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LASER ULTRASONIC THICKNESS MEASUREMENTS OF VERY THICK WALLS AT HIGH TEMPERATURES

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ABSTRACT. Laser-ultrasonics presents many advantages compared to conventional ultrasonics, but is, generally, considered as less sensitive. As a consequence, laser-ultrasonics should not be adequate for ultrasonic measurements in coarse microstructure materials or measurements of large thicknesses. However, since the generated waves extend to very low frequencies, measurements in such conditions can be successfully performed if a photorefractive interferometer sensitive also to these low frequencies and properly balanced is used for detection. This is demonstrated by measurements of thicknesses up to 100 mm (4") for various steel grades and at temperatures up to 1250 °C.

Keywords: Laser-ultrasonics, Thickness measurement
PACS: 81.70.Cv, 42.62.Cf

INTRODUCTION

Laser-ultrasonics, which allows non-contact and at a distance ultrasonic generation and detection, has found many applications for testing materials at high temperatures. It has been not only applied to laboratory measurements [1-5], but was also demonstrated and is actually used on production lines [6-8]. Although this technique has the unique capability of allowing material characterization during processing and at elevated temperatures, and this has been reported many times [1-8], more straightforward applications, like measuring thickness, are often the most needed by industry. In this case it should be noted that the technique is now commercially used for measuring the wall thickness and eccentricity of seamless tubes in production [6]. These tubes have usually thicknesses of less than 25 mm (one inch) and the technique has been proven to be quite effective for this application. Measuring thickness at elevated temperatures is also of interest for forging operations. However in this case, much larger thicknesses may be encountered, even exceeding 50mm. Therefore this paper addresses specifically such cases and will provide an answer regarding the maximum thickness that can be measured in such conditions.

The most important challenge for such application is to generate sufficiently strong ultrasonic waves and detect them with high sensitivity to surmount the high attenuation found in such conditions. This high attenuation is also known to be smaller for low ultrasonic frequencies. Since the generated stress waves are essentially unipolar, they have strong contents in the low ultrasonic frequencies range (their spectrum extends essentially from 0 Hz). On the detection side, interferometers based on two-wave mixing in photorefractive crystals should be preferred for detection to Fabry-Perot interferometers since they have better sensitivity in this range (i.e. below 1 MHz) [9]. Also two-wave mixing photorefractive interferometers equipped with a balanced receiver and with equal lengths over the pump and signal paths, have been shown to be essentially immune to laser intensity and phase noise, which are stronger in the frequency range of interest [10,11].

ULTRASOUND PROPAGATION IN HIGH TEMPERATURE METALS

Metals show very high attenuation as temperature approach the melting temperature. This is due to two main mechanisms. First there is a significant grain growth that causes strong scattering of the ultrasonic waves. Second, there is an absorption mechanism that grows exponentially with temperature (also known as the background absorption) and becomes a major contribution at very high temperatures. For example, in steels above about 1200 °C, most of precipitates that are able to retain the excessive grain growth are dissolved and grain sizes, that are typically a few tens of microns bellow 1000 °C, can reach several hundred microns at 1250 °C. The absorption is often of the same order of magnitude as that of scattering for steels at about 1200 °C and for frequencies around 5 MHz.

Figure 1 shows an ultrasonic signal obtained at 1300 °C in a 20 mm thick steel sample heated in an inert atmosphere furnace (50 times averaging). The ultrasonic waves are generated by a 1 J, 8ns pulse Nd:YAG laser and detected on the other sample side by a long pulse laser coupled to a two-wave mixing photorefractive interferometer. The obtained signal illustrates the high attenuation but also its strong frequency dependence. Figure 2 shows the spectrum for the first and fifth echoes of the signal of Figure 1, which corresponds to ultrasonic propagation distances of 20 mm and 180 mm, respectively

