# LASER-ULTRASONICS FOR

# INDUSTRIAL APPLICATIONS

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## INTRODUCTION

Increased use of advanced materials and more stringent requirements for process and quality control are creating new needs for nondestructive inspection techniques. Ultrasonics is a widely used technique for defect detection in various materials and is being developed, and even in some cases actually applied for microstructural characterization. However, ultrasonics in its present state of implementation in industry suffers several limitations. Probing materials at elevated temperature is made difficult by fluid coupling problems. Inspecting specimens of complex shapes requires sophisticated robotic manipulators to properly orient the Furthermore, since the technique relies on a piezoelectric transducer. resonator to generate and receive ultrasound, it does not have the adequate bandwidth or sensitivity for some applications.

Laser-ultrasonics which is based on lasers to generate and detect ultrasound could possibly eliminate these limitations. In this technique, generation of ultrasound originates from the absorption of light at the surface of the material, which creates a transient heat source, which in turn produces the thermoelastic stress at the origin of ultrasound. At higher laser power density a thin surface layer is vaporized which, by the recoil effect produces the normal stress at the origin of ultrasound. The characteristics of ultrasonic sources produced by lasers have been the object of intensive studies which have been reviewed (1, 2). Concerning the detection aspect, the various techniques have also been reviewed recently (3) and the most appropriate for industrial inspection appear to be based on velocity or time-delay interferometry. The principle of these techniques is to make the wave scattered by the surface to interfere with itself after a delay. In practice, it is possible to build an interferometer in which the delayed wavefront matches sufficiently well the incoming wavefront to give a light gathering efficiency large enough for useful application. Two-wave interferometers were found perfectly suitable for detection at high frequency (above 100 MHz) whereas multiple-wave interferometers (Fabry-Pérot) appear to be more appropriate in the low MHz range (1 - 20 MHz), generally used for inspecting grained or heterogenous materials. Our detection system is based on this last type of interferometer and in this paper we are presenting various results obtained by using it to detect laser generated ultrasound on steel and reinforced composites.

# EXPERIMENTAL SETUP

The experimental arrangement is sketched in Fig. 1. A Q-switched Neodymium-YAG laser is used for generation and a cw one-watt single mode Argon ion laser for receiving. In this system, all three beams, the generating beam, the illuminating beam and the received scattered beam are colinear to minimize dependence on exact specimen location. The receiving interferometer is a 50 cm long confocal Fabry-Pérot with a bandwidth of about 10 MHz. Properties of such a receiver have already been presented (4) and will not be discussed here. The specimen is located at about 1.5 m from the front receiving lens of the system which is 15 cm in diameter.

### **RESULTS AND DISCUSSION**

# a) Oxidized carbon steel

Rolled carbon steel products shaped as bars, rods or plates have, except if they have been machined, a rough surface and a black appearance. Receiving ultrasound from such a surface at a distance of a meter or more is difficult except if a large receiving laser power is used. We present below a method which permits to use a commercially available laser of moderate power, namely a one-watt cw single mode Argon ion laser.

This method is based on surface cleaning and oxide removal with a high power laser. The laser we have used is Neodymium YAG laser producing up to 3/4 J in a 8 ns pulse. Fig. 2 shows the echo sequence observed with the confocal Fabry-Pérot receiver from a 3/8 inch plate placed approximately normal to the beams. The same laser is used for cleaning and for ultrasound generation. The cleaned zone is about 2 mm in diameter and detection is performed with the receiving laser near its center. The first pulse observed in Fig. 2 comprises a fast positive-going part, which corresponds to stray light from the generating/cleaning laser picked up by the detector, followed by the signal produced by the vaporized and plasma products ejected from the surface. Echoes are only clearly seen following the second laser shot and generally grow at the subsequent shots, which shows that these shots contribute to further cleaning and improve the reflectivity of the surface. Signal enhancement by more than one order of magnitude is observed, as shown in Fig. 2. This continues until a bare



Fig. 1. Schematic of the experimental setup



Fig. 2. Echoes observed from a "dirty" 3/8 inch carbon steel plate using the cleaning-for-receiving method and generation at the same location as cleaning and receiving. The plate is approximately perpendicular to the beams.

metal surface is obtained. Since oxide removal lasts a time much longer than the laser pulse duration, typically several tens of microseconds, no echo is clearly seen following the first shot, the surface being not sufficiently cleaned to reflect adequately.

