N-63-4-3

245200

May 15, 1963
DMIC Memorandum 166

LITERATURE SURVEY ON THE EFFECT OF SONIC AND ULTRASONIC VIBRATIONS IN CONTROLLING GRAIN SIZE DURING SOLIDIFICATION OF STEEL INGOTS AND WELDMENTS

DEFENSE METALS INFORMATION CENTER
BATTELLE MEMORIAL INSTITUTE
COLUMBUS 1, OHIO

The Defense Metals Information Center was established at Battelle Memorial Institute at the request of the Office of the Director of Defense Research and Engineering to provide Government contractors and their suppliers technical assistance and information on titanium, beryllium, magnesium, refractory metals, high-strength alloys for high-temperature service, corrosion- and oxidation-resistant coatings, and thermal-protection systems. Its functions, under the direction of the Office of the Secretary of Defense, are as follows:

1. To collect, store, and disseminate technical information on the current status of research and development of the above materials.

2. To supplement established Service activities in providing technical advisory services to producers, melters, and fabricators of the above materials, and to designers and fabricators of military equipment containing these materials.

3. To assist the Government agencies and their contractors in developing technical data required for preparation of specifications for the above materials.

4. On assignment, to conduct surveys, or laboratory research investigations, mainly of a short-range nature, as required, to ascertain causes of troubles encountered by fabricators, or to fill minor gaps in established research programs.

(15) Contract No. AF 33(616)-7747
(16) Project No. 2(8)(8975)

TABLE OF CONTENTS

LITERATURE SURVEY ON THE
EFFECT OF SONIC AND ULTRASONIC VIBRATIONS IN CONTROLLING GRAIN SIZE
DURING SOLIDIFICATION OF STEEL INGOTS AND WELDMENTS

J. G. Kura and H. W. Mishler*

PART I - STEEL INGOTS

INTRODUCTION

The literature on the metallurgical effects of vibrational treatments is fairly extensive. For example, Hiedemann(1)**, in his review in 1954, referenced 100 publications. Of these, 22 were review articles, 51 were patents, and 27 were original research papers.

The first reference to the application of ultrasonics to the grain refinement of steel was a British Intelligence Objectives Subcommittee report(2) on the unsuccessful work performed by Schmid and co-workers during World War II. Since then, appreciable gains have been made in utilizing sonics and ultrasonics for grain refinement of steel.

Although active interest in the treatment of molten metals with vibrational energy has existed for over 30 years, progress has been slow. A major reason for this was the lack of experimental details in the earlier publications, which made it difficult to duplicate experiments and resolve conflicting results. In turn, the lack of experimental details was probably a consequence of a lack of understanding of the parameters controlling the observed results. Many of the controlling parameters are now known, but a theory to explain the mechanism by which sonic or ultrasonic vibrations achieve grain refinement during solidification has not yet been universally accepted.

A review is presented here in detailed abstract form of the pertinent papers dealing with grain refinement of ferrous alloys by vibrational energy. The present state of the art is summarized, and the directions that may lead to fruitful further progress are indicated.

SUMMARY OF REPORTED INVESTIGATIONS

Ferrous Alloys

Hinchliff and Jones(3) obtained grain refinement and improved mechanical properties in gas turbine blades cast in investment molds

*Research Associate, Process Metallurgy Division, and Senior Welding Engineer, Metals Joining Division, Battelle Memorial Institute.

**References are listed at the end of Part I.

vibrated at low frequencies. The composition of the steel was: 0.20C, 0.40Mn, 1.60Si, 23Cr, 11.5Ni, 3W. The steel was poured at 2630 to 2820 F in silicate-bonded sillimanite molds preheated to 1830 F. The molds were vibrated in a vertical direction at frequencies up to 1000 cps. Ranges for the amplitude at the various frequencies were not stated, but a value of 0.005 inch was mentioned. Structural change in the castings was attributed to both the frequency and the amplitude, with the frequency being the more important factor. This conclusion is questionable, since the effect would be zero at zero amplitude for any frequency, and vice versa. If the product of frequency and amplitude is what counts, then both factors are of equal importance. A value of 2π times this product is the velocity amplitude of the vibration generator. The particle velocity of the sound wave in the metal, the maximum stress amplitude, the energy flux in a progressive wave, and the stored energy in a standing wave are all directly related to the velocity amplitude of the generator through the specific acoustic impedance of the medium (density x propagation speed), the geometry of the vessel (which determines the resonant nodes of vibration), and other factors as well. If it does turn out that, for the grain-refinement process, the velocity amplitude of the generator ($2\pi fA$) is an important factor over a wide range of frequencies, this result would correspond to that applicable to other sonic processing methods.) Improvement in properties was most marked at the higher pouring temperature with a vibration frequency of 48 cps.

	Static Casting	Vibrated Casting
Ultimate Tensile Strength, psi	81,800	95,000
Elastic Limit, psi	35,200	47,300
Elongation, %	33	41
Reduction in Area, %	27	36
Balanced Impact, ft-lb	9.6	13
Grain Size, grains/sq in.	3	15

Leont'ev[4] reported grain refinement in a free-cutting steel cast in an ingot mold vibrated at 440 cps at a velocity of 8 inches per second by impact from the bottom of the mold. However, segregation of a eutectic band occurred toward the periphery of the 66-pound ingot. He considered the pressure in a sound wave to be proportional to the vibration velocity of the melt. At a sufficiently high pressure, droplets (from cavitation) were ejected from the melt and he reasoned that violent mixing in this area created a uniform temperature and a fine-grained structure. Thus, he used vibration velocity as the parameter for measuring when grain refinement would occur.

Grain refinement was most marked when the ingot was separated from the mold. (The significance of this statement is not clear. Also, one would deduce that the ingot must be vibrated at an intensity severe enough to produce violent cavitation in order to obtain grain refinement and that such an ingot contains numerous entrapped gas bubbles.) To produce a sound ingot, he stated that the vibrational velocity must be low enough to avoid ejection of droplets from the melt. The velocity is found from the equation $v = 2\pi fA$, where f is the frequency and A is the amplitude.

N. P. and E. N. Nikolaichik[5] gave very few details for their experiments with rimming steel, medium-carbon steel, and cast iron. The rimming steel was cast in a bottom-gated iron mold measuring 8 by 8 by 20 inches. A magnetostriction vibrator supplied energy (at an unstated frequency) through a coupling rod inserted in the top of the melt. (It was not clear whether the carbon steel and the cast iron were investigated in this mold or in a 2-3/16-inch-diameter by 6-inch iron mold with the coupling bar from the magnetostriction vibrator fitted through a sliding seal in the bottom of the mold.)

Details on ingot structure were given only for the rimming steel. Its composition was: 0.07C, 0.34Mn, trace of Si, 0.021P, 0.023S, 0.059 O, and 0.026N. After treatment, only a trace of oxygen and nitrogen remained as a result of the strong stirring and rapid gas evolution during the treatment. The ingot had blowholes ranging from 0.02 to 0.08 inch in a region 1 to 1-1/2 inches from the surface and only in a small percentage of the cross section. Without treatment, the ingot had blowholes ranging from 0.2 to 1 inch clustered as close as 3/8 inch from the surface and spread over half of the cross section. The following properties were given for the materials studied:

	Tensile Strength, psi		Elongation, %		Grain Size No.	
	Treated	Not Treated	Treated	Not Treated	Treated	Not Treated
Rimming Steel	66,900	49,800	50	30	8	5-7
0.45C Steel	106,700	64,000	20	15	-	-
Cast Iron	79,700	25,600	5	0	-	-

About a year later, Unterweiser[6] reported on the reaction by a major United States steel company to the use of ultrasonic treatment by the Russian investigators to produce a nonaging rimming steel. Although the marked reduction in the oxygen and nitrogen content was impressive, it was suggested that equal results might be achieved by vacuum stream degassing. Ultrasonic treatment on a commercial scale was considered to be basically inefficient (probably meant uneconomical). (No comment was made on alternative means for the grain refinement produced by the ultrasonic treatment of the rimming steel.)

The paper by Kasumzade[7] was not available to present here the details of his experiments. He postulated that small crystals formed on the mold wall were carried into the body of the steel melt under the action of vibrations, and that this accounted for the observed grain refinement.

Gurevich, et al.,[8] investigated the effect of ultrasonic vibrations on stainless steels cast in steel molds as 2.2 to 4.4-pound ingots. The coupling rod from a magnetostriction vibrator was fitted through a sliding seal in the bottom of the mold. A steel disk in the bottom of the mold prevented sticking of the ingot to the mold bottom. The smallest ingot measured

3 inches by 1-1/2 inches in diameter. The 10-kw tube oscillator produced a frequency of 18 kc with an output of 1 kw.

Ultrasonic treatment reduced the grain size to 1/5 that of unvibrated ingots of the 25Cr-20Ni alloy. Dendrites (probably means columnar grain structure) were eliminated and segregation was greatly reduced in this alloy and in cast iron. In the 27Cr alloy, the grain size was reduced to 1/2 to 1/3 that of unvibrated ingots. In both stainless steels, the nonmetallic inclusions were distributed more uniformly by the ultrasonic treatment.

Although ultrasonic treatment did not reduce the gas content of the ingots, the 25Cr-20Ni alloy developed macrocavities in the lower portion of the ingot when the vibration intensity was high. Cavitation was believed to be the cause for the macrocavities. The 27Cr steel resisted cavitation and it was free of these defects.

Mechanical properties of the cast metal and workability of the ingot were improved by the ultrasonic treatment. The difference in the mechanical properties of treated and untreated ingots was reduced somewhat after they were given a homogenization heat treatment and were hot reduced 80 per cent.

N. P. and E. N. Nikolaichik(9) found a remarkable improvement in the structure and properties of ultrasonically treated iron having the composition 3.1C, 2.0Si, 0.7Mn, 0.25P, 0.07S. A 20-kc magnetostriction vibrator was coupled by an iron rod through the bottom of a chilled metal mold. The vibrated ingot had a fine, uniform structure rather than the normal pearlite and cementite. The tensile strength was raised from 28,400 to 85,300 psi, and the elongation was raised from zero to a range of 0.5 to 1 per cent. Hardness remained at the initial level but was more uniform.

