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NON-CONTACT ULTRASONIC TREATMENT OF METALS IN A MAGNETIC FIELD

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Abstract

A high-field EMAT (Electromagnetic Acoustical Transducer) has been used for non-contact ultrasonic processing of aluminum samples during solidification. The magnetic field for the EMAT is supplied by a high-field (20 Tesla) resistive magnet, and the current is provided by an induction coil. This resulted in a highly efficient EMAT that delivered 0.5 MPa of acoustic drive to the surface of the sample while coupling less than 100 watts of incidental induction heating. The exceptionally high energy efficiency of the electromagnetic transducer is due to the use of high magnetic field, which reduces the current needed to achieve the same acoustic pressure. In the initial experiments, aluminum samples of A356 alloy were heated to the liquid state and allowed to solidify at a controlled cooling rate while subjected to the non-contact ultrasonic stimulation (0.5 MPa @ 165 kHz) provided by an induction coil located within the bore of a 20-T resistive magnet.

Introduction

Ultrasonic processing of materials in both the melt and solid phase is proving to be highly beneficial to material properties of metallic alloys.[i] In the melt phase, acoustic treatment can be used to enhance diffusion, dispersion, and dissolution processes, resulting in improvements in the cleaning, refining, degassing, and solidification of the melt. Ultrasonic processing can be used to assist in grain refinement and to minimize segregation during solidification. Degassing with ultrasonics has resulted in reduced gas concentration, higher density, and improved mechanical properties. It has been demonstrated that non-dendritic structures can be produced with ultrasonic cavitation treatment, resulting in increased plasticity and enhanced strength. In the solid state phase, ultrasonic treatment could potentially be utilized to minimize residual stress, accelerate phase transformation processes, enhance nucleation and growth during phase transformations, enhance diffusive processes by enhancing the mobility of diffusing species, and enhance processes that have a threshold activation energy. The method can be coupled with high-field magnetic processing,[ii,iii] but can also be used where only ultrasonic treatment is beneficial.

Commercially available ultrasonic processing systems require direct contact with the melt, resulting in undesirable chemical interactions when the acoustic probe/horn is inserted directly into the molten material. Ultrasonic transducers are limited in temperature range, and therefore must be thermally isolated from high-temperature environments by using an acoustical waveguide, or horn. Acoustic impedance mismatches between the transducer and the waveguide,

as well as between the waveguide and the melt can limit the transfer of energy. Various types of probe coatings have been investigated in an effort to minimize the chemical interactions of the probe surface with the melt. In addition, the localized nature of the horn probe results in a very non-uniform distribution of acoustical energy within the melt crucible. The ability to couple acoustic energy efficiently via a non-contacting method would overcome a huge technological barrier to the more widespread use of ultrasonic processing.

Theory

When induction heating is applied in a high magnetic field environment, the induction heating coil is typically configured in such a way that high intensity ultrasonic treatment occurs naturally. The resulting configuration is that of a highly effective electromagnetic acoustical transducer (EMAT). This approach is unique because the magnetic field strength of the high-field magnet can greatly exceed that used in a typical EMAT device. As a consequence, the synergistic interaction of a high surface current density (induced via induction heating) with the steady-state high magnet field results in an especially effective method for creating a high energy density acoustic environment. The exceptionally high energy efficiency of the resulting electromagnetic transducer is due to the use of high magnetic field, which greatly reduces the current needed to achieve the same acoustic pressure. This provides an efficient non-contact method for applying high-intensity ultrasonic energy to the processing of metals. Furthermore, the applied ultrasonic excitation can be uniformly distributed over most of the surface of the metal sample.

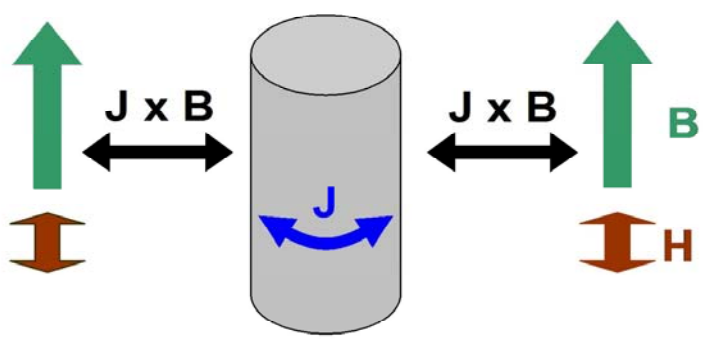

Figure 1. Induction heating in a high-field magnet, showing the applied H-field of the induction coil, the induced surface current in the sample (J), the static field of the magnet (B), and the resulting JxB force. The H-field of the induction heating coil is insignificant (μH << B) by comparison with the static B-field of the high-field magnet.

