APPLICATIONS OF LASER-INDUCED STRESS WAVES

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INTRODUCTION

When light from a pulsed laser is incident on the surface of an absorbent material, part of the light is absorbed and vaporizes a small amount of surface material. The rapid vaporization and blowoff of this material generates a stress wave at the surface. As this pressure pulse propagates into the material, it changes the metal's microstructure, which is the source of the observed improvements in material properties. This laser shock process has been successfully used to increase the strength and hardness of stainless steel. The strength properties of heat-affected zones in welded aluminum structures have been increased to values up to the strength of the parent material. Recent studies have demonstrated that laser shock processing can also be used to improve the fatigue life and stress corrosion of some aluminum alloys. In general, all alloys which are strain hardenable have a good chance of responding favorably to the laser shock process.

Active investigation of the effects of laser induced stress waves to materials began in our laboratories in 1971. Results of several years of research have led to a good understanding of the pressure environments generated by pulsed lasers and their effects to materials. Certain facets of this area of technology still require additional studies of a basic character. However sufficient knowledge has been gained from past research to realistically look at the use of laser induced stress waves for the solution of specific material related problems. This paper addresses materials problems presently under investigation and looks at other areas where laser stress waves have potential application. As a prelude to the discussion of laser applications, a review is given of the types of pressure environments generated by pulsed lasers. The application section is followed by a discussion of the types of present and future laser systems possessing appropriate parameters for shock processing applications.

LASER STRESS WAVE ENVIRONMENTS

Laser stress wave amplitudes of interest extend from about l GPa (10 kilobars) up to values exceeding 10 GPa. Generation of these high amplitude stress waves normally requires modification of the target surface to efficiently couple the laser energy into the solid. This is particularly true when the work is conducted in air or gaseous environments. An effective method of doing this involves placing a material which is transparent to the incident laser beam on the surface. This material must be selected to accommodate the wavelength of the laser radiation and can be solid or liquid. Several cheap materials can be used if the wavelength of the laser lies between the near ultraviolet and near infrared. Suitable overlay materials are much more restricted for lasers emitting in the far ultraviolet or far infrared.

The purpose of the overlay is to confine surface material which is vaporized by the incident laser beam. This vapor is heated to sufficiently high temperatures for electrons to be stripped from the vaporized atoms and form a plasma. The electrons ionized from the atoms strongly absorb the incident laser light. If the surface is not confined by a transparent overlay, the rapidly expanding vapor/plasma will absorb the incident laser energy away from the solid surface where it cannot be efficiently converted into a pressure pulse.

The shape and amplitude of the resultant stress wave depends on the temperature history of the heated vapor. This in turn depends on the laser power density at the interaction surface and the laser energy deposition time. The laser energy must be deposited in a relatively short time to avoid diffusion of energy away from the interaction zone and the effect of hydrodynamic processes which reduce the amplitude of the stress wave. The thermal conductivity and heat of vaporization of the absorbent material also can affect the stress wave environment, particularly as one goes to lower power densities. Materials with low thermal conductivities tend to confine the absorbed energy to the interaction zone for longer times, thus maintaining the high temperatures needed to generate high amplitude pressures. With low heat of vaporization material, more energy is available for heating purposes and less energy is lost to internal energy of the phase change.

At the higher laser power densities, deposition of laser energy is sufficiently intense to almost totally negate the effect of the target's thermal properties on stress wave generation. The dense ionized plasma formed at the target surface is the dominant mechanism controlling the amplitude and duration of the stress wave. Also at very high laser power densities, reflection of laser light by the dense surface plasma and/or optical breakdown of the transparent overlay is expected to ultimately limit the magnitude of stress waves which can be generated at target surfaces confined by transparent overlays.

