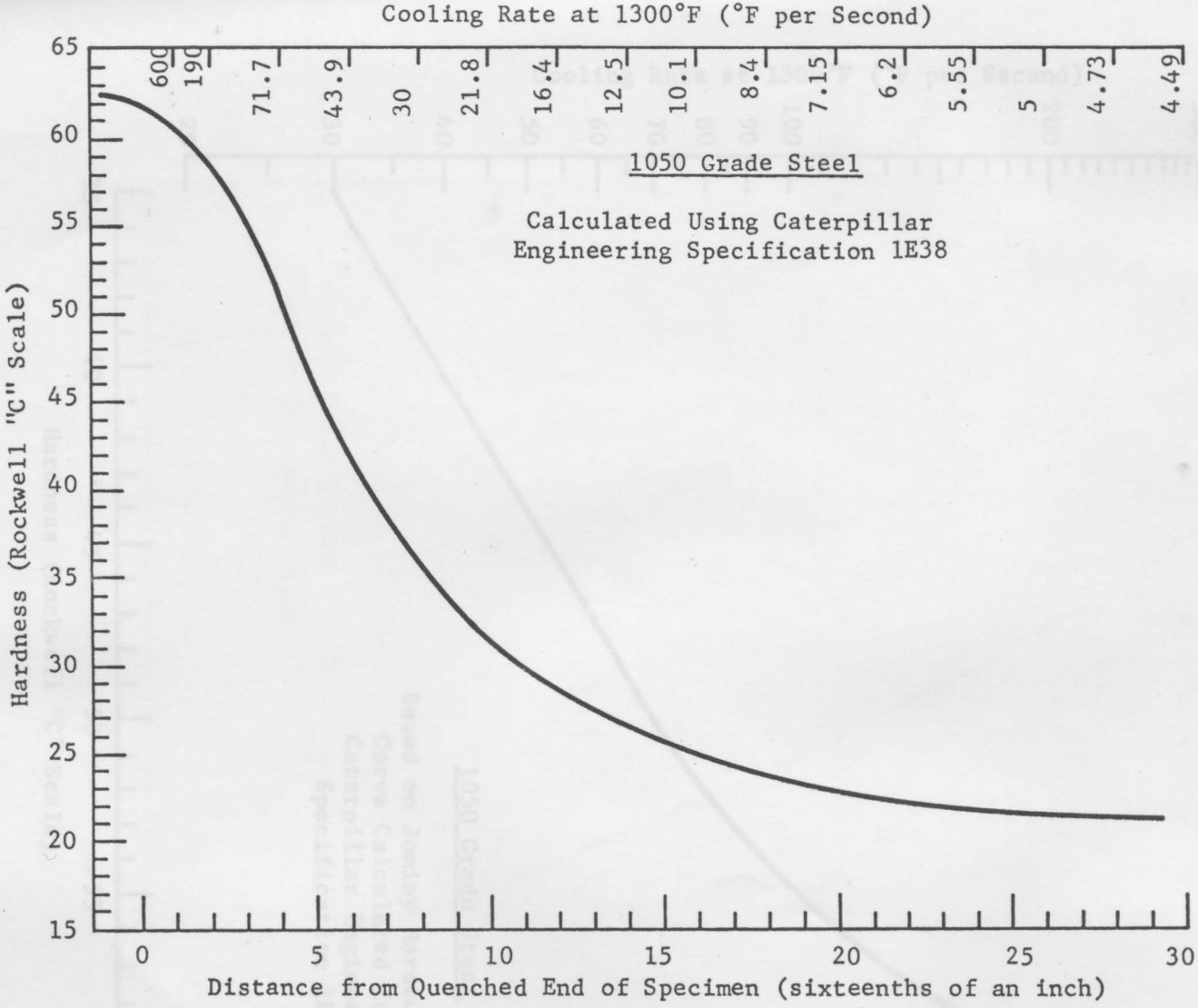



Fig. 34. Standard Jominy Hardenability Curve for 1050 Grade Steel.

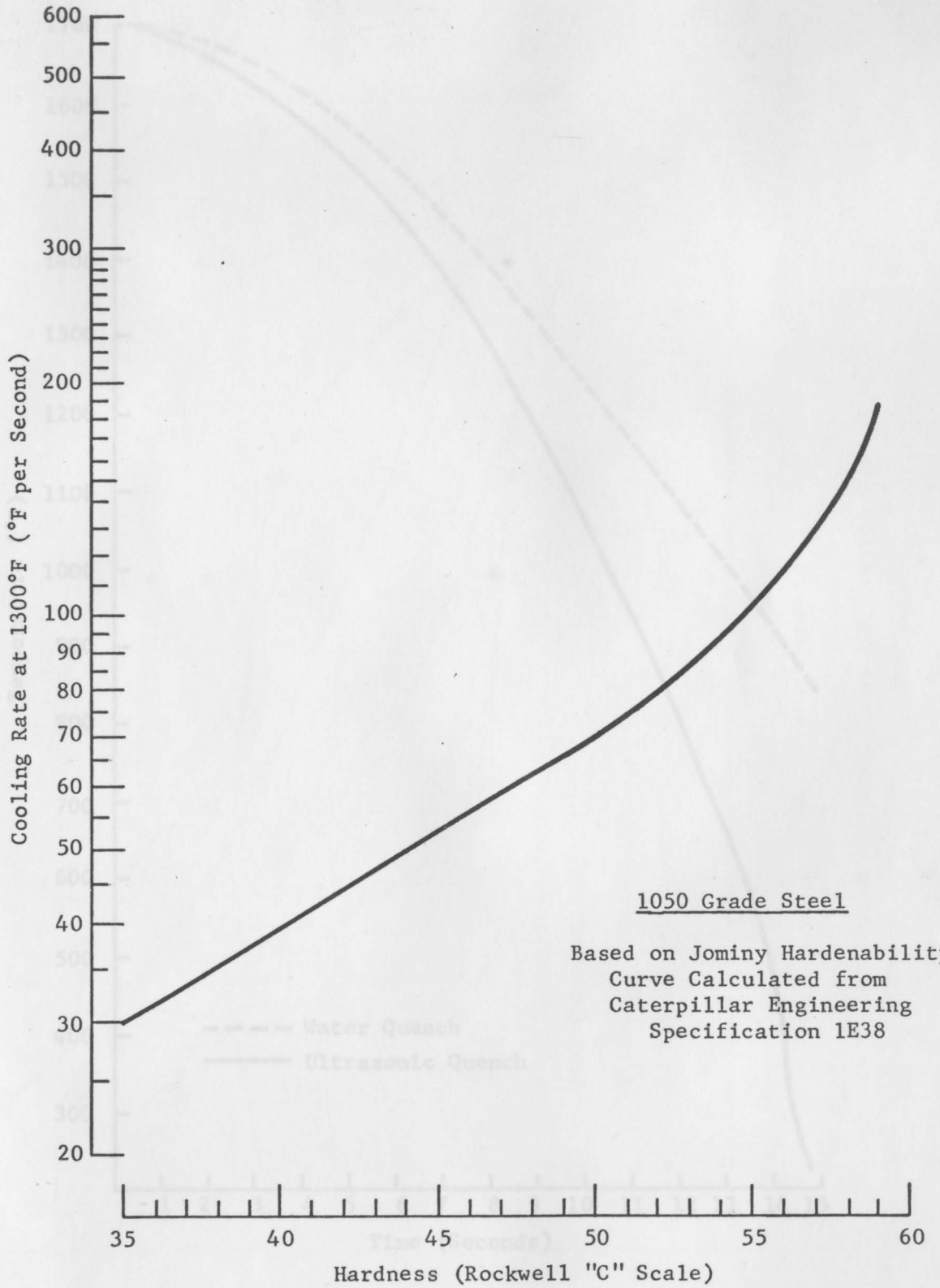



Fig. 35. Curve of Hardness Plotted Against Cooling Rate at 1300°F for 1050 Grade Steel.

