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NONDESTRUCTIVE DETERMINATION OF
GRAIN SIZE IN METALS

By
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August 1955

Sylvania Electric Products, Inc.
Bayside, New York

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Bayside, New York

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ABSTRACT

The grain size of a metal is a good indication of its inherent physical character. Grain size determination can also serve as a process control. Current methods of grain size determination are described: optical, X-ray, ultrasonic, and eddy current.

The technical and economical significance of nondestructive testing is considered.

The ultrasonic methods explored were: through transmission and pulse technique; amplitude decay, and back reflections counting. An explanation is given of the underlying principles. The results obtained on brass, steel, and zirconium are described. Generalizations of the test methods extend to metals with body-centered cubic, face-centered cubic, and hexagonal close-packed structures. The effects of certain concomitant factors, like grain shape, pearlite distribution in steel, are briefly explored. All tests are confined to metals with homogeneous structures.

This work indicates that ultrasonics can be used to determine the grain size of metals nondestructively.

I. INTRODUCTION

In the classical treatments of elasticity and the application of strength calculations to engineering structures, some of the basic assumptions are that the material is homogeneous and isotropic. The introduction of such an idealized material is a great aid in formalizing the analytical relationships between deformation and the resulting stresses for various geometries. The basic studies formulating the mode of transmission of mechanical vibrations in solids - including sound waves - again uses the model of an ideal, homogeneous, isotropic material.

Engineering metals are composed of aggregates of grains which have distinct properties. The grain size, grain shape, and grain orientation are among the most important variables which affect the properties of physical materials. This is why engineers are concerned with the grain structure of metals and alloys. The grain size affects the ductility, hardness and strength, ability to be hot or cold worked, and creep, magnetic, and damping properties. Above a certain dimension the grain size affects additional properties because the material ceases to be homogeneous in the engineering sense. When the majority of the grains has specific orientation, the material is said to have preferred orientation, which in turn affects the behavior under loading because the material is no longer isotropic.

Since the knowledge of grain size is of importance to designers, various testing methods have been developed to determine them. This paper reviews the known methods in use, with special emphasis on the ultrasonic techniques.

II. PREPARATION OF SUITABLE SAMPLES

The time-consuming and somewhat involved aspect in grain size studies is the preparation of suitable samples. It is desired to have equiaxed, uniform, randomly oriented grains. Certain metals are well adapted to techniques which will produce such samples. In the present study three different metals were investigated:

Brass (face-centered cubic)
Steel (body-centered cubic)
Zirconium (close-packed hexagonal).

A. Brass

Commercially obtained 1-1/2" round brass rods were used. The chemical analysis is listed in Table I.

TABLE I

CHEMICAL COMPOSITION OF BRASS SPECIMENS

	<u>Copper</u>	<u>Lead</u>	<u>Tin</u>	<u>Zinc</u>
Analytical Percent	64.1	3.5	0.0	32.4

In order to obtain specimens with different grain sizes, 2-1/2" long cylinders were cut from the bar and heat treated at a suitable temperature for different lengths of time. After several trials, 1500°F was found to be a suitable temperature for this purpose; the time for the heat treatment to yield specimens with the desired grain sizes is listed in Table II.

TABLE II

HEAT TREATMENT AND MECHANICAL PROPERTIES

<u>Specimen No.</u>	<u>Length of Heat Treatment at 1500°F</u>	<u>Average Grain Size, mm.</u>	<u>Hardness, Rockwell B</u>
1	As Received	0.015	71
2	15 min.	0.025	23
3	45 min.	0.035	21
4	90 min.	0.045	19
5	8 hrs.	0.065	14
6	24 hrs.	0.090	10
7	96 hrs.	0.150	3
A*	None	0.015	77

* Axially compressed to 10% permanent deformation

All specimens were finish machined to 1-1/2" diameter and 2" long. Representative photomicrographs are shown in Figs. 1 and 2.

B. Steel

There are three variables in a given plain carbon steel with a pearlitic structure:

1. Grain size
2. The spacing of the pearlitic lamellae
3. The amount of free ferrite.

These variables are not completely independent of each other, and the range over which they can vary will be limited by the chemical composition and the mill history of the steel. In the present investigation two variables were controlled: the grain size and the pearlitic spacing. Chemical composition and mechanical properties are listed in Table III.