When the iron was cast in a sand-clay mold, the ultrasonic treatment produced finer ferrite and pearlite grains and the graphite nodules were also finer and rounder. Tensile strength was raised from 24,200 to 66,800 psi, and the elongation was raised from zero to a range of 3 to 5 per cent. Hardness was more uniform and at a higher average value.

Romanov and Umrikhin(10) used a system of rotating eccentric weights (a cam system) to vibrate an ingot mold at frequencies ranging from 3-1/3 to 33-1/3 cps at an amplitude of 0.02 to 0.08 inch. The compositions of the steels studied are shown in Table 1.

Degassing, improved soundness, grain refinement, and improvement in mechanical properties were obtained when the acceleration due to vibration was greater than the acceleration of gravity (1 G). Best results with ingots weighing up to 440 pounds were obtained with a frequency of 19 cps and an amplitude of 0.04 inch. (From the photographs it appeared that the ingots ranged in length from 4 to 6 times the diameter.)

In 35-pound gassed melts of the 12KhN3A alloy, blowholes collected at the periphery of the ingot when the mold was not vibrated, but were randomly distributed at the axis when vibration was applied. In 220-pound rimming-steel ingots, the bubble-free rim was 0.08 to 0.12 inch thick when

TABLE 1. COMPOSITIONS OF STEELS STUDIED(10)

Designation	Composition, %							
	C	Mn	Si	Cr	Ni	P	S	Others
12KhN3A	0.17 max	0.30-0.60	0.17-0.37	0.60-0.90	2.75-3.25	0.040 max	0.040 max	
12KhN4A	0.17 max	0.30-0.60	0.17-0.37	1.25-1.75	3.25-3.75	0.040 max	0.040 max	
38KhM10A	0.35-0.42	0.30-0.60	0.17-0.37	1.35-1.65	0.40 max	0.035	0.030	0.15-0.25Mo 0.80-1.10Al
18KhNMA	0.15-0.22	0.40-0.70	0.17-0.37	0.40-0.60	1.6-2.0	0.040	0.040	0.20-0.30Mo
18KhGM	0.16-0.24	0.90-1.20	0.17-0.37	0.40-1.2	0.40	0.040	0.040	0.20-0.30Mo
18KhGT	0.16-0.24	0.80-1.10	0.17-0.37	1.00-1.30	0.40	0.040	0.040	0.08-0.15Ti

not vibrated and 1.2 to 1.4 inch thick when vibration was applied. The gas holes were drastically reduced in size and quantity in the vibrated ingots.

Vibrated ingots of the 38KhM10A alloy developed a banded structure 0.6 to 0.8 inch away from the surface. These bands were rich in C, S, P, and Cr. Because this steel was known to be viscous in the liquid state, it was reasoned that the segregation, which normally would be distributed in the columnar grain regions, accumulated ahead of the freezing front during vibration and became trapped by the freezing front because the viscosity of the melt did not permit sufficiently rapid diffusion or mixing. In steels less viscous than the 38KhM10A, vibration would be expected to promote banding if the melt had a high gas content and a slow solidification rate, such as might be encountered in a 5-ton ingot of 18KhGT alloy. Under the same conditions, banding would not be expected in vibrated ingots of the 18KhGM alloy. (The reasons for this statement were not given.)

Leont'ev(11) used the identical mold and ultrasonic generator and coupling system used by Gurevich(8) to study the same stainless steels that Gurevich studied. However, many more details were presented.

The coupling bar from the magnetostriction vibrator had a conical shape. Power intensity at the small end is greater than at the large end, in proportion to the area by which the large end exceeds the small end. The length of the bar is determined by

$$l_k = \frac{C}{2f_v}\sqrt{1 + \left[\frac{\ln\frac{D_o}{D_k}}{\pi}\right]^2} ,$$

where C = speed of sound in the rod

f_v = resonance frequency of the vibrator

D_o = diameter at the wide end of the conical bar

D_k = diameter at the narrow end of the conical bar.

(The radical in the above formula is essentially equal to unity and hence has little effect, unless

$$\frac{D_o}{D_k} \geq \sim 10.)$$

The length of the rod coupling the conical bar to the mold bottom is determined by

$$l_c = \frac{C}{2f_v} .$$

The coupling bars and the disk serving as a false bottom in the mold were made of steel. As a result of the ultrasonic vibration, the melt welded to the false bottom, thus isolating the ingot from direct coupling in the mold. At the same time, the melt welded to the coupling bar to provide efficient transfer of the acoustical energy into the melt. When the melt temperature was in excess of 3270 F, the face of the coupling bar was melted to a depth of over 3/8 inch. For this reason and because of cracking, this portion of the coupling system was frequently replaced.

It was found that the minimum power input having a noticeable effect on the structure had to be exceeded by a factor of 2 to 2-1/2 to assure a stable (probably meant reproducible) structural change was obtained in the ingot. The noticeable effect was associated with the power intensity that started to initiate wetting between the melt and the coupling rod. However, the high power intensity for stable structural change in the ingot frequently developed stresses large enough to break the weld between the ingot and the coupling bar.

A 25Cr-20Ni steel ingot weighing 2.2 pounds had a total solidification time of 40 to 45 seconds. Little structural change was noted until the time of ultrasonic treatment exceeded 3 to 4 seconds. If a rupture occurred in the weld between the ingot and the coupling bar after this critical time period, the whole ingot had a grain-refined structure as if the coupling efficiency had not been lost.

As was found by Gurevich, the 25Cr-20Ni steel was more readily grain-refined by ultrasonic treatment than the 27Cr steel. Microporosity observed in the bottom portion of the ingots was attributed to ruptures initiated by severe cavitation and the ingress of gas into these cavities. Rapid solidification of the 2-1/4-pound ingots trapped these gas cavities essentially where they were formed.

Two theories were considered to explain grain refinement by ultrasonic treatment. One was that the initial crystals formed on the coupler face were fragmented and dispersed throughout the melt to serve as nuclei. The other theory was that nuclei were developed as a result of induced supercooling. The former process was verified by direct observation of crystallizing hyposulfite. The latter process was also observed directly in supercooled organic substances.

Leont'ev reasoned that liquid metals required a critical time period for loss of superheat and attainment of sufficient supercooling for ultrasonic energy to be effective in refining the structure. The lack of grain refinement in 1Kh18N9 steel (composition not given) was attributed to lack of sufficient ultrasonic energy to achieve the high degree of supercooling that this steel normally undergoes.

Ultrasonic vibrations caused aluminum particles suspended in benzene to flow in a central path away from the coupler and return along the path of the mold wall. This mixing action of simulated nuclei was more pronounced in wide than in narrow molds. (This "ultrasonic wind" phenomenon has been observed in many liquids and gases and is predicted by nonlinear wave propagation theory.) Experiments with steel melts showed that a larger percentage of the ingot volume was fine-grained in the wider molds. It was stated that this result could also be attributed to the slower cooling rate of a wider ingot, causing slower growth of columnar grains on the mold walls and permitting time for nuclei to be distributed throughout the melt.

Thus, the preferred theory was that ultrasonic energy stirs the melt and supercools it so that conditions are reached under which numerous stable nuclei appear. These nuclei grow simultaneously to produce a fine-grained structure.

Wright, et al.,[12] successfully eliminated the large columnar grains in a vacuum-arc-melted rotor steel by applying ultrasonic energy during the melting process. The columnar grains formed in the 6-foot, 12-inch-diameter ingot under normal melting practice promoted segregation. This segregation produced a banded structure and directional properties in the forging. The composition of the steel was: 0.30C, 0.60Mn, 0.20Si, 2.75Ni, 0.50Mo, 0.10V.[13]

The magnetostriction generator was an electronic type with an output rating of 10 kw. The transducer had a resonant frequency of 18 kc and a rating of 1.5 kw. It was cooled with water flowing at a rate of 2 to 3 gallons per minute. The coupling bar was a converging horn which was inserted in the bottom of the furnace and threaded to a starting plate. An O-ring seal insulated the starting plate from the furnace wall. The initial arc created a weld that covered 60 per cent of the interface between the starting plate and the ingot.

During melting there was little change in the resonant frequency as the ingot length increased. Some change was observed in electrical impedance at the start, probably as a result of increased mechanical loading as the ingot started to grow.

When no vibration was applied, the ingot had large columnar grains in the lower 15 inches. The rest of it was fine grained. The vibrated ingot was fine grained in the lower 17 inches. The rest of it was slightly coarser than in the nonvibrated ingot. A void in a localized area at the center of the vibrated ingot was not directly attributed to the vibration treatment, even though this spot was at a node in the wave pattern.

It was speculated that grain refinement did not extend beyond 17 inches because of attenuation; i.e., metals at high temperature are less efficient conductors of acoustical energy. Because the limiting factor appeared to be the distance over which the sound waves could be transmitted effectively, rather than the power input per pound, it was predicted that 1-ton ingots could be grain refined with reasonable vibrational energy input by increasing the ingot diameter. (This makes sense in accordance with our knowledge of wave propagation.)

Wright questioned whether the relatively low acoustic energy which he used could produce a strain large enough to fracture the plastic primary crystallites, and thus account for the nucleation effect. He also thought that nucleation by cavitation at the solid-liquid interface was unlikely, because the power density which he used would not cause cavitation a few inches beyond the coupling bar.

Lane, et al.,[14] applied ultrasonic vibration to a melt of a 0.5C-18Mn-5Cr alloy in a 2-1/2-inch-diameter, vacuum-arc-melting furnace in a manner similar to that of Wright[13]. The 400-watt transducer with an unloaded resonance frequency of 20 kc could be tuned from 5 to 60 kc.

The initial arc was struck at a high current to obtain a maximum weld area between the ingot and the starting plate for minimum loss in transmission of the acoustical energy. Then the arc current was reduced to the lowest value that would produce a sound ingot, and the transducer was energized.