Surface cleaning was previously mentioned (5) for generating reproducible ultrasonic deformations and we have verified this assumption with a piezoelectric transducer bonded to the sample. However, cleaning is used here for a quite different purpose, namely to enhance surface reflectivity for receiving and, consequently, the sensitivity of the laser-ultrasonic Even greater sensitivity would be obtained when generation is method. performed on an uncleaned area adjacent to the cleaned zone, because the strong absorption of the oxidized and dirty surface contribute to a larger mass of products being vaporized and consequently to a stronger ultrasonic In all the work on steel reported here, the cleaned and deformation. generation spots were identical, mostly because of convenience and equipment limitations, since generating from a spot different from the cleaned zone would have required a means of rapidly deflecting the laser or the use of another high power laser.

A very important feature of this cleaning-for-receiving method is the optical scattering property of the oxide-free zone produced. In the conditions we have used, we have always noted that the cleaned surface scatters light over a broad angle with no specular spot like an isotropic scattering target. This feature permits easy inspection when the surface is tilted off the normal to the beams direction as shown in fig. 3.



Fig. 3. Same as Fig. 2, but with the specimen tilted by 15°



Fig. 4. Detection of a 1/16 inch side-drilled hole in a "dirty" block of steel. The offset of the receiving/cleaning/generating location is measured from the vertical passing through the hole center. The echo at  $\approx$  4.5 µs corresponds to the reflection from the hole whereas the echoes at  $\approx$  9 and  $\approx$  18 µs are associated to reflections by the bottom of the specimen.

This cleaning-for-receiving technique was used to demonstrate artificial defect (a side-drilled hole) detection from a "dirty" block of steel as shown in Fig. 4.

# b) Hot Steel in Air

The same laser cleaning-for-receiving technique was used for ultrasonic measurements on hot carbon steel (up to  $1000^{\circ}$ C). A 1/4 inch thick specimen was located deep inside a 3 inch diameter 20 inch long tubular oven. One side of the oven was sealed with a refractory plate while the other side was left open for the generating/cleaning and receiving laser beams. At elevated temperature surface oxidation occurs rapidly, so it is important that the generating shot follows quickly the cleaning shot. A laser repetition rate of 20 Hz was found appropriate for this purpose. Nonadherent oxide grows eventually, especially if laser cleaning is stopped and was removed with a scraper (in the steel industry mechanical scrapers or strong water jets are used for this purpose). Fig. 5 shows some typical signals observed at various temperatures during sample heating. Changes of ultrasonic attenuation are clearly seen in these data, but we have limited so far our analysis to the measurement of the change of velocity. Ultrasonic velocity is plotted in Fig. 6 which shows that velocity decreases with temperature. The transition from the ferrite phase to the austenite phase is shown by a change of slope in the plot. The large variation observed shows that the technique can be used in principle to measure internal temperature of hot steel.

The same confocal Fabry-Pérot receiving setup has also been used to evaluate another application of interest to steel industry, namely the determination of zinc coating thickness in the hot-dip galvanization process by measuring the velocity of laser-generated surface waves. Results of this study will be reported elsewhere.



Fig. 5. Echoes observed from a 1/4 inch carbon steel plate at several increasing temperatures.



Fig. 6. Variation of longitudinal ultrasonic velocity of A-36 carbon steel with temperature.

