USE OF LASER GENERATED SHOCKS TO IMPROVE THE PROPERTIES OF METALS AND ALLOYS*

B. P. Fairand and A. H. Clauer
Battelle Columbus Laboratories
Columbus, Ohio 43201

Abstract

Pulsed lasers are being used to generate high amplitude stress waves in metals and change their mechanical properties. Peak pressures greater than 5 GPa are generated in a metal or alloy when it is covered with a transparent material. These pressures exceed the Hugoniot elastic limit of most metals and produce networks of tangled dislocations in the metals substructure, which is the source of the observed change in material properties. The strength, hardness, and fatigue properties of 7000 series aluminum alloys are improved in this manner. Weld zones in aluminum are strengthened up to the bulk level and the surface hardness of stainless steel is increased.

Introduction

Laboratory studies have established that the mechanical properties of different aluminum and iron base alloys can be improved by laser shock treatment. When the energy from a powerful pulsed laser is trained on the surface of a metal, a high amplitude stress wave is generated. This wave propagates into the material and alters its microstructure, which is the source of the observed improvement in the metal's mechanical properties. The ability to generate stress waves in materials with short duration bursts of laser energy has been known for some time, (1-6) but it has only been in recent years that these stress waves have been shown to provide an effective

* The research work leading to this paper was supported in part by the National Science Foundation (NSF).

method of altering the in-depth mechanical properties of metals. (7) Various methods have been used to increase the amplitude and duration of these stress waves in order to increase the depth and degree of change introduced into the metal. (8-15) These techniques have generally taken the form of adding to the surface of the material various coatings and layers of material which may be opaque or transparent to the incident laser energy. The most effective method found up till now for increasing the efficiency of converting laser energy into mechanical stress wave energy has involved the use of transparent overlays. This technique has produced pressure with peak values several times greater than the Hugoniot elastic limit of most metals and alloys. When a pressure of this amplitude propagates through a material, the metal is plastically deformed in a manner similar to that observed in explosively shocked materials.

This paper discusses methods of generating high amplitude stress waves in materials with pulsed lasers and demonstrates by selected examples how these stress waves can be used to improve the properties of metals and alloys.

Laser Generation of Stress Waves

Two different Q-switched neodymium glass lasers were used in the laser generated stress wave studies. The high energy experiments were performed with a CGE VD-640 Q-switched neodymium glass laser, which consists of an oscillator followed by six amplifier stages. This system is capable of emitting up to 500 J of laser energy in a pulse with a full width at half-maximum (FWHM) of up to 200 nanoseconds. A 5 joule AO Model 30 Q-switched neodymium glass laser with a pulse width at one-half maximum of 40 nanoseconds was used in the low energy experiments. Dielectric beam steering optics were used in all of the experiments and simple convex convergent optics were used to focus the laser radiation on the specimens.

The change in the stress wave environment introduced by different transparent overlays and addition of absorbent films of material to the metal surface were investigated. A solid in the form of fused quartz and liquid water were selected for the transparent overlays. Because quartz has a much higher acoustic impedance than water, it was expected to produce higher amplitude stress waves in the shocked metal than those obtainable with water. However, liquids appear to provide a more flexible and practical overlay material for future laser shock processing applications and, therefore, water was included in the study. The results of adding various absorbing materials to the metal surface are reported elsewhere. (16) Results of these studies have shown that coatings do not significantly affect the magnitude of the laser generated stress wave over the range of laser power densities investigated except at the lower laser power densities where reflection of laser radiation from a bare metal surface becomes significant. Even though coatings were not observed to enhance the size of the stress wave, their use is still important in those cases where melting and vaporization of the metal is not desirable.

All of the laser generated stress wave experiments reported in this paper were performed in an air environment at ambient conditions, and pressures were measured with commercially available X-cut quartz crystal transducers.