A small piezoelectric transducer near the base of the prime transducer was used to measure the amplitude of the generated waves. By observing the wave form on an oscilloscope, the frequency could be adjusted to keep the amplitude of the wave at a maximum. Thus, power input to the transducer was maintained at a maximum level and, as the ingot length increased, the ingot was vibrated at a point near resonance at all times.

The vibrated ingot had markedly suppressed columnar grain growth.

Lane, et al.,[15] presented much more detail in their continued studies of ultrasonic energy applied to a 2-1/2-inch-diameter, vacuum arc furnace for producing ingots of a 0.5C-18Mn-5Cr steel. The work was expanded to include melting of Type 316 stainless steel in a 6-inch furnace.

The coupling bar in the small furnace was pure iron and was energized by a variable-frequency ultrasonic generator providing 400 watts of power input. As melting progressed, the frequency was varied to maintain the system near resonance in order to achieve maximum energy introduction to the freezing front.

In the large furnace, the power input to the transducer was 2200 watts and the coupling bar was Type 304L stainless steel. When the Type 316 stainless steel ingot was melted and irradiated with an electrical input of 12 watts/cm^2, the columnar mode of solidification was suppressed and a predominantly equiaxed grain structure was produced in the 18-1/2-inch-long ingot. Similar results were obtained in the irradiated, 6-3/4-inch-long ingot of austenitic iron-base alloy melted in the small furnace. A pause in the application of vibration in the small ingot resulted in a return to columnar growth until vibration was resumed.

In the small ingot, less than half of the coupler area was welded to the ingot. In the large ingot, about 3/4 of the area was welded. Thus, grain refinement was achieved in spite of some small loss in transmission efficiency resulting from the above degrees of reduced coupling area. (This result is not surprising since there should be very little loss in transmission efficiency if about 1/3 or more of the coupler area is welded to the ingot, because of the increase in resonance with decreased coupling. However, below a certain coupling area ratio, which depends upon the maximum transducer

$$Q\left(\frac{\text{stored energy}}{\text{dissipated energy}}\right),$$

transmission efficiency drops off rapidly.)

To increase the welded area between the ingot and the coupler, the coupler was made of the same alloy as the ingot. This changed the acoustical impedance and limited the energy that could be stored in the vibrating member during resonance. The reactive impedance in the coupler is a maximum at multiples of 1/4 of the wavelength and is a minimum at multiples of 1/2 of the wavelength. The acoustical impedance is a function of the area of the path and of the density and modulus of elasticity of the medium. Radical changes in these quantities cause reflection as the acoustical energy traverses from the transducer to the surface of the melt. Reflections can be minimized by (1) tapering the crucible bottom which serves as the coupling bar, (2) using low-impedance attachment of the crucible wall to the coupling bar, and (3) obtaining a more complete weld bond between the coupling bar and the ingot. Reactive impedance can also be minimized by keeping the acoustic path equal to an integral number of wavelengths so that a reflected wave is in phase with and reinforcing the incident wave. In practice, this resonance is maintained by adjusting the frequency to have a maximum electrical power input to the transducer.

The authors estimated that the efficiency of transforming and transmitting electrical energy as acoustical energy to the freezing front is probably less than 50 per cent. Yet less than 5 watts/cm^2 to the solid-liquid interface refined the structure. Although no details were given, it was mentioned that ultrasonic treatment during arc melting made it possible to forge Stellite 31 and a Ni-Al alloy, which normally are nonforgeable alloys.

The informative discussion on theories for explaining the grain-refining effect of ultrasonics is summarized as follows. First it must be understood that the grain structure of an ingot will be more equiaxed and less columnar as (1) the degree of superheat is decreased, (2) the critical degree of constitutional supercooling is decreased, and (3) the freezing range of the alloy is increased. Also, acoustic energy is attenuated in an exponential manner with respect to distance. Energy reflection will occur at the interface of two media. As the wave travels from a solid to a liquid, attenuation is increased if cavitation occurs in the liquid at the freezing interface. This attenuation increases with increase in viscosity of the liquid. Close to the liquidus temperature, liquid metals have a viscosity high enough to cause a 5- to 10-fold increase in attenuation within a distance of 1/4 inch from the surface of a transducer coupling bar.

Ultrasonic radiation may effect equiaxed solidification by (1) achieving equilibrium temperature distribution by changing the solute distribution and thus changing the freezing range at the solid-liquid interface, (2) changing the actual temperature distribution near the interface as a result of the absorption of ultrasonic energy in the solid and liquid in this region, and (3) changing the number of catalysts in the liquid and altering their effectiveness as nucleation centers.

With regard to the first postulation, irradiation can have only a minor effect on the thermodynamic properties of solid and liquid phases. Thus, the change in freezing range effected by change in solute distribution is possible only by convective mixing induced by cavitation agitation at the interface. But mixing would reduce the degree of constitutional supercooling with the reduced probability of formation of equiaxed grains.

With regard to the second postulation, heat contributed by attenuated acoustic energy in the bulk of the solid and liquid is too small to make a significant change in the thermal environment. If the energy develops enough heat at the interface, the freezing rate of the solid can be controlled. If it is sufficient to double the true latent heat of fusion, the freezing velocity is halved and the columnar zone is halved. For example, for iron freezing at a velocity of 0.8 inch/min without irradiation, the latent heat evolved per square centimeter of interface per second is about 60 watts. Thus attenuation at the interface must exceed 60 watts/cm^2 to increase the ratio

$$\frac{\text{equiaxed zone width}}{\text{columnar zone width}}$$

by more than a factor of 2.

With regard to the third postulation, if the acoustic energy is great enough to produce cavitation at the interface, the critical value of constitutional supercooling required for nucleation can be decreased by several mechanisms. It is assumed that sound vibrations at 20 kc at an intensity below the threshold for cavitation do not effect nucleation in the liquid.

Mechanism 1 - Cavitation will produce turbulence and temperature fluctuations which may be sufficient to initiate nucleation when the average value of the supercooling is smaller than the value required for general nucleation.

Mechanism 2 - Cavitation may erode the catalysts and change their state of surface adsorption, thus changing their efficiencies as centers of nucleation. It is an unlikely mechanism because irradiation prior to freezing has no effect on nucleation.

Mechanism 3 - Irradiation can impart relative motion to subcritical nuclei to cause them to collide and attain critical size in a manner analogous to the effect of ultrasonic vibrations on agglomeration of colloidal suspensions.

Mechanism 4 - Nuclei can be generated from fragmentation of primary crystals.

Mechanism 5 - A sound wave of sufficient pressure can cause nucleation at less than the normal degree of supercooling, as shown by the Clausius-Clapeyron equation

$$\delta T = \delta T_c - \alpha \Delta p ,$$

where δT is the degree of supercooling required for formation of a nucleus

δT_c is the normal degree of supercooling

α is a constant for a particular system

Δp is the pressure above atmospheric.

Since cavitation sets up intense local pressure and rarefaction waves, it may be sufficient to reduce the value of δT a significant amount in isolated volumes of the liquid to cause high nucleation rates.

From the above considerations, the authors concluded that nucleation is dependent upon the existence of cavitation. They estimated that the cavitation threshold in liquid metals is about 1 watt/cm^2 of interface area. It has been observed that the threshold value decreases with increased irradiation time.

For transmission of sound through the frozen metal to the solid-liquid interface, they deduced that the energy input to the transducer must be greater than twice the energy required for cavitation to occur at the interface. For transmission of sound through the liquid to the liquid-solid interface, the cavitation at the coupling bar-liquid interface will cause high attenuation and the electrical energy to the transducer will have to be 20 times greater than the threshold energy for this cavitation in order to induce cavitation at the freezing front. In such a case, sufficient heat would be generated at the coupling bar-liquid interface to influence the solidification pattern.

From the experimental work, they concluded that the refined grain structure was a result of change induced in the nucleation characteristics of the liquid and not a result of change in the thermal environment. Ultrasonic vibrations increased the probability of nucleation in the liquid adjacent to the solid-liquid interface. There appeared to be no limit in the size of ingot that can be grain refined by ultrasonic treatment. However, the ratio of

$$\frac{\text{wave length}}{\text{ingot diameter}}$$

must be greater than unity to avoid excessive scattering of waves from the ingot walls, which would make it difficult to maintain resonance. Thus, if a ratio less than unity exists during solidification of ingots of large diameter, constant frequency may be equally as effective as variable frequency (varying the frequency to maintain resonance as the ingot cools and the freezing front changes position), but a larger power input will be required to achieve grain refinement.

Lane and Tiller[16] studied ultrasonic technology with a horizontal zone-melting apparatus. The charge consisted of a 30-inch length of Type 316 stainless steel, 3/4 inch square. It was contained in an alumina flame-sprayed graphite boat under a flowing argon atmosphere at a pressure of 15 inches of mercury. The boat and charge were encased in a molybdenum susceptor. A conical transducer horn was brazed to one end of the bar. An induction coil produced a molten zone about 3 inches long.

When the ultrasonic power was applied, the zone melted back toward the transducer about 3/8 inch. As the induction coil and the molten zone were moved, the freezing front was maintained at a position of resonance by varying the frequency. The required frequency was a linear function of the distance of the interface from the transducer, e.g., 21 kc for an interface distance of 1 inch; 17.5 kc for an interface distance of 4 inches.

Grain size decreased as the electrical energy input was increased from 3.13 to 50 watts/cm^2 for both constant and variable frequency. With variable frequency, grain refinement was achieved in a 20-inch length irradiated with an electrical energy input of 6.25 watts/cm^2. With constant frequency, periodic grain refinement occurred when the solid-liquid interface was at a position of resonance. At 25 and 50 watts/cm^2, several areas had hot tears.

As the freezing velocity was changed from 0.004 to 0.024 in./sec with an electrical power input of 12.5 watts/cm^2, the grain size increased as the velocity increased.

A carefully machined screw joint between the coupler and the transducer was as efficient in producing grain refinement as a brazed joint.

Energy transmitted through the liquid to the freezing interface (moving the liquid zone toward the transducer) produced a very small amount of grain refinement when the electrical energy input was 6.25 watts/cm^2. Cavitation at the melting interface greatly attenuated the energy. When irradiation took place while the liquid zone was moving away from the transducer, grain refinement was very marked.

