

# Laser Shock Hardening of Weld Zones in Aluminum Alloys

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The feasibility of using a high energy, pulsed laser beam to shock-harden weld zones in 5086-H32 and 6061-T6 aluminum sheet was investigated. The tensile strength, hardness, and microstructure of samples 0.3 cm thick were studied before and after laser shocking. After laser shocking, the tensile yield strength of 5086-H32 was raised to the bulk level and the yield strength of 6061-T6 was raised midway between the welded and bulk levels. The increases in ultimate tensile strength and hardness were smaller than the increases in the yield strength. The microstructures after shocking showed heavy dislocation tangles typical of cold working.

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.<sup>1</sup> However, these approaches are often either not practicable or are undesirable. Recently, another approach, laser induced shock hardening of the weld zone, has become a possibility. It was demonstrated earlier that a high energy, pulsed laser beam could strengthen 7075 aluminum alloy sheet,<sup>2</sup> and the feasibility of using the laser to shock harden weld zones in 5086 and 6061 aluminum alloys is demonstrated in this paper. The use of a laser beam is attractive because the hardening can be localized to the desired region, is rapid, and can be easily adapted to numerical control.

Alloy 5086 is solid-solution strengthened (Al, 4.0 Mg, 0.45 Mn, 0.15 Cr, wt pct), is not age hardenable, and is widely used in the cold-worked condition. Therefore, the HAZ is subject to softening by recrystallization or recovery and can only be returned to the pre-weld strength levels by strain hardening. Alloy 6061 is age hardenable (Al, 1.0 Mg, 0.27 Cu, 0.6 Si, 0.2 Cr, wt pct) and is often used in the age hardened, T6, condition. Welding this alloy not only introduces a softer weld metal into the structure, but it also causes over-aging and resolutioning in the HAZ. The weld strength can be raised by a postweld heat treatment, but this isn't always possible in welded structures. An alternative is to raise the strength of the weld zone by strain hardening, i.e., shock hardening.

## EXPERIMENTAL PROCEDURE

The starting materials were 0.47 cm thick 5086-H32 and 0.32 cm thick 6061-T6 sheet. (The H32 temper consists of strain hardening followed by a stabilizing low temperature anneal. The T6 temper is

the peak aged condition.) The welded specimens were produced by welding together along their long edges two strips of an alloy, 5 cm wide by 25 cm long. Both alloys were welded by the gas metal arc process using 5356 filler alloy (4.5 to 5.5 Mg, 0.05 to 0.2 Mn, wt pct). The starting gap before welding was 0.38 and 0.25 mm for the 5086 and 6061 welds, respectively. The weld zones in several of the tensile specimens of each alloy contained fine porosity, usually one pore of 0.05 to 0.1 mm diam, except 6061 specimen No. 5 in Table I which contained 3 pores of the smaller size. The maximum cross-sectional area fraction occupied by the porosity was less than 1 pct in any specimen.

The tensile strength and microhardness of each alloy was measured before and after welding, and after welding plus laser shocking. All tensile specimens were oriented with the tensile direction parallel to the rolling direction on flat specimens having a gage section 1.5 cm long and 0.5 cm wide. The specimens were cut from the welded strips with the weld zone aligned perpendicular to the tensile direction at the center of the gage section. After machining, all tensile specimens were ground to a thickness of 0.30 cm.

Coupons 0.30 cm thick, containing a weld zone, were laser shocked for hardness studies and to provide thin foils for transmission electron microscopy (TEM). The microhardness measurements of the as received and welded coupons were made on a transverse section parallel to the rolling direction. The thin foils for TEM were oriented in the plane of the sheet and the areas examined were in the HAZ immediately adjacent to the weld.

The laser-shock experiments were performed with a Q-switched neodymium-glass laser system which consists of an oscillator followed by six amplifiers. This system is capable of delivering up to 500 J of laser energy onto a specimen surface in a pulse that is approximately triangular in shape with a full width at half-maximum (FWHM) of about 25 ns. The laser was also operated in a longer pulsed mode (FWHM of 150 to 200 ns) by placing a glass plate in the lasing cavity of the oscillator. During each of the laser radiations, the laser energy was measured by splitting off a few percent of the laser beam and directing it into a carbon calorimeter. The shape of the laser pulse was monitored in a similar way with a photodiode detector whose output was fed into a fast oscilloscope. The laser beam was focused down to the desired spot size on the specimen surface by the use of 100 cm focal length convergent lenses.