Results of calculated and measured peak pressure are shown in Figure 1 for different target films and overlay materials. This work was conducted with a neodymium-glass laser. Other laser systems also are capable of generating these high amplitude stress waves. These systems are discussed in a later section. The peak pressures shown in Figure 1 are plotted in terms of peak laser power density which is laser energy density, e.g., energy per unit area, divided by the width of the laser pulse. As seen from Figure 1, thermal properties of the absorbent material have a significant effect on peak pressure at laser power densities below 10^9 W/cm^2 while they have essentially no affect on pressure above 10^9 W/cm^2 . The change in pressure resulting from the use of different transparent overlays also is illustrated in Figure 1. The controlling factor in this case is the acoustic impedance of the overlay material. Water has an acoustic impedance about 1/10 that of glass which is the reason the pressures generated with water overlays are lower than glass. It is important to note, however, that water still provides an effective method of generating high amplitude stress waves needed to shock process materials. From a practical standpoint liquids such as water have obvious advantages over solid overlays.

At laser power densities above 1 x 10^9 W/cm^2, calculations predict that most of the absorbed energy initially goes into heating of the vapor. For this reason, the shape of the stress wave closely follows the shape of the laser pulse until the laser pulse begins to decay. The decay time of the stress wave is much slower because it is governed by the rate at which work is done on surrounding materials and the rate at which heat is conducted out of the vapor into the colder adjacent materials. Experimental measurements of pressure confirm this type of behavior. This is illustrated in Figure 2 which compares the measured time history of the laser pulse with the measured and predicted pressure pulse for the case of a transparent water overlay on aluminum.

For laser power densities below 1 x $l0^9$ W/cm^2, it is found that the heat of vaporization of the target material can become a significant fraction of the total absorbed energy. For this reason, it is desirable to pick a material with a low heat of vaporization. Lead is a good example of such a material, as are zinc and black paint. We looked at the effect of using lead coatings to increase the amount of plastic deformation introduced in Fe-3wt% Si specimens. More deformation was observed in the lead-coated iron specimens than in the bare iron. Computer calculations showed that the presence of lead significantly increased the duration of the high pressure portion of the pulse compared to the bare iron configuration. This is illustrated in Figure 3. The longer duration stress wave generated in a lead coated target is expected to increase the amount of shock induced deformation which is the result observed in the Fe-3wt% Si experiments.

SHOCK PROCESSING OF MATERIALS

The response of materials to laser shocking was first investigated by looking at changes in hardness and tensile properties of alloys and studying the modified microstructures. Aluminum and iron base alloys were included in these studies. The iron alloys consisted of stainless steel and an Fe-3wt%. Si alloy which was selected for research purposes because it can be etch-pitted for visual evaluation of the laser-shock-induced strain field. Both non-heat-treatable and heat-treatable alloys in the peak and overaged conditions also were investigated. The non-heat treatable alloy was 5086 H32. Peak aged alloys were 2024-T8, 7075-T6, and 6061-T6 and the overaged alloys were 2024-T3 and 7075-T73.

It was observed that deformation of the Fe-3wt% Si alloy occurred by both slip and twinning. Uniform shock hardening, corresponding to about 1 percent tensile strain, was observed in specimens 0.02 cm thick. Studies with stainless steel were quite interesting. For example, the surface hardness of 304SS showed little increase after one shock. Several shocks, e.g., 5, however, were able to increase surface hardness by more than 20 percent. The ability to multiple shock a material and improve properties in an ac-cumulative way is an important aspect of laser shock processing because multiple shocking with a laser is relatively straightforward and significant improvements in material properties
can be realized while maintaining the shock pressure below the threshold for gross material deformation.

Experiments with aluminum showed that the strength and hardness properties of the non-heat treatable and overaged alloys were significantly improved over the unshocked properties. It was observed that a threshold pressure needed to be exceeded before much change in properties occurred in the heat treated alloys. For an overaged alloy such as 2024-T3, this threshold pressure was approximately 2.5 GPa. Little improvement in the tensile and hardness properties of the peak aged alloys was noted for laser shock environments up to approximately 5 GPa. Based on a comparison to shock data generated with flyer plates, the threshold pressure needed to generate significant changes in the overaged alloys appears to be about 7.5 GPa. Tests still need to be run to confirm this point. The higher pressure requirements for improving the properties of overaged alloys are due to the lower strain hardening rates and higher yield strengths of the materials.