Because the acoustical energy at the freezing interface is about half of the electrical energy input, grain refinement was achieved with an energy of only 1 to 2 watts/cm^2 at the interface.

At an energy input of 45 watts/cm^2 and a freezing velocity as low as 0.001 in./sec, spectrographic chemical analysis showed no long-range segregation in the ingot. Thus, it was concluded that irradiation does not alter the solute distribution at the interface, even when the acoustic energy is high enough to produce cavitation with expectation of mixing in the solute layer. However, the solute-rich layer extended about 0.004 inch ahead of the freezing interface, whereas the zone of constitutional supercooling extended about 0.394 inch ahead of the interface. If cavitation began well beyond 0.004 inch from the interface, then the supercooled layer could be irradiated to produce nuclei without detectable mixing of the solute-rich layer of liquid. This was verified by noting that the rate of erosion was greater on a metal sheet placed a small distance from the end of a coupling bar than it was on the face of the coupling bar. [Pressure antinode (velocity node) would be expected to be beyond the end of the coupling bar, in general.]

It was expected that the zone-melting technique would be very useful for determining the critical value of

$$\frac{Q_o \text{ (acoustic energy at the interface)}}{V \text{ (freezing velocity)}}$$

to yield a given grain size in a particular material. The grain size would decrease as the total flux of ultrasonic radiation,

$$\frac{Q_o}{V},$$

increased.

Nagy and Kelman[17] apparently used the same facility that was used by Wright, et al.,[12] for studying grain refinement by ultrasonic treatment during vacuum arc melting. They presented the same information on a 12-inch-diameter ingot of rotor forging steel. However, they mentioned that five transducers were constructed in parallel to increase the acoustical energy input so that grain refinement could be effected for the full length of the 67-inch ingot. With one transducer, grain refinement had been restricted to the bottom 17-inch portion of a 70-inch-long, Type 316 stainless steel ingot. With the improved irradiation system, a 65-inch-long, 12-inch-diameter ingot of W-545 alloy appeared to be grain refined over its entire length. A firm conclusion was difficult to formulate because the nonirradiated ingot had a predominantly equiaxed grain structure. Periodic irradiation during melting showed a definite variation in grain structure that corresponded to that with the cyclic application of irradiation.

It was stated that high-frequency generators are available with ratings of up to several hundred kilowatts. In comparison with the power of 200 kw that was used to melt a 12-inch-diameter ingot weighing 2500 pounds, only 10 kw for generating ultrasonic energy was necessary to achieve grain refinement.

A simple method was found for tuning the ultrasonic system before making a trial with a melt. Sand was placed on top of the transducer horn. The parameters were then varied until a maximum activity occurred in the layer of sand. (This method may be suitable for initial, coarse tuning. However, the resonant frequency may be appreciably different when the melt is introduced into the system.)

Nonferrous Alloys

The literature on the refinement of the structure of nonferrous metals by the application of vibration[18-45] is more extensive than that on ferrous alloys. Much of the information may be considered as historical, but it served as the breeding place for the present theories on nucleation by ultrasonic energy, and led to an understanding of the parameters and the development of effective techniques.

A few points of interest from this literature are as follows. Atlas-Werke[23] in 1947 in Germany developed a system for continuously casting fine-grained duralumin ingots up to 11.4 inches in diameter. Four magnetostriction vibrators produced a total intensity of 2 watts/cm^2 in the constant level of the melt. The transducers were coupled to the melt by hard porcelain rods.

Several investigators[24,26,41] studied the effect of ultrasonic vibrations on the crystallization of transparent organic substances or salt solutions to find analogies with the behavior of metals solidified under ultrasonic irradiation.

Without identifying the melt, Teumin(33) in 1955 very clearly defined many of the parameters for grain refinement when the acoustical energy is introduced into the bottom of a solidifying ingot.

Garlick and Wallace(39) applied a frequency of 60 cps to various metals having a wide difference in degree of solidification shrinkage. Their results supported the theory that a pressure wave favors formation of a solid (nucleation) when the solid is more dense than the liquid, and a rarefaction wave favors formation of a solid (nucleation) when the solid is less dense than the liquid.

The application of ultrasonic energy for degassing and grain refining castings on a custom-engineered basis was considered by an ultrasonics equipment manufacturer to be feasible, according to a 1962 news item.(45)

CONCLUSIONS

Steel ingots up to 12 inches in diameter and up to 5 feet in length have been grain refined by the application of vibrational energy during solidification. The cold-mold, consumable-electrode, arc-melting process and the electron-beam-melting process appear to be the most adaptable for efficient irradiation of an ingot. They permit low-impedance sealing of the crucible wall to the coupling bar. They can provide liquid metal with a freezing velocity sufficiently low that effective nucleation can take place in the liquid adjacent to the freezing front. Coupling to the melt and attenuation of energy by cavitation are not serious problems when the energy is introduced through the bottom of the ingot. For example, if irradiation with an electrical energy input of 6 watts/cm^2 is assumed to be adequate for grain refinement, a 24-inch-diameter ingot would require a total power input to the transducer of 17-1/2 kw, which is not an unreasonable power demand.

Grain refinement by sonic or ultrasonic treatment may not be economically attractive for steels going into mundane applications. It could be a very acceptable method for avoiding or minimizing the undesirable properties attributed to banded structures. Banding can present serious problems in fabricating steels that are normally prone to segregation during solidification. It could be the only solution for achieving forgeability in those alloy ingots which have very low yield because of the planes of weakness resulting from their normal growth pattern of large columnar grains. It would be particularly applicable to those steels which suffer serious reduction in ductility or in other important properties when grain refinement is achieved by inoculation.

RECOMMENDATIONS FOR FUTURE EFFORT

Most researchers in this field recognize the need for an acceptable explanation of the mechanism by which vibrational energy yields grain refinement. A true understanding would permit proper applications to be realized most advantageously and would avoid unnecessary waste in attempts that cannot now be recognized as misapplications. In addition to the metallurgical aspects of the problem, many complexities exist in the nature and physical actions of the sound field. Fundamental acoustical studies are therefore equally essential to the understanding of the problem. The various postulated mechanisms by which sound energy effects grain refinement could be studied analytically, with crucial experiments devised to test the credibility of each. Complicating factors present in actual application could then be introduced in a systematic manner.

Considerable progress in practical application of sonic and ultrasonic vibrations to solidifying steel has been achieved despite the lack of a complete understanding of the grain-refining mechanism. Therefore, practical developments should be continued simultaneously with the basic research on the mechanism. Such work could include (1) investigations on more effective and reproducible coupling of the transducer to the ingot; (2) studies on coupler materials for maximum efficiency in transmission of the acoustical energy; (3) development of instrumentation to provide a reasonably accurate indication of the acoustical power reaching the solidifying interface; (4) large-scale experiments to demonstrate the practical limitations of ingot length as well as ingot diameter; and (5) consideration of the problems that may exist in making available efficient ultrasonic generators of a size that will be needed for ingots weighing up to 5 or 10 tons.

In the programs dealing with development of practical applications, steels should be chosen which normally solidify by growth of columnar grains and which show severe segregation. Details should be reported on (1) the melting practice, (2) the acoustical system, (3) the structure of the ingot, (4) the forgeability of the ingot, and (5) the mechanical properties of the fabricated product. Any advantages in improved fabricability or properties should be weighed against the added cost of the ultrasonic treatment. The report should include any significant improvement in gas content and soundness of irradiated ingots. When a successful practice has been developed for a given furnace, it should be ascertained whether equally satisfactory results can be achieved in other furnaces of different design. An effort should be made to determine whether a satisfactory practice for a given steel is applicable to other steels of widely different alloy composition, or what changes in practice are necessary. Prompt application should be made of pertinent results from fundamental studies, as these studies progress.

REFERENCES

(1) Hiedemann, Egon A., "Metallurgical Effects of Ultrasonic Waves", Acoustical Society of America, Journal, 26, 831-842 (September, 1954).

(2) Hiedemann, E. A., "Ultrasonic Material Testing and Other Applications", B.I.O.S. Final Report No. 1679.

(3) Hinchliff, S., and Jones, Josiah W., "The Application of Sub-sonic Vibrations During Solidification of Castings, With Particular Reference to a Material for Gas Turbine Blades - H. R. Crown Max", Report No. 89, College of Aeronautics, Cranfield, England (April, 1955); digested as "Vibration During Casting of Gas Turbine Blades", Metal Progress, 69 (2), 134-138 (February, 1956).

(4) Leont'ev, V. I., "Influence of Low-Frequency Vibrations of the Mold Upon Ingot Crystallization", Problems of Metallography and Metal Physics, 4th Collection of Papers, State Scientific and Technical Publishing House for Ferrous and Nonferrous Literature Under Ministry for Ferrous Metallurgy, Moscow, 70-76 (Brutcher Translation No. 3716) (1955).

(5) Nikolaichik, N. P., and Nikolaichik, E. N., "Improvement of the Quality of Ingots With Ultrasound", Stal, No. 4, 322-325 (Iron and Steel Institute, Translation No. 598) (1957).

(6) Unterweiser, P. M., "Can Ultrasonics Improve Steel Ingot Quality?", Iron Age, 182, 178-180 (September 11, 1958).

(7) Kasumzada, N. G., Changes in Structure and Properties of Steel, Aznefteizdat, 324 (1957).

(8) Gurevich, Ya. B., Leont'ev, V. I., and Tuemin, I. I., "Influence of Ultrasonics on the Structure and Properties of Steel Ingots", Stal, 17, 406-411 (Brutcher Translation No. 4035) (May, 1957).

(9) Nikolaichik, N. P., and Nikolaichik, E. N., "Casting Cast Iron Parts Using Ultrasound", Liteinoe Proizvodstvo, No. 2, 25 (1958).

(10) Romanov, A. A., and Umrikhin, P. V., "Improvement of the Structure of the Ingot During Vibrations of the Crystallizing Steel", Izvestiya Vysshikh Uchebnykh Zavedeniy Chernaya Metallurgiya, No. 7, 37-43 (Brutcher Translation No. 4610) (1958).