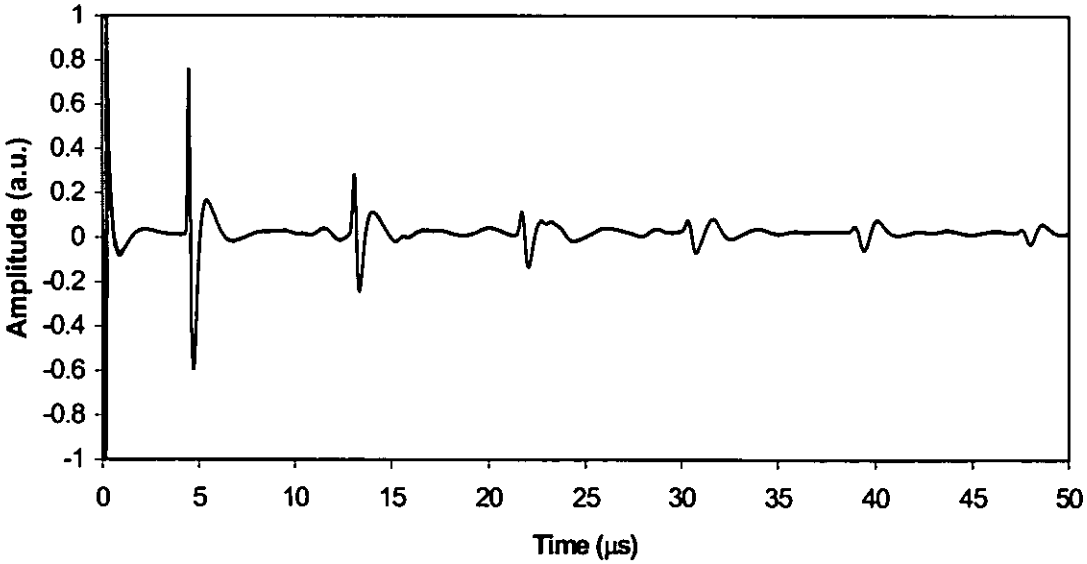

FIGURE 1. Ultrasonic signal obtained by laser-ultrasonics in a 20 mm steel bar at 1300 °C.

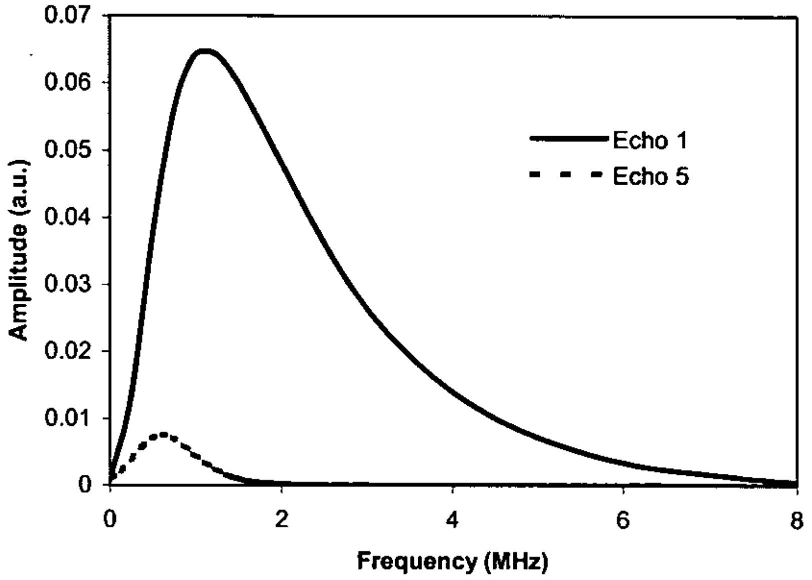

FIGURE 2. Spectra for the first and fifth echoes of the signal shown in Figure 1.

By the frequency content of the fifth echo, it is clear that in order to measure thickness in the range of 100mm at high temperature, the laser-ultrasonic system must have good sensitivity for frequencies below 1 MHz.

EXPERIMENTAL SETUP

In order to demonstrate the feasibility of thickness measurement of thick steel pieces at high temperatures in industry, samples of various steel grades with thicknesses from 20 to 70 mm were heated in air in a radiation furnace up to 1200 °C while laser-ultrasonic measurements were done. Figure 3 shows a hot sample inside the furnace exposed to the testing laser beams. The furnace door remains closed during the heating (that takes about one hour) and is open for the laser-ultrasonic measurements. If non-adherent scale is present on the sample surface, it is mechanically removed by hitting it with a metal bar. A Nd:YAG laser pulse, frequency tripled, with energy of about 600 mJ and duration of about 7 ns is directed to the sample surface for ultrasonic generation. For detection, a pulsed Nd:YAG with pulse duration of about 100 μs and peak power of about 1 kW was directed to the sample and the collected light was demodulated by a GaAs two-wave mixing photorefractive interferometer. As mentioned above, the intensity noise of the detection laser is cancelled by using a balance receiver (two detectors in differential configuration). As required by this type of interferometer, part of the detection light is deviated to 'pump' the photorefractive crystal. More details on the two-wave mixing photorefractive interferometer can be found in reference 9. Also as mentioned above, in order to cancel the phase noise from the detection laser, the optical paths for the beam probing the material and that of the pump should have about the same length. This is easily achieved by proper selection of the fibers lengths.