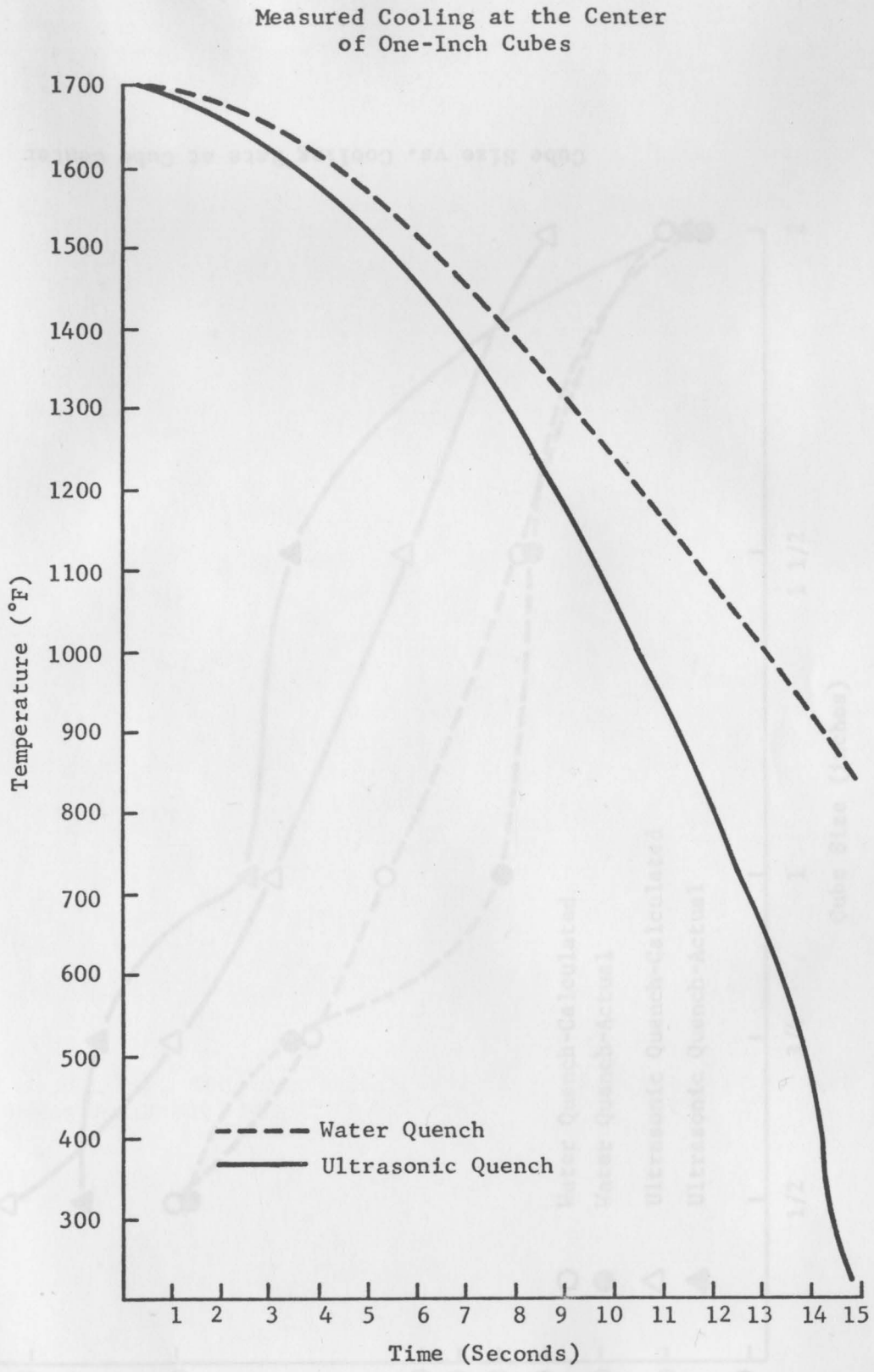



Fig. 36. Measured Cooling Rates at the Center of One-Inch Cubes for Both Regular and Ultrasonic Quench.

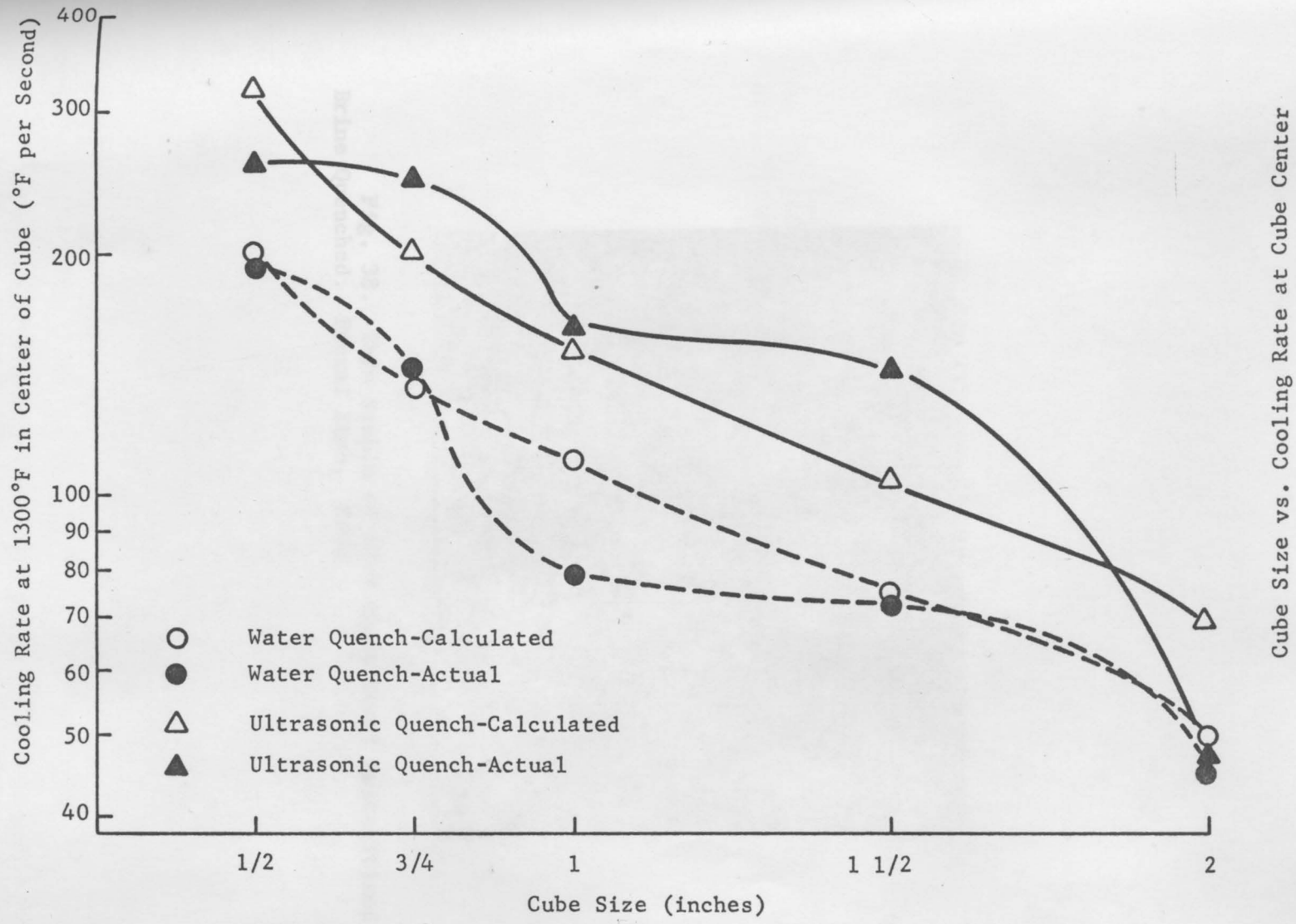



Fig. 37. Curves of Cube Sizes Plotted Against the Cooling Rate at 1300°F at the Center of 1050 Grade Steel both Calculated and Actual.

Fig. 38. Thin Sample of 4340 Grade Steel Austenitized at 1600°F, Brine Quenched. Picral Etch. X600.

Fig. 39. Thin Sample of 4340 Grade Steel Austenitized at 1600°F. Regular Quenched in 500°F Salt for 5 Seconds. Brine Quenched. Picral Etch. X600.

Fig. 40. Thin Sample of 4340 Grade Steel Austenitized at 1600°F. Ultrasonic Quenched in 500°F Salt for 5 Seconds. Brine Quenched. Picral Etch. X600.

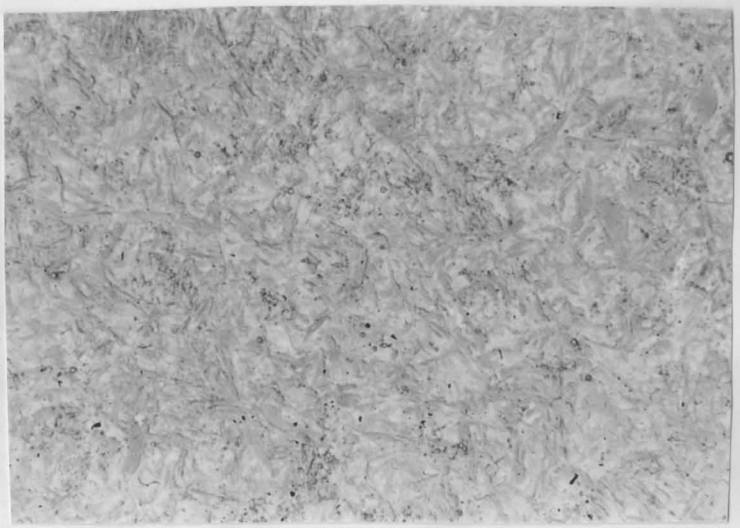


Fig. 41. Thin Sample of 4340 Grade Steel Austenitized at 1600°F. Regular Quenched in 580°F Salt for 5 Seconds. Brine Quenched. Picral Etch. X600.

Fig. 42. Thin Sample of 4340 Grade Steel Austenitized at 1600°F. Ultrasonic Quenched in 580°F Salt for 5 Seconds. Brine Quenched. Picral Etch. X600.

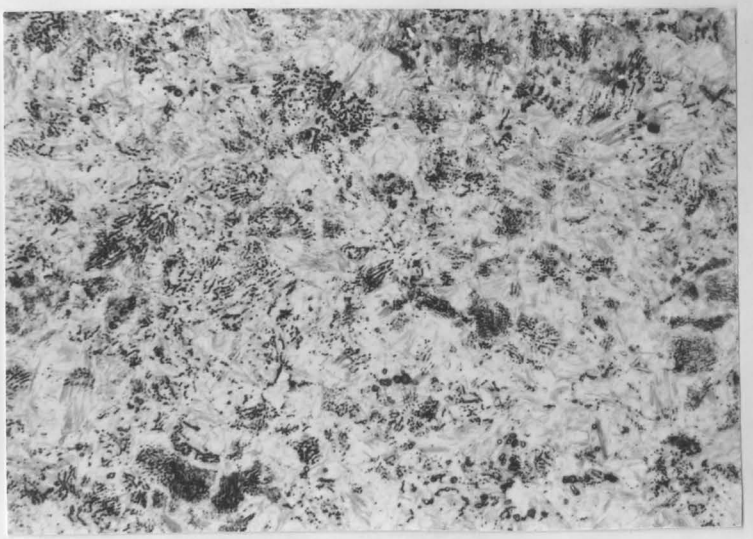


Fig. 43. Thin Sample of 4340 Grade Steel Austenitized at 1600°F. Regular Quenched in 450°F Salt for 5 Seconds. Tempered at 1000°F for 5 Seconds. Brine Quenched. Picral Etch. X600.