Pressure Measurements

The variation in the measured peak pressures through thin aluminum foils is shown in Figure 1 as a function of the overlay material and laser peak power density. The curves shown in Figure 1 represent extrapolations of lines drawn through pressure measurements made at lower laser power densities. (14,16) Earlier studies with iron targets and quartz overlays suggested that the peak pressure was approximately proportional to the square root of the laser peak power density.(15) However, the curves shown in Figure 1 predict that peak pressure is nearly proportional to the laser peak power density. Calculations with a one-dimensional radiation hydrodynamic computer cede are presently being undertaken in an effort to explain the reasons behind the linear relationship between pressure and laser power. The fact that peak pressure is a more sensitive function of laser power than previously expected is a positive feature insofar as the future applicability of laser shock processing of materials is concerned. For example, examination of the data shown in Figure 1 shows that it may be possible to achieve pressures as high as 10 GPa at laser power densities as low as 4 x $l0^9$ W/cm^2.

As noted earlier, the higher peak pressures generated with a quartz overlay compared to water was an expected result. However, the degree of difference between the pressures is not as great as one might expect on the basis of the large difference in the acoustic impedances of the two materials, i.e., ~10.

Because rate dependent effects play an important role in the property changes introduced by laser stress waves the duration as well as magnitude of the pressure wave affects the process. A consistent feature in all pressure pulse measurements is the observation that the shape of the stress wave measured near the front surface of the laser irradiated metal corresponds to the shape of the laser pulse, particularly during the initial rise of the pulse to its peak value. By increasing the duration at the laser pulse it is possible to increase the duration of the pressure pulse. An example of this feature is shown in Figure 2. The laser pulses corresponding to these pressure pulses are shown in Figure 3.

As a laser generated stress wave propagates into a metal or alloy, its amplitude and shape will change because of attenuation and dispersive effects. An example of this effect is shown in Figure 4, which shows the pressure pulse measured through a vapor deposited aluminum target and after propagating through two thicknesses of a 5086 aluminum alloy. The laser peak power densities were about $10^9 W/cm^2$ and FWHM of the laser pulse was approximately 26 nanoseconds. An interesting feature in Figure 4 is the two component structure of the pressure wave at 0.127 cm. The leading edge of this pressure pulse is due to the elastic precursor, which is followed by the slower moving plastic wave component.

Laser Shock Induced Changes in Material Properties

Aluminum Alloys

Initial studies of laser shock induced changes in material properties were conducted with a 7075 aluminum alloy. (7) The alloy was studied in its peak aged (T6) and overaged (T73) conditions. The 7075 T73 alloy, which has excellent stress corrosion resistance properties but lower yield and tensile strength properties than the 7075 T6 alloy, was the main reason for conducting these tests. Effects of explosively initiated shocks on this alloy were previously investigated by Jacobs. (17) He was able to improve the strength properties of the 7075 T73 alloy by explosive shocking and, apparently in the process, did not decrease its excellent stress corrosion properties. The results of the laser shock experiments on the 7075 T73 alloy also were quite encouraging. The ultimate tensile strength was increased to a value somewhat greater than the T6 alloy and the 0.2 percent yield strength was increased by about 30 percent over the unshocked value. The improvement in the ultimate strength of the T73 alloy is particularly interesting since this parameter is related to the fatigue properties of the alloy, and alloys that exhibit an increase in ultimate strength may also show an improvement in fatigue properties. Recent laser shock experiments on a 7475 aluminum alloy in the T73 condition have demonstrated that the low cycle fatigue properties were improved by at least 100 percent over the unshocked value.