(11) Leont'ev, V. I., "Ingot Solidification Controlled by Ultrasonics", Problems of Metallography and Metal Physics, 6th Collection of Papers, Moscow, Metallurgizdat, 100-116 (1959).

(12) Wright, E. B., Carnahan, D. R., and Kelley, J. H., "Ultrasonics Cuts Grain Growth During Casting of Forging Ingot", Iron Age, 184, 84-87 (August 6, 1959).

(13) "Homogeneous Steel", Metal Progress, 63-65 (December, 1958).

(14) Lane, D. H., Cunningham, J. W., Tiller, W. A., "Ultrasonic Vibrations Refine Grain Size", Metal Progress, 108-110 (September, 1959).

(15) Lane, D. H., Cunningham, J. W., and Tiller, W. A., "The Application of Ultrasonic Energy to Ingot Solidification, Part I", Metallurgical Society of AIME, Trans., 218 (6), 985-996 (December, 1960).

(16) Lane, D. H., and Tiller, W. A., "The Application of Ultrasonic Energy to Ingot Solidification II", Part 2, Metallurgical Society of AIME, Trans. 218, 991-994 (December, 1960).

(17) Nagy, M. J., and Kelman, D. M., "Application of Ultrasonic Vibrations During Solidification of Vacuum-Arc-Melted Ingots", paper presented March 21, 1961, at Western Metal Congress, Los Angeles.

(18) Sokoloff, S., "The Effect of Supersonic Waves on the Solidification of Molten Metals", Ministry of Aircraft Production R.T.P. Translation No. 2568 (from report issued by the Electro-Technical Institute, Leningrad) (1935).

(19) Schmid, G., and Roll, A., "The Importance of Frequency and Intensity of Vibration on Grain Refinement", Z. Electrochem., 45, 769 (1939).

(20) Schmid, G., and Roll, A., "The Effect of Ultrasonics on Molten Metals", Z. Electrochem., 46 (12), 653-657 (December, 1940).

(21) "Supersonics in Metallurgy", Metal Industry, 69, 136-138 (August 16, 1946). Based on a paper by N. Marinesco presented to the Centre de Perfectionement Technique.

(22) Siebers, Charlotte, and Bulian, Walter, "Vibration of Liquid Mg-Al Alloys", Metal Progress, 59, 560 (April, 1951). (Translated and condensed from "The Effect of Sonic and Ultrasonic Vibrations on the Structure of Magnesium-Aluminum Alloys With 4 to 12% Al", Metallforschung, 1, 158-160 (October-November, 1946).

(23) Seemann, H. J., and Menzel, H., Zeitschrift für Metallkunde, 1, (3/4), 39-46 (October, 1947) (German).

(24) Kapustin, A. P., (a) J. Tech Phys. (U.S.S.R.), 20 (10), 1157-1159 (1950); (b) 22 (5), 769-772 (1952); (c) Doklady Akad. Nauk. U.S.S.R., 71, 451-452 (1950).

(25) Jones, J. B., "Ultrasonics Applied to Solidification and Solid State Transformation", AF Technical Report No. 6675, WADC, Materials Laboratory, Contract No. AF 33(038)-11208 (October, 1951).

(26) Van Hook, A., and Frulla, F., "Nucleation in Sucrose Solutions", Industrial and Engineering Chemistry, 44, 1305 (1952).

(27) Sproul, D. O., "Ultrasonic Techniques: Some Effects and Applications", Times Science Review, 14-15 (Autumn, 1952).

(28) Alder, K. F., "Ultrasonic Vibrations and Their Metallurgical Applications", Australasian Engineer, 53-59 (December 8, 1952).

(29) Crawford, Alan E., "Some Metallurgical Applications of Ultrasonics", Metallurgia, 47, 109-113 (March, 1953).

(30) Rostoker, W., and Berger, M. J., "Effects of Vibration During Solidification of Castings", Foundry, 81, 100-105, 260-265 (July, 1953).

(31) Bradfield, G., "Summarized Proceedings of Symposium on Applications of Ultrasonics", Proc. Phys. Soc. (London), 63, Sec. B., 305-322 (May 1, 1950); Research (London), 6, 68-79 (1953).

(32) Jones, J. B., Thomas, J. G., and De Prisco, C. F., "The Effect of Ultrasonics on Molten Metals", Aeroprojects, Inc., report for Wright Air Development Center, Technical Report No. 54-490, U. S. Office of Technical Services, P. B. 121403, Washington 25, D. C. (January, 1955).

(33) Teumin, I. I., "Theory and Calculation of Induction of Elastic Oscillations in Molten Metals", Problems of Metallography and Metal Physics, 4th Collection of Papers, Moscow, 50-69 (Brutcher Translation No. 3930) (1955).

(34) Richards, R. S., and Rostoker, W., "The Influence of Vibration of the Solidification of an Aluminum Alloy", Trans. ASM, 48, 884-903 (1956).

(35) Southgate, P. D., "Action of Vibration on Solidifying Aluminum Alloys", Journal of Metals, AIME, 514-517 (April, 1957).

(36) Freedman, A. H., and Wallace, J. F., "The Influence of Vibration on Solidifying Metals", Trans. AFS, 65, 578-589 (1957).

(37) Freedman, A. H., Wallace, J. F., and Carbonaro, F. A., "Vibration Can Improve Casting Quality", Foundry, 85, 98-99 (November, 1957).

(38) Novikov, I. I., Korolkov, G. A., Solov'eva, V. V., and Freilikh, A., "Grain of Solidifying Metal Refined by Vibration", Liteinoe Proizvodstvo, 42 (Brutcher Translation No. 4563) (February, 1954).

(39) Garlick, R. G., and Wallace, J. F., "Grain Refinement of Solidifying Metals by Vibration", AFS Trans. 67, 366-374 (1959).

(40) Balandin, C. F., "Crystallization of Castings Under the Action of Sonic and Ultrasonic Vibrations in the Liquid Metal", Izvestiya Vyssihikh Uchelnykh Zavedeniy Machinostronie, 24-31 (Brutcher Translation No. 4898 (April, 1960).

(41) Novikov, I. I., Korolkov, G. A., and Zolotorevskii, V. S., "Mechanism of Grain Refinement by Low Frequency Vibrations During Crystallization", Izvestiya Vyssihikh Uchelnykh Zavedeniy Chernaya Metallurgiya, 130-134 (Brutcher Translation No. 4900) (May, 1960).

(42) Walker, J. L., "Grain Refinement by Vibration", AIME Journal of Metals, 379 (May, 1961).

(43) Wallace, J. F., Form, G. W., Turnbull, G. K., Gould, G., and Merchant, H., "Grain Refinement", Modern Castings, 60, 62, 64, 66, 68, Abstract of AFS exchange paper presented at International Foundry Conference, Zurich, Switzerland (November, 1961).

(44) Carnahan, D. R., "The establishment of a Vacuum Arc Melting Capability at ASD", ASD Technical Report 61-385, Part I, USAF Contract No. AF 33(616)-7459 (December, 1961).

(45) Lewis, A., "Ultrasonic Energy Cited as Refiner of Grain Size", Metal-working News, New York, N. Y., 11 (June 25, 1962).

PART II - STEEL WELDMENTS

INTRODUCTION

Investigation of the use of vibrational energy to refine the grain structure of weld metals has been reported in the United States, Germany, England, and the USSR. Investigators in the USSR have studied the technique to the greatest extent, while only a limited amount of work has been done elsewhere. In general, this method of grain refinement appears promising, although there apparently are some practical limitations to its use. The work that has been reported has dealt with both ferrous and nonferrous weldments. Although this literature survey is concerned specifically with steel weldments, results of investigations on nonferrous weldments are included because much of the latter information is applicable to steel weld joints.

Ultrasonic vibrations can be introduced into the weld metal by vibrating either: (1) the whole weld specimen, (2) an electrically neutral filler wire, (3) the welding electrode, or (4) a nonconsumable-electrode probe in the weld pool. Several theories have been proposed to explain the grain refinement that results. These theories are summarized as follows:

(1) Ultrasonic vibration of the molten metal can create pressure waves within the molten metal, thus causing fragmentation of the growing dendrites. These fragments then act as nuclei for further grain growth.

(2) Stirring or turbulence of the molten metal induced by the vibrations can mix higher-melting phases of the metal, which solidify first, into lower temperature areas, where they may serve as centers of nucleation.

(3) A high-shear gradient just ahead of the freezing front can encourage the formation of growth nuclei.

(4) Cavitation may occur in the molten metal. The collapse of the cavitation bubbles creates additional pressure waves which cause additional grain fragmentation. The high-pressure areas resulting from the collapse of these bubbles may also be sites of nuclei formation.

Whatever the mechanism associated with the application of ultrasonic vibrations to molten weld metal may be, the technique has been shown to refine the grain structure, suppress the formation of hot cracks, and improve the mechanical properties of the weld metals.

SUMMARY OF REPORTED INVESTIGATIONS

In 1950, H. O. Willrich[(1)*], a German investigator, reported the early use of ultrasonic vibration to refine the grain structure of weld metal. He noted that the chief problem was the selection of the method of introducing the ultrasonic vibrations into the weld pool. The best results were obtained by vibrating the electrode rather than the base metal. Apparently this was an exploratory study with most of the effort being put into the development of the ultrasonic vibrator. Mild steel was welded manually with vibrating covered electrodes. Willrich felt that the technique would be more successful if applied in conjunction with automatic or semiautomatic welding. No specific data were given, although the author stated that a definite weld-metal grain refinement was obtained.

Silverstein, et al.,[(2)] at Battelle, used ultrasonic vibrations for grain refinement of TIG welds in tantalum sheet (0.040 inch thick). This work, carried out in 1956, was not a detailed study of the technique, but was conducted to determine the feasibility of the use of vibrations for grain refinement. Test coupons were attached to a transducer in such a manner that the weld was vibrated longitudinally, i.e., parallel to the direction of welding. Without vibration, the weld metal grain size was limited only by the thickness of the sheet. The individual grains extended from the top to the bottom surface of the weld bead. Welds vibrated ultrasonically had grains about one-third the size of the nonvibrated welds.