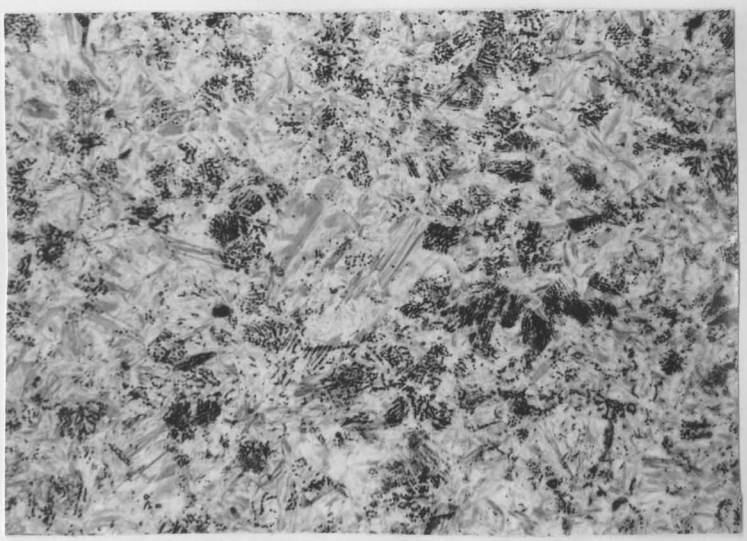


Fig. 44. Thin Sample of 4340 Grade Steel Austenitized at 1600°F. Ultrasonic Quenched in 450°F Salt for 5 Seconds. Tempered at 1000°F for 5 Seconds. Brine Quenched. Picral Etch. X600.

Fig. 45. Thin Sample of 4340 Grade Steel Austenitized at 1600°F, Regular Quenched in 600°F Salt for 5 Seconds. Tempered at 1000°F for 5 Seconds. Brine Quenched. Picral Etch. X600.

Fig. 46. Thin Sample of 4340 Grade Steel Austenitized at 1600°F. Ultrasonic Quenched in 600°F Salt for 5 Seconds. Tempered at 1000°F for 5 Seconds. Brine Quenched. Picral Etch. X600.

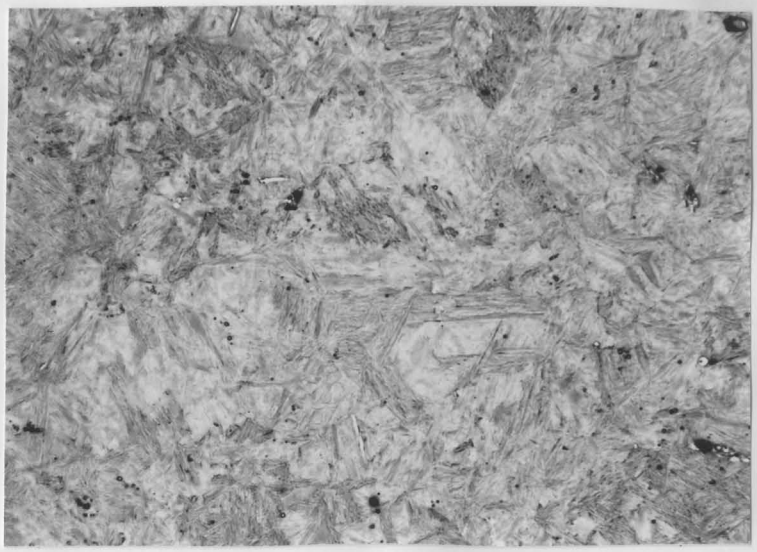


Fig. 47. Thin Sample of 4340 Grade Steel Austenitized at 1600°F. Regular Quenched in 700°F Salt for 5 Seconds. Tempered at 1000°F for 5 Seconds. Brine Quenched. Picral Etch. X600.

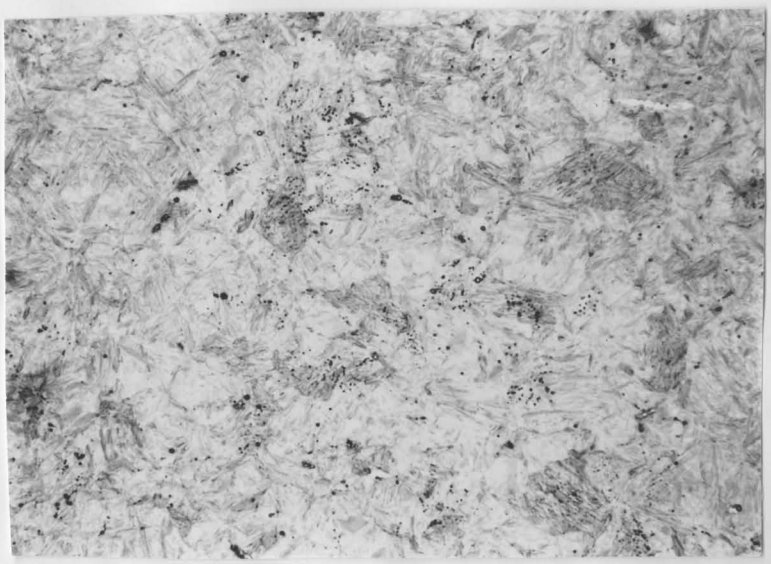


Fig. 48. Thin Sample of 4340 Grade Steel Austenitized at 1600°F. Ultrasonic Quenched in 700°F Salt for 5 Seconds. Tempered at 1000°F for 5 Seconds. Brine Quenched. Picral Etch. X600.

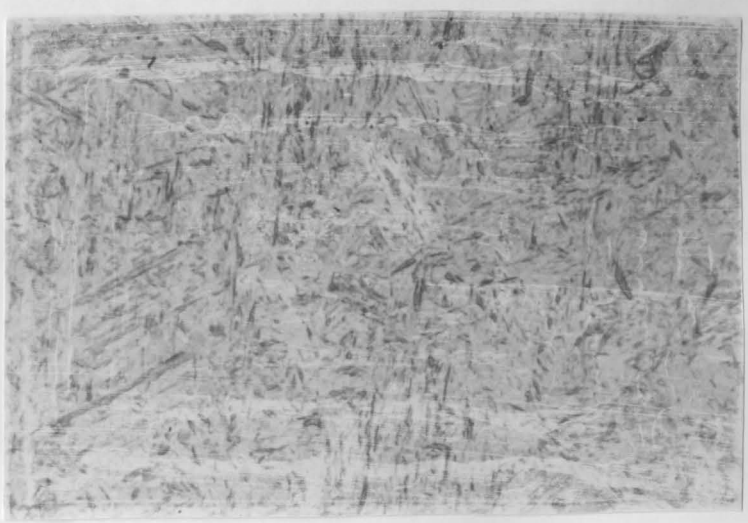


Fig. 49. Center of One-Inch Cube of 1050 Grade Steel Austenitized at 1900°F for 60 Minutes. Regular Quenched. 2% Nital Etch. X600.

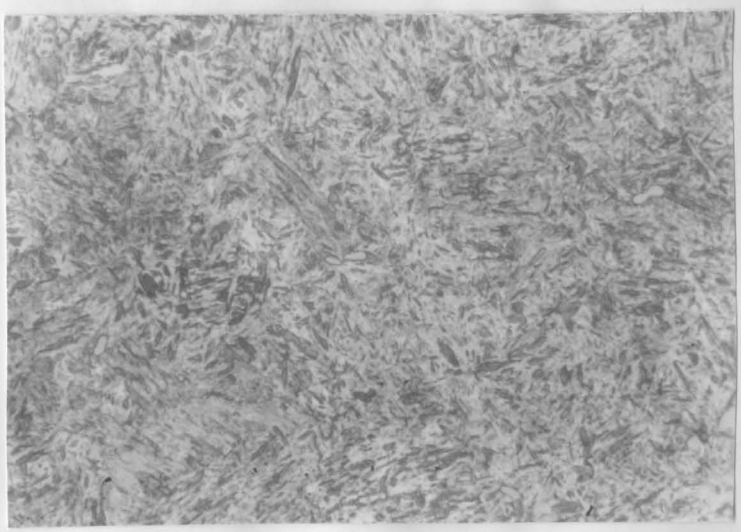


Fig. 50. Center of One-Inch Cube of 1050 Grade Steel Austenitized at 1900°F for 60 Minutes. Ultrasonic Quenched. 2% Nital Etch. X600.

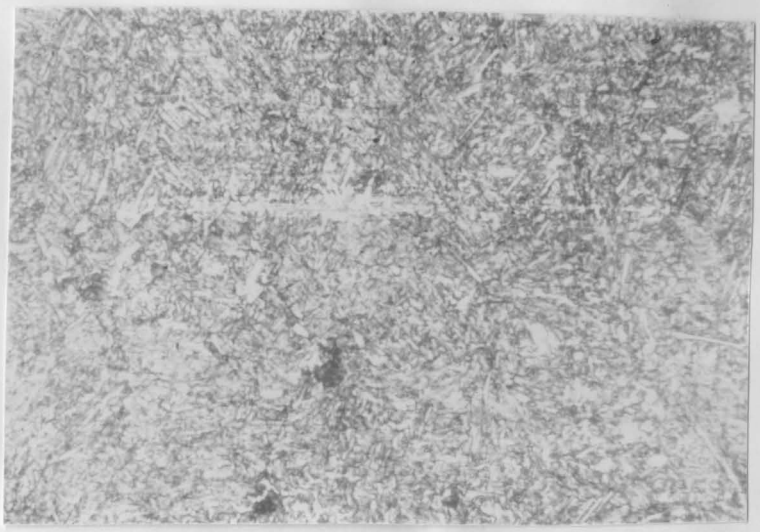


Fig. 51. Center of One-Inch Cube of 1050 Grade Steel Austenitized at 1900°F for 60 Minutes. Regular Quenched. Tempered for 15 Minutes at 800°F and Regular Quenched. 2% Nital Etch. X600.