Another area where laser generated stress waves can be used to improve the properties of materials is shock hardening of weld zones in aluminum alloys. The weld and adjacent heat affected zone in welded aluminum structures quite often are weaker than the remaining structure. Post weld heat treatment or mechanical working can be used in some instances to improve the strength of these regions. Laser shocking offers another approach that is particularly amenable for treating formed structures. The effect of laser shocking on weld zones in two common structural aluminum alloys (5086 H32 and 6061 T6) have been investigated. After laser shocking, the yield strength of 5086 H32 was increased to the bulk value and the yield strength of 6061 T6 was raised midway between the welded and bulk value. Transmission electron micrographs taken from the center section of laser shocked specimens showed the heavy dislocation tangles typical of cold working. An example of the change in the microstructure of a 5083 H32 alloy from laser shocking is shown in Figure 5. The bulk microstructure is shown in Figure 5a. A region in the heat affected zone near the weld is shown in Figure 5b, and the same region after laser shocking is shown in Figure 5c.

Iron Base Alloys

The first iron base material to be analyzed for laser shock induced changes in its microstructure and mechanical properties was an Fe-3wt% Si alloy. (18) It was selected primarily as a model material because it can be readily etch pitted to show the magnitude and distribution of plastic deformation. (19) Quartz overlays were used in these studies and peak laser power densities ranged from 5 x 10^8 W/cm^2 to approximately 2 x 10^9 W/cm^2. The study showed that shock-induced strain could be introduced through 3-mm-thick material, although the average strain intensity was of the order of 1 percent equivalent tensile strain. Deformation of the Fe-3wt% Si alloy occurred by both slip and twinning. Thin sections of the material (about 0.02-cm thick) were uniformly hardened by as much as 25 percent over the hardness of the unshocked material.

Strain hardenable stainless steels are another class of alloys where a laser shock treatment could be beneficial. The surface of these materials tend to cold flow and gall when subjected to high load situations which has limited their applicability as bearing members. Only limited laser shock studies have been conducted on these alloys. However, initial experiments with a 316 stainless steel have demonstrated that surface hardness can be improved by 20 percent over a machine worked surface and by more than a factor of two over the bulk hardness.

Conclusions

Pulsed lasers can generate sufficiently intense stress waves in metals and alloys to change their in-depth mechanical properties. This can be done in an air environment at ambient conditions. The laser energy requirements to treat a unit area of material are quite modest and for a laser pulse less than 100 nanoseconds long, they typically do not exceed 100 J/cm^2.

References

1. Askar'yan, G. A., and Moroz, E. M., JETP Lett. Vol. 16, p. 1638. 1963.
2. Neuman, Frank, Appl. Phys. Lett. Vol. 4, p. 167. 1964.
3. Gregg, David W., and Thomas, Scott J., J. Appl. Phys. Vol. 37, p. 2787. 1966.
4. Skeen, C. H., and York, C. M., Appl. Phys. Lett. Vol. 12, p. 369. 1968.
5. Fox, Jay A., and Barr, Dallas N., Appl. Phys. Lett. Vol. 22, p. 594. 1973.
6. Lowder, J. E., and Pettingill, L. C., Appl. Phys. Lett. Vol. 24, p. 204. 1974.
7. Fairand, B. P., Wilcox, B. A., Gallagher, W. J., and Williams, D. N., J. Appl. Phys. Vol. 43, p. 3893. 1972.
8. Anderholm, N. C., Appl. Phys. Lett. Vol. 16, p. 113. 1970.
9. Yang, L. C., and Menichelli, Vincent J., Appl. Phys. Lett. Vol. 19, p. 473. 1971.

10. O'Keefe, J. D., and Skeen, C. H., Appl. Phys. Lett. Vol. 21, p. 464. 1972.
11. Siegrist, M., and Kneubuhl, F. K., Appl. Phys. Vol. 2, p. 43. 1973.
12. O'Keefe, J. D., and Skeen, C. H., J. Appl. Phys. Vol. 44, p. 4622. 1973.
13. Fox, Jay A., Appl. Phys. Lett. Vol. 24, p. 461. 1974.
14. Yang, L. C., J. Appl. Phys. Vol. 45, p. 2601. 1974.
15. Fairand, B. P., Clauer, A. H., Jung, R. G., and Wilcox, B. A., Appl. Phys. Lett. Vol. 25, p. 431, 1974.
16. Fairand, B. P., and Clauer, A. H., Optics Communications, Fall 1976.
17. Jacobs, A. J., Fundamental Aspects of Stress Corrosion Cracking (National Association of Corrosion Engineers, Houston, Tex. 1969), p. 530.
18. Clauer, A. H., Fairand, B. P., and Wilcox, B. A., Metallurgical Transactions, A, submitted April 1976.
19. Hahn, G. T., Mincer, P. N., and Rosenfield, A. R., Exp. Mech. Vol. 1, p. 284. 1971.

