NONCONTACTING LASER ULTRASONIC GENERATION AND DETECTION AT THE SURFACE OF MOLTEN METAL

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INTRODUCTION

The use of pulsed lasers for noncontacting generation of ultrasound in solid materials is expanding rapidly [1], as is optical detection of ultrasound [2]. The noncontacting nature of laser ultrasonics is opening new areas of research where physical contact of transducers to the material under study is impossible or inadvisable. One example is in the titanium melting industry. Currently, vacuum arc remelting (VAR) is used to produce much of the nation's titanium from Kroll process sponge. However, the process provides only limited means of removing oxynitride and carbide inclusions from the melt, which can become stress intensifiers in the ingot. VAR of titanium can be replaced with plasma or electron beam hearth melting, both of which have the potential to eliminate these stress-intensifying inclusions by increasing the residence time of the molten titanium in the hearth so that the oxynitrides dissolve and the carbides settle out of the melt. This process is so important that industry is starting to replace VAR with hearth melting for titanium to be used in critical applications such as rotating turbine parts. The new process has other advantages as well. Processing steps will be eliminated because sponge will no longer need to be consolidated into electrodes and fewer melting steps will be required. The improved quality of the melted product will result in less scrap, and the ability to recycle scrap into high value products will also be a major improvement. The most important aspect, though, is the capability to produce superior ingots with the potential of allowing turbine engines to be lighter and more efficient. However, industry has identified a critical requirement for these hearth melting processes: measurement of the volume of molten metal to ensure sufficient residence time in the melt. Ultrasonic sensing is one possible way for locating the interface between molten and solid metal so that the depth of the molten metal, the volume, and thus the residence time may be determined. Because the titanium hearth operates at high temperatures (1650°C), contacting transducers with buffer rods are not practical; it is also a potential source of melt contamination. Therefore, a totally noncontacting sensor system is needed. This sensing technology would also be widely applicable to other metals, including other reactive and refractory metals, superalloys, and steel.

This paper describes proof of principle for using lasers to generate and detect ultrasound for the measurement of molten metal pool depth. Tin was chosen for these experiments because it has a low melting point and does not require any special equipment to produce a molten metal pool. To keep initial experiments simple, the depth of the molten pool was determined using a noncontacting sensor without any solid/liquid interfaces present. The results are compared with the published value provided by Parker [3].

FABRY-PEROT INTERFEROMETER

Several types of optical laser-based ultrasonic detectors have been developed for noncontacting measurement of surface motion due to ultrasonic waves [2]. In some cases these devices have been employed at high temperatures to record material properties during heating [4]. However, the majority of these systems depend on phase sensitive detection of the light and require polished surfaces and strict alignment for adequate signal-to-noise ratio, and thus are suitable only for laboratory environment.

A Fabry-Perot interferometer was chosen as the detector in this work because this unit is sensitive to the frequency, rather than the phase, of light scattered off the sample surface [5]. Thus light can be collected from a diffuse surface and processed with this unit to yield the velocity of the surface. The primary requirement is that a sufficient amount of scattered light be collected and passed through the interferometer. This is accomplished by using a source laser capable of delivering a sufficient amount of light to achieve an acceptable signal-to-noise ratio.

The Fabry-Perot interferometer frequency response is shown in Figure 1. The oscillating sample surface causes the reflected or scattered light to be Doppler shifted in frequency. This light can be demodulated by passing it through the interferometer. This is done by setting one of the response peaks of the interferometer so that the laser frequency is at the position shown in Figure 1, thus giving an output intensity proportional to the Doppler frequency shift of the scattered or reflected light, and hence proportional to the velocity of the sample surface.

A schematic of the detection system is shown in Figure 2. A 1-W argon ion laser beam is divided into two beams using a 1/2 wave plate and a polarizing beam splitter cube. Part of the light goes to the sample for the detection of ultrasound while the rest is used to position the interferometer frequency response so that the laser frequency is at the operating point in Figure 1, near the half maximum of the curve. This provides the best sensitivity. The two beams are kept separate using the beam splitter cubes and wave plates. A collection lens is used to capture scattered light off the molten surface. The light then travels through the interferometer where it is demodulated and through a lens that focuses the light onto a signal photodiode used to detect the ultrasound.

EXPERIMENT

The experimental setup, shown in Figure 3, uses a 100 mJ/pulse ND:YAG pulsed laser to produce a longitudinal wave that travels through the molten tin to the bottom surface and back to the top surface. The Fabry-Perot interferometer detects the longitudinal wave at the surface of the molten tin. A resistive furnace coupled with a temperature controller is used to maintain the tin in a molten state. The temperature profile and the depth of the pool are measured using a thermocouple attached to a vernier caliper (not shown).