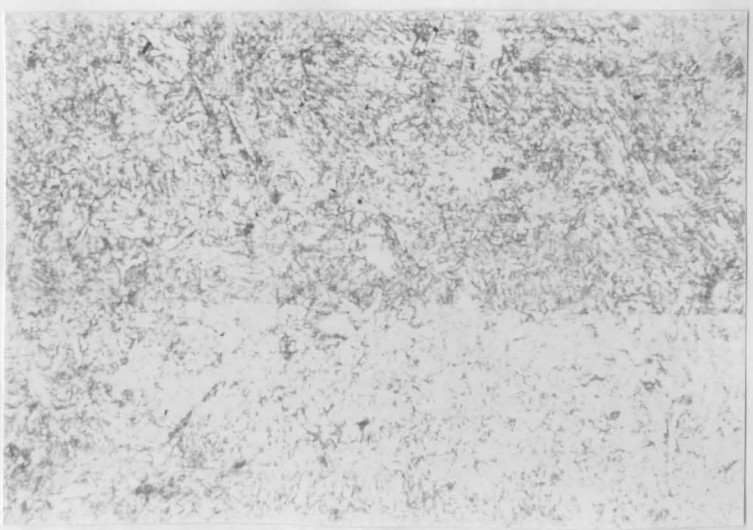


Fig. 52. Center of One-Inch Cube of 1050 Grade Steel Austenitized at 1900°F for 60 Minutes. Ultrasonic Quenched. Tempered for 15 Minutes at 800°F and Ultrasonic Quenched. 2% Nital Etch. X600.

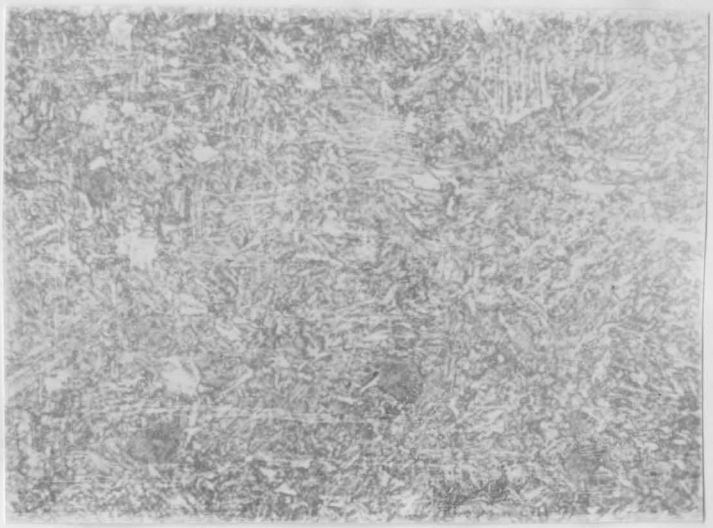


Fig. 53. Center of One-Inch Cube of 1050 Grade Steel Austenitized at 1900°F for 60 Minutes. Regular Quenched. Tempered for 15 Minutes at 1200°F and Regular Quenched. 2% Nital Etch. X600.

Fig. 54. Center of One-Inch Cube of 1050 Grade Steel Austenitized at 1900°F for 60 Minutes. Ultrasonic Quenched. Tempered for 15 Minutes at 1200°F and Ultrasonic Quenched. 2% Nital Etch. X600.

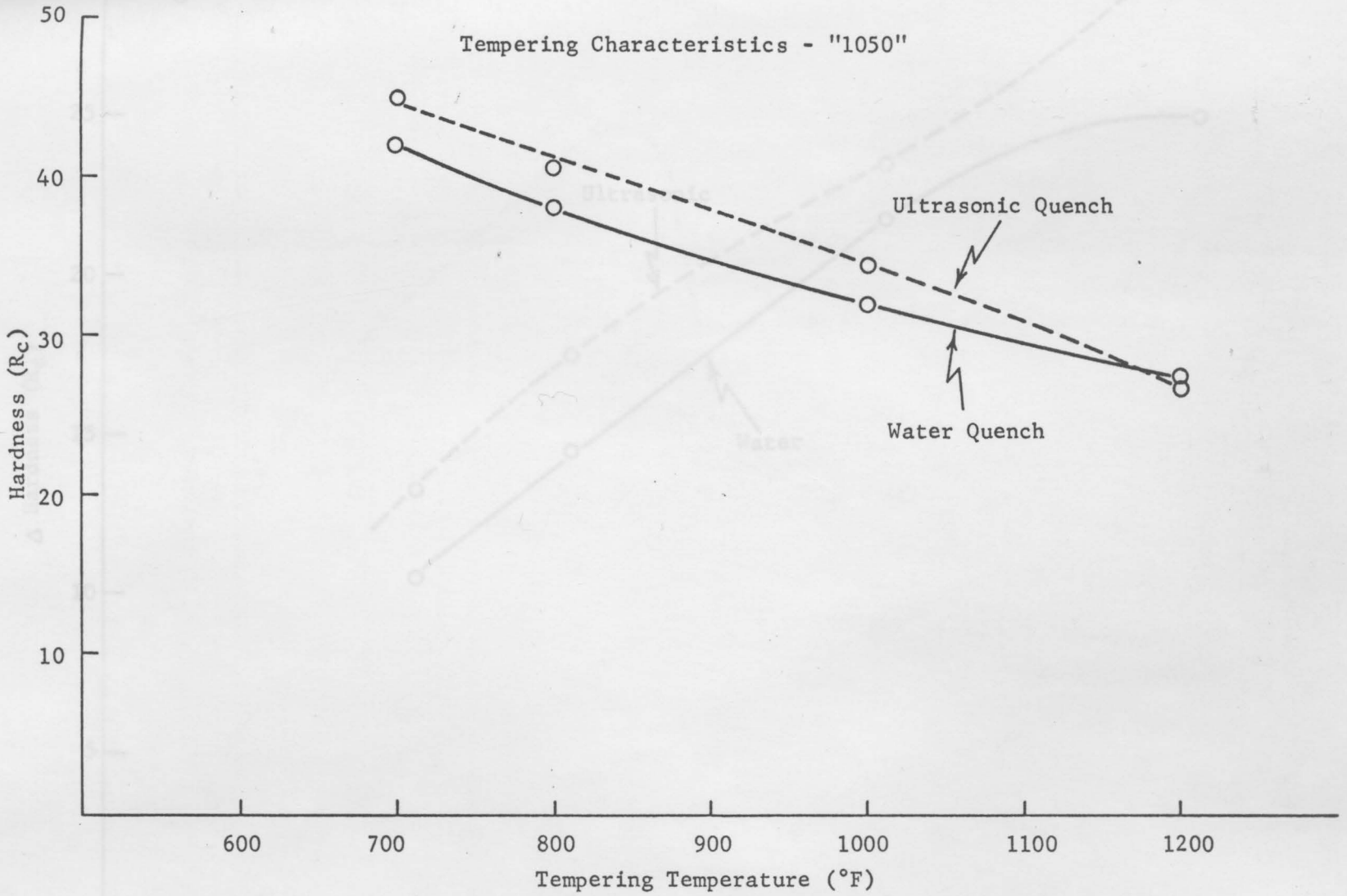



Fig. 55. Absolute $R_C$ Hardness as a Function of Tempering Temperature for 1050 Grade Steels.