At least two potential applications for laser shock processing were identified in the above studies with steel and aluminum alloys. First, plastic flow and galling in stainless steel has limited its usefulness in bearing applications. Laser shock-induced surface hardening could remove this limitation. Second, the 7075-T73 alloy is tailored to have a high stress corrosion resistance. In order to achieve this property, there is a 10-20 percent sacrifice in strength properties. By laser shocking the alloy, its strength properties are increased by more than 20 percent while maintaining its excellent stress corrosion properties. This is a desirable combination of parameters to possess, particularly in aerospace applications.

In many welded aluminum structures, the weld and its adjacent heat affected zone (HAZ) are a region of weakness having a lower strength than the rest of the structure. The strength of this region can be increased by a post-weld heat treatment or by mechanical working, such as rolling the weld bead or explosive shocking. These approaches, however, are often either not practicable or are undesirable. Laser shocking offers an alternate technique for increasing the strength properties of weld zones without introducing the undesirable aspects of other post weld treatment processes. To test the lasers ability to shock process weld zones, tensile specimens were cut from welded plates of 5086-H32 and 6061-T6 aluminum and laser shocked. Tensile tests were run on shocked and unshocked specimens. Results of these tests are shown in Figure 4. As seen in this figure, after laser shocking, the tensile yield strength of 5086-H32 was raised to the bulk value and the strength of 6061-T6 who raised midway between the welded and bulk levels. The change in micro-structure which is responsible for this change in strength properties is illustrated in Figure 5. The shocked microstructure shows heavy dislocation tangles typical of cold working.

Laser shocking of weld zones has potential application in several areas of industry. A shock treatment could be beneficial wherever welded aluminum structures are used and the structure, or part, is designed to accommodate the mechanical properties of the weld. For example, in seam-welded aluminum pipe, a postweld laser shock treatment would increase the strength properties in the welded area and thus reduce the wall thickness required for safe operation. A laser shock process also may find application in welded rail structures or in the welded aluminum hulls of high speed surface ships.

Another application area presently being investigated is that of laser generated shocks to improve the fatigue properties of regions around fasteners in airplane structures. Tests conducted to date show large improvements in fatigue life are produced by the laser shock process.