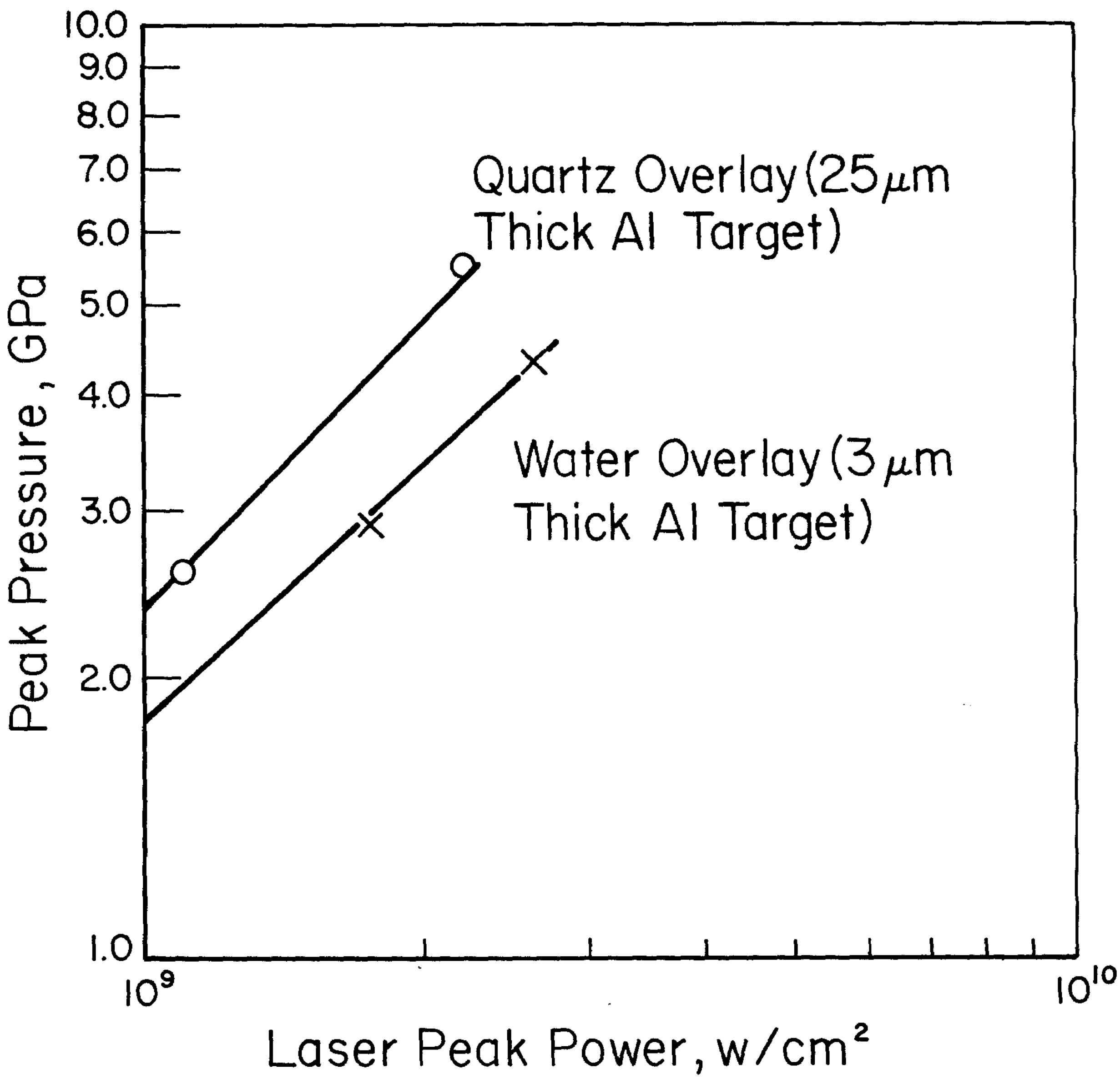

Fig. 1. Peak pressures measured through thin aluminum targets. Lines through the data represent extrapolations of published results at lower laser peak powers.

