3

Mechanical Properties of Ultrasonically Irradiated Metals

The mechanical properties of metals are largely controlled by structural imperfections such as interstitials, vacancies, dislocations, grain boundaries, and second-phase particles.

The microplastic deformation which results from the variation of dislocation structure of materials exposed to ultrasonic treatment also has an effect on mechanical properties. Kulemin[4] and Polotskii,[9] among others, investigated the influence of ultrasonic pretreatment on the mechanical properties of metals. Blaha and Langenecker[3] revealed the unusual effect of decreasing resistance to plastic deformation as a result of simultaneous application of static and ultrasonic loads. This effect was further investigated by Severdenko and coworkers in Minsk.[61–69]

3.1 THE EFFECT OF ULTRASONIC PRETREATMENT

The variation of structure caused by cyclic stressing at low and ultrasonic frequency will modify the mechanical properties of metals. In fact, work completed up to date demonstrated that cyclic loading would either increase or decrease the strength of materials. The actual change depends on the metal's initial material condition and cyclic treatment regime.

Below we will discuss the major trends in the variation of mechanical properties of annealed and predeformed metals of different lattice types following ultrasonic treatment.

The mechanical properties were generally evaluated by tensile and hardness testing. Conceptually the latter method offers an advantage since it allows resistance to plastic deformation to be measured in microscopic regions and the specimens to be repeatedly used.

The application of an ultrasonic stress amplitude higher than some critical level for each metal will harden the as-annealed material. This involves increases in yield point, tensile strength, and hardness and a decrease in ductility.

Kulemin[4] investigated the effect of 20-kHz vibrations on the mechanical properties of face-centered cubic (FCC) metals. The vibrations were fed to the specimen using a waveguide system illustrated in Figure 2.3. The specimens were either round in section, 12 mm in diameter, with a narrowing in the midzone, or 12 mm square; they were all half a wave long.

4

Diffusion in an Ultrasonic Field

Early work[5-10] indicated that it was possible to increase the penetration of nitrogen (N), chromium (Cr), nickel (Ni), and carbon (C) to steel exposed to combined high-frequency vibrating and chemical heat treatment using induction heating.

The discovery of this effect paved the way for a whole series of studies dealing with the influence of mechanical vibrations on diffusion-related processes in solid metals.[4]

Most studies focused on the relation between ultrasonic vibrating and heat treatment. It was generally found that heat treatment efficiency was improved, sometimes dramatically. However, all these programs suffered a major limitation that the acoustic parameters could not be controlled because of the inadequate ultrasonic technology.

The experimental arrangement that was almost exclusively used for feeding vibrations to the specimen is illustrated in Figure 4.1*a*. The vibrations were generated by magnetostrictive or piezoceramic transducer 1 and transmitted to specimen 4 via waveguide-radiator system 2, 3 and a layer of liquid. The vibration intensity, cavitation, and radiator-specimen spacing could hardly be controlled in this system. Thus, the results of these tests are only of general historical interest.

However, the advent of the experimental arrangement depicted in Figure 4.1*b* ensured real progress.

Specimen 4, which was of relatively small size, i.e., much smaller than the wavelength, was gripped between two waveguides *3* of one-quarter wavelength. In this method, the displacement amplitude could be estimated at the waveguide end.

A further improvement of the method involved the use of a half-wave specimen (see Part 3, Figure 2.3) which was fixed to the booster. As already noted, a clear advantage of this method, in addition to the possibility of controlling acoustic parameters, is the variability of achievable strain in a single specimen. This substantially reduces the number of tests necessary for revealing the relation between ultrasonic efficiency and strain.

The research completed to date in the field of acoustically enhanced diffusion in solid metals can be broadly classified into two categories: (1) direct tests to measure diffusion coefficients and (2) experiments to evaluate the ultrasound effect on heat treatment processes including chemical heat treatment.

This chapter will closely scrutinize the first line of research. The overview will include the diffusion of C in Ni and iron (Fe)[4], Cr in Fe and Fe base alloys,[17,18] various admixtures such as antimony (Sb), gallium (Ga), indium (In), aluminum (Al) and lithium (Li) in germanium (Ge),[16,23] and zinc (Zn) and Al in copper (Cu),[11-15] and Zn in Fe.[13]

The above experimental studies were performed on metals of different lattice types, forming both substitutional and interstitial solutions, and can be used to formulate the theoretical approach to the understanding of the effect of ultrasound on diffusion.

5

Phase Transformations in Ultrasonically Irradiated Metals

The preceding chapters dealt with the effect of ultrasound on the structure of metals and diffusion in metals. Those studies indicated that ultrasound could also influence phase transitions in solids. Ayzentson, Kulemin, and this author discussed some trends in kinetics of phase transformations in metals exposed to ultrasound, although the mechanism of this effects has not been finally clarified.