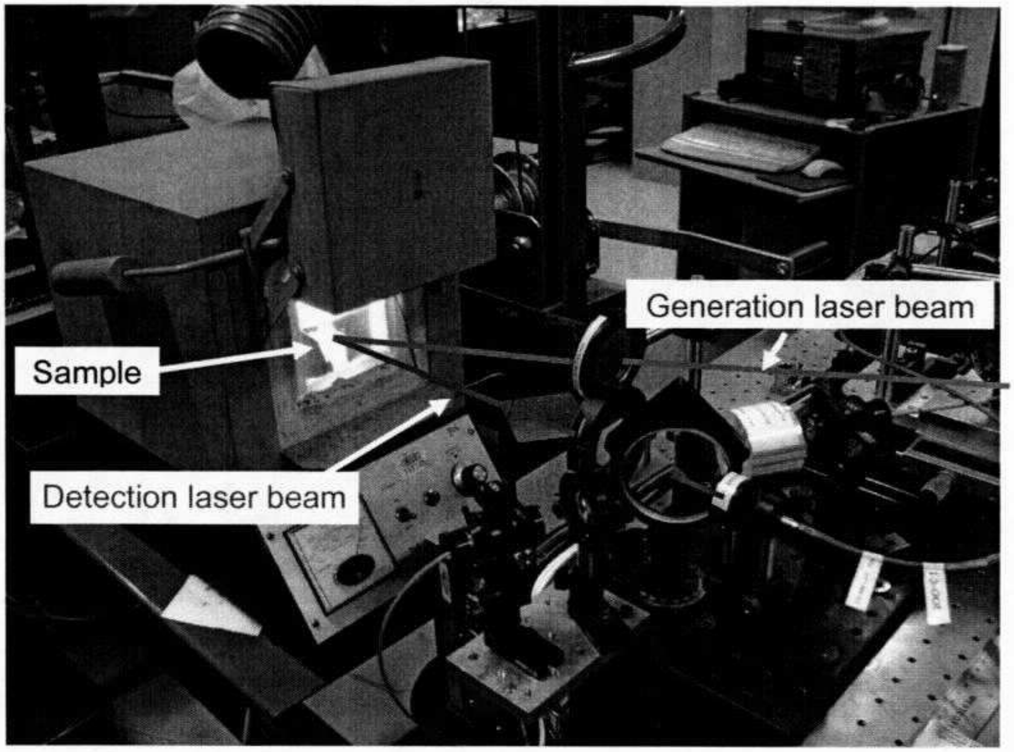

FIGURE 3. Open furnace view with the laser generation and detection beams indicated.

RESULTS

Figures 4 and 5 show typical single shot signals obtained on hot samples. At least two echoes are clearly visible for thicknesses of 50 mm and 60mm, meaning that a sample with double thickness could have a first echo identified and its thickness could be determined. The low frequency character of the detected echoes is shown in Figure 6 by the spectrum of the second echo of the signal of Figure 5. Most of the ultrasonic pulse energy is below one megaherz, as already evidenced by Figure 2. The frequency response of the system was limited on the low frequencies side by a 500 kHz Bessel high pass filter. This filter explains the shape of the spectrum shown in Figure 6 where the high frequencies are filtered by the material attenuation and the low frequencies by the analog high pass filter. These are examples of one-shot (non averaged) signals. By averaging, the signal-to-noise ratio can be improved, but some attention must to be paid to avoid 'bad' signals to be included in the averaging. These 'bad' signals were found to be essentially related to the formation of non-adherent oxide or scale on the sample surface at high temperatures. As the oxide detaches from the bulk material, the generated ultrasound reverberates in the oxide layer and the detected signals show distinctive features as illustrated in Figure 7. These signals are easily recognized and experience shows that mechanical removing of undesired non-adherent scale is, in general, a relatively easy task.