If the axis of a helical induction heating coil is aligned with the static magnetic field of a high-field magnet, the azimuthally-directed surface current induced in the process metal interacts with the static field of the magnet. The result is a large oscillatory electromagnetic force, or pressure, that acts directly on the metal surface, at the induction heating frequency. In cylindrical coordinates, the force is in the radial direction. Figure 1 shows the applied H-field of the induction coil, the induced azimuthally-directed surface current (J), the static externally applied magnetic field (B), and the resulting radially-directed electromagnetic force (J x B). The acoustic driving force is bi-directional, alternately compressing and stretching (tensioning) the sample in the radial direction. In liquids, the later leads to cavitation that can be very beneficial for ultrasonic processing of the melt phase. The acoustic pressure can be quite substantial since both the induced surface current and the static magnetic field are quite large.

The effectiveness of acoustical excitation can be enhanced if the frequency happens to coincide with a natural resonant frequency of the sample. Because of the large mismatch in the acoustic

impedance at a material-air interface, most of the acoustic energy can be trapped within the sample and the sample container, forming an acoustical resonator. If the acoustic drive frequency is chosen to match a natural resonant frequency of the sample, then the peak acoustic pressure in the resonator can be enhanced by a factor that is equal to the quality factor of the resonator. Quality factors for liquid metal columns with large length-to-diameter ratios are expected to be in the range of 10-100.[iv] Although a somewhat smaller quality factor might be anticipated for a typical experimental configuration, due consideration should be given to the potentially advantageous use of acoustical resonances.

Using this high-field EMAT method, non-contacting ultrasonic treatment can be applied to the processing of metal alloys in either the solid and melt phase. Molten metals can be contained in a non-metallic ceramic crucible that is readily penetrated by the electromagnetic induction fields. Ultrasonic treatment in the solid phase can be achieved either at near-ambient temperatures, or at elevated temperature. When applied under high temperature conditions, temperature control can be achieved via the induction heating process, whereas at ambient temperatures, gas cooling might be required to remove the incidental heat coupled by the induction system.

Experimental

Aluminum samples processed ultrasonically with the high magnetic field EMAT were compared with samples processed in the absence of EMAT excitation (no-field), but with the same thermal treatment. Aluminum samples of A356 alloy were inductively heated and melted in an alumina crucible located within the 8-inch diameter bore of the high-field solenoidal resistive magnet, in an argon atmosphere. The sample temperature was measured using a sheathed thermocouple inserted into a thin-walled stainless steel well that allowed the thermocouple to be withdrawn after solidification of the melt. When the melt temperature reached 700 C, the magnetic field was ramped up to the desired value, usually either 9 or 18 Tesla. Since the ultrasonic pressure resulting from the EMAT effect is proportional to the externally applied B-field, the ultrasonic excitation of the sample increased linearly during the ramp-up of the magnetic field. The samples were then allowed to solidify at a controlled cooling rate while being subjected to the non-contact ultrasonic stimulation (0.5 MPa @ 165 kHz) provide by the EMAT. Forced flow helium gas was used to cool down and solidify the samples while continuing to power the induction coil at the maximum current level. This procedure maintains a constant level of ultrasonic drive throughout the cool down and solidification of the sample, as both the induction current and the external field were held constant during the cool down phase. The cooling rate was controlled by adjustment of the flow rate of the helium coolant gas.

In Figure 2, two sets of cooling curves are shown, corresponding to two different flow rates of coolant gas. Each set includes the measured sample temperature data for two different values of magnetic field including a no-field case and an 18 T field case. Each plot shows two inflections in the cooling rate due to exothermic events. These recalescence events, one at 610 C and the other at 570 C, are associated with the onset and completion of alloy solidification, respectively. These temperatures are consistent with liquidus and solidus temperatures of 615 C and 575 C predicted by Thermocalc, Al-DATA database,[v] for this alloy. For the slower cooling rate achieved with a 10 psi helium feed pressure, solidification is completed in approximately 11 minutes. To effect a faster cooling rate, the helium feed pressure was increased to 40 psi, which decreased the cooling and solidification time by more than a factor of two, to approximately 4 minutes. For the 18 Tesla case, the ultrasonic drive pressure is the maximum achievable value of approximately 0.5 MPa. For the no-field case, there remains a residual EMAT effect arising from the induction heating along, but this is much weaker, and at twice the induction frequency.