LASER SHOCK PROCESSING SYSTEMS

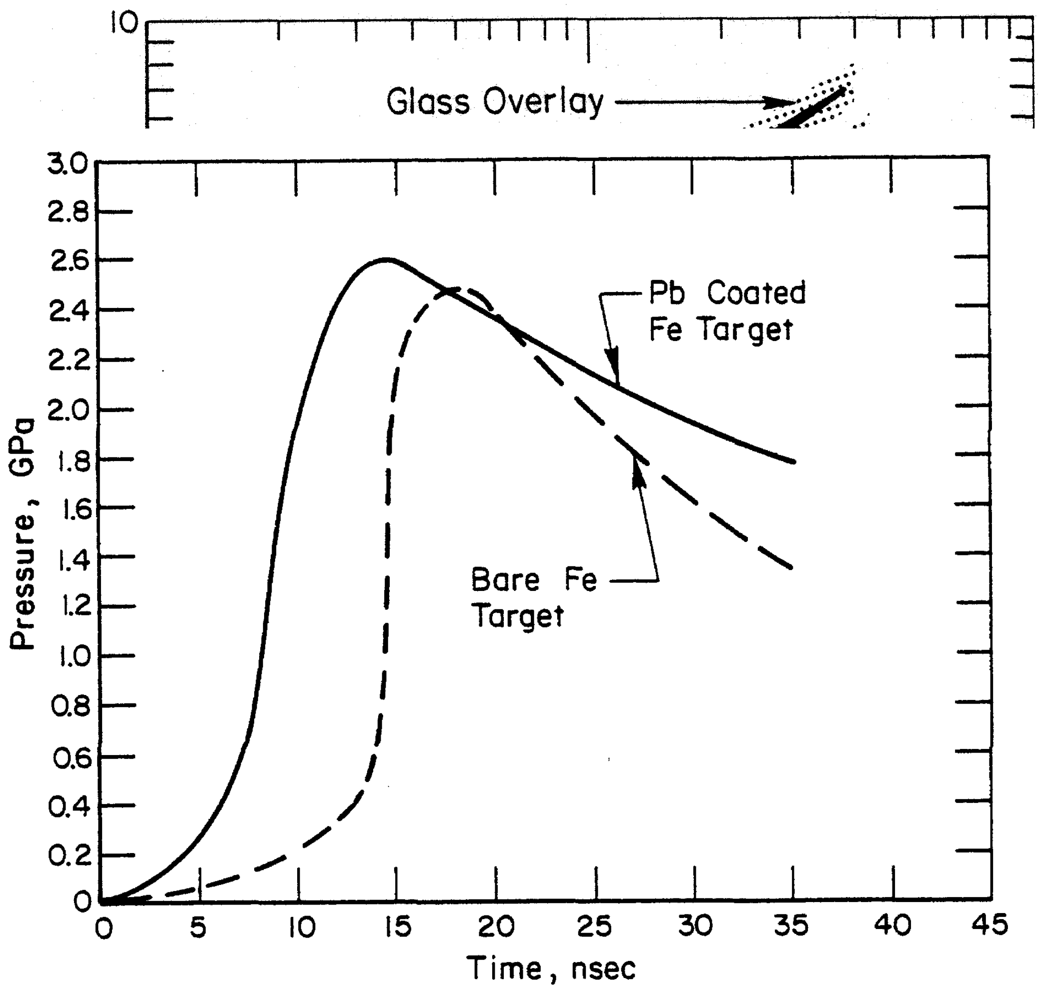
Cost, efficiency, ruggedness, maintenance, and part-replacement requirements are all important considerations in selection of the laser system for laser shock processing. There are additional requirements which also are critically important in selection of a laser system. The laser must possess sufficient energy output per pulse and a high enough pulse repetition rate to meet production requirements. The wavelength of the laser is very important since it controls how the laser beam will interact with the target to generate high amplitude shock waves. In the case of gas lasers, economics require closed cycle operation as well as a regenerative system. These constraints reduce the rather large number of available laser systems to only two or three viable candidates. For example, a pulsed CO_2 is an efficient and rugged laser which has a proven track record as an industrial tool. Its use in shock processing applications, however, is very questionable because of the 10.6 μm wavelength. Most liquids are not transparent at this wavelength and even transparent solid overlays are either too costly or impractical.

A similar problem occurs at very short wavelengths in the ultra-violet regime. Lasers emitting in the visible spectrum are ideal from the standpoint of availability of low cost transparent overlay materials. Ruby presently is the best candidate in this wavelength band. Unfortunately, its energy output is limited to values which make it a marginal system for use in production applications.

Most laser shock processing studies have been conducted with a neodymium-glass laser. This laser meets all of the laboratory requirements for successful shock processing studies, but still needs additional analysis to determine its suitability for use in production environments.