TABLE III

CHEMICAL COMPOSITION AND MECHANICAL PROPERTIES (AS RECEIVED)

	<u>%C</u>	<u>%Mn</u>	<u>%P</u>	<u>%S</u>	<u>%Si</u>	<u>Grain Size, mm.</u>
Ladle	.15	.47	.014	.035	.09	5 to 7
Check	.17	.48	.012	.039	.09	

Yield Point, psi Tensile Strength, psi Elongation, % in 8 in.

35,520

58,770

25.5

Prior to the heat treatment of test bars, it was necessary to determine the limits between which the grain size and spacing in the pearlite could be varied and the degree to which desired combinations of these two variables could be reproduced. To determine the grain growth characteristics of this steel, samples were cut from the bar and heated to temperatures varying from 1500° to 2000°F in 50° steps. Microscopic examination of these samples revealed that it was possible to produce only two grain sizes; a fine grain size with austenitizing temperatures between 1550° and 1750°F and a coarse grain size over the range from 1850° to 2000°F. Within these two temperature ranges, only slight variations in grain size occurred. The interval between 1750° and 1850° represents the range over which the transition from fine to coarse grains took place. Representative photomicrographs are shown in Fig. 3.

As a result of this study, 1650°F was chosen to produce the fine-grained test bars, A.S.T.M. grain size No. 8 (approx. 25 microns), and 1900°F for the coarse-grained A.S.T.M. grain size No. 2 (approx. 200 microns).

A variation of pearlitic spacing was obtained by hot quenching a second series of specimens from the chosen austenitizing temperature to a series of lower temperatures and isothermally transforming the austenite to pearlite at these temperatures. The hot quenching temperatures tried were 1050°, 1100°, 1200°, and 1300°F. The transformation produced at 1300°F was fairly coarse pearlite, the spacing gradually becoming finer at the lower temperatures. Two holding times at the hot quenching temperatures were tried, one hour and six hours, but the longer time produced too much spheroidization of the carbide to be useful. In the preparation of the test bars four heat treating cycles were employed: (a) heated to 1900°F, held for one hour, furnace cooled to 1650°F, then hot quenched to 1300°F and held for one hour (large grain, coarse pearlite); (b) 1900°F, held for one hour, furnace cooled to 1650°F then hot quenched to 1100°F and held for one hour (large grain, fine pearlite); (c) 1650°F held one hour, then hot quenched to 1300°F and held for one hour (small grain, coarse pearlite); (d) 1650°F held for one hour, then hot quenched to 1100°F and held there for one hour (small grain, fine pearlite). The intermediate cooling step for the large grain specimens - i.e., furnace cooling from 1900° to 1650°F - was employed to insure a variation in grain size while still maintaining identical cooling curves during the hot quenching operation; thus obtaining similar pearlitic spacing, regardless of grain size. The resulting photomicrographs are illustrated in Fig. 4.

All samples were finish machined to 1-1/2" diameter, 2" long.

C. Zirconium

Prior history of the stock material as received: Grade 1 crystal bar which had been chopped up, arc melted, heated to 1450°F for two hours, and forged to 1-7/16-inch square.

A section of as-received billet was cold rolled to 1-1/4-inch round (45% area reduction of as-received stock). Appropriate annealing temperatures and times were determined using samples of the cold-rolled material. The test specimens were inserted into a furnace at temperatures, annealed for the desired length of time and withdrawn into a cooling chamber. Surface protection was afforded by sealing the bars in vycor capsules or

by heating the bare specimens in tank argon atmosphere. The specimens were machined to the same lengths before testing. The effect of annealing temperature on the hardness of zirconium is shown in Fig. 5. Results of mechanical tests are shown in Table IV.

TABLE IV

ANNEALING CONDITIONS, RESULTING HARDNESSES & GRAIN SIZES-ZIRCONIUM

<u>Specimen Number</u>	<u>Annealing Temp., °F</u>	<u>Time at Temp., Min.</u>	<u>Vickers Hardness No. (a)</u>	<u>Avg. Grain Size, mm.</u>
As received			100 (b)	
Cold rolled			128	
9	1020	30	90	0.005
10	1200	30	82	0.011
6	1200	60	78	0.025
7	1470	40	72	0.007
8	1520	30	69	0.094

(a) 30 kg. load; average of two center and two edge hardnesses.

(b) 30 kg. load; average of 25 impressions.

The photomicrographs are shown in Fig. 6. All samples were machined to 1-1/8" diameter, 2" long.