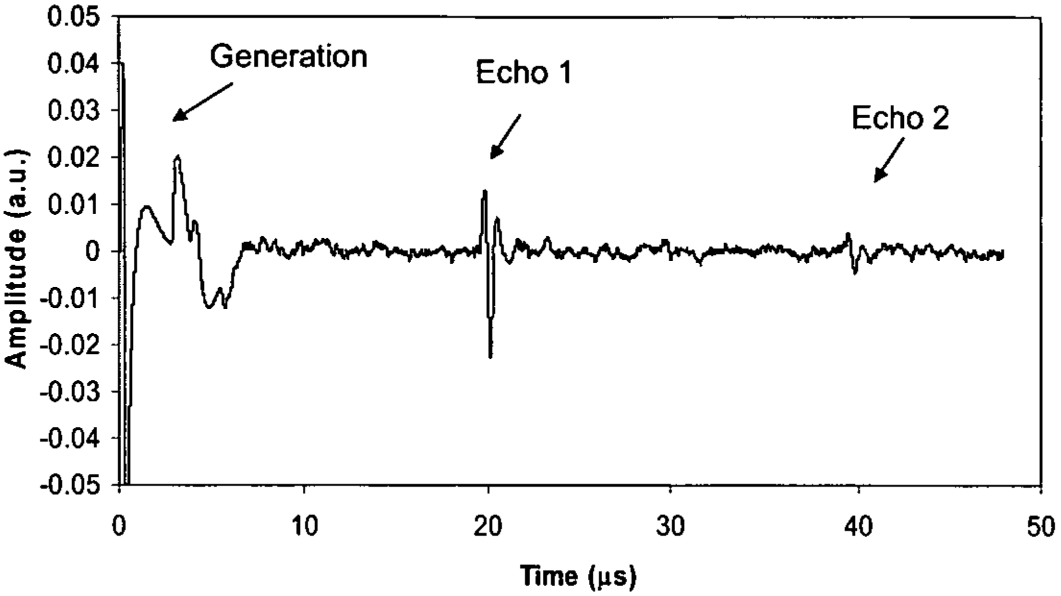

FIGURE 4. Ultrasonic signal obtained for a 50 mm thick steel sample at about 1200 °C.

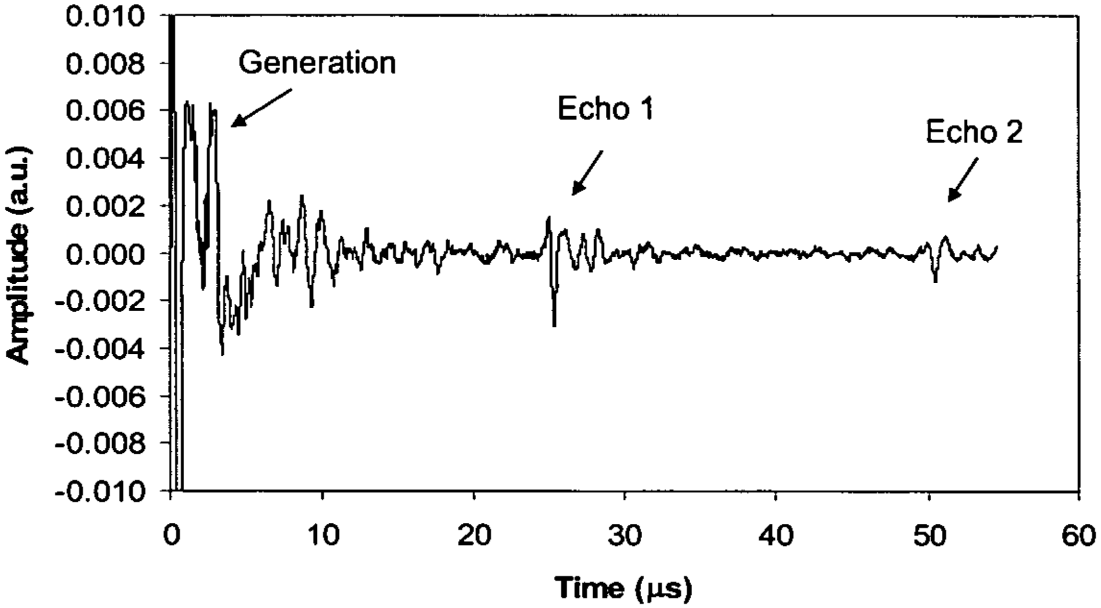

FIGURE 5. Ultrasonic signal obtained for a 60 mm thick steel sample at about 1200 °C.