These investigators noted a disadvantage of ultrasonic vibration. Metallographic studies of heat-affected zones showed that etching attack at grain boundaries of specimens vibrated during welding was greater than for nonvibrated specimens. This indicated that the grain boundaries of vibrated specimens were more highly stressed. As a result, ultrasonically vibrated tantalum might be more susceptible to intergranular corrosion.

In 1957 and 1958, three Soviet studies on the vibration of welds were reported. Benua, Vologdin, and Katler[(3)] used low-frequency vibrations to attempt to break up the grain structure of electroslag welds** in carbon steel containing 0.10 per cent carbon. Vibrations with a frequency of 30 to 43 cps were applied to the molten weld metal by a vibrating probe. The probe was immersed only in the flux bath on top of the molten weld metal. A significant break-up of the dendritic grain structure of the weld metal was achieved. (Normal electroslag welds are characterized by a very coarse dendritic grain structure.) The impact value (room temperature) of the vibrated weld metal was 12.5 kg-m/cm^2 (which may be converted to a value of 72 ft-lb) as opposed to 6.2 kg-m/cm^2 (36 ft-lb) for the unvibrated weld metal. The type of impact specimen was not indicated.

*References are listed at the end of Part II.

**Electroslag welding is used for making single-pass welds in thick material. All welding is done in the vertical position. Sliding copper shoes are positioned on the front and back sides of the weld to contain the molten weld metal. As welding progresses upward, these shoes slide along the weld seam. This is a process widely used in the USSR, but as yet has found little acceptance in the U.S.

Alov and Vinogradov[4,5] of the Moscow Aviation Technology Institute used low-frequency vibrations in the submerged-arc welding of 0.4-inch-thick low-carbon steel and 1/4-inch-thick aluminum. (The aluminum also was MIG-welded using argon shielding.) The electrode was vibrated in a direction transverse to the weld joint at frequencies of 5 to 80 cps and amplitudes of 0.002 to 0.10 inch. The authors contended that the electrode vibration reduced the size of the metal drop transferred from the electrode to the weld pool. (They did not say how they observed this decrease in drop size, or whether this effect was observed in both MIG and submerged-arc welding.) Other advantages achieved by these techniques were: (1) a more stable arc, which resulted from the smaller drop size; (2) a smoother weld-bead surface with lower reinforcement and less penetration; (3) finer grain size; and (4) reduced weld-metal porosity. The impact strength (room temperature, Mesnager specimens) of the steel weld metal deposited without vibration was 9.6 kg-m/cm^2 (55 ft-lb). The impact strength of the vibrated weld metal depended on the amplitude of the vibration and was 11 kg-m/cm^2 (63 ft-lb) for a 0.006-inch amplitude and dropped to 9.6 kg-m/cm^2 (55 ft-lb) as the amplitude increased to 0.04 inch. The vibration amplitude also affected the tensile strengths of aluminum weld joints. The tensile strength values were:

Base metal	11,550 psi
MIG weld joint, not vibrated	10,500 psi
Submerged-arc weld, not vibrated	11,250 psi
Submerged-arc weld, vibrated, 0.004-inch amplitude	11,430 psi
Submerged-arc weld, vibrated, 0.020-inch amplitude	11,900 psi
Submerged-arc weld, vibrated, 0.040-inch amplitude	11,250 psi

V. L. Russo[6] mathematically analyzed both low-frequency and ultrasonic vibration of the weld pool. He also described experimental work that was supposed to verify his calculations. (The experimental results were rather meager, however, and did not necessarily support his theoretical discussion.)

As a basis for his analysis, Russo assumed that grain refinement occurred through fragmentation of the dendrites during the crystallization process. The vibration set up force waves in the liquid weld metal which broke the ends off the growing dendrites, thus creating new crystallization points. The vibrational forces were calculated from the formula:

$$P = yj\left(1 \pm \frac{f}{g}\right),$$

where

P = the intensity of the pulses, g/mm^2
y = the height of an individual column of the liquid metal at the center of the weld pool
$j = 4\pi^2 f^2 S$ is the value of initial acceleration
g = the acceleration of gravity
f = the vibration frequency, cps
S = the vibration amplitude, mm.

(This formula is not dimensionally correct. It should be:

$$P = y\rho \ (1 \pm \frac{j}{g}) \quad \text{for } y \ll \lambda$$

ρ = density of the weld pool liquid metal.)

The vibrational forces were calculated for aluminum and steel at various vibration rates between 1500 and 3000 vibrations per minute and at amplitudes between 0.01 and 2.5 mm. The maximum vibrational force in steel for these conditions was 1.7 g/mm^2, and for aluminum the maximum force was 0.65 g/mm^2. Russo referenced other Soviet work which showed that, at the moment of crystallization, the strength of steel is greater than 5 g/mm^2 while the strength of aluminum is 1 g/mm^2. Since the vibrational forces set up in the aluminum and steel weld pools are below these values, complete breakup of the dendrites could not be expected. However, some grain refinement could occur because of the fracture of the dendrites near their ends, where the cross-sectional area is small. The degree of grain refinement would be expected to be greater in aluminum welds than in steel welds, since, with aluminum, the vibrational forces are nearer to the strength of the dendrites.

Experimental welds were made in 10-mm-thick AMg6 (5456) aluminum plate by manual TIG welding. The welds were vibrated at 1500, 2800, and 3300 vibrations per minute and at amplitudes of 0.01 to 2.3 mm. The base plate was vibrated longitudinally (parallel with the weld joint) during welding. Maximum grain refinement occurred at amplitudes of 0.5 mm. At any specific amplitude, increasing the frequency of vibration decreased the grain size. The average grain cross-sectional area of an unvibrated weld was 0.25 mm^2. A weld vibrated 3300 times per minute at an amplitude of 0.6 mm had an average grain area of 0.05 mm^2. Submerged-arc welds were made in 32-mm-thick 12KhNMA (Cr-Ni-Mo steel containing 0.12 per cent carbon), vibrated at various frequencies (the amplitude of vibration was not given). Apparently, some degree of grain refinement was achieved even though the vibrational pressures in the weld pool were considerably lower than the strength of the steel dendrites. The author did not discuss this point except to show that the impact strength of the weld metal was improved by vibration. The results of Mesnager impact tests were:

Temperature, F	Vibration Frequency, vib/min	Impact Strength $kg\text{-}m/cm^2$	Impact Strength ft-lb
68	0	8.5	48
	1500	13	75
	2800	14.5	83
	3300	15	87
-5	0	6.5	38
	1500	10	58
	2800	12.5	72
	3300	13.5	78
-70	0	5.5	32
	1500	8.5	48
	2800	11	63
	3300	10	58

From the results of the low-frequency studies, Russo concluded that effective breakup of the weld-metal dendrites can be achieved only if the intensity of the pressure pulses in the weld pool is at, or near, the strength of the dendritic grains. If the intensity of the pressure pulses is very much less than the strength of the dendrites, effective breakup of the dendrites can be achieved if the weld pool is relatively large. A large weld pool results in lower freezing rates and allows the vibrational forces a longer time to act on the dendrites. The larger weld pools result from the use of automatic welding. Apparently this was the case with the submerged-arc welds in the 12KhNMA steel.

The intensity of the vibrational forces can be raised by increasing either the vibrational frequency or amplitude. By the author's calculations, an amplitude of 10 to 20 mm would be required for low-frequency vibration of steel in order for the vibrational force to equal the strength of the dendrites. Therefore, high-frequency (ultrasonic) vibrations are more suitable in the welding of steels. Through a rather lengthy mathematical analysis, Russo established optimum vibrational frequencies for the breakup of dendrites in steel welds. These frequencies are listed below:

	For Pool Weighing 100 G		For Pool Weighing 10 G	
Depth-to-Width Ratio of Weld Pool	Depth of Weld, cm	Required Frequency, cps	Depth of Weld, cm	Required Frequency, cps
1.08	2.5	38,640	1.15	92,000
2.5	1.6	61,950	0.75	120,700
4.5	1.1	89,760	0.5	200,000

It was assumed that the vibrations were to be introduced to the weld from the bottom. (Since none of these calculations was verified experimentally, it is difficult to ascertain their applicability. However, a general conclusion can be made that, as the size of the weld pool increases, the vibrational frequency can be decreased. No subsequent publications by Russo were available, so whether he continued this work experimentally is not known.)

Investigators at the A. A. Baikov Institute of Metallurgy[7-10] of the USSR Academy of Sciences studied ultrasonic vibration of weld metals and developed methods of introducing the vibrations into the weld pool. This work encompassed electroslag welding of Kh25N20 (25Cr-20Ni) stainless steel and argon-shielded MIG welding of 1Kh18N9 (19Cr-9Ni) stainless steel, and covered electrode welding of 77Ni-21Cr and 25Ni-15Cr-6Mo heat-resistant alloys.