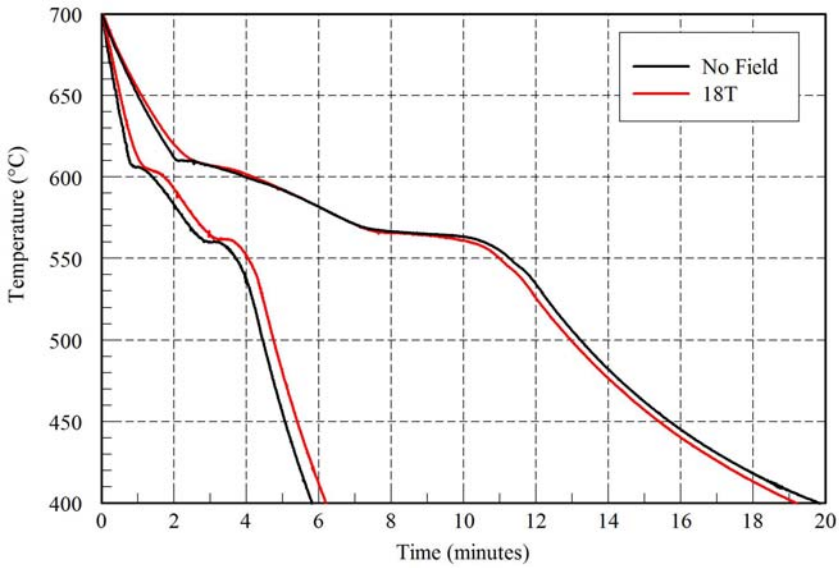

Figure 2 Cooling curves for two different flow rates of helium coolant gas

Results and Discussion

Aluminum samples processed with the high magnetic field EMAT were compared with samples process in the absence of magnetic field (no EMAT) but with the same thermal treatment. Based on visual appearance, samples processed with EMAT stimulation showed notably improved surface conditions as compared with samples solidified in the absence of EMAT stimulation under no-field conditions. This difference is illustrated by the photos shown in Figure 3. The processed samples were approximately 35 mm in diameter, and about 52 mm in length.

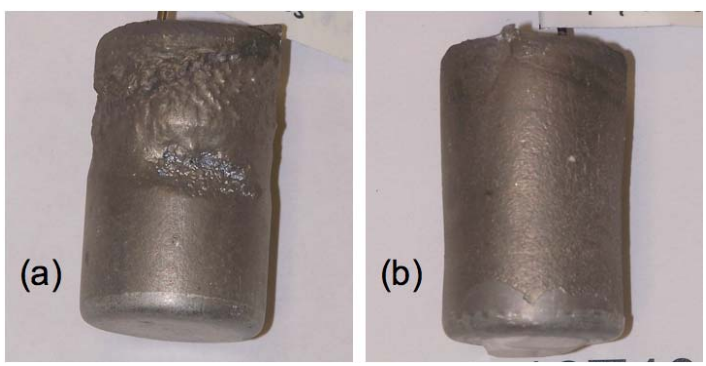

Figure 3 The sample on the left (a) was processed in the absence of EMAT stimulation under no-field conditions, whereas the sample on the right (b) was solidified with maximum EMAT stimulation using an external magnetic field of 18 T.

Optical micrographs reveal that there were obvious differences in microstructure uniformity for the samples that were subjected to ultrasonic processing using the high-field EMAT. Micrographs for a no-field sample, shown in Fig. 4, reveal a very obvious difference in microstructure between the top and the bottom of the sample, suggesting a segregation of the Silicon, which is manifest in different amounts of primary alpha (~pure Al) versus eutectic (alpha plus Si-rich phase). By comparison, similar micrographs for a high-field EMAT sample, shown in Fig. 5, do not show any variations in microstructure uniformity between the top and bottom of the sample. This sample was processed with maximum EMAT stimulation using an external magnetic field of 18 T. Additional analysis of the samples is needed to provide a more complete assessment of the differences attributable to high field EMAT processing.