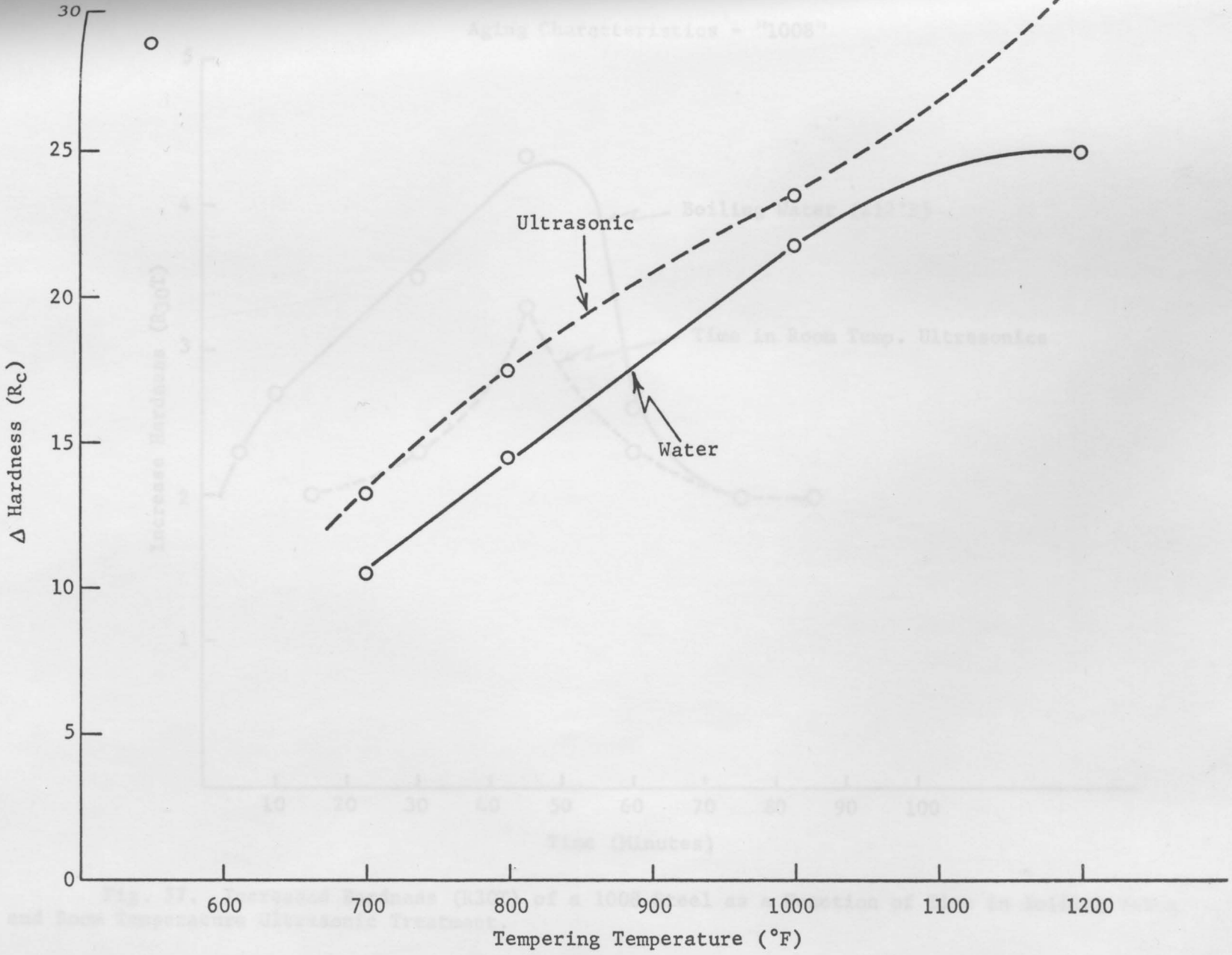



Fig. 56. $R_c$ as a Function of Tempering Temperature for "1050" Grade Steels.

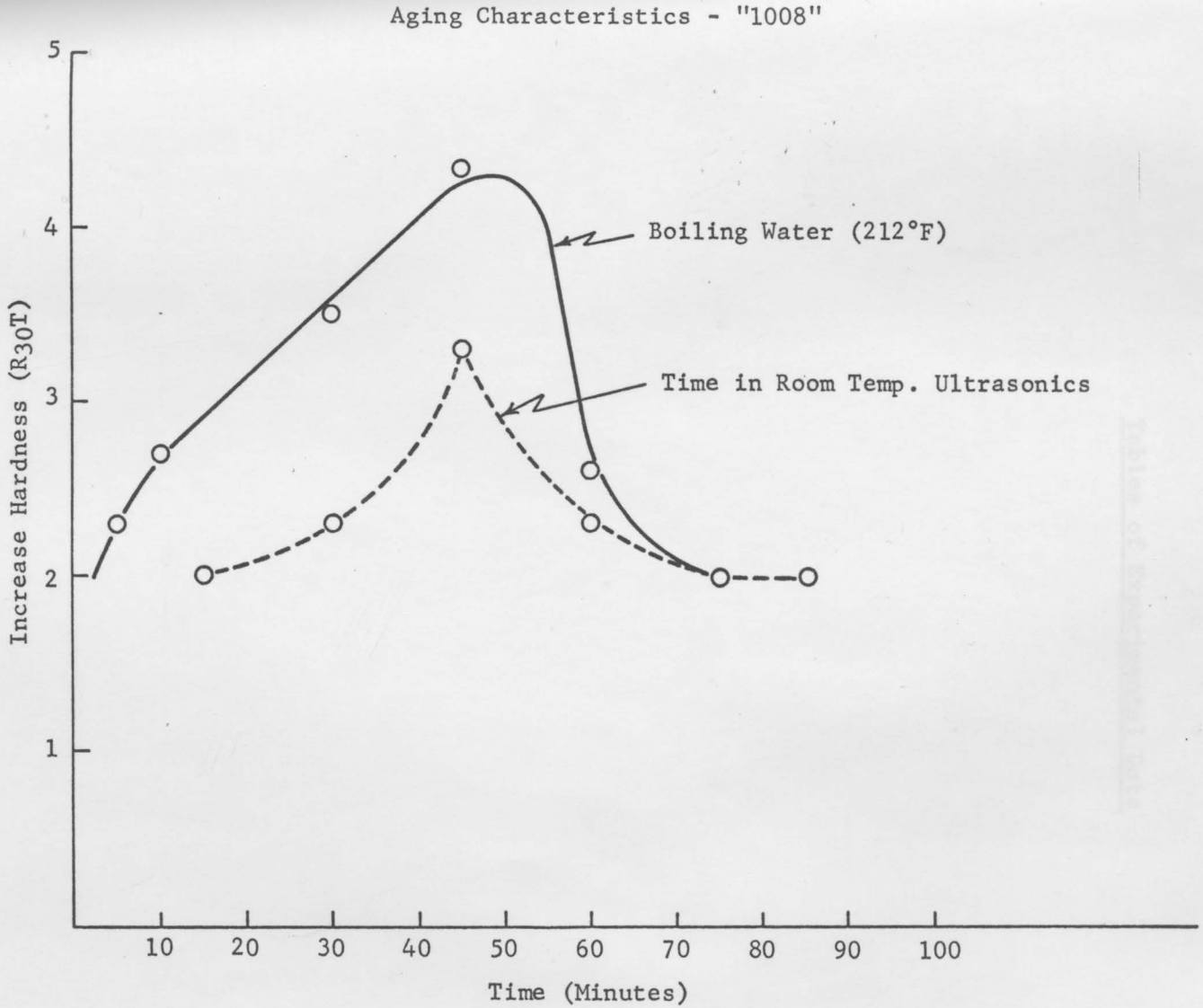



Fig. 57. Increased Hardness (R30T) of a 1008 Steel as a Function of Time in Boiling Water and Room Temperature Ultrasonic Treatment.

# APPENDIX B

## Tables of Experimental Data

TABLE 13

CHEMICAL COMPOSITION OF THE STEEL USED FOR THE INVESTIGATIONS

| Grade | C | Mn | P | S | Si | Ni | Cr | Mo | Al |
|---|---|---|---|---|---|---|---|---|---|
| 1008 | .06 | .31 | .004 | .020 | .01 | .02 | .02 | - | - |
| 1018 | .17 | .72 | .011 | .024 | .20 | .11 | .10 | .04 | .036 |
| 1041 | .41 | 1.48 | .010 | .030 | .23 | .11 | .11 | .03 | .025 |
| 1050 | .51 | .80 | .015 | .028 | .27 | .10 | .14 | .03 | .041 |
| 1085 | .85 | .83 | .011 | .029 | .26 | .08 | .08 | .03 | .038 |
| 4140 | .43 | .88 | .013 | .018 | .28 | .15 | 1.04 | .16 | .021 |
| 4340 | .40 | .72 | .012 | .023 | .28 | 1.71 | .80 | .21 | .012 |

TABLE 14

1018 GRADE STEEL SAMPLES USED FOR REGULAR AND ULTRASONIC QUENCH WITH ROOM TEMPERATURE TREATMENT

| Sample No. | Austenitizing Temperature | Type Quench[1] | Minutes of Room Temp. Ultrasonic Treatment | Average Hardness Rockwell "A" |
|---|---|---|---|---|
| 1A | 1700°F | Reg | 0 | 58.75 |
| 1B | 1700°F | Reg | 5 | 59.45 |
| 1C | 1700°F | Reg | 10 | 61.95 |
| 1D | 1700°F | Reg | 15 | 58.50 |
| 1AA | 1700°F | Reg | 30 | 57.36 |
| 1DD | 1700°F | Reg | 141 | 58.79 |
| 1E | 1700°F | Ult | 0 | 60.12 |
| 1F | 1700°F | Ult | 5 | 57.95 |
| 1G | 1700°F | Ult | 10 | 57.84 |
| 1H | 1700°F | Ult | 15 | 57.78 |
| 1EE | 1700°F | Ult | 30 | 60.10 |
| 1HH | 1700°F | Ult | 141 | 59.29 |
| 1I | 1500°F | Reg | 0 | |
| 1J | 1500°F | Reg | 5 | |
| 1K | 1500°F | Reg | 10 | |
| 1L | 1500°F | Reg | 15 | |
| 1M | 1500°F | Ult | 0 | |
| 1N | 1500°F | Ult | 5 | |
| 1O | 1500°F | Ult | 10 | |
| 1P | 1500°F | Ult | 15 | |
| 1Q | 1900°F | Reg | 0 | |
| 1R | 1900°F | Reg | 5 | |
| 1S | 1900°F | Reg | 10 | |
| 1T | 1900°F | Reg | 15 | |
| 1U | 1900°F | Ult | 0 | |
| 1V | 1900°F | Ult | 5 | |
| 1W | 1900°F | Ult | 10 | |
| 1X | 1900°F | Ult | 15 | |

[1]Reg = Quenched without ultrasonic energy.
Ult = Quenched with ultrasonic energy applied to the quench media.

TABLE 15

1041 GRADE STEEL SAMPLES USED FOR REGULAR AND ULTRASONIC QUENCH WITH ROOM TEMPERATURE TREATMENT

| Sample No. | Austenitizing Temperature | Type Quench[1] | Minutes of 70°F Ultrasonic Treatment | Hardness Rockwell "C" |
|---|---|---|---|---|
| 2A | 1750°F | Reg | 0 | 54.3 |
| 2B | 1750°F | Reg | 5 | 53.5 |
| 2C | 1750°F | Reg | 10 | 54.2 |
| 2D | 1750°F | Reg | 15 | 50.5 |
| 2E | 1750°F | Ult | 0 | 50.5 |
| 2F | 1750°F | Ult | 5 | 47.2 |
| 2G | 1750°F | Ult | 10 | 45.0 |
| 2H | 1750°F | Ult | 15 | 45.0 |

[1]Reg = Quenched without ultrasonic energy.
Ult = Quenched with ultrasonic energy applied to the quench media.