5.1 THE EFFECT OF ULTRASOUND ON POLYMORPHOUS TRANSFORMATIONS

The effect of ultrasound on diffusion processes also alters the kinetics of phase transformations controlled by diffusion. Several reports are currently available on the effect of ultrasonic vibration on polymorphous transformations in materials.

Ayzentson and Spivak[1] investigated the effect of ultrasound on polymorphous transformation of tin and found that the process was enhanced.

Kapustin[2] studied the influence of ultrasound on polymorphous transformation in mercury iodide. He revealed that the application of ultrasound improved both the rate and the extent of transformation.

It should be noted that the lack of reliable control of acoustic parameters and the uncertainty involved in measuring the sample temperature in ultrasonic tests compound the interpretation of results. The above effects may well be due to an increase in temperature during ultrasonic irradiation.

The ultrasound effect on polymorphous α-γ transformation in iron is of vast practical interest.

Kulemin and Nekrasova[3] selected a 0.07% carbon (C)-7% chromium (Cr)-2% nickel (Ni) steel for their tests. In this steel, the transformation does not involve any concentration changes. It occurs at a slow rate, is caused by disordered displacements of the atoms over the interface, and is controlled by boundary self-diffusion. The extent of transformation was evaluated as a variation of natural resonance frequency f_0 of specimen during transformation with due regard to the fact that the latter changes the elastic constants, and hence the vibration propagation velocity.

The tests were made by two methods. In the first, the sample was heated to a temperature of 900°C and held at this temperature for 10 min. The sample was then quickly taken to a tin melt held at a temperature below the γ-α transformation temperature and placed in an ultrasonic field which exerted a constant strain amplitude.

1

Ultrasonic Degassing of the Melt

The interaction of high-intensity ultrasound with liquid reduces the amount of liquid-contained gas, leading to degassing. This effect can be used for degassing metal melts.

The initial work on melt degassing dates back to the early 1930s. A whole range of degassing methods using both piezo-electric and magnetostrictive transducers was developed at that time.[1, 2] In the 1940s, Esmarch[3] proposed a melt degassing method in which the elastic vibrations were excited by superimposing a permanent magnetic field on the alternating field of the induction furnace. This process was called *electrodynamic excitation* and used for degassing aluminum alloys with 5–7% magnesium (Mg). A melt 8–10 kg in weight was vibrated for 30–60 min at a temperature of 700°C. The vibration frequency excited in the metal was 10 kHz. The low process efficiency was due to the inadequate vibration intensity.

In the late 1950s, Soviet researchers began extensive investigations of ultrasonic degassing of aluminum and Mg base alloys, using the direct transmission of vibrations to the melt through a rod-type resonator.[4–8] Along with applied research, the mechanism of ultrasonic degassing of liquid was also examined by several authors. Based on the earlier work, the ultrasonic degassing process can now be recommended for large-scale applications.

1.1 DEGASSING KINETICS

It is well known that ultrasonic vibration of liquids leads to their degassing because of the variation of the solubility of dissolved gas with pressure. An increase in pressure raises the solubility and suppresses the evolution of gas. A decrease of pressure and eventually generation of vacuum reduces solubility and results in the degassing of liquid. In fact, for metallic melts, the solubility of gas at a given temperature is proportional to the square root of pressure.[9]

Thus it is clear that an ultrasonic method that allows alternating pressure to be applied to the entire liquid bath will have an important effect on gas solubility and gas evolution kinetics.[16–21]

Kapustina[5, 10–15] carried out a comprehensive series of tests to study the mechanism and kinetics of ultrasonic degassing.

Experimental study[15] revealed that the bubbles grow at a faster rate in the presence of ultrasonic vibration than in its absence, with the mass transfer rate being dependent on acoustic pressure amplitude (Figures 1.1, 1.2).

When the sound frequency and acoustic pressure amplitude are constant, the diffusion flow is generally controlled by the ratio of actual R_0 and resonant R_r bubble radii.

2

Solidification of Metals in an Ultrasonic Field

Chernov[1] was the first to propose that the quality of metal can be improved by imposing vibration on the solidification process. The vibrating of solidifying melt refines the metal macrostructure, improving the metal properties.

Low-frequency vibrations generally modify only the macrostructure, producing little if any effect on microstructure. although it is largely a beneficial factor, vibration can also produce undesirable effects such as increased segregation and pinholes.