III. VARIOUS TESTING TECHNIQUES

A. Light Waves

With the visible spectrum of the light waves, the suitably prepared surfaces of metals can be examined under magnification to determine the grain size and grain shape. If confined to the metal surface itself, the examination can be nondestructive. This is the most frequently used method and the only one that gives a direct measurement.

B. X-Ray Methods

X-rays can be used under certain conditions to determine the grain size of metals. The results can be both qualitative and semi-quantitative. There are three techniques in use:

1. Diffraction Method

The specimen of any geometry can be tested. A fine X-ray beam is aimed at the surface, and the resulting diffracted wave is photographed. If the sample consists of randomly orientated, stress-free, fine-grained materials, the resulting pattern is a sharp continuous line. Large grained, randomly oriented metals show a broken up, but sharply defined pattern. Preferred grain orientation gives a discontinuous pattern, symmetrical about an axis. If the metal has residual stresses, the diffraction pattern becomes broadened and blurred. Thus, it is possible to distinguish between grain size and grain orientation in one single test. Schematic diagrams are shown in Fig. 7. (For detailed treatment of the diffraction method see standard textbooks).

2. Geiger Counter Method

Specimens with flat surfaces are irradiated at an angle by an X-ray beam and slowly moved under the beam. The reflected energy is measured with a Geiger counter. Groups of small, randomly oriented grains will not differ much in reflectivity as the beam scans a given volume. If the grains are large, however, the reflectivity will vary. Thus the fluctuations in the recorded energies are a measure of the grain size. This is a qualitative method and can be used as a "go, no-go" test.

3. Radiographic Transmission Method

For very thin metal foils of only a few grain layers, stereo-radiography is useful. When the stereo-radiographs are examined with a stereoscopic viewer the grain size and shape can be fairly accurately determined; this technique is limited, however, to metals that have some precipitation along the grain boundaries.

The X-ray method is limited to the spot checking of a small area and to a very limited depth below the surface. In certain applications it has the advantage that additional information concerning the grain orientation and shape can be gleaned from the test data.

C. Eddy Current Tests

A high-frequency alternating current passed through a suitable coil will have certain electromagnetic characteristics. When a metal core is placed inside this coil the characteristics of the system are affected. The changes are a function of such variables as the chemical composition of the core, the shape and size of the core, as well as other structural properties. In the modern eddy current test methods, the electric circuit has been refined to compensate a number of variables such as size and shape factors and to allow the determination of the other variables such as composition, structure, and hardness.

Using the commercially made testing equipment, the Cyclograph and the Forster Institute's Multitest, numerous experiments were conducted to determine the ability of eddy current instruments to measure grain size. The test results indicated that both types of instruments are capable of discriminating among specimens with different grain sizes, if the grain size ratio is greater than 5 to 1. The chief drawback of these equipments at present seems to be that it is most suitable for circular cross sections and in most instances it is confined to rod-shape specimens. The eddy currents penetrate only the skin layer of the samples, and therefore these testing techniques are most useful where the effects of surface heat treatment are to be measured and controlled.

The newer type of eddy current instruments using "probe" contacts which allow freedom from geometrical restrictions were not explored in the present study.

IV. ULTRASONIC TESTING

Oscillations which have a frequency of over 20,000 cps are designated as ultrasonic waves or vibrations. The velocity of propagation of waves is a constant for an ideally elastic medium - at a given temperature and vibration frequency. This problem was first considered by Navier⁽¹⁾ and later solved by St. Venant⁽²⁾. This analytical expression relates the velocity of wave propagation to the elastic constants and the density of the medium.* These ultrasonic waves are similar to light waves in that they tend to travel in straight lines, are reflected by the proper surfaces and can be deflected, and scattered by inhomogeneities.

Forced mechanical vibrations are attenuated as they traverse any real, physical medium. The practical significance of this attenuation or absorption is a diminishing in transmissibility to a level where the waves can no longer be detected and measured. It is quite likely that there are a number of contributing factors which diminish the transmissibility of these waves, and make the medium opaque or impermeable. The purpose of this investigation was to study one of these factors, namely the effects of grain size on ultrasonic transmissibility in a polycrystalline metal.