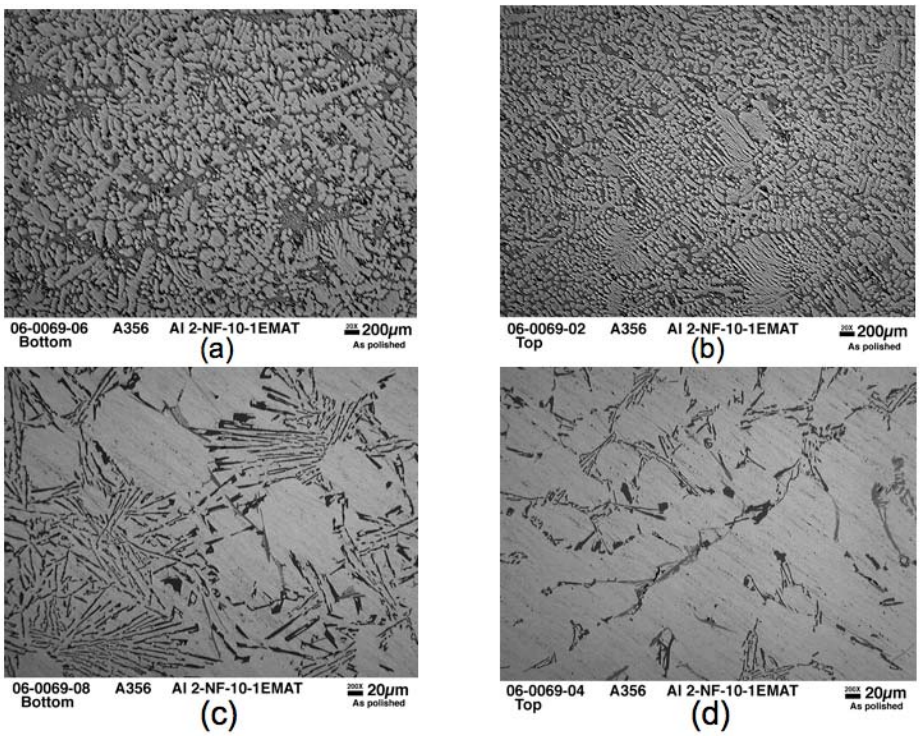

Figure 4 Optical micrographs of no-field sample comparing low resolution images near the bottom (a) and top (b) of the sample, as well as 10x higher resolution images near the bottom (c) and top (d) of the sample.

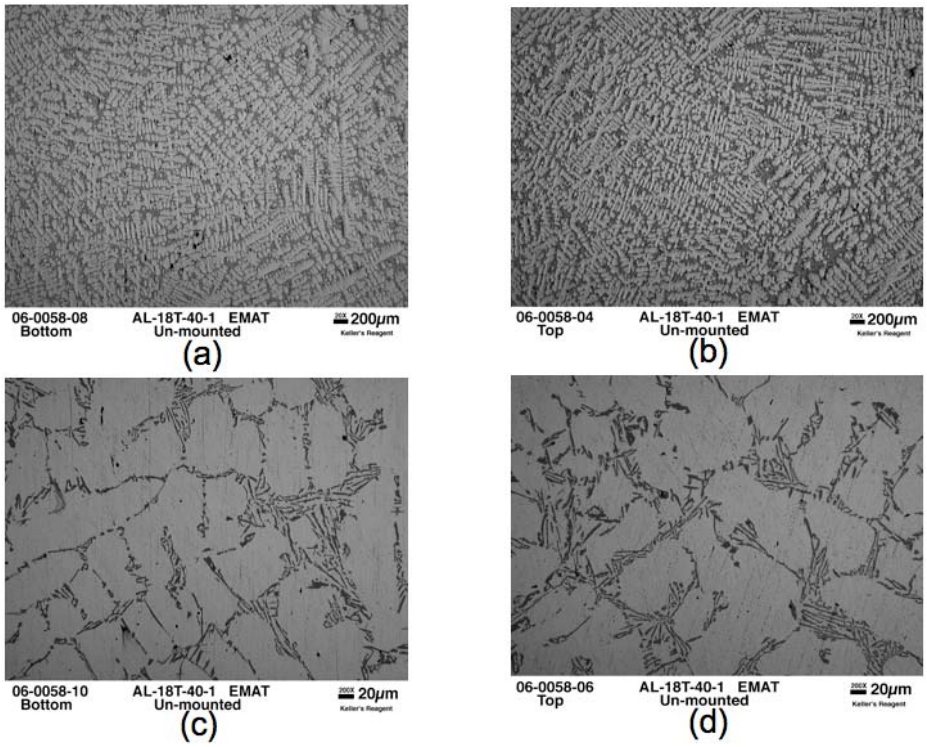

Figure 5 Optical micrographs of a high-field EMAT processed sample comparing low resolution images near the bottom (a) and top (b) of the sample, as well as 10x higher resolution images near the bottom (c) and top (d) of the sample.

Summary and Conclusions

A high-field EMAT has been used to effect non-contact ultrasonic solidification processing of aluminum samples in a high field magnet. An advantage of using a high magnetic field environment is that this allows the induced surface current in the sample to be decreased proportionately. As a result, the incidental induction heating associated with the use of the EMAT transducer is greatly reduced, which favorably affects the energy efficiency of the EMAT approach. In the initial experiments, aluminum samples of A356 alloy were heated to the liquid state and allowed to solidify at a controlled cooling rate while subjected to the non-contact ultrasonic stimulation (0.5 MPa @ 165 kHz) provided by an induction coil located within the bore of a 20-Tesla resistive magnet. An initial analysis of the samples produced during these experiments shows improved microstructure uniformity and a reduction in porosity near the radial surface. Additional analysis of the samples will provide a more complete assessment of the benefits attributable to non-contact high-field EMAT processing, and additional experiments are needed to explore the parameter space, including optimization of the ultrasonic frequency.

Acknowledgement

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