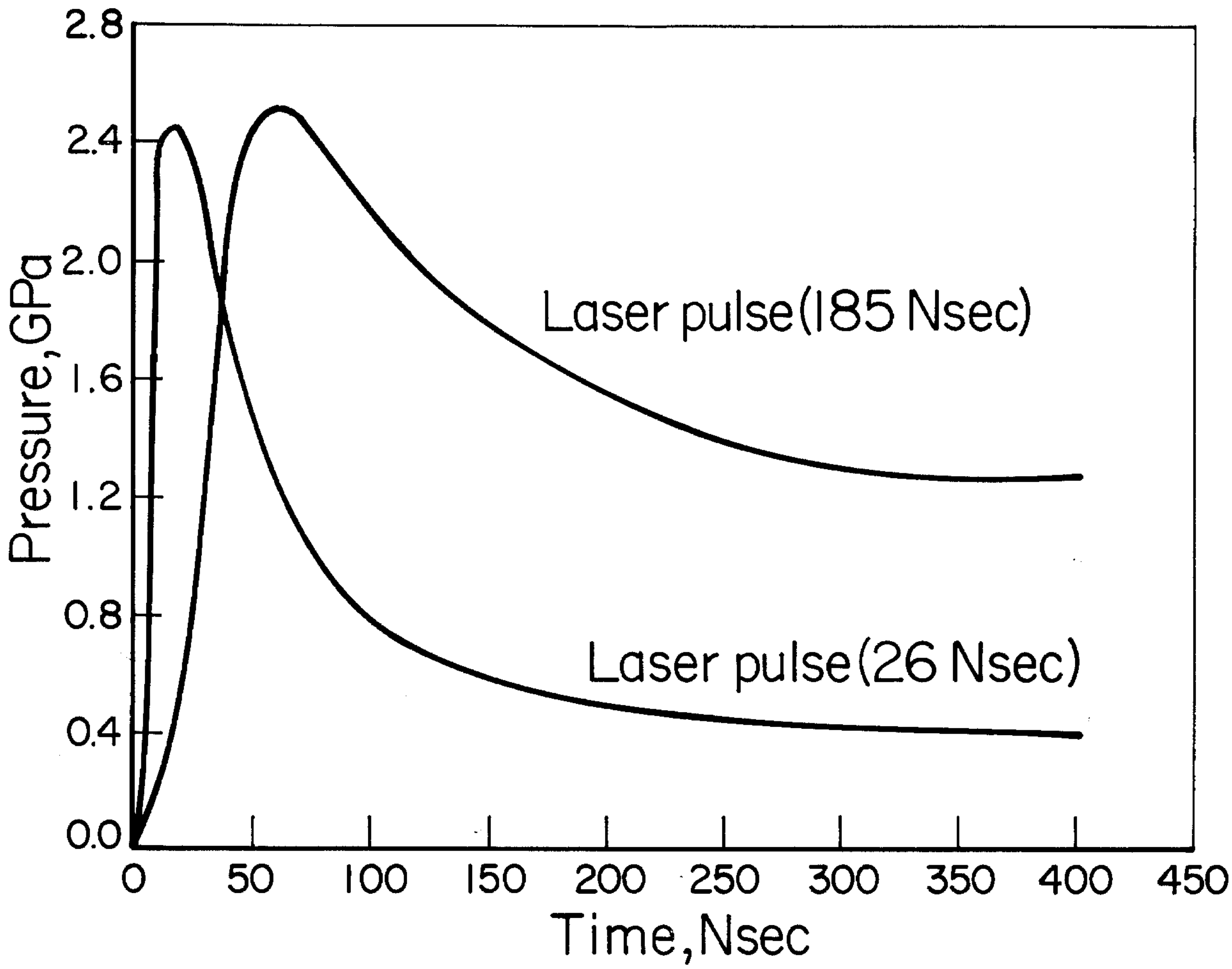

Fig. 2. Comparison of pressure pulses generated by different laser pulses, Pressures measured through 1.27 x 10^{-3} cm thick Zn foils covered with 0.3 cm thick quartz discs.