Ultrasonic vibrations may be introduced into electroslag welds quite easily. The vibrating probe is inserted into a hole in one of the copper shoes (Figure 1). This hole is positioned so that the tip of the probe contacts the molten weld metal. Some grain refinement can be achieved if the probe is in contact with the frozen weld metal, but best results are obtained if the vibrations are transmitted directly to the molten metal. A water-cooled copper probe is the most reliable. Steel probes with replaceable

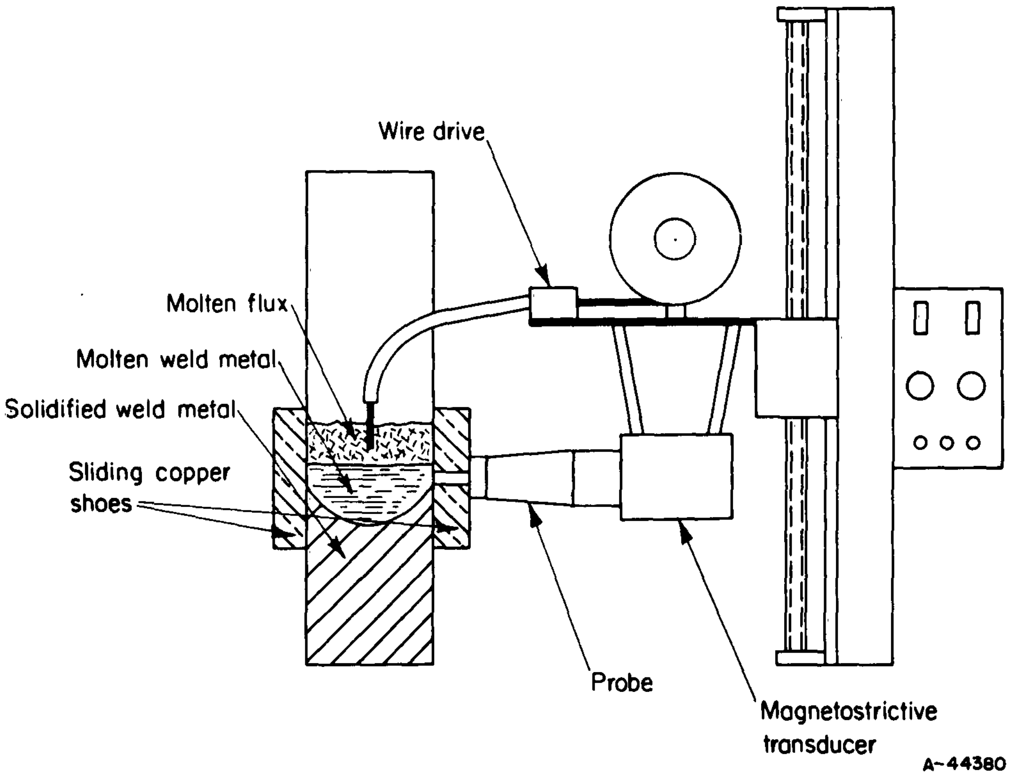

FIGURE 1. SETUP FOR ELECTROSLAG WELDING USING ULTRASONIC WELD-METAL VIBRATION

copper tips have been used, but, since such a probe has a threaded joint where the tip is attached, a loss of vibrational energy occurs at this location.

Vibrations can also be introduced into the weld pool through a vibrating filler wire. This technique can be used for electroslag welding or any of the horizontal arc-welding processes, such as submerged-arc or MIG welding. In horizontal welding, the vibrating filler wire is introduced into the weld pool a short distance behind the electrode wire (Figure 2). This distance is governed by the various welding parameters, since the vibrations are more effective if introduced into the cooler portion of the weld pool. The degree of grain refinement depends on the feed rate of the wire, the wire diameter, and the "stickout", or length of wire between the vibrating transducer and the weld pool. The stickout should be kept as small as possible and should not exceed 50 or 60 mm. Two types of vibrators are shown in Figure 3. The diameter of the hole through which the wire passes should be 1 to 1.5 mm larger than the diameter of the wire. The vibrator with the thickened tip (B, Figure 3) has a larger area of contact between the wire and the vibrator, thus improving the efficiency of transmission of the vibrations. However, the thickening of the tip reduces the vibration amplitude. Consequently, such a vibrator must be shorter than those with an even taper to the tip.

The simplest method for introducing vibrations into a horizontal weld is by immersing the tip of the vibrator into the weld pool. This is satisfactory for short, experimental welds, but the technique cannot be used for production applications because of tip failure. No tip material tested, including tungsten, aluminum with zirconium oxide coatings, and various ceramic materials, could stand up in the heat of the arc and weld pool, or could resist erosion by the molten weld metal.

Ultrasonically treated electroslag welds in Kh25N20 steel had much smaller grain sizes than untreated welds. The thickness of the welds was not indicated. Vibrations were introduced through a vibrating wire at a frequency of 20 kilocycles per second. A second advantage of the ultrasonic treatment also was noted. All untreated welds had hot cracks while only two of ten vibrated welds contained hot cracks. Work with the Ni-Cr heat-resistant alloys indicated that the amplitude of the vibrations is a critical parameter which varies with the composition of the weld metal. The optimum amplitude range at a frequency of 20 kc was found to be 2.0 to 4.5 microns for the 77Ni-21Cr alloy and 1.5 to 3.5 microns for the 25Ni-15Cr-6Mo alloy. At amplitudes above the optimum, major disturbances in the welding process occurred, such as extensive spatter, formation of slag inclusions, and formation of surface defects. Hot cracks also can be created if the amplitude is too high.

At the E. O. Paton Institute of Electric Welding(11) in Kiev, USSR, a series of tests was conducted to determine the ultrasonic power required to achieve grain refinement in submerged-arc and electroslag welding. Mild steel and 1Kh18N9 (0.1C-18Cr-9Ni) stainless steel were submerged-arc welded. Vibrations were fed to the weld pool through an auxiliary wire from a 1-kw ultrasonic transducer. Complete breakdown of the columnar structure of the weld bead was reportedly achieved at a frequency of 26.4 kc. Structural steel (composition not given), 100 mm thick, was electroslag

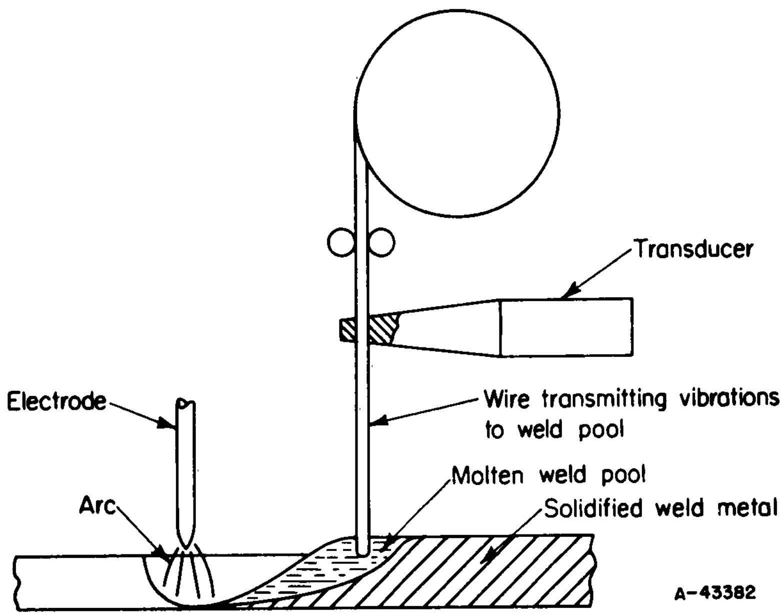

FIGURE 2. SETUP FOR INTRODUCING
VIBRATIONS INTO WELD POOL

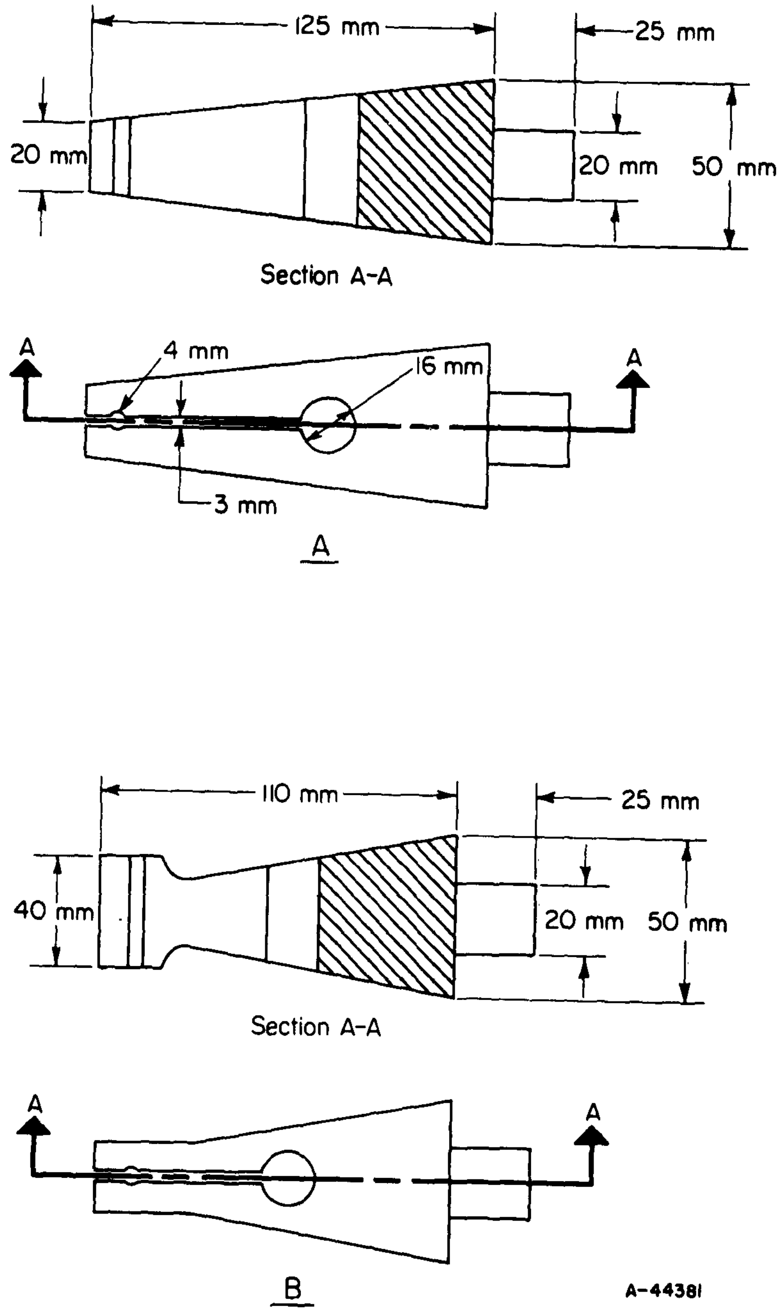

FIGURE 3. DEVICES USED TO IMPART VIBRATIONS TO FILLER WIRE

welded. Vibrations at a frequency of 19.8 kc from a 3-kw transducer were fed to the weld pool by a probe inserted in one of the sliding shoes. Again, complete breakdown of the columnar structure reportedly occurred, and the weld metal contained fine, equiaxed grains.