A. Apparatus

The Sperry Ultrasonic Reflectoscope Model UR was used for this investigation. A detailed description of the circuits and the use of the instrument is described in the Operating Manual. This instrument has fixed operating frequencies of 1/2, 1, 2-1/4, 5 and 10 megacycles per second. It can be used with any commercial search unit which generates longitudinal, shear, or surface waves. It is designed for one-crystal (reflection, echo-pulse) or two-crystal (transmitted, continuous wave) operation. See Figs. 8 and 9.

B. Testing Technique

Three different testing techniques were used during the course of investigation. They all gave consistent and congruent results. For detailed analyses the method which appeared most reproducible and easily measured was utilized.

1. Pulse-echo method measuring the amplitude of the first back reflections. The crystal was placed on the circular base of the cylindrical specimen and after proper electronic adjustments the reflectogram of the smallest grain sample (least energy wave) was taken. Without changing any of the test conditions the same procedure was then repeated for all the test samples. When it was desired to switch to another frequency the electronic circuit was usually readjusted and then the same test series performed again.
2. Two-crystal transmission technique. To observe whether the testing procedure had an influence on the results a continuous wave was sent out by placing the transmitting crystal on the circular base of the cylindrical samples and the receiving crystal on the axially opposite face. Otherwise, the testing procedure remained essentially the same as under "1" above.

* Carefully conducted experiments showed good agreement with these theoretically derived values.(3,4)

3. Number of back reflections for a given constant setting of the Reflectoscope for the selected frequency was utilized. In this series of tests the height of the back-reflection was unimportant, and the measurements were oriented toward the determination of the number of visible multiple reverberations.

Of the methods described above, the multiple back-reflection technique proved to be most useful from a practical standpoint. Impurities or internal defects which influence the amplitude of the reflections do not affect the number of multiple reverberations. This technique yielded consistent and reproducible results and was utilized in the quantitative evaluation of the data.

V. RESULTS

A typical set of reflectograms, i.e., photographs of the cathode ray tube showing the ultrasonic reflections as a visual pattern, are illustrated in Fig. 10. The particulars of the test are given in Table V.

TABLE V

REFLECTOSCOPE SETTINGS FOR AMPLITUDE MEASUREMENTS

<u>Testing Technique</u> <u>Frequency</u>	<u>Pulse-echo Method</u>	
	<u>2-1/4 mc</u>	<u>5 mc</u>
Sensitivity	3	3
Sweep Length	0	0
Pulse Length	0	0
Pulse Tuning	7	3
Marker	Off	Off

This method of measuring the height of the first back reflection as a relative measure of transmissibility appeared very attractive because as in all wave motions the energy is proportional to the square of the amplitude. Tests which were performed at 1, 2-1/4, 5, and 10 mc all showed the same general trend: for a given setting of the Reflectoscope the amplitude of the reflection remained essentially the same and then as the ratio of the wave length to the grain size approached about 5 to 1 the amplitude rapidly diminished.

A word of caution is in place at this point. This whole investigation had a singular aim, namely, to study the effect of grain size on ultrasonic transmissibility. To get the most clearly cut indications, laboratory techniques were frequently used, instead of recommended commercial practices for this type of instrument. To briefly summarize these anomalous conditions, abnormally large grains were produced for these tests; frequencies were chosen which were not the optimum for the material tested; sensitivity (amplification) was not utilized to its fullest extent. In other words, it is not stated or implied anywhere in this report that in a short two-inch rod the ultrasonic transmission is attenuated to a level where it is hardly detectable. Rather, these results should be interpreted that just as it is possible to have the ultrasonic waves fade out in a short brass rod by purposely setting the Reflectoscope for such a condition, the reverse should be true also. For material and geometries which unduly attenuate the waves

of the present commercially marketed instruments the remedy is a more powerful Reflectoscope with suitable wavelengths and auxiliary circuits.

The second testing method explored was the use of continuously transmitted waves, using two crystals. The results thus obtained did not materially differ from those of the echo-pulse technique, and since the latter method is simpler to conduct, and especially lends itself to one-man operation, it was utilized for all of the tests reported herewith.

The third testing method made use of the number of back reflections for a given setting of the Reflectoscope. The particulars of the tests are listed in Table VI.