TABLE 16

1085 GRADE STEEL SAMPLES USED FOR REGULAR AND ULTRASONIC QUENCH WITH ROOM TEMPERATURE TREATMENT

| Sample No. | Austenitizing Temperature | Type Quench[1] | Minutes of 70°F Ultrasonic Treatment |
|---|---|---|---|
| 3A | 1750°F | Reg | 0 |
| 3B | 1750°F | Reg | 5 |
| 3C | 1750°F | Reg | 10 |
| 3D | 1750°F | Reg | 15 |
| 3E | 1750°F | Ult | 0 |
| 3F | 1750°F | Ult | 5 |
| 3G | 1750°F | Ult | 10 |
| 3H | 1750°F | Ult | 15 |

[1]Reg = Quenched without ultrasonic energy.
Ult = Quenched with ultrasonic energy applied to the quench media.

TABLE 17

1050 GRADE STEEL SAMPLES USED FOR REGULAR AND ULTRASONIC QUENCH WITH ROOM TEMPERATURE TREATMENT

| Sample No. | Austenitizing Temperature | Type Quench[1] | Minutes of Room Temp. Ultrasonic Treatment | Hardness Rockwell "C" |
|---|---|---|---|---|
| 5A | 1900°F | Reg | 0 | 61.2 |
| 5B | 1900°F | Reg | 5 | 60.2 |
| 5C | 1900°F | Reg | 10 | 57.1 |
| 5D | 1900°F | Reg | 15 | 55.3 |
| 5A-1 | 1900°F | Reg | 180 | |
| 5A-2 | 1900°F | Reg | 510 | |
| 5E | 1900°F | Ult | 0 | 60.5 |
| 5F | 1900°F | Ult | 5 | 58.2 |
| 5G | 1900°F | Ult | 10 | 59.4 |
| 5H | 1900°F | Ult | 15 | 58.5 |
| 5E-1 | 1900°F | Ult | 180 | |
| 5E-2 | 1900°F | Ult | 510 | |
| 5Q | 1700°F | Reg | 0 | 59.0 |
| 5R | 1700°F | Reg | 5 | 58.9 |
| 5S | 1700°F | Reg | 10 | 59.6 |
| 5T | 1700°F | Reg | 15 | 60.2 |
| 5U | 1700°F | Ult | 0 | 60.7 |
| 5V | 1700°F | Ult | 5 | 60.2 |
| 5W | 1700°F | Ult | 10 | 59.2 |
| 5X | 1700°F | Ult | 15 | 59.2 |

[1]Reg = Quenched without ultrasonic energy.
Ult = Quenched with ultrasonic energy applied to the quench media.

TABLE 18

4140 GRADE STEEL SAMPLES USED FOR REGULAR AND ULTRASONIC QUENCH WITH ROOM TEMPERATURE TREATMENT

| Sample No. | Austenitizing Temperature | Type Quench[1] | Minutes of Room Temp. Ultrasonic Treatment |
|---|---|---|---|
| 4A | 1550°F | Reg | 0 |
| 4B | 1550°F | Reg | 5 |
| 4C | 1550°F | Reg | 10 |
| 4D | 1550°F | Reg | 15 |
| 4E | 1550°F | Ult | 0 |
| 4F | 1550°F | Ult | 5 |
| 4G | 1550°F | Ult | 10 |
| 4H | 1550°F | Ult | 15 |

[1]Reg = Quenched without ultrasonic energy.
Ult = Quenched with ultrasonic energy applied to the quench media.

TABLE 19

HARDNESS (ROCKWELL "C") AND CORRESPONDING COOLING RATE (°F PER SECOND) FOR ONE-HALF INCH CUBES OF 1050 GRADE STEEL AUSTENITIZED AT 1900°F FOR THIRTY MINUTES

| Distance from Cube Edge (inches) | Regular Quenched | | Ultrasonic Quenched | |
|---|---|---|---|---|
| | Hardness Rockwell "C" Scale[1] | Cooling Rate at 1300°F[2] | Hardness Rockwell "C" Scale[1] | Cooling Rate at 1300°F[2] |
| 1/16 | 59.0 | ≥ 190 | 59.0 | ≥ 190 |
| 2/16 | 59.1 | ≥ 190 | 59.3 | ≥ 190 |
| 3/16 | 59.2 | ≥ 190 | 59.3 | ≥ 190 |
| 4/16 | 59.1 | ≥ 190 | 59.4 | ≥ 190 |

[1]Hardness results are the averages of three trials.

[2]Determined by converting hardness determinations to cooling rates at 1300°F by means of the Jominy hardenability curve.

TABLE 20

HARDNESS (ROCKWELL "C") AND CORRESPONDING COOLING RATE (°F PER SECOND) FOR THREE-FOURTHS INCH CUBES OF 1050 GRADE STEEL AUSTENITIZED AT 1900°F FOR FORTY-FIVE MINUTES

| Distance from Cube Edge (inches) | Regular Quenched | | Ultrasonic Quenched | |
|---|---|---|---|---|
| | Hardness Rockwell "C" Scale[1] | Cooling Rate at 1300°F[2] | Hardness Rockwell "C" Scale[1] | Cooling Rate at 1300°F[2] |
| 1/16 | 59.0 | ≥190 | 59.0 | ≥190 |
| 2/16 | 59.0 | ≥190 | 59.0 | ≥190 |
| 3/16 | 59.1 | ≥190 | 59.3 | ≥190 |
| 4/16 | 59.4 | ≥190 | 59.2 | ≥190 |
| 5/16 | 58.7 | 165 | 59.3 | ≥190 |
| 6/16 | 57.7 | 142 | 59.3 | ≥190 |

[1]Hardness results are the averages of three trials.

[2]Determined by converting hardness determinations to cooling rates at 1300°F by means of the Jominy hardenability curve.

TABLE 21

HARDNESS (ROCKWELL "C") AND CORRESPONDING COOLING RATE (°F PER SECOND) FOR ONE INCH CUBES OF 1050 GRADE STEEL AUSTENITIZED AT 1900°F FOR SIXTY MINUTES

| Distance from Cube Edge (inches) | Regular Quenched | | Ultrasonic Quenched | |
|---|---|---|---|---|
| | Hardness Rockwell "C" Scale[1] | Cooling Rate at 1300°F[2] | Hardness Rockwell "C" Scale[1] | Cooling Rate at 1300°F[2] |
| 1/16 | 59.0 | ⩾190 | 59.0 | ⩾190 |
| 2/16 | 58.4 | 158 | 59.0 | ⩾190 |
| 3/16 | 58.0 | 149 | 58.4 | 158 |
| 4/16 | 57.7 | 142 | 57.9 | 145 |
| 5/16 | 57.3 | 135 | 58.3 | 156 |
| 6/16 | 56.7 | 125 | 58.4 | 158 |
| 7/16 | 54.6 | 100 | 58.9 | 185 |
| 8/16 | 51.9 | 79 | 58.5 | 162 |

[1]Hardness results are the average of three trials.

[2]Determined by converting the hardness determinations to cooling rates at 1300°F by means of the Jominy hardenability curve.

TABLE 22

HARDNESS (ROCKWELL "C") AND CORRESPONDING COOLING RATE (°F PER SECOND) FOR ONE AND ONE-HALF INCH CUBES OF 1050 GRADE STEEL AUSTENITIZED AT 1900°F FOR NINETY MINUTES

| Distance from Cube Edge (inches) | Regular Quenched | | Ultrasonic Quenched | |
|---|---|---|---|---|
| | Hardness Rockwell "C" Scale[1] | Cooling Rate at 1300°F[2] | Hardness Rockwell "C" Scale[1] | Cooling Rate at 1300°F[2] |
| 1/16 | 59.0 | ≥190 | 59.0 | ≥190 |
| 2/16 | 58.7 | 165 | 58.6 | 163 |
| 3/16 | 58.5 | 162 | 58.8 | 180 |
| 4/16 | 58.0 | 149 | 58.8 | 180 |
| 5/16 | 56.5 | 120 | 58.8 | 180 |
| 6/16 | 55.0 | 103 | 58.5 | 163 |
| 7/16 | 54.0 | 95 | 58.8 | 180 |
| 8/16 | 54.2 | 97 | 58.8 | 180 |
| 9/16 | 54.5 | 99 | 58.4 | 158 |
| 10/16 | 53.5 | 91 | 58.8 | 180 |
| 11/16 | 52.7 | 85 | 58.5 | 163 |
| 12/16 | 50.5 | 73 | 57.8 | 143 |

[1]Hardness results are the average of two trials.

[2]Determined by converting hardness determinations to cooling rates at 1300°F by means of the Jominy hardenability curve.