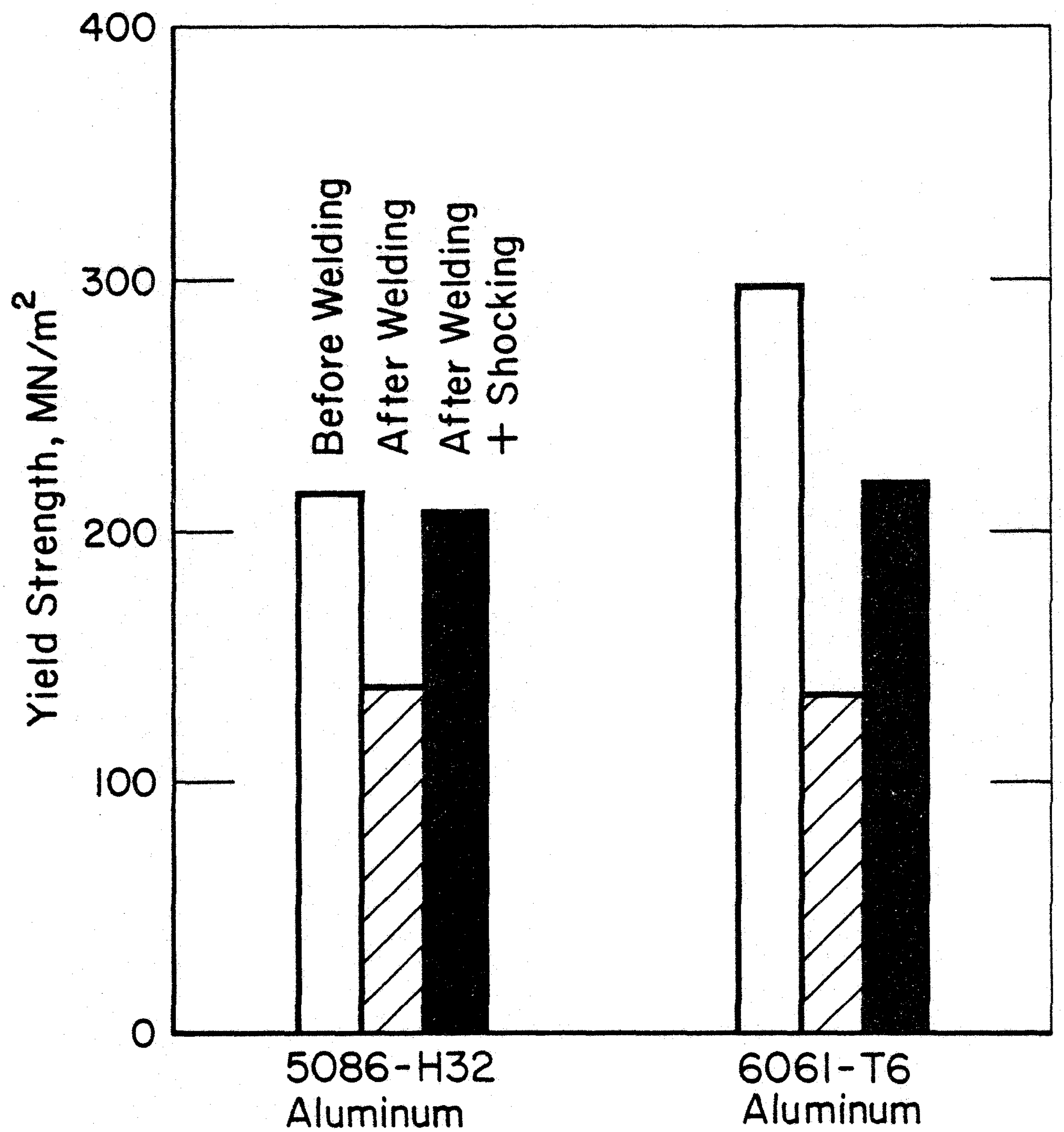
Another laser system appears to possess parameters which make it a good choice for laser shock processing applications is the iodine laser. Technology is now developed for construction of closed-cycle regenerative laser systems. Because iodine is a flow system, higher laser pulse repetition rates are possible than with a solid state laser such as neodymium-glass. A large amount of energy also can be extracted per pulse, thus providing significantly higher average power operation than possible with neodymium-glass. Finally, projected costs for an iodine laser appear to be significantly less than for an equivalent neodymium-glass laser. These advantages are mitigated to some extent by the fact that the iodine laser wavelength is somewhat longer than neodymium-glass, i.e., 1.315 μm compared to 1.06 μm. While this does not appear to be much of a change, absorption characteristics of some overlay materials may undergo significant variation in going from 1.06 μm to 1.315 μm. This point needs further study.