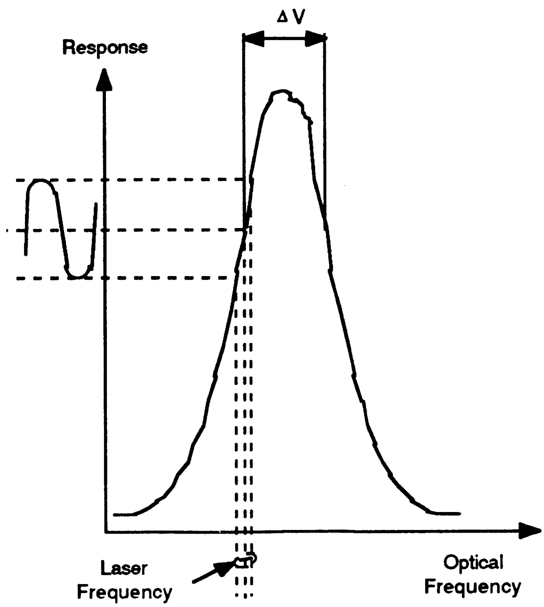

Fig. 1. The reflected light is demodulated by setting the laser frequency on the slope of one of the response peaks of the interferometer.

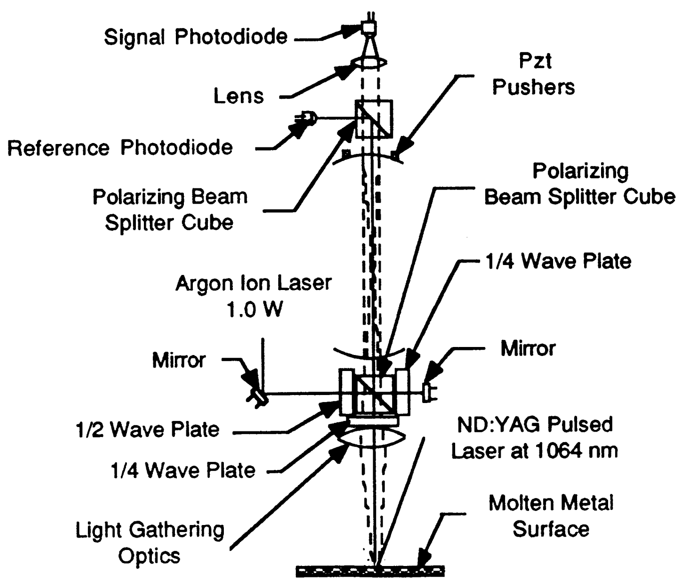

Fig. 2. Laser detection of ultrasound using a confocal Fabry-Perot interferometer.

RESULTS

The ultrasonic echoes from laser-generated ultrasound observed for four different molten tin depths are shown in Figure 4. From the timing of the multiple echo compression waves and the speed of sound in the molten tin, the depth of the molten pool can be determined. In this case,

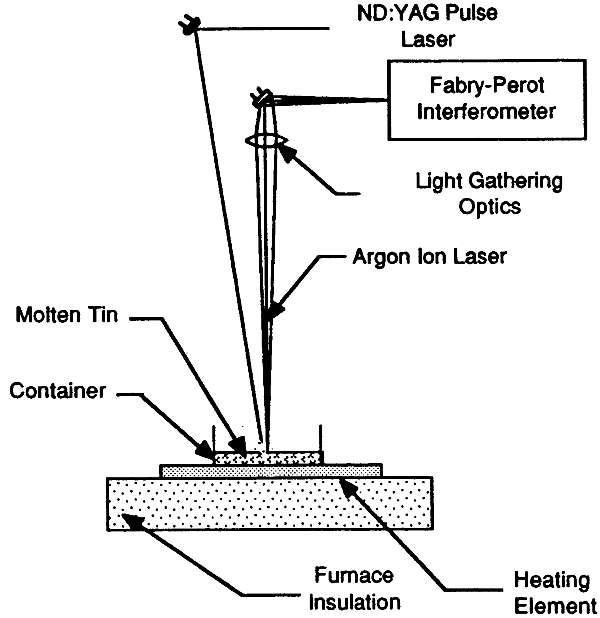

Fig. 3. Experimental setup.