Ultrasonic irradiation involves the propagation of elastic waves through the melt. As a result, the structure changes are enhanced and variegated in as-cast material. In addition to the macrostructure variation, the micrograin is refined and the segregation is better controlled.

Sokolov[77,78] was the first to use ultrasonic irradiation of low-melting melts. However, the technical difficulties with the feeding of vibrations to the melts and the lack of ultrasonic oscillators in the kilohertz range delayed effective research along this line.

From the 1950s on, Teumin,[2–7] Pogodin-Alekseev,[8,9,47] Polotskii,[10–12] Eskin,[13,15,16] Eskin and Fridlyander,[14] Dobatkin and Eskin,[17] Abramov and Teumin,[18] Abramov,[19–21,25] and Abramov et al.[22,23,49,75] carried out a broad range of research and development programs and built ultrasonic equipment for metallurgical applications.

The effects of ultrasound on as-cast material structure can be summarized as follows:

1. The reduction of mean grain size
2. The control of columnar structure and formation of equiaxed grains
3. The variation of phase distribution in terms of relative amounts, structure refinement, and mutual geometry
4. Better material homogeneity and segregation control
5. More uniform distribution of nonmetallic inclusions

The above effects, however, do not exhaust the scope of structure changes that can occur during solidification in an ultrasonic field. In fact, the columnar structure will sometimes persist but the thickness of columnar crystals will be reduced.[35,77,78] On the other hand, Pogodin-Alekseev[8] observed the coarsening of excess phase crystals in eutectic alloys when the intensity of ultrasound was increased above a certain level.

Thus the available experimental evidence suggests that there are many important changes in the micro- and macro-structure of as-cast metals, which can be achieved by the use of ultrasonics. The combination of these structure changes can be defined as

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1

Ultrasound in Metalworking Processes

It has already been demonstrated that the transmission of high-intensity ultrasound to a solid metal increases the density of structure imperfections such as dislocations and vacancies. This modifies the properties of the workpiece and so has an effect on the metalworking process.

At the solid-solid interface, ultrasonic vibrations change the surface condition and reduce the friction of boundary lubrication.

These physical mechanisms pave the way for using ultrasound in metalworking processes. Currently ultrasound has proven its effectiveness in processes such as wire and tube drawing, extrusion, forging, and rolling.

The use of ultrasound in metalworking processes reduces the energy requirement, increases the process rate, improves tooling lives, upgrades workpiece surface quality, and extends metalworking technology to materials that break up under conventional metalworking conditions.

In the 1950s, Blaha and Langenecker[1] were the first to investigate the effect of ultrasonic vibrations on mechanical properties of metals. They demonstrated that the superimposition of alternating stresses on the workpiece greatly changed the flow conditions. The force necessary for deforming the workpiece is significantly reduced (see Figure 3.18 in Part 3).

This problem was studied extensively in the USSR. In Minsk, Prof. Severdenko and his colleagues Dr. Klubovich and Dr. Stepanenko carried out a wide range of research into the potentials of using ultrasound in various metalworking processes.[2–6]

1.1 ULTRASONIC SYSTEMS USED IN METALWORKING

The ultrasonic assembly used for metalworking consists of a power supply and vibratory system. The latter is a structural part of the metalworking machine. In modern practice, the power supplies and metalworking machines are normally of standard design, although some machines have been modified for fitting the vibratory systems.

The vibratory system generally consists of one or two transducers for converting electrical oscillations to elastic vibrations, a booster, and a horn which is combined with the work tool to provide an integral piece of equipment. In this arrangement, the ultrasonic load is represented by the workpiece.

The metalworking ultrasonic assembly should be able to meet a number of acoustic and structural requirements. These requirements have been formulated in a general

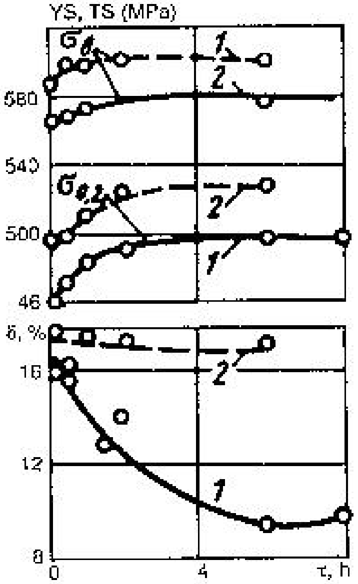

FIGURE 2.12. Effect of ultrasound on mechanical properties of as-aged grade D16 Al alloy: (1) control, (2) irradiated.

2.3 AGING AND TEMPERING

Aging belongs among the heat treatment processes whose kinetics are controlled by diffusion.