TABLE 23

HARDNESS (ROCKWELL "C") AND CORRESPONDING COOLING RATE (°F PER SECOND) FOR TWO INCH CUBES OF 1050 GRADE STEEL AUSTENITIZED AT 1900°F FOR ONE HUNDRED TWENTY MINUTES

| Distance from Cube Edge (inches) | Regular Quenched | | Ultrasonic Quenched | |
|---|---|---|---|---|
| | Hardness Rockwell "C" Scale[1] | Cooling Rate at 1300°F[2] | Hardness Rockwell "C" Scale[1] | Cooling Rate at 1300°F[2] |
| 1/16 | 59.0 | ≥190 | 59.0 | ≥190 |
| 2/16 | 58.6 | 167 | 59.0 | ≥190 |
| 3/16 | 57.6 | 140 | 58.6 | 167 |
| 4/16 | 56.7 | 125 | 58.3 | 156 |
| 5/16 | 54.6 | 98 | 56.1 | 116 |
| 6/16 | 53.2 | 88 | 54.2 | 96 |
| 7/16 | 51.7 | 79 | 52.9 | 87 |
| 8/16 | 51.6 | 78 | 51.9 | 80 |
| 9/16 | 49.3 | 68 | 50.3 | 73 |
| 10/16 | 48.5 | 65 | 48.6 | 65 |
| 11/16 | 47.4 | 60 | 48.4 | 64 |
| 12/16 | 47.2 | 59 | 47.9 | 62 |
| 13/16 | 46.2 | 56 | 46.0 | 55 |
| 14/16 | 46.2 | 56 | 45.9 | 54 |
| 15/16 | 45.4 | 53 | 45.2 | 52 |
| 16/16 | 42.9 | 45 | 43.3 | 47 |

[1]Hardness results are the average of three trials.

[2]Determined by converting hardness determinations to cooling rates at 1300°F by means of the Jominy hardenability curve.

TABLE 24

CALCULATION OF POINTS OF JOMINY HARDENABILITY CURVE USING THE PROCEDURE OUTLINED IN THE APPENDIX OF CATERPILLAR ENGINEERING SPECIFICATION IE38

| Element | Composition Factor |
|---|---|
| Carbon (.51) | 0.343 (Grain Size 2) |
| Manganese (.80) | 3.667 |
| Silicon (.27) | 1.189 |
| Sulfur (.028) | 0.980 |
| Phosphorus (.015) | 1.039 |
| Chromium (.14) | 1.3024 |
| Nickel (.10) | 1.036 |
| Copper (.15) | 1.000 |

DI = Product of Composition Factors = 2.05462

Hardness at 1/16 Inch = 62.5

For DI = 2.05462

| Distance from Quenched End | Factor (Table B) | $\frac{62.5}{\text{Factor}}$ = Hardness |
|---|---|---|
| 4/16 inch | 1.225 | 51.0 |
| 8/16 inch | 1.745 | 35.8 |
| 12/16 inch | 2.195 | 28.5 |
| 16/16 inch | 2.51 | 24.9 |
| 20/16 inch | 2.73 | 22.9 |
| 24/16 inch | 2.87 | 21.8 |
| 28/16 inch | 2.975 | 21.2 |
| 32/16 inch | 3.065 | 20.4 |

TABLE 25

MEASURED COOLING DATA AT THE CENTER OF A ONE INCH CUBE QUENCHED FROM 1700°F TO 70°F IN WATER

| Time (seconds) | Regular Quenched, Temperature (°F) | Ultrasonic Quenched, Temperature (°F) |
|---|---|---|
| 0 | 1680 | 1686 |
| 1 | 1672 | 1666 |
| 2 | 1652 | 1643 |
| 3 | 1615 | 1595 |
| 4 | 1558 | 1530 |
| 5 | 1493 | 1459 |
| 6 | 1439 | 1379 |
| 7 | 1379 | 1301 |
| 8 | 1315 | 1184 |
| 9 | 1246 | 1077 |
| 10 | 1169 | 945 |
| 11 | 1093 | 816 |
| 12 | 1008 | 644 |
| 13 | 920 | 400 |
| 14 | 845 | 220 |
| 15 | 761 | - |
| 16 | 693 | - |
| 17 | 530 | - |
| 18 | 286 | - |

TABLE 26

COOLING DATA FOR CENTER OF ONE INCH CUBE OF 1050 GRADE STEEL AUSTENITIZED AT 1700°F AND REGULAR QUENCHED INTO 70°F WATER

| $\theta$ | x | $t_c$ | $t_c$-70 | $Y_c$ $(\frac{t_c-70}{1630})$ | $\text{Log}_{10}\ Y_c$ |
|---|---|---|---|---|---|
| 1 | .036 | 1672 | 1602 | .983 | .007 |
| 2 | .072 | 1652 | 1582 | .971 | .012 |
| 3 | .108 | 1615 | 1535 | .942 | .026 |
| 4 | .144 | 1558 | 1488 | .912 | .040 |
| 5 | .180 | 1493 | 1423 | .874 | .059 |
| 6 | .216 | 1439 | 1369 | .839 | .076 |
| 7 | .252 | 1379 | 1309 | .802 | .096 |
| 8 | .288 | 1315 | 1245 | .764 | .117 |
| 9 | .324 | 1246 | 1176 | .722 | .142 |
| 10 | .360 | 1169 | 1099 | .673 | .172 |
| 11 | .396 | 1093 | 1023 | .628 | .202 |
| 12 | .432 | 1008 | 938 | .575 | .240 |
| 13 | .468 | 920 | 850 | .521 | .283 |
| 14 | .504 | 845 | 775 | .475 | .323 |
| 15 | .540 | 761 | 691 | .423 | .374 |
| 16 | .576 | 693 | 623 | .382 | .418 |
| 17 | .612 | 530 | 460 | .282 | .550 |
| 18 | .648 | 286 | 216 | .133 | .876 |

$$N_e = \frac{.323-.142}{.504-.324} = \frac{.181}{.180} = \underline{\underline{1.00}}$$

$$m = \frac{3}{2.3\ N_e} = \underline{\underline{1.30}}$$

$$h = \frac{K}{m\ r_m} = \frac{0.00044}{(1.30)(.5)} = \underline{\underline{0.000677}}\ \text{BTU/°F in}^2\ \text{sec}$$

TABLE 27

COOLING DATA FOR CENTER OF ONE INCH CUBE OF 1050 GRADE STEEL AUSTENITIZED AT 1700°F AND ULTRASONIC QUENCHED INTO 70°F WATER

| $\theta$ | x | $t_c$ | $t_c$-70 | $Y_c$ $(\frac{t_c-70}{1630})$ | $\text{Log}_{10}\ Y_c$ |
|---|---|---|---|---|---|
| 1 | .036 | 1666 | 1596 | .980 | .009 |
| 2 | .072 | 1643 | 1573 | .965 | .016 |
| 3 | .108 | 1595 | 1525 | .935 | .029 |
| 4 | .144 | 1530 | 1460 | .895 | .048 |
| 5 | .180 | 1459 | 1389 | .852 | .069 |
| 6 | .216 | 1379 | 1309 | .803 | .095 |
| 7 | .252 | 1301 | 1231 | .755 | .122 |
| 8 | .288 | 1184 | 1114 | .684 | .165 |
| 9 | .324 | 1077 | 1007 | .618 | .209 |
| 10 | .360 | 945 | 875 | .537 | .270 |
| 11 | .396 | 816 | 746 | .458 | .338 |
| 12 | .432 | 644 | 574 | .352 | .443 |

$$N_e = \frac{.338-.095}{.396-.216} = \frac{.243}{.180} = \underline{\underline{1.50}}$$

$$m = \frac{3}{2.3\ N_e} = \underline{\underline{0.870}}$$

$$h = \frac{K}{m\ r_m}\quad \frac{0.00044}{(.870)(.5)} = \underline{\underline{0.00101}}\ \text{BTU/°F in}^2\ \text{sec}$$

TABLE 28

CALCULATED COOLING PARAMETERS FOR CUBES OF 1050 GRADE STEEL BASED ON MEASURED COOLING OF THE CENTERS OF ONE INCH CUBES

| Cube Size | Kind of Quench | h | m | $N_e$ |
|---|---|---|---|---|
| 1/2 inch | regular | 0.000677 | 2.60 | 0.502 |
| 1/2 inch | ultrasonic | 0.00101 | 1.74 | 0.750 |
| 3/4 inch | regular | 0.000677 | 1.73 | 0.755 |
| 3/4 inch | ultrasonic | 0.00101 | 1.165 | 1.12 |
| 1 inch | regular | 0.000677 | 1.30 | 1.00 |
| 1 inch | ultrasonic | 0.00101 | 0.870 | 1.50 |
| 1 1/2 inch | regular | 0.000677 | 0.867 | 1.50 |
| 1 1/2 inch | ultrasonic | 0.00101 | 0.580 | 2.25 |
| 2 inch | regular | 0.000677 | 0.650 | 2.00 |
| 2 inch | ultrasonic | 0.00101 | 0.435 | 3.00 |

TABLE 29

CALCULATED COOLING FOR 1/2 INCH CUBES OF 1050 GRADE STEEL AUSTENITIZED AT 1900°F AND QUENCHED IN WATER AT 70°F

| | | Regular Quench | | | Ultrasonic Quench | | |
|---|---|---|---|---|---|---|---|
| $\theta$ | x | $\text{Log}_{10}$ Y (.502X) | Y | $t_c$ | $\text{Log}_{10}$ Y (.750X) | Y | $t_c$ |
| 1 | .144 | .072 | .847 | 1595 | .108 | .780 | 1500 |
| 2 | .288 | .144 | .717 | 1380 | .216 | .608 | 1180 |
| 3 | .432 | .216 | .608 | 1180 | .324 | .486 | 960 |
| 4 | .576 | .288 | .515 | 1010 | .432 | .369 | 745 |
| 5 | .720 | .360 | .436 | 865 | .540 | .288 | 595 |
| 6 | .864 | .432 | .369 | 745 | .648 | .225 | 480 |
| 7 | 1.008 | .504 | .318 | 650 | .756 | .175 | 390 |
| 8 | 1.152 | .576 | .265 | 555 | .864 | .137 | 320 |