There are two additional classes of lasers which show considerable promise as future shock processing systems. The first is the excimer laser, such as the rare-gas monohalides, XeF, KrF, XeCl, etc. These operate in the near ultraviolet, but Raman up-conversion to the visible has been successful with high efficiency. Other excimer lasers, such as the mercury monohalides HgCl and HgBr, lase in the glue-green visible region and are presently being intensively investigated as high-power pulsed systems for military mission. The second class now under development is based on the auroral or transauroral transitions of column-VI elements, particularly the au $^1S_0 \rightarrow {}^1D_0$ on of atomic oxygen at 0.558 μm. Both classes of lasers have the potential for operating in a closed-cycle regenerative mode at high energy output per pulse and high pulse repetition rates. Further development of these lasers is required and additional information needs to be generated on laser material interactions before they are serious candidates for production systems. They do, however, provide a next generation class of lasers for use in shock processing which hold great promise of providing more efficient operation and higher average power than present systems.



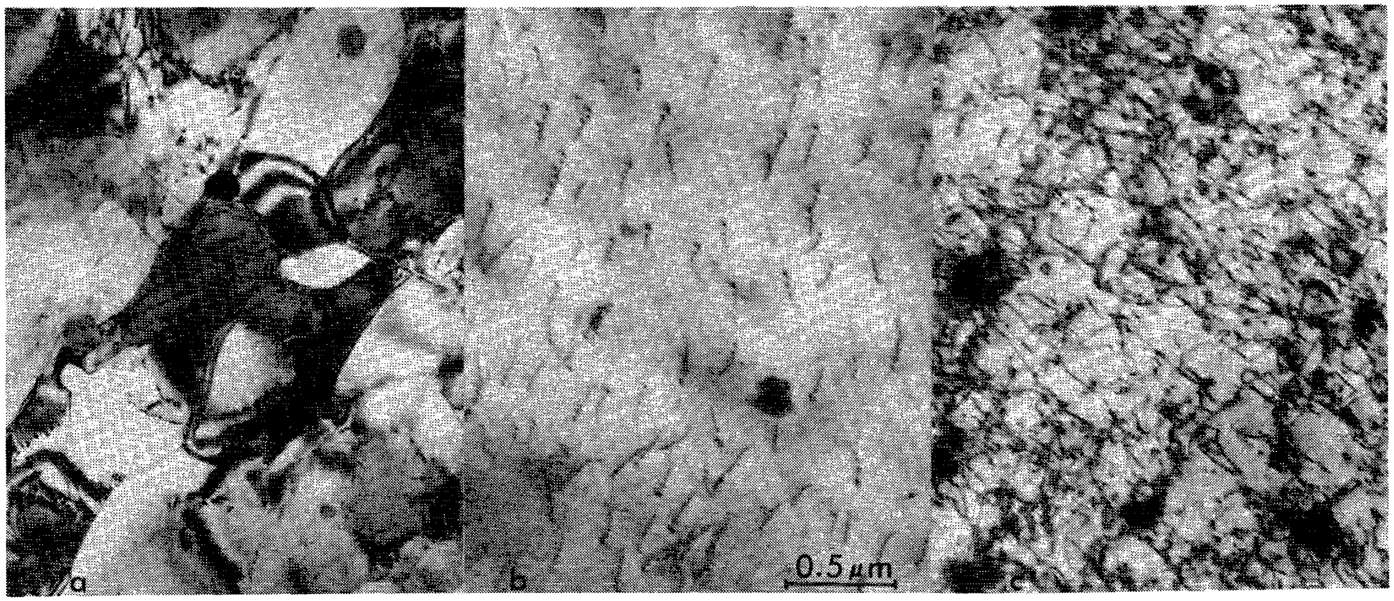
COMPARISON OF COMPUTED PRESSURES IN IRON TARGET AND LEAD COATED IRON TARGET WITH QUARTZ OVERLAYS AT 6×10^8 W/CM^3

FIGURE 3



COMPARISON OF THE 0.2% OFFSET YIELD STRENGTH OF WELDED AND LASER SHOCKED ALUMINUM ALLOYS

FIGURE 4



MICROSTRUCTURE ALUMINUM SHEET BEFORE AND AFTER WELDING AND LASER SHOCKING. (a) INITIAL CONDITION, (b) AFTER WELDING, AND (c) AFTER LASER SHOCKING.

FIGURE 5