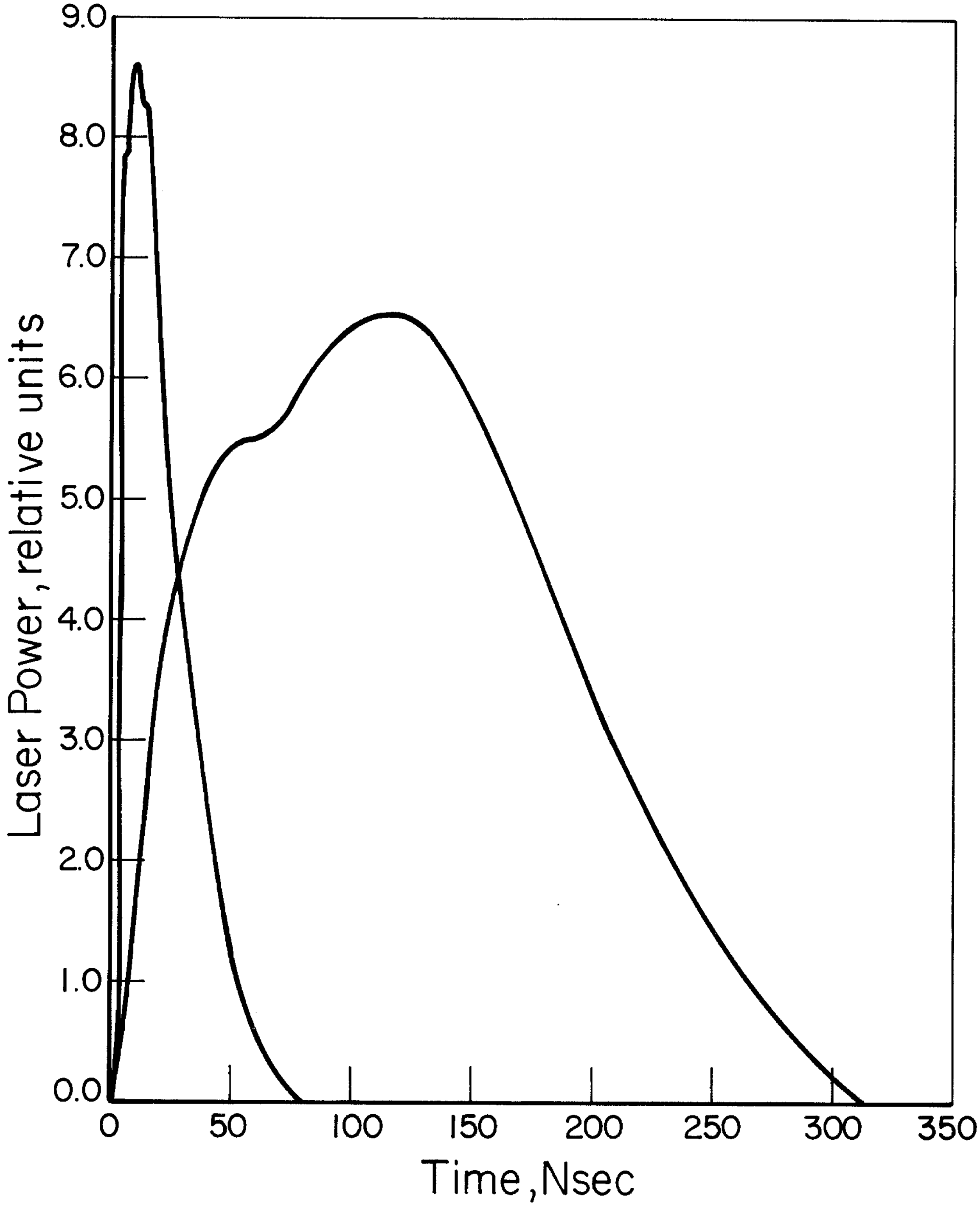

Fig. 3. Comparison of laser pulses used in pressure generation.