TABLE VI
REFLECTOSCOPE SETTINGS FOR MULTIPLE BACK REFLECTIONS

Testing Technique Frequency	Pulse-echo Method		
	2-1/4 mc	5 mc	10 mc
Sensitivity	2.5	3.5	3.5
Sweep Length	6	5	4.8
Pulse Length	0	0	0
Pulse Timing	5	4.8	4.5
Marker	Off	Off	Off

Representative Reflectograms are shown in Fig. 11. Results obtained by the multiple reflection method appeared more reproducible and less sensitive to test conditions than the other methods and were utilized to obtain a semi-quantitative evaluation of these tests. Fig. 12 and 13 show a plot of the number of back-reflections vs. the ratio of the wave length to the grain size. At least twelve readings were made for each test condition. The number of the back-reflections was determined from the various reflectograms; the velocity of sound in brass was taken as 11,480 feet per second⁽⁶⁾, and the grain sizes were as listed, Table II of this paper. For illustrative computation, see Appendix. This graphical plot confirms and illustrates the previously stated results, namely, the decrease of transmissibility takes place rather abruptly as the ratio of wave length to grain size approaches some critical value. At this time it is not known what this critical value depends upon, or all the factors affecting this value.

The transmissibility, as measured by the number of back reflections, is essentially constant for wavelength-to-grain-size ratios over 30 to 1. The reduction of transmissibility is quite rapid, as it can be observed in Fig. 12 and 13 when the wavelength - grain-size ratio is reduced below that value. The rate of decay, as indicated by the slopes of these portions of the curves is a complex function of several factors, and no conclusion should be drawn as to their significance on the basis of these tests alone.

The compressed specimen, which had internal residual stresses due to a 10% axial plastic deformation, exhibited the same ultrasonic properties as the specimen with the same grain size, but no axial compression. This indicates that the ultrasonic transmissibility effects, as observed in the present investigation, may be attributed to variation in grain size, and not some concomitant factor, like the level of stress relief occurring during the heat treating cycle which was utilized to produce the different grain sizes.

This does not imply, however, that residual stresses might not affect the ultrasonic transmissibility; it merely states that with the current experimental techniques employed, such a contributing factor - if it existed - could not be detected and identified.

Steel

Two of the variables were controlled in the present investigation: the grain size and the pearlitic spacing. At frequencies of 1, 2-1/4, 5, and 10 mc it was possible to distinguish between the large and the small grains by proper settings of the instrument. For sensitive determinations the 5 and 10 mc frequencies are preferred. The proper choice in practical application will depend, however, on the dimensions of the piece being tested.

No significant effect could be detected due to pearlitic spacing. It may be assumed that when the energy of the sound wave is sufficiently strong to travel freely across the grain boundaries without too much loss in energy, the intrinsic effects of the pearlite lamellae are inoperative. Corollary, if the energy level were reduced or the beam confined to such dimension as to be effected by the subgrain structure in the metal, no significant penetration within the metal would be obtained. Thus, it appears that ultrasonic waves are not suitable for simultaneous determination of grain size and subgrain properties.

Brass and Zirconium

A suitable graphic presentation of the effect of grain size on ultrasonic attenuation is to plot the number of back reflections as a function of the ratio of wavelength of grain size. In computing this ratio the average grain size was metallographically determined. The wavelength was determined by using the nominal sonic frequency of the instrument and the velocity of the sound wave in the metal obtained from handbooks. The results are plotted in Fig. 12 and 13. The critical value seems to vary with the material and the frequency. It appears that for brass the ratio is 30 to 1 and for zirconium about 50 to 1. Because of the metallurgical nature of the materials investigated, it was possible to produce wavelength-to-grain-size ratios of about 3-1/2 to 680 for zirconium; and a range of 4 to 105 for brass.

In a comparison of the two metals, a number of differences may be observed:

- a. The shape of the curves is the same for both materials.
- b. The shape of the curve is the same for any given test frequency.
- c. The effect of frequencies is much more pronounced for zirconium than for brass.
- d. The slope of the curve is more abrupt for brass, indicating greater sensitivity to grain size.
- e. The increase in testing frequency tended to decrease the number of back reflections in brass but had the opposite tendency in zirconium. Whether this is an intrinsic property of the material or a general property of the crystal structure is not known at this time.

VI. DISCUSSION

Most of the earlier references cited in connection with sonic and ultrasonic vibrations in solids assumed that the materials are ideally isotropic, perfectly and linearly elastic. It was only during recent years, when ultrasonics was commercially applied, that experiments were performed to account for deviations from this idealized medium. Among the first tests described were those by Firestone⁽⁷⁾ who used brass with different grain sizes and counted the number of multiple back reflections. Firestone used a frequency of 5 mc and the corresponding wavelength was given as 0.88 mm. The different grain sizes were obtained by varying the annealing temperature. His results are shown in Table VII.

