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ABSTRACT

A noncontacting ultrasonic method has been investigated for probing the solidification front in molten titanium for the purposes of profiling the channel depth in a plasma hearth re-melter. The method, known as Laser Ultrasonics, utilized a pulsed laser for generation of ultrasonic waves at the surface of a molten metal pool. The ultrasonic waves propagated into the liquid titanium reflected from the solidification front and the boundaries of the solid plug. A Fabry-Perot interferometer, driven by a second laser, demodulated the small displacements caused by the ultrasonic wave motion at the liquid surface. The method and results of measurements taken within a small research plasma melting furnace will be described. Successful results were obtained even directly beneath the plasma arc using this all optical approach.

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INTRODUCTION

Manufacturers of aircraft engines view cold hearth melting as a desirable technique for refining rotating grade titanium alloys. This process removes inclusions, which are stress risers and limit the strength of the alloy, provided that the titanium is kept molten in the hearth long enough. The residence time in the hearth is dependent on the melt rate of the titanium and the volume of the pool. Because the crucible is water-cooled, a titanium skull forms between the pool and the crucible. The skull thickness depends on the heat flow from the molten pool to the crucible, and in general is unknown. Currently, residence times are conservatively estimated from empirical data for the pool volume, melt rate, and arc parameters, but a real-time method of locating and characterizing the shape of the solidification front would permit a more accurate assessment of the residence time.

Ultrasonic waves travel in all materials, and can be used to locate discontinuities in material properties, such as at material boundaries. In particular, ultrasonic waves can reflect from the solid / liquid interface, also known as the solidification front, within a molten metal. Measuring the transit time of these reflected waves provides a means of measuring the location of interface and, therefore, the depth of the pool. It is undesirable in many applications to immerse a measurement probe into the molten pool because of deterioration of the probe and possible contamination of the pool. A non-contacting laser-based ultrasonic approach is well suited to such applications [Scruby and Drain, 1990]. Optical measurements are compatible with the high temperatures needed for melting industrial materials, so long as both the generation and detection laser beams can reach the molten surface and the detection beam can be captured for processing outside of the chamber. Experience has shown that even though ultrasonic attenuation is markedly increased at high temperature, depths of 1-2 inches can be easily investigated in molten industrial metals at frequencies on the MHz range, with potentially greater depth measurement possible using large laser powers. This paper describes the results from laser ultrasonic depth measurements that have been applied to plasma hearth melting of titanium in a small research furnace.

EXPERIMENTAL

In plasma hearth re-melting of titanium, the metal is continually fed into a water-cooled crucible where it is melted by heating with a high energy density plasma arc. Molten titanium flows from the far side of the pool to form an ingot. High-density inclusions of contaminant materials (HDI's) sink in the molten titanium and are trapped in the hearth skull which forms between the molten pool and the crucible. Low-density inclusions (LDI's) float to the surface and dissolve. It is critical that the molten titanium reside in the hearth long enough to remove these inclusions by both of these mechanisms. The pool depth and uniformity determine the residence time and are important parameters in controlling the quality of the ingot produced. For this investigation, a small research plasma hearth furnace was used to create a stationary pool of molten titanium. Ultrasonic waves were generated on the surface of the pool using a pulsed laser, and detected with a second, continuous laser, and a Fabry-Perot interferometer. Ultrasonic echoes from the solidification front and the bottom of the titanium skull were identified and maximum pool depth of approximately one centimeter was measured. Changes in the current to the plasma arc altered the pool depth in a predictable manner.

<u>Cold Hearth Furnace</u>

The pool depth measurements were conducted in the small research furnace shown in figure 1. It included a vacuum controlled chamber, a copper crucible, and a stinger, each cooled by water. The purpose of the stinger was to hold a tungsten electrode, conducting current to it and heat from it, and providing height adjustment for the arc. The crucible served as the return electrode for the circuit, and supported about 1.7 kg of titanium in a 13 cm diameter by 3 cm thick volume. The chamber was evacuated with a vacuum pump and backfilled with argon to prevent corrosion. The length of the arc, the cover gas, and the current in the arc determined the heat transfer into the titanium, and the geometry of the resultant molten pool. With a maximum current of 600A, the furnace could produce a pool depth of a couple of centimeters. A typical pool was 6-7 cm diameter by 1 cm deep for 400 A arc in 1 atmosphere of argon with a 3 cm liftoff distance.