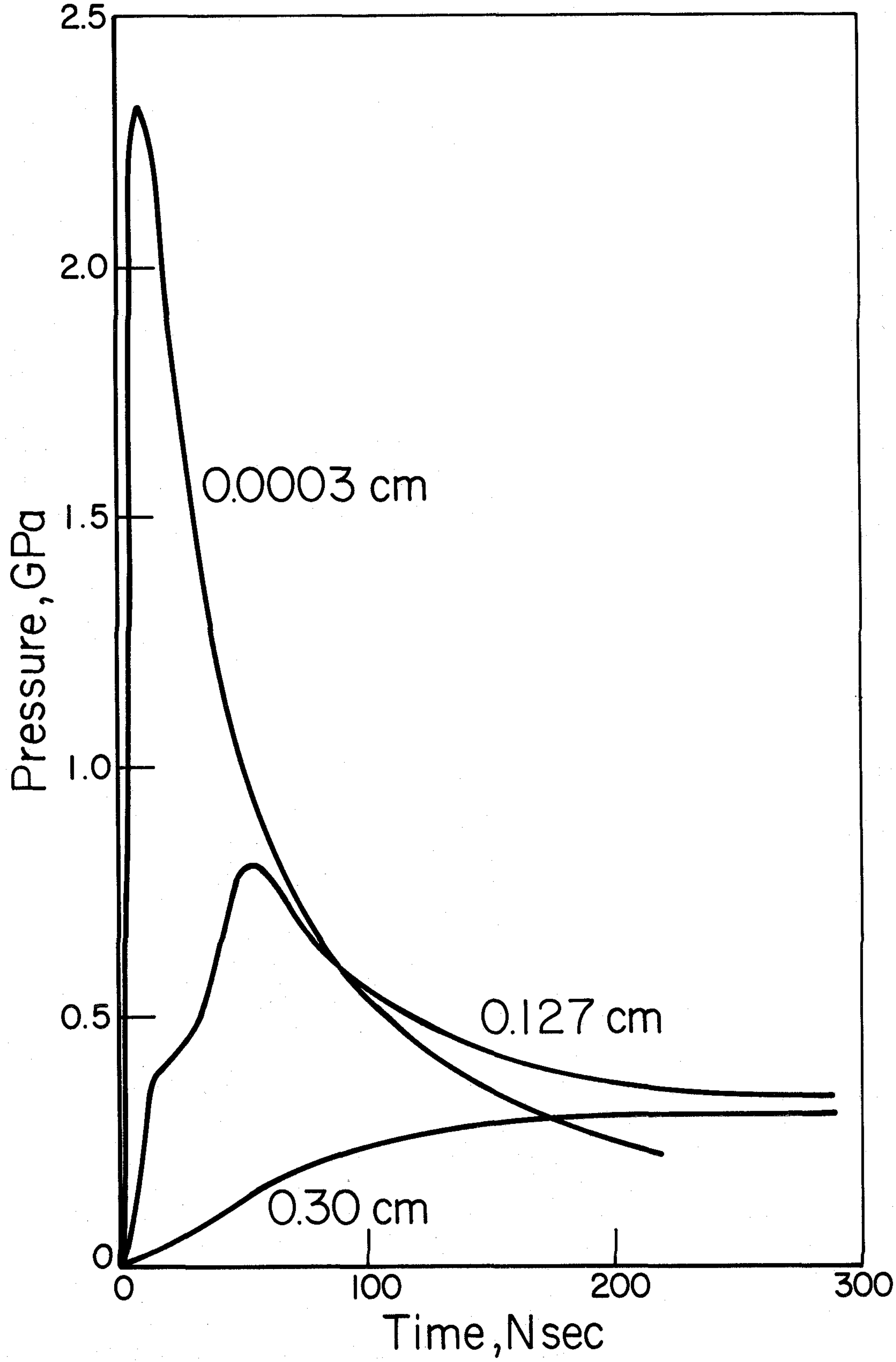

Fig. 4. Pressure pulse in aluminum for various penetration distances (Water overlay).

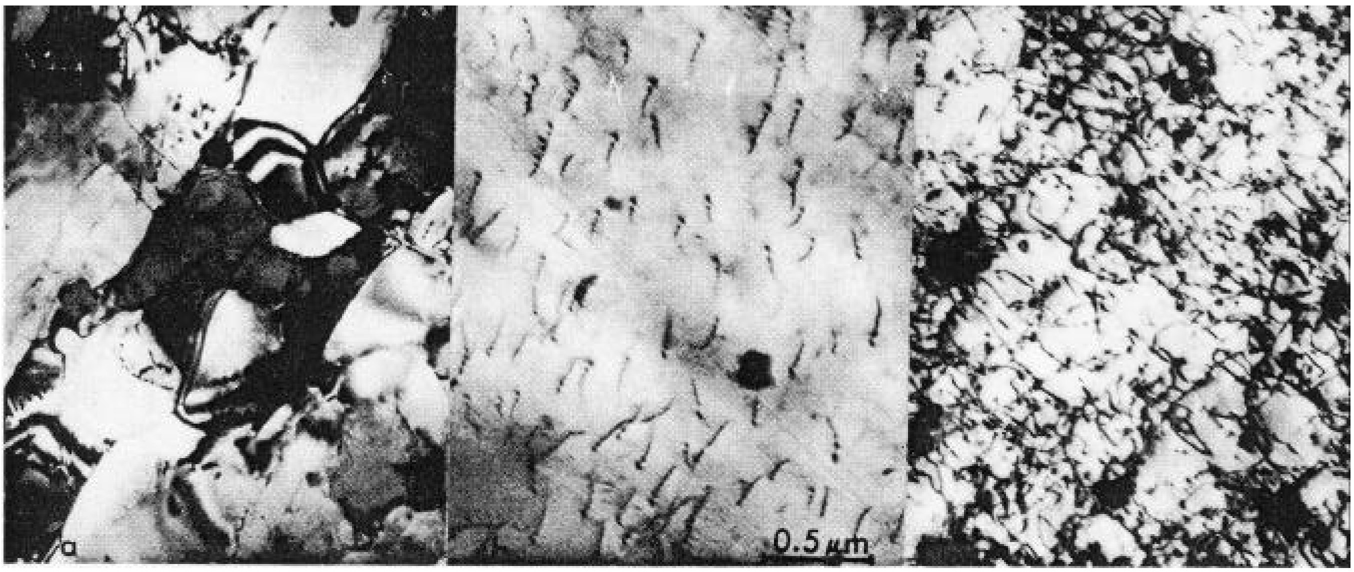

Fig. 5. Microstructure of 5086 H32 aluminum sheet before and after welding and laser shocking. (a) Initial condition - 5086 H 32, (b) After welding - in the heat-affected zone adjacent to the weld zone, and (c) After laser shocking - in the heat-affected zone adjacent to the weld zone.