TABLE VII

F. H. Firestone's Results

GRAIN SIZE VS. BACK-REFLECTIONS

<u>Grain Size</u> <u>mm</u>	<u>Number of</u> <u>Back-Reflections</u>
0.03	12
0.075	6
0.105	3

While the early ultrasonic instrument used in these tests worked on the same principle as the present commercial sets, no further comparisons are possible as far as settings, etc. are concerned. It is interesting to note however, that if the results in Table VII are plotted along with the data in Fig. 12 they show a surprisingly close agreement.

There is no adequate theory at the moment to explain the scattering and attenuation of ultrasonic waves in polycrystalline metals. Mason and McSkimin⁽⁸⁾ found that the energy absorption is proportional to the fourth power of the frequency, provided the ratio of the wavelength to grain size is greater than 3 to 1. They further attributed this attenuation to two components: one component of the loss is proportional to the frequency to the fourth power; the second is a normal hysteresis loss and its intensity is directly proportional to the frequency. Still another possible mechanism is listed for the case when the ratio of grain size to wavelength is 3 to 1 or greater, in which case the attenuated energy becomes independent of the wavelength, and is inversely proportional to the grain diameter. No adequate theory is suggested for the transition region.

Roth⁽⁹⁾ performed experiments on aluminum and magnesium. He found that when the wavelength to grain size is quite small (10 to 80 mc/sec frequency; grain size 2 mm) the attenuation is hardly affected by the frequency. As the grain size is reduced to about 0.21 mm, the degree of transmissibility becomes a function of the frequency.

Unfortunately the results of the above two investigations cannot be quantitatively compared with those of the present study, because of the entirely different experimental techniques used. They do confirm, however, one salient aspect. The ultrasonic transmissibility in polycrystalline metals is a complex mechanism with a number of independent variables.

The findings of Bastien and co-workers⁽¹⁰⁾ are essentially the same. When the wavelength-to-grain-size ratio became less than 2.1 to 1 for nickel-chromium-molybdenum steel plates, the material became impermeable to ultrasonic waves.

In the present investigation three commercial metals (alloys) were studied. Because of the limited range under which the grain size of mild steel can be varied only qualitative results were obtained for mild steel. The results indicated an increased attenuation with increasing grain size which made it possible to differentiate between large and fine grained material of the same chemical composition by the proper setting of the ultrasonic testing instrument. The subgrain structure of the metal did not perceptibly affect the traversing sound waves. Brass and steel can readily be made into a series of experimental samples having a wide range of uniform grain sizes. When the number of back reflections were plotted as an index of the transmissibility in the metal against the ratio of the wavelength to grain size, a family of curves were obtained indicating the same basic trend; there is a critical value above which the grain size did not affect the sound transmission and below which there is a sharp attenuation in energy. The order of these curves were in the opposite for brass and zirconium. Whether this is an intrinsic property of the crystal structure - brass (face-centered cubic) zirconium (close-packed hexagonal) - is not known at this time. Further experimental work using other metals having the same crystal structure may shed more knowledge on this topic.

In an attempt to tie in the mechanical-acoustical properties of the materials with the test results, the acoustic impedance of the metals was computed. Table VIII lists some of the important mechanical constants used in computing the acoustic impedance.

TABLE VIII

<u>Material</u>	<u>Modulus of Elasticity</u> <u>lb/in²</u>	<u>Density</u> <u>lb/in³</u>	<u>Velocity of Sound</u> <u>Propagation</u> <u>ft/sec.</u>	<u>Acoustic</u> <u>Impedance</u> <u>lb/sec/in³</u>
Brass*	16 x 10 ⁶	0.30	11,480	110
Steel**	30 x 10 ⁶	0.28	16,410	144
Zirconium**	11 x 10 ⁶	0.23	11,350	81

* "Mark's Mechanical Engineers' Handbook", McGraw Hill, 1951 - pp. 598,1676

** "Metals Handbook", A.S.M., 1948 Edition - pp. 20,21.

The acoustical impedance is defined as the product of the density and the velocity of the sound in the metal - using the correct and consistent units for both the density and the velocity. From the values in Table VI it appears that the acoustic impedances for the three materials are of the same order of magnitude and do not explain the differential behavior of brass and zirconium. It is interesting to point out the physical significance of the specific acoustic impedance of a metal: the units are pound-seconds per cubic inch. The pound-second is the measure of the impulse in mechanics of the materials. Thus, the acoustic impedance can be defined as the impulse per unit volume. The decay curve of the attenuated sound wave can be considered therefore as a measure of the resistance to impulse per unit volume.