Investigators in Great Britain[12] have patented the technique of introducing ultrasonic energy into a molten weld pool using the filler wire as the vibrating member. (Whether they are doing work similar to that of the Soviets is not known. It can be presumed, however, that they have been investigating this technique to establish data on which to base their patent application.)

In the U.S., Mellon Institute[13] investigated ultrasonic grain refinement as part of their program for the development of ultrahigh-strength steel alloys. Their initial experiments consisted of depositing a longitudinal weld on a tubular specimen. Vibrations were introduced from a roller connected to the transducer and riding on the weld bead. Subsequent work included making girth welds on rings of 6 to 14-1/2-inch diameter. These welds simulated those used in rocket-motor-case fabrication. TIG welding was used throughout and the base material was Rocoloy 270, an ultrahigh-strength steel developed by Mellon.

For the welds on the tubular specimens, the power input and vibrational frequency required for successful grain refinement were 40 watts to 85 watts at 15 kc to 28 kc, respectively, for weld beads ranging in thickness from 0.050 to 0.150 inch. From the work with the ring specimens, it was found that best results were achieved when the roller probe was positioned "on the weld puddle trailing the arc at a specified distance dictated by the freezing characteristics of the weld filler wire composition and bead thickness". Specific distances were not given. Some tensile and fatigue tests were made of ultrasonically treated weld joints. No data were given on these tests other than mentioning that the ultrasonically treated joints were unquestionably superior to untreated joints.

D'Antonio and Vecchio[14] of the Polytechnic Institute of Brooklyn ultrasonically vibrated 0.032-inch-thick Ti-13V-11Cr-3Al sheet during TIG welding. They found that the weld-metal grain size was greatly reduced, being even smaller than that of the base metal. No details of the experimental work were discussed.

At Armour Research Foundation,[15] low-frequency (25 to 1000 cps) vibration was used to refine the grain structure of MIG welds in 5083 aluminum. The vibrational direction was vertical and the vibration was applied to the back side of the weld joint by an electromechanical vibrator. Best results were obtained when an impact vibration of 25 cps was applied. When sufficient vibrational power (800 watts) was used, a fine, equiaxed grain structure resulted. At lower power settings, e.g., 375 watts, no grain refinement occurred. Sinusoidal vibrations at frequencies of 60 to 1000 cps applied in the same manner had little effect on the grain structure of the weld metal, unless the vibrational amplitude was so great that the weld-bead geometry was distorted. Apparently, the acceleration of the weld metal during sinusoidal vibration was too low to cause dendritic fragmentation. No increase in tensile properties was noted for the vibrated welds, as opposed to the nonvibrated welds.

From p. 15

CONCLUSIONS

Most of the investigators have concluded that grain refinement of weld metals by the application of vibrational energy, be it subsonic, sonic, or ultrasonic, holds great promise. The technique definitely has been shown to be effective. However, none of the investigations appear to have been extended to the application of vibrational treatment to industrial welding. The specialized welding equipment that would be needed has not been developed, and equipment service problems, although not mentioned, would present a major obstacle to practical adaptation of vibrational techniques. Undoubtedly, problems also exist in obtaining reproducibility of the degree of grain refinement achieved.

Investigators in the Soviet Union have achieved a marked degree of success in their studies, especially with the grain refinement of electroslag welds. In spite of this, they still consider vibrational techniques to be of questionable value, primarily because the vibrations have no grain-refining effect on the heat-affected zone.[16] A fine-grained weld metal may be of little advantage if no reduction of grain size is obtained in this zone.

Vibration of the solidifying weld metal is not without its adverse effects. Improper energy or improper vibrational intensity can cause weld-metal hot cracks, weld-metal voids, poor weld-bead contour, or gross spatter of weld metal. These effects also must be controlled before the application of vibrational energy becomes an effective industrial tool.

The crux of the problem is that all of these studies to date have been empirical. No attempts have been made to obtain an understanding of the mechanism of weld-metal grain refinement. As a result, the various problems which have been encountered have been resolved almost by chance, and these solutions may not be the optimum ones. Fundamental studies to determine the mechanism of grain refinement, the pattern of the vibrational field, and the action of the vibrational field would provide a basis for study of the more practical aspects of vibrational grain refinement of solidifying weld metals. Unfortunately, no studies of this type have been conducted (or at least reported), so no analytical background has been available for the work described in this survey. Until fundamental studies are carried out, the solutions to the various problems will probably be haphazard and the practicability, both technically and economically, of using vibration to refine weld-metal grain will remain unknown.

RECOMMENDATIONS FOR FUTURE EFFORT

As stated in the Conclusions, a fundamental study of vibrational grain refinement of steel weldments is a major requirement. Such an investigation could be made in conjunction with similar work with ingots. Although the over-all principles probably would be similar in these two areas, there would be some significant differences. Specifically, the volume of molten metal would be much smaller in a weld than in an ingot or casting, the weld metal would solidify at a much higher rate, and temperature gradients would be much steeper in the weld pool. It is suspected that these differences would cause significant change in the action and effectiveness of the vibratory field and would require welding parameters different from those necessary to effectively supply vibrational energy to solidifying ingots.

In any fundamental study, precise measurements would be required. To be most meaningful, these measurements should be taken as near to the solidification surfaces as possible. The welding studies probably would require different instrumentation from the ingot studies, since much smaller specimens would be used.

In conjunction with a broad-based fundamental study, the areas of practical application should be investigated. All of the investigations summarized in this survey have been in or have bordered on practical usage. Because the fundamental knowledge of the process has been lacking, these investigations have been of the hit-and-miss variety. On the other hand, if armed with results issuing from a fundamental study, the investigator should be able to solve the application problems more quickly, more confidently, and with the knowledge that the results will be more nearly reproducible. The practical problems of using this technique would include methods of introducing vibrations, equipment design, probe material, and selection of optimum parameters for a given thickness and type of material.

In recommending any work, fund limitations are important. It appears that none of the investigators have had sufficient funding to carry out a thorough technical research program. A program of this type will probably be expensive, but nevertheless will be imperative to developing an understanding of the technique. Thus, unless sufficient financial backing for an effective fundamental research study is provided, the practical applicability of vibratory techniques for the grain refinement of weld metals will remain in doubt.

REFERENCES

(1) Willrich, H. O., "Application of Ultrasonic Waves", Welding, 18 (1), 61-66 (1950).

(2) Silverstein, S. M., Antonevich, J. N., Sopher, R. P., and Rieppel, P. J., "Welding Tantalum for High-Temperature Systems", Metal Progress, 80 (6), (June, 1960).

(3) Benua, F. F., Vologdin, I. V., and Katler, A. I., Svarochnoe Proizvodstvo (Welding Production), No. 5, 1-5 (1958).

(4) Alov, A. A., and Vinogradov, V. S., Svarochnoe Proizvodstvo, No. 7, 9-10 (1957).

(5) Alov, A. A., and Vinogradov, V. S., Svarochnoe Proizvodstvo, No. 9, 19-22 (1958).

(6) Russo, V. L., "Investigation of the Effect of Elastic Vibrations of Varying Frequencies on the Crystallization of the Weld Pool", Svarka Sbornik Statey (Welding, Collection of Articles), Sudpromgiz, Leningrad, Vol. 1, pp 3-15 (1958).

(7) Yeroklin, A. A., Balandin, G. F., and Kodolov, V. D., "Effects of Ultrasonic Vibrations on Weld Crystallization in Electroslag Welding", Avtomaticheskaya Svarka (Automatic Welding), (1), 15-20 (1960).

(8) Yeroklin, A. A., and Silin, L. L., "Methods of Introducing Ultrasonic Oscillations Into Weld Pools", Svarochnoe Proizvodstvo, No. 5, 4-7 (1960).

(9) Silin, L. L., "The Influence of an Ultrasonic Field on the Structure and Formation of Cracks in the Metal of a Seam During Arc Welding", Izvestia Akademii Nauk USSR-Otdeleniye Tekhnicheskikh Nauk-Metallurgiya i Toplivo (News of the Academy of Sciences of the USSR-Department of Technical Sciences-Metallurgy and Fuel), No. 3, 39-43 (1960).

(10) Kodolov, V. D., "Introduction of Elastic Ultrasonic Vibrations in Weld Pools", Avtomaticheskaya Svarka, No. 4, 35-39 (1961).

(11) Lebiga, V. A., "Effects of Ultrasonic Vibrations on Weld Pool Crystallization in Automatic Welding", Avtomaticheskaya Svarka, No. 1, 21-26 (1960).

(12) Eaton, N. F., "Improvements in or Relating to Welding", British Patent No. 875,035 (August 16, 1961).

(13) "Evolution of Ultrahigh-Strength Steels, and Research on Materials and Various Novel Techniques of Fabrication of High Performance Rocket Motor Cases", Mellon Institute, Final Report to Bureau of Naval Weapons, Code SP-271, Contract NOrd 18169 (October, 1961).

(14) D'Antonio, C., and Vecchio, A. J., "Effect of Ultrasonic Agitation on Grain Size in Welds", Welding Journal, 41 (4), Welding Research Supplement, 166-s (April, 1962).

(15) Brown, D. C., Crossley, F. A., Rudy, J. F., and Schwartzbart, H., "The Effect of Electromagnetic Stirring and Mechanical Vibration on Arc Welds", Welding Journal, 41 (6), Welding Research Supplement, 214-s-250-s (June, 1962).

(16) Personal conversation with D. A. Dudko, Deputy Director, E. S. Paton Institute of Electrowelding, Kiev.

LIST OF DMIC MEMORANDA ISSUED
(Continued)

A list of DMIC Memoranda 1-164 may be obtained from DMIC, or see previously issued memoranda.

DMIC Memorandum Number	Title
165	Review of Uses for Depleted Uranium and Nonenergy Uses for Natural Uranium, February 1, 1963