Cooling Rate at 1300°F

Regular Quench 200°F/second
Ultrasonic Quench 320°F/second

TABLE 30

CALCULATED COOLING FOR 3/4 INCH CUBES OF 1050 GRADE STEEL AUSTENITIZED AT 1900°F AND QUENCHED IN WATER AT 70°F

| | | Regular Quench | | | Ultrasonic Quench | | |
|---|---|---|---|---|---|---|---|
| θ | x | $\text{Log}_{10}$ Y (.755X) | Y | $t_c$ | $\text{Log}_{10}$ Y (1.12X) | Y | $t_c$ |
| 1 | .064 | .0485 | .892 | 1695 | .0715 | .848 | 1595 |
| 2 | .128 | .097 | .800 | 1535 | .143 | .719 | 1380 |
| 3 | .192 | .1455 | .712 | 1375 | .2145 | .610 | 1180 |
| 4 | .256 | .1940 | .640 | 1240 | .286 | .518 | 1020 |
| 5 | .320 | .2425 | .571 | 1115 | .3575 | .439 | 875 |
| 6 | .384 | .2910 | .510 | 1005 | .429 | .372 | 750 |
| 7 | .448 | .3395 | .458 | 910 | .5005 | .317 | 650 |
| 8 | .512 | .388 | .408 | 815 | .572 | .268 | 560 |
| 9 | .576 | .4365 | .365 | 740 | .6435 | .228 | 485 |
| 10 | .640 | .485 | .327 | 665 | .715 | .193 | 425 |
| 11 | .704 | .5335 | .293 | 605 | .7865 | .163 | 370 |

Cooling Rate at 1300°F

Regular Quench 135°F/second
Ultrasonic Quench 200°F/second

TABLE 31

CALCULATED COOLING FOR 1 INCH CUBES OF 1050 GRADE STEEL AUSTENITIZED AT 1900°F AND QUENCHED IN WATER AT 70°F

| | | Regular Quench | | | Ultrasonic Quench | | |
|---|---|---|---|---|---|---|---|
| θ | x | $Log_{10}$ Y (1.00X) | Y | $t_c$ | $Log_{10}$ Y (1.50X) | Y | $t_c$ |
| 1 | .036 | .036 | .920 | 1750 | .054 | .882 | 1690 |
| 2 | .072 | .072 | .848 | 1620 | .108 | .780 | 1485 |
| 3 | .108 | .108 | .780 | 1500 | .162 | .688 | 1330 |
| 4 | .144 | .144 | .718 | 1390 | .216 | .608 | 1180 |
| 5 | .180 | .180 | .660 | 1280 | .270 | .538 | 1050 |
| 6 | .216 | .216 | .608 | 1180 | .324 | .463 | 915 |
| 7 | .252 | .252 | .560 | 1095 | .378 | .418 | 835 |
| 8 | .288 | .288 | .515 | 1010 | .432 | .370 | 745 |
| 9 | .324 | .324 | .463 | 915 | .486 | .327 | 665 |
| 10 | .360 | .360 | .436 | 865 | .540 | .288 | 595 |
| 11 | .396 | .396 | .401 | 800 | | | |
| 12 | .432 | .432 | .370 | 745 | | | |
| 13 | .468 | .468 | .340 | 690 | | | |
| 14 | .504 | .504 | .314 | 645 | | | |
| 15 | .540 | .540 | .288 | 595 | | | |

Cooling Rate at 1300°F

Regular Quench 110°F/second
Ultrasonic Quench 150°F/second

TABLE 32

CALCULATED COOLING FOR 1 1/2 INCH CUBES OF 1050 GRADE STEEL AUSTENITIZED AT 1900°F AND QUENCHED IN WATER AT 70°F

| | | Regular Quench | | | Ultrasonic Quench | | |
|---|---|---|---|---|---|---|---|
| θ | x | $\text{Log}_{10}$ Y (1.50X) | Y | $t_c$ | $\text{Log}_{10}$ Y (2.25X) | Y | $t_c$ |
| 1 | .016 | .024 | .946 | 1800 | .036 | .920 | 1750 |
| 2 | .032 | .048 | .895 | 1710 | .072 | .847 | 1620 |
| 3 | .048 | .072 | .848 | 1620 | .108 | .780 | 1500 |
| 4 | .064 | .096 | .801 | 1535 | .144 | .718 | 1385 |
| 5 | .080 | .120 | .758 | 1460 | .180 | .660 | 1280 |
| 6 | .096 | .144 | .718 | 1385 | .216 | .608 | 1185 |
| 7 | .112 | .168 | .680 | 1310 | .252 | .560 | 1095 |
| 8 | .128 | .192 | .642 | 1245 | .288 | .515 | 1015 |
| 9 | .144 | .216 | .608 | 1185 | .324 | .474 | 940 |
| 10 | .160 | .240 | .575 | 1120 | .360 | .436 | 885 |
| 11 | .176 | .264 | .545 | 1065 | .396 | .402 | 805 |
| 12 | .192 | .288 | .515 | 1015 | .432 | .370 | 745 |
| 13 | .208 | .312 | .488 | 965 | .468 | .340 | 695 |
| 14 | .224 | .336 | .462 | 915 | .504 | .314 | 645 |
| 15 | .240 | .360 | .436 | 870 | | | |
| 16 | .256 | .384 | .413 | 825 | | | |
| 17 | .272 | .408 | .391 | 785 | | | |
| 18 | .288 | .432 | .370 | 750 | | | |
| 19 | .304 | .456 | .350 | 710 | | | |
| 20 | .320 | .480 | .331 | 675 | | | |

Cooling Rate at 1300°F

Regular Quench 75°F/second
Ultrasonic Quench 105°F/second

TABLE 33

CALCULATED COOLING FOR 2 INCH CUBES OF 1050 GRADE STEEL AUSTENITIZED AT 1900°F AND QUENCHED IN WATER AT 70°F

| | | Regular Quench | | | Ultrasonic Quench | | |
|---|---|---|---|---|---|---|---|
| θ | x | $\text{Log}_{10}$ Y (2.00X) | Y | $t_c$ | $\text{Log}_{10}$ Y (3.00X) | Y | $t_c$ |
| 1 | .009 | .018 | .960 | 1825 | .027 | .940 | 1790 |
| 2 | .018 | .036 | .920 | 1750 | .054 | .884 | 1690 |
| 3 | .027 | .054 | .883 | 1685 | .081 | .830 | 1590 |
| 4 | .036 | .072 | .848 | 1620 | .108 | .780 | 1500 |
| 5 | .045 | .090 | .812 | 1555 | .135 | .732 | 1410 |
| 6 | .054 | .108 | .780 | 1500 | .162 | .688 | 1330 |
| 7 | .063 | .126 | .748 | 1440 | .189 | .648 | 1260 |
| 8 | .072 | .144 | .718 | 1385 | .216 | .608 | 1185 |
| 9 | .081 | .162 | .688 | 1330 | .243 | .572 | 1115 |
| 10 | .090 | .180 | .561 | 1280 | .270 | .537 | 1055 |
| 11 | .099 | .198 | .634 | 1230 | .297 | .505 | 995 |
| 12 | .108 | .216 | .608 | 1180 | .324 | .485 | 960 |
| 13 | .117 | .234 | .584 | 1140 | .351 | .446 | 885 |
| 14 | .126 | .252 | .560 | 1095 | | | |
| 15 | .135 | .270 | .537 | 1055 | | | |
| 16 | .144 | .288 | .515 | 1015 | | | |
| 17 | .153 | .306 | .494 | 975 | | | |
| 18 | .162 | .324 | .474 | 940 | | | |
| 19 | .171 | .342 | .455 | 905 | | | |
| 20 | .180 | .360 | .437 | 870 | | | |

Cooling Rate at 1300°F

Regular Quench 50°F/second
Ultrasonic Quench 70°F/second

TABLE 34

MEASURED AND CALCULATED VALUES FOR HARDNESS AND COOLING RATE FOR CUBES OF 1050 GRADE STEEL AUSTENITIZED AT 1900°F AND QUENCHED IN WATER AT 70°F

| Cube Size | Kind of Quench | Measured | | Calculated | |
|---|---|---|---|---|---|
| | | R"C" | °F/second | R"C" | °F/second |
| 1/2 inch | regular | 59.1 | ≈200 | 59.2 | 200 |
| 3/4 inch | regular | 57.7 | 142 | 57.1 | 135 |
| 1 inch | regular | 51.9 | 79 | 55.5 | 110 |
| 1 1/2 inch | regular | 50.5 | 73 | 50.8 | 75 |
| 2 inch | regular | 42.9 | 45 | 44.8 | 50 |
| 1/2 inch | ultrasonic | 59.4 | ≈250 | 59.5 | 320 |
| 3/4 inch | ultrasonic | 59.3 | ≈250 | 59.2 | 200 |
| 1 inch | ultrasonic | 58.5 | 162 | 58.1 | 150 |
| 1 1/2 inch | ultrasonic | 57.8 | 143 | 55.4 | 105 |
| 2 inch | ultrasonic | 43.3 | 47 | 49.8 | 70 |

TABLE 35

VOLUME, WEIGHT AND HEAT CONTENT OF THE VARIOUS CUBE SIZES CONSIDERED AT 1900°F

| Cube Size (in) | Volume ($in^3$) | Weight[1] (pounds) | Heat Content at 1900°F[2] (BTU) |
|---|---|---|---|
| 1/2 | 0.125 | 0.0354 | 11.6 |
| 3/4 | 0.422 | 0.1194 | 39.1 |
| 1 | 1.000 | 0.2830 | 92.5 |
| 1 1/2 | 3.370 | 0.9540 | 312.0 |
| 2 | 8.000 | 2.2610 | 740.0 |

[1]Calculated using 0.283 pounds per cubic inch.

[2]Calculated using 327.6 BTU per pound based on specific heat and heat contents from Butts (III-7).

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