The accuracy of the grain size measurements by ultrasonics depends upon the average grain size and the frequency of the sound waves. Under the conditions specified in this report and for the metals tested, the limits of accuracy can be expressed as: $D \pm 1/4 D$, where D is the average grain diameter.

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APPENDIX

COMPUTATION OF WAVELENGTH-TO-GRAIN-SIZE RATIO

Velocity = Frequency x Wavelength

$$\text{Wavelength} = \frac{\text{Velocity}}{\text{Frequency}} \text{ or } L = \frac{V}{f}$$

Example 1.

Brass, frequency 5 mc
(See Table VIII.)

$$L = \frac{11,480 \times 12 \text{ in/sec}}{5,000,000 \text{ 1/sec}} = 0.275 \text{ in.}$$

Specimen No. 6, average grain size 0.090 mm
(See Table II.)

$$\frac{\text{Wavelength}}{\text{Grain Size}} = \frac{0.0275 \text{ in.}}{\frac{0.090}{25.4} \text{ in.}} = \underline{\underline{7-3/4}}$$

Example 2.

Zirconium, frequency 10 mc
(See Table VIII.)

$$L = \frac{11,350 \times 12 \text{ in/sec}}{10,000,000 \text{ 1/sec}} = 0.0136 \text{ in.}$$

Specimen No. 10, average grain size 0.011 mm.
(See Table IV.)

$$\frac{\text{Wavelength}}{\text{Grain Size}} = \frac{0.0136 \text{ in.}}{\frac{0.011}{25.4} \text{ in.}} = \underline{\underline{31-1/2}}$$

LONGITUDINAL

0.015

0.025

0.035

0.045

TRANSVERSE

Average Grain Size in Millimeters
For Brass Specimens Tested

Fig. 1

LONGITUDINAL

TRANSVERSE

0.065

0.090

0.150

After 10% Compression

0.015

Fig. 2

Average Grain Size in Millimeters
For Brass Specimens Tested

21

-21-

Fig. 3

1900°F 1 HR. COOLED TO 1650°F IN FURNACE,
HOT QUENCHED TO 1100°F. HELD 1 HR.

LARGE GRAINS

1650°F FOR 1 HR.,
HOT QUENCHED TO 1100°F. HELD 1 HR.

SMALL GRAINS

FINE PEARLITE

1900°F 1 HR. COOLED TO 1650°F IN FURNACE,
HOT QUENCHED TO 1300°F. HELD 1 HR.

1650°F FOR 1 HR.,
HOT QUENCHED TO 1300°F. HELD 1 HR.

COARSE PEARLITE

MAGNIFICATION • 1500 X

GRAIN SIZES AND PEARLITIC SPACINGS OF LOW CARBON STEEL SPECIMENS TESTED

Fig. 4

THE EFFECT OF ANNEALING TEMPERATURE ON THE
HARDNESS OF ZIRCONIUM.

Fig. 5

Average Grain Size in Millimeters of Zirconium
Specimens Tested

As Received

0.025

0.005

0.087

0.011

0.094

Magnification 250X

TRANSVERSE SECTIONS

Fig. 6

SCHEMATIC X-RAY DIFFRACTION PATTERNS

RANDOMLY ORIENTATED, STRESS FREE
FINE GRAINED METAL

RANDOMLY ORIENTATED, LARGE
GRAINED METAL

PREFERRED GRAIN ORIENTATION

RESIDUAL STRESSES

Fig. 7

26

Fig. 8

27

Fig. 9

REFLECTOGRAMS

HEIGHT OF FIRST BACK REFLECTION AS A FUNCTION OF GRAIN SIZE

Fig. 10

REFLECTOGRAMS

NUMBER OF BACK REFLECTIONS AS A FUNCTION OF GRAIN SIZE

Fig. 11

30
BRASS

Fig. 12

THE NUMBER OF BACK REFLECTIONS COMPARED WITH WAVE LENGTH TO GRAIN SIZE RATIO — ZIRCONIUM

Fig. 13

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