The chamber had two 5 cm diameter windows, one on either side of the stinger, to

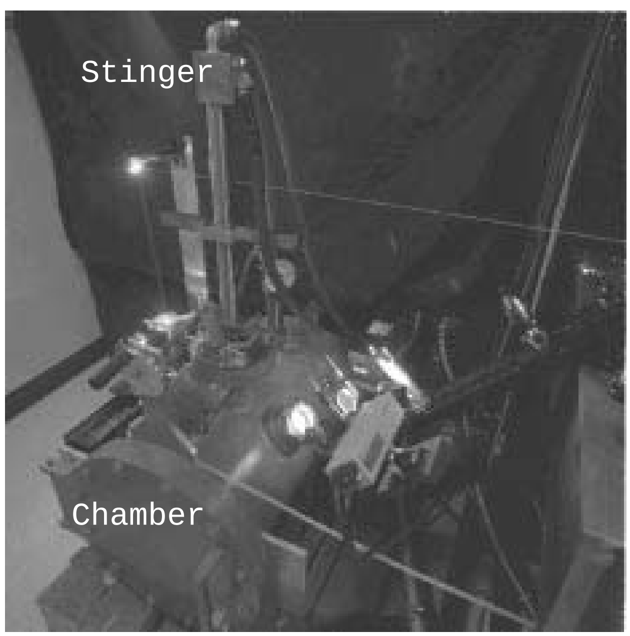

Figure 1 – Small plasma arc furnace for molten pool experiments. The stinger, chamber, and copper crucible (not shown) are water cooled.

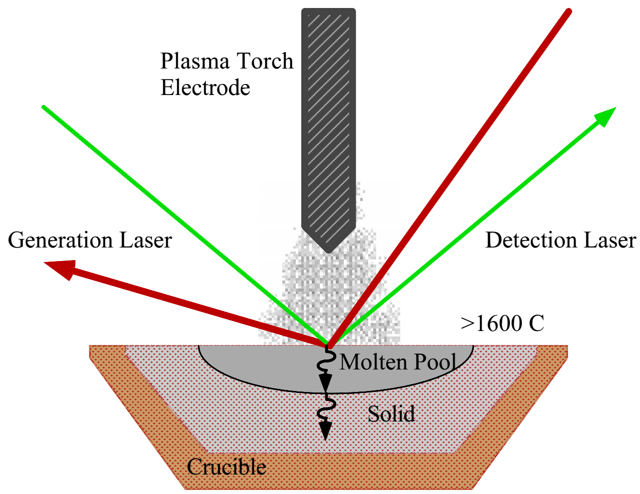

Figure 2 - Geometry for laser ultrasonic measurements directly beneath a plasma arc electrode.

provide access for the laser beams. The generation laser pulses were incident through the near window, seen on the right side of the chamber in figure 1, with the reflected pulses missing the far window, harmlessly striking the interior of the chamber. The detection light was incident at 45° through the far window, reflected from the pool, and exited through the near window before being collected and processed by a Fabry-Perot interferometer, which is outside of the photograph of figure 1 to the right.

<u>Laser Ultrasonic Method</u>

A pulsed laser incident on a metal can generate ultrasonic waves by two mechanisms, thermoelastic expansion and ablation. On the free surface of a molten pool, both mechanisms produce a dipole radiation pattern, similar to that from conventional piezoelectric transducers [Walter, Telschow and Conant, 1995]. The incident pulse energy heats the liquid to the point of vaporization, producing ultrasound by thermoelastic expansion. Excess energy, beyond that required for vaporization, ejects material from the pool, producing ultrasound by ablation. The ablation mechanism is far more efficient than thermoelastic generation. In mercury, for example, ablation produces about 100 times larger ultrasonic pulse amplitudes than the thermoelastic mechanism [Telschow, Walter, Conant and Garwick, 1996]. For this reason and since there is no damage to a liquid surface, the ablation source is preferred for molten metal applications

A Fabry-Perot interferometer was used to detect the ultrasonic waves returning to the surface. For this technique, a second continuous laser beam was reflected from the molten metal surface. The Doppler effect produced by the ultrasonic motion of the surface shifted the frequency of the light by a small amount. A confocal Fabry-Perot interferometer transformed this frequency modulation into an intensity modulation that