Two arrangements were used to irradiate the specimens. In one case, the specimen was firmly clamped between a 1.9 cm thick 6061 aluminum back-up disc and a 0.2 cm thick transparent fused quartz overlay on the front face. To irradiate both sides, the specimen was sometimes turned over between successive shots. In all other cases, the specimens were clamped firmly between the two 0.3 cm thick fused quartz disks and both sides were irradiated by splitting the laser beam into two parts and directing these beams onto both specimen surfaces simultaneously. Before tensile testing, the surfaces of the laser

Table I. Influence of Laser Shocking on the Tensile Properties of 5086-H32 and 6061-T6 Aluminum

Condition	0.2 pct Yield Strength, MN/m <sup>2</sup>	Ultimate Tensile Strength, MN/m <sup>2</sup>	Total Elongation, pct	Reduction in Area, pct	Beam Peak Power Density † 10 <sup>9</sup> W/cm <sup>2</sup>	Spot Size, cm	Pulse Length § nsec	Sequence of Irradiations
5086-H32 Aluminum								
5086-H32*	215.4	312.7	15.9	2.1	—	—	—	
Welded †	139.2	248.1	16.8	27.5	—	—	—	
Welded plus laser shocked, No. 1	155.4	246.6	9.2	32.0	1.13	3.0	25	Single side
Welded plus laser shocked, No. 2	208.5	253.0	12.2	17.9	1.36, 1.03	1.9	25	Two sides, simultaneously
Welded plus laser shocked, No. 3	180.0	271.0	14.3	19.6	3.67, 4.39	1.0	25	Two sides, separately
6061-T6 Aluminum								
6061-T6*	298.0	325.3	17.5	24.4	—	—	—	
6061-T6 plus laser shocked	296.5	316.5	14.5	15.8	1.38, 1.36	2.0	25	Two sides, simultaneously
Welded	135.7	236.9	19.6	14.5	—	—	—	
Welded plus laser shocked, No. 4	202.7	253.7	14.4	15.7	1.37, 1.34	2.0	25	Two sides, simultaneously
Welded plus laser shocked, No. 5	219.5	252.1	10.5	7.0	2.13, 2.13 2.16, 2.16	1.6	25	Two sides, simultaneously with two separate irradiations overlapping in the weld zone
Welded plus laser shocked, No. 6	216.8	253.7	9.5	15.4	0.81, 0.79 0.47, 0.46	1.0	185	Two sides, simultaneously with two separate irradiations overlapping in the weld zone

\*Average of two tests.

†Average of three tests.

‡Where two beams were used, either separately or split, the power densities of both beams are shown, separated by a comma. The peak pressure at the specimen surface is approximately proportional to the peak power density. For a range of peak power densities of 1 to 3 × 10<sup>9</sup> W/cm<sup>2</sup>, the peak pressures vary in the range 2 to 6 GPa.

§Pulse length at half of the maximum intensity.

shocked specimens were ground lightly (about 0.025 cm removed) to remove the slight depression created by the laser beam in the weld area, except in the instances where the beam covered the entire gage length.

The pressure environment generated in the aluminum specimens was measured in selected cases with commercially available X-cut quartz piezoelectric transducers. The pressure generated near the front surface of the aluminum specimens was checked by placing a transducer at the back surface of a 25 μm thick aluminum foil that was covered with a 0.3 cm thick fused quartz overlay. To obtain information on the attenuation of the pressure pulse through thicker aluminum specimens, pressure measurements were made at the back surface of different thickness aluminum up to 0.3 cm thick. (All

pressure measurements were made under uniaxial strain conditions. In all cases, the laser spot diameter was greater than twice the quartz pressure gage diameter, and the gage finished recording the main planar shock wave before the release waves from the edge of the laser spot reached the gage.)

## RESULTS AND DISCUSSION

### Pressure Measurements

Pressure measurements made through different aluminum specimen thicknesses are shown in Figure 1. These measurements were made with the 25 ns FWHM laser pulse at a peak power density of  $1.16 \times 10^9 \text{ W/cm}^2$  (laser energy density =  $29 \text{ J/cm}^2$ ). The structure observed in the rise of