Biront[1] provided an overview of studies dealing with the aging kinetics in alloys placed in fluids vibrated at sonic and ultrasonic frequencies. In Biront's studies, the intensity of irradiation varied from 1.4 to 6.7 W cm^{-2}, and widely different materials such as duralumin, lead (Pb)-base alloys, Ni-base alloys, and steels were used. In most cases, irradiation led to higher aging rates which were increased by a factor ranging from 2 to several hundred. Sometimes irradiation was found to substantially change the aging effect, for example, material hardness, as compared with conventional aging.

The ambiguity of the data seems to be due to the method of irradiation through a layer of liquid. In this instance it is extremely difficult to evaluate the true alternating stress amplitudes that arise directly in the specimen and compare the test results. The increase in aging rate could be due to radiation heating.

All these limitations can be avoided if one uses the test arrangement illustrated in Figure 6.1 of Part 3.

A similar method of feeding ultrasound to the specimen was used by Pogodina-Alekseeva[21] who used aluminum alloy grades V95, AK6, AK4-1, and D16. The alloys were aged at temperatures which produced the maximal effects in the absence of ultrasound. As an example, Figure 2.12 shows the mechanical properties of alloy grade D16 aged with the use of ultrasonics at a temperature of 178°C. It is obvious that ultrasonic irradiation improved the overall performance of material. Interestingly enough, the process time was drastically reduced as well.

Similar results were obtained for other alloys. For example, study of aging behavior in the alloy grade D16 and binary Al-Cu models revealed[1] that the strength of materials

Ultrasonics also has been used with chemical etching to machine materials to controlled shapes. The application of ultrasound increases the etching rate by a large factor which depends upon the material to be machined and the chemical being used.

Other methods include (1) revolving a workpiece and ultrasonically energizing a conventional drill bit to drill materials otherwise difficult to machine, (2) energizing a lathe tool to obtain improved surfaces and reduce chatter in materials that have a tendency to chatter normally, and (3) energizing reamers to increase feed rates and improve surface finish. There are reports of improved grinding effects under the influence of ultrasonic energy.

Ultrasonic rotary drills with conventional diamond tips are commercially available. These units are capable of drilling holes in ceramic materials as well as in metals. A commercially available rotary-type ultrasonic drill is shown in Fig. 12.7. Several typical specimens machined with the rotary drill are shown in Fig. 12.8. The bit is water-cooled but no slurry is required. This equipment is primarily of value for machining ceramic-type materials but shows promise for improved machining of certain metals as well. The effectiveness of the imposed ultrasonic forces in improving the machining effectiveness is a function of the ratio of maximum vibratory tip velocity to the peripheral velocity of the tool relative to the work surface. The effectiveness is diminished as this ratio decreases below unity. Increasing the ratio above unity should be beneficial if the cutting edges of the tool remain in good condition. At very high ratios, heating is a factor and careful cooling is required to prevent damage to the tool.

III.B. Metal Forming

A plate of soft-annealed copper as thick as 1/8 in. can be reduced to a thin foil by forcing it between a flat tip of an ultrasonically vibrating tool and an anvil when the spacing between the anvil and the tool is fixed. The force necessary to maintain a continuous feed rate can be applied easily by hand. This example illustrates the reduction in drawing force that can be accomplished with the application of ultrasonic energy to drawing dies and other forming operations.

The drawing force necessary for some forming processes can be reduced by more than 50% by using ultrasound. Langenecker [7] claims that drawing forces can be reduced by 80% at drawing speeds of 100 ft/min. Two factors believed to improve formability of metals with the application of ultrasonic energy are (1) the softening effect on the crystals (volume effect) and (2) the reduction of frictional forces between the workpiece and the tool. The potential advantages are the increase in metal formability and the beneficial influence of ultrasonic energy in forming difficult-to-form materials such as case-

ULTRASOUND *in* LIQUID *and* SOLID METALS

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Translated by
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CRC Press
Boca Raton Ann Arbor London Tokyo

Library of Congress Cataloging-in-Publication Data

Abramov, O. V. (Oleg Vladimirovich)
Ultrasound in liquid and solid metals / O. V. Abramov.
p. cm.
Includes bibliographical references and index.
ISBN 0-8493-9355-8
1. Ultrasonic waves—Industrial applications. 2. Metals—Effect of radiation on. I. Title.
TA367.A26 1993
620.1'6—dc20
93-25193
CIP

Direct all inquiries to CRC Press, Inc., 2000 Corporate Blvd., N.W., Boca Raton, Florida 33431.

International Standard Book Number 0-8493-9355-8

Library of Congress Card Number 93-25193

Printed in the United States of America 1 2 3 4 5 6 7 8 9 0

Printed on acid-free paper

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