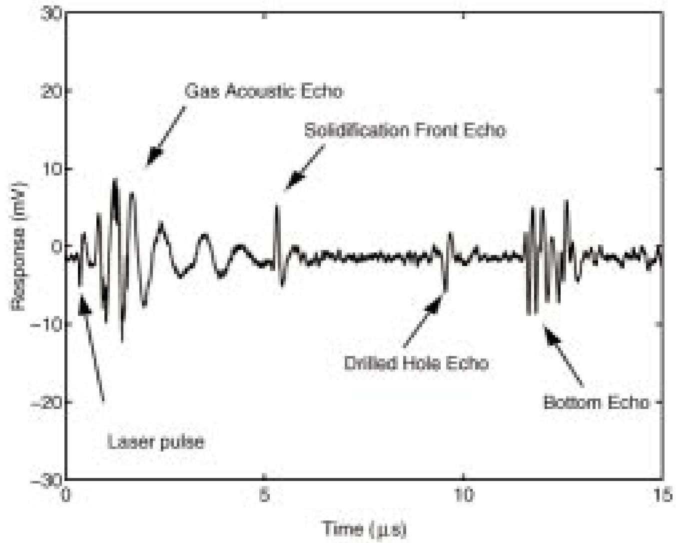

Figure 3 – Ultrasonic signals recorded from the molten titanium pool.

was subsequently recorded by a fast photodiode producing a voltage proportional to the surface velocity. The detector had a bandwidth of 20 MHz, and could detect sub-nanometer motion at ultrasonic frequencies. This technique can be used with optically diffuse surfaces in addition to the specular surface of a clean molten pool, and is applicable to many industrial situations [Monchalin, 1986].

The measurement geometry is shown schematically in figure 2. The generation pulse, shown as incident from the right, is a 300 mJ, 15 ns pulse at 1064 nm from a Nd:YAG laser, with a 2 mm diameter spot at the surface. The ablation mechanism also produces a surface wave and a shock wave in the gas or plasma. The surface wave, though only moving at about 1 m/s, is large and visibly disturbs the path of the reflected light, disrupting detection. The shock wave in the gas crosses the path of the detection light, and can be evident in the response of the Fabry-Perot detector as an 'artifact' signal. The detection light, 2 W, 514 nm from a CW argon ion laser, is focussed a few millimeters from the generation spot to reduce the strength of the shock wave and to allow the surface wave to arrive well after the ultrasonic echoes. While both generation and detection occur within the arc, the white arc light is blocked from the detector by a narrow optical filter that only passes light at the laser wavelength.

Figure 3 displays a typical response of the Fabry-Perot detector, showing ultrasonic reflections from the solidification front, a bottom-drilled hole, and the bottom of the titanium skull. Also evident are the shock wave 'artifact,' extending from about 1-5 μs, and a trace of the 1064 nm generation pulse at 0.5 μs. The surface wave disrupts the detection light a few milliseconds after the ultrasonic signals have been detected.

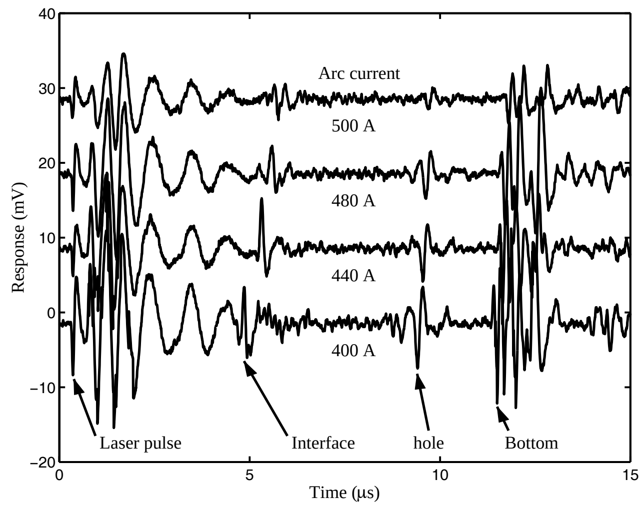

Figure 4 – Laser ultrasonic - interface, drilled hole and skull bottom echoes vary with depth of titanium pool.

RESULTS / DISCUSSION

Echoes were recorded from a titanium pool for various arc currents. Figure 4 shows that the solidification front echo arrives later for higher currents as the larger heat input produces a deeper pool. Also, the transit time for echoes from a bottom-drilled hole within the solid skull and the skull bottom varied weakly with the current. This is to be

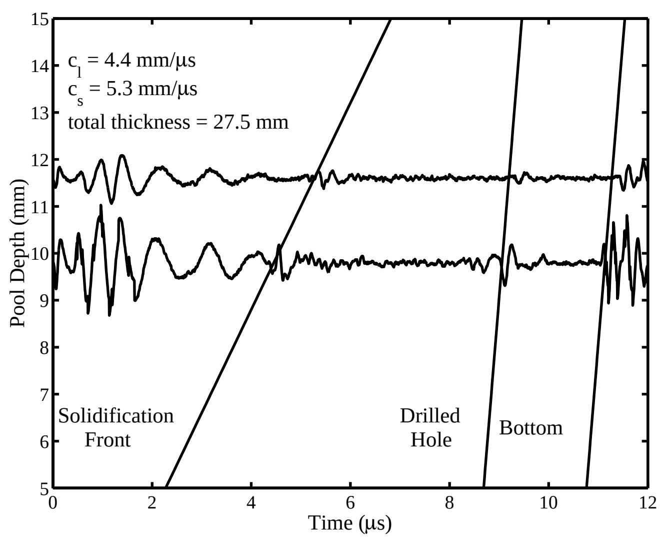

Figure 5 – Expected relationship between pool depth and echo arrival times in 27.5 mm thick titanium disk.