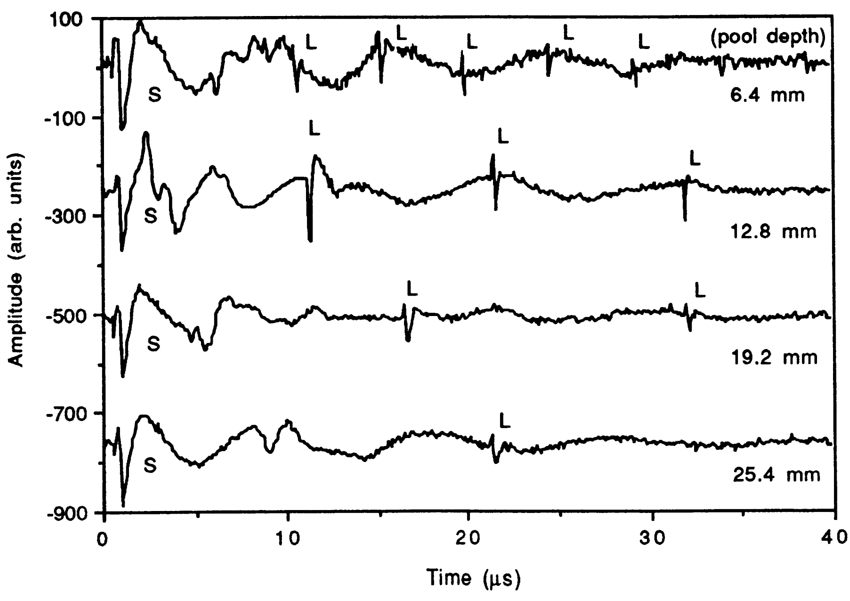

Fig. 4. Ultrasonic detection for four different pool depths (L = Longitudinal waves, S = Surface waves).

the pool depths are known and the sound speed in the molten tin was calculated to demonstrate the relationship. The mean velocity of 2.44 mm/μs was calculated using six different pool depths and is shown in Figure 5. This value for the velocity agrees well with the literature value of 2.46 mm/μs [3]. Thus, noncontacting laser ultrasonics can be used for determining the depth of molten metals.

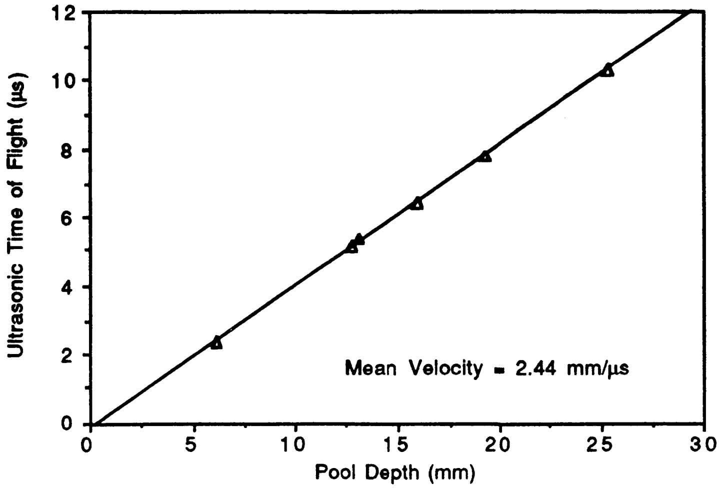

Fig. 5. Mean velocity calculation using six different pool depths.

A surface wave can be observed when using this technique to determine the pool depth. These waves are shown in Figure 6 and can also be seen in Figure 4 at the beginning of each trace. The time at which the surface wave is detected is dependent on the location of the detection laser relative to the location of the laser used to generate the ultrasound.

Further research on the acoustic properties of the molten/solid interface of titanium in hearth melting is needed in order to determine the potential precision of the depth measurement under hearth conditions. The effects of temperature gradients in the titanium melt need to be determined since the sound speed is dependent on temperature. From the results of this experiment, and of other experiments involving ultrasonic detection in molten metals, the development of a molten metal depth sensor for hearth melting of titanium looks promising.

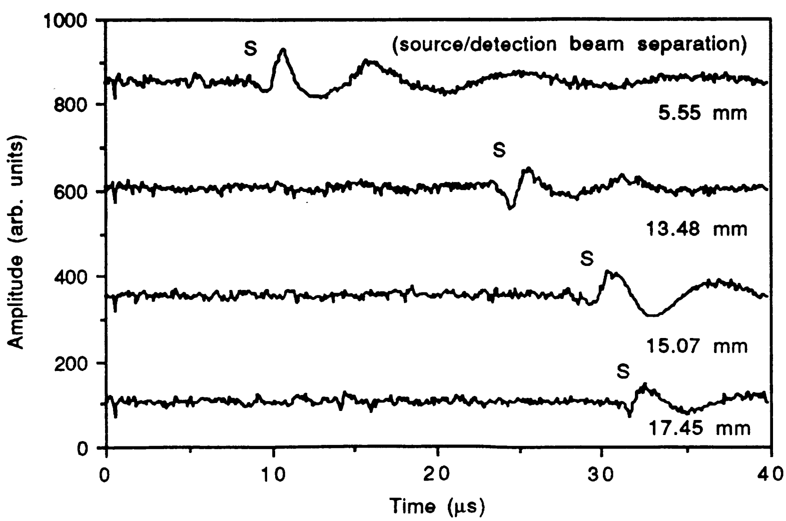

Fig. 6. Surface waves due to laser generated ultrasound for different separation distances between the detection and source lasers (S = Surface waves).

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