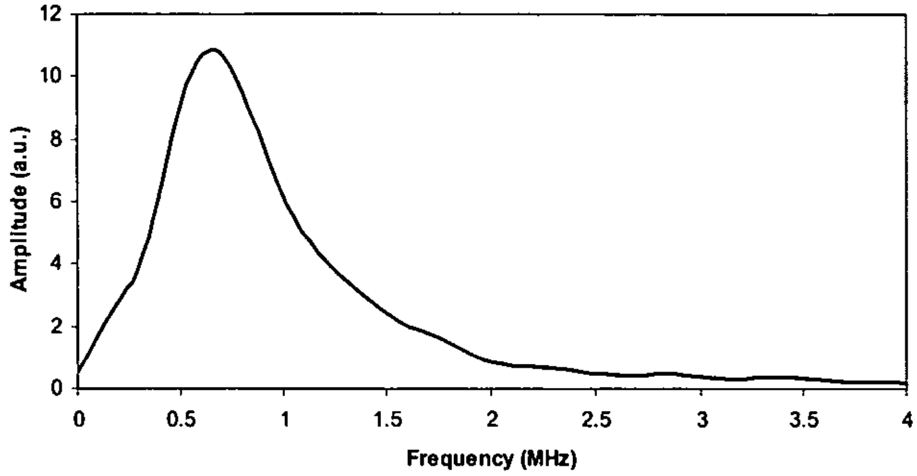

FIGURE 6. Spectrum of the second echo of the signal shown in Fig. 5.

To obtain the material thickness by ultrasound, the ultrasonic velocity must be known. A calibration curve for the dependence of ultrasonic velocity on temperature can be done in laboratory conditions using also laser-ultrasonics. Experience obtained with the system implemented for measuring on-line the wall thickness of seamless tubes has shown that the thickness measurement by laser-ultrasonics can be very precise and usually exceeds quality or process control requirements [6].

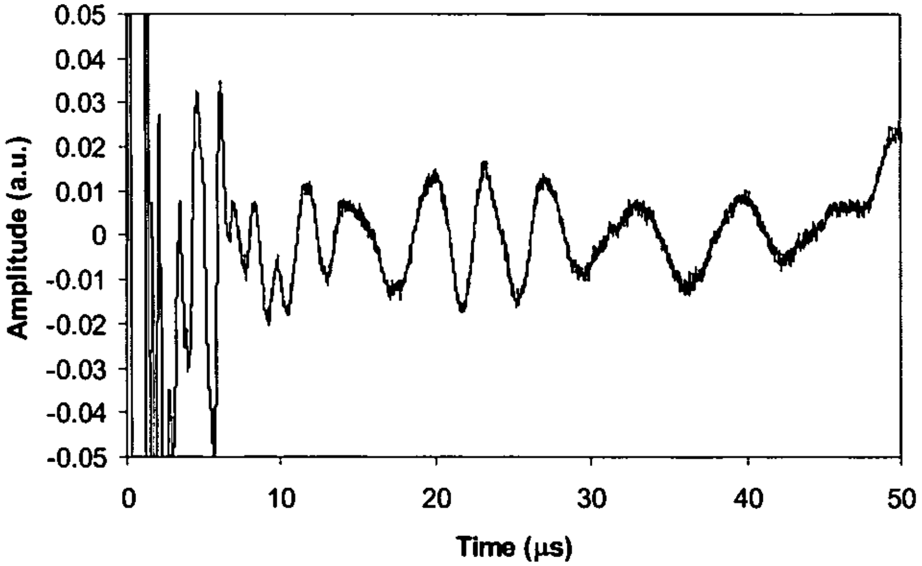

FIGURE 7. Ultrasonic signal obtained on a hot sample surface when non-adherent oxide or scale is present.

CONCLUSION

Laser-ultrasonic measurements of thickness of up to 100 mm in steel samples at about 1200 °C has been demonstrated. These measurements were made possible by the high performance of the generation and detection system used and in particular their good frequency response in the 0.5 to 1 MHz range. This work also shows that laser-ultrasonics could be used to measure thicknesses during forging operations and could very advantageously replace manual measurements on hot parts and thus contributes to improved productivity.

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Silvio E. Kruger, Martin Lord and Jean-Pierre Monchalin,

Laser-ultrasonics presents many advantages compared to conventional ultrasonics, but is generally considered as less sensitive. As a consequence, laser-ultrasonics should not be adequate for ultrasonic measurements in coarse microstructure materials or measurements of large thicknesses. However, since the generated waves extend to very low frequencies, measurements in such conditions can be successfully performed if a photorefractive interferometer sensitive also to these low frequencies and properly balanced is used for detection. This is demonstrated by measurements of thicknesses up to 100 mm (4") for various steel grades and at temperatures up to 1250 °C that we report in this paper.

Abstract of a paper to be presented at QNDE 2005