expected as these slight changes in heating produce only a small change in average acoustic velocity along the propagation path from the liquid surface. As the heat input is increased, a larger portion of the path becomes molten lowering the average velocity since the velocity of the liquid is lower than the solid. In addition, both acoustic velocities decrease with temperature. However, the net effect was only a minor increase in the acoustic transit time.

Figure 5 depicts the expected relationships between the pool depth and the timing of the three echoes [Casas, Keita and Steinemann 1984], ignoring the difference in density and the temperature dependence of the sound velocities. Also displayed are two of the traces from figure 4, offset by a nominal depth that was selected to have the echoes fall on the respective lines. The relative transit times, between the solidification front echo and the hole and bottom echoes, are consistent with the expected changes in pool depth. The furnace was not equipped to mark the pool with an impurity for metallurgic determination of the depth, but the drilled hole provided a known marker echo to aid in calibration of the ultrasonic determination.

Two aspects of the geometry of the experiments limited the range of depths for which measurements were made: (1) the shallow depth of titanium in the crucible and (2) the temperature gradients along the path of the detection light. The laser ultrasonic technique was able to detect the solidification front as long as both the generation and detection laser beams were injected into the chamber and the detection beam successfully extracted for processing outside of the chamber.

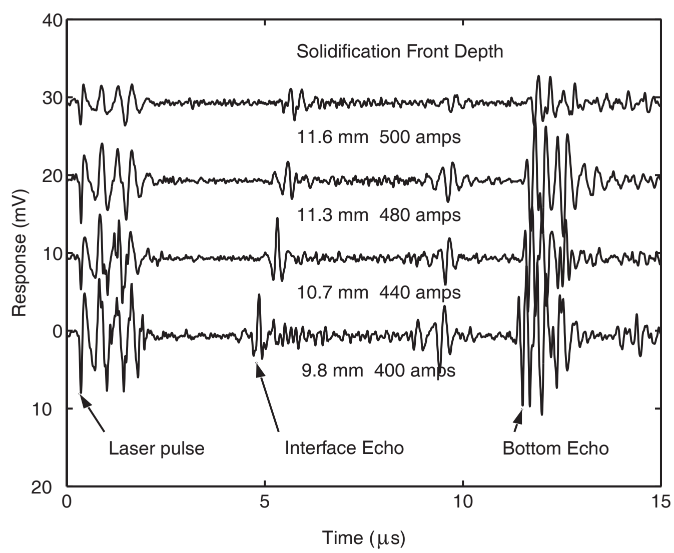

Figure 6 – Processing the laser ultrasonic signal with high pass filter enhances the echo from the solidification front.

The temperature gradients bent the path of the light, which, along with the fixed window size, limited the range of arc currents for which the detection light reached the extraction window. While there will be temperature gradients in all cases, appropriate design of the insertion and extraction should allow depth measurements for the required range of interest for a production furnace.

The precision and accuracy of the ultrasonic pool depth determination depended on a number of factors, including the repeatability of the echoes, and the accuracy with which the echo times were determined. The speed of sound in the liquid and solid depends on temperature and on the alloy, hence the accuracy to which these are known or can be estimated is also important.

Determination of the timing of the echoes in figure 4 can be improved by processing the signal with a 1 MHz high pass filter. As is seen in figure 6, this limits the shock wave artifact, which had been extending into the echo from the solidification front.