## c) Graphite-epoxy

Parts made of graphite-epoxy composites have an all-black strongly absorbing surface and are therefore difficult specimens for optical detection of ultrasound. Fortunately, these are rarely found in practice with a bare surface. When they are used as elements of an aircraft structure they are generally painted, at least on their external surface, upon which laser-ultrasonic inspection can be performed more easily. Parts which have been just manufactured, are generally provided with a protective cover (peel-ply) which can be later removed at assembly. The reflecting properties of the various peel-plies used in aircraft industries are quite variable from one to another but they are always better than those of the bare graphite-epoxy and this makes optical reception much easier. These peel-plies are also generally partially transmitting for the generating laser, which, because of the strong absorption of the graphite-epoxy, results in a buried thermoelastic source. It is well known that this case produces a much stronger ultrasonic deformation than the free-surface specimen (6).

Inspecting fiber-reinforced composites with the laser-ultrasonic technique is interesting in practice because it could lead to more rapid inspection than with the traditional squirter method. Successful implementation may be more difficult to realize for planar specimens because of various limitations of laser technology (power, stability, repetition rate), but in the case of curved samples laser-ultrasonics has a definite advantage. In this case the ultrasonic source is located on the specimen surface, always matched at once to its curvature, whereas the tradional technique requires precise transducer orientation which takes additional time.

Fig. 7 shows the echoes observed from a corner-shaped graphite-epoxy specimen which is  $\approx$  3 mm thick and peel-ply covered. The generating spot is  $\approx$  5 mm in diameter, detection is performed approximatively in the center and an energy of  $\approx$  20 mJ from the Nd-YAG laser is used. The first

tall pulse seen in Fig. 7 corresponds to the initial surface elevation. This pulse can be used for normalizing the echoes in order to eliminate any dependence upon laser power and sample absorption. The small pulse ahead of the surface elevation pulse is a parasitic pick-up of the generating laser light by the detector. As seen in fig. 7, when artificial de-laminations (teflon tape) have been introduced at mid-thickness, they are easily detected.

Images of planar specimens have been obtained by moving them with a computer-controlled X-Y table. Fig. 8 shows the tri-dimensional image of a 5 mm thick peel-ply covered graphite-epoxy sample with 2 cm X 2 cm artificial delaminations introduced at 1/8, 1/4, 1/2 and 3/4 of total thickreal image was color-coded with different levels assigned to ness. The the normalized height of the first echo. Normalized height is determined from the RF echo signal, by measuring its magnitude from a predetermined baseline and dividing it by the magnitude of the initial surface deformation signal taken from the same baseline. This procedure is not perfect and will need some improvement in order to minimize the effect of noise and the deviation of the baseline from a horizontal straight line, but all defects can however be seen from a C-scan view only. The tridimensional image of an impacted composite panel has also been obtained in the same way and the impacted zones have clearly been detected. In all this work on composites, the generating laser power was kept at a level below any observable damage.



Fig. 7. Inspection of a corner-shaped graphite-epoxy specimen. Above: zone free of delamination, below: delamination introduced at midthickness.



Fig. 8. Tri-dimensional image of a 5 mm thick graphite-epoxy plate with delaminations buried at 1/8, 1/4, 1/2, 3/4 total thickness, respectively from right to left. For the sake of clarity, the top surface of the specimen is not shown. The defects are clearly seen as well as their "shadow" on the bottom of the plate. Scan area is 3 cm X 20 cm

#### CONCLUSION

We have presented several experimental results obtained in the laboratory which show that laser-ultrasonics could have several industrial applications, in particular in the steel and aeronautic industries. We have presented a method to increase the receiving sensitivity in the case of hot steel by cleaning the surface with a high power laser to vaporize the oxide layer. We have shown that laser-ultrasonics can detect delaminations from curved fiber-reinforced composites without the need of precise alignment procedures. We have also obtained ultrasonic images of delaminations in composite panels which, we believe, are the first obtained by laser-ultrasonics.

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