Echo reproducibility was examined by recording several traces in quick succession (one for each laser pulse) while the interface was nominally stable. Filtered traces are displayed in figure 7, showing that although the timing appears the same from trace to trace, the signal strength varies substantially. This is likely due to surface motion between traces, which affects the signal at generation as well as detection. For generation, the ultrasonic pulse is directed normal to the surface due to the finite spot size [Telschow, Walter, Conant and Garwick, 1996]. Consequently, as the surface tilts, the strength of the

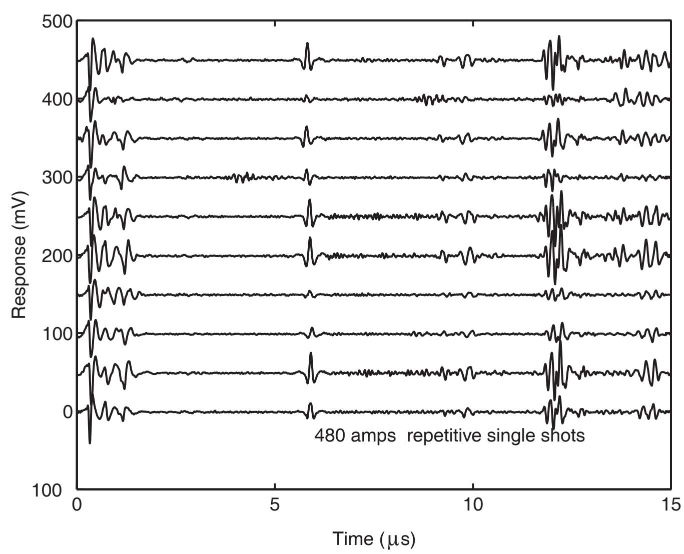

Figure 7 – Repeated measurements of the laser ultrasonic signal at 400 A. The signal is high pass filtered at 1 MHz to enhance the echo from the solidification front.

ultrasonic wave propagating normal to the solidification front varies. The amount of ultrasonic energy reflected from the solidification front that is ultimately detected depends on the front interface tilt with respect to the liquid surface, among other parameters. This can actually be helpful, since the front may not be exactly horizontal.

For detection, the Fabry-Perot detector is sensitive to the component of the surface velocity normal to the surface, but more importantly, a small change in the direction of the reflected beam can result in a poorer collection by input aperture of the detector. Extreme tilts can cause the detection light to miss the aperture entirely. The variations in figure 7 may also be due in part to fluctuations in the arc and the temperature gradients, producing changes particularly in the detection path.

The effect of pool dynamics on the reflection from the interface echo was examined by establishing a stationary pool and then changing the current in the arc. Figure 8 displays traces from the stationary pool at 420 A with three traces after the current has been increased to and held at 480 A. The molten pool becomes deeper, but it is interesting that the laser ultrasonic signal can track changes occurring in the solidification front as it stabilizes over several minutes. There is a gap of a few minutes, before the first trace at 480 A, where the solidification echo was much diminished, presumably because the solidification front microstructure contained a "mushy" zone resulting in a poorly defined interface and correspondingly greatly decreased ultrasonic reflection.

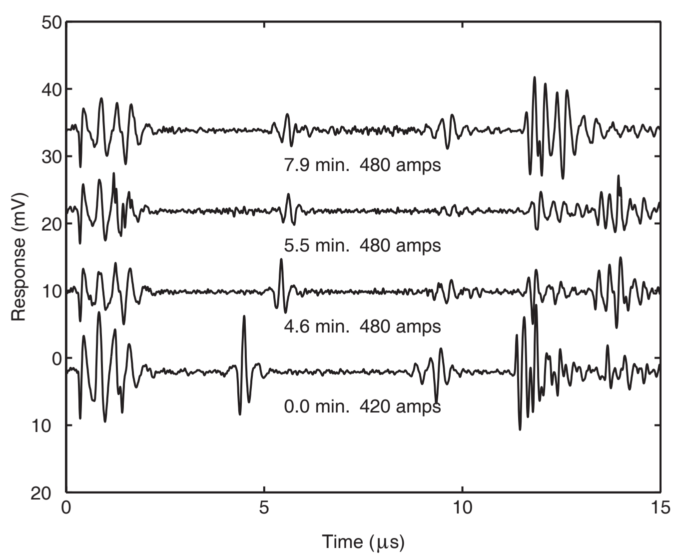

Figure 8 – Laser ultrasonic signals from a changing titanium pool. This data is high passed filtered at 1 MHz.

CONCLUSIONS

The solidification front was successfully detected in molten titanium with a laser ultrasonic approach using a Fabry-Perot detector. Echoes from the skull bottom and a bottom-drilled hole in the skull were also detected, with timing consistent with the timing of the solidification front echo. Measurements were made for both stationary and moving solidification fronts directly under the torch in a research plasma arc furnace at temperatures of around 1600 – 1700 C. Laser ultrasonic depth measurements required monitoring times of only microseconds and could be repeated every few seconds, limited by surface wave reflections from the edge of the small pool. For a production furnace, the pool would be larger and surface waves would reverberate less. Signal averaging, to compensate for the longer sound path, could be employed to improve the signal to noise ratio. The detection geometry can be optimized for the production situation, hence the limited range of arc currents in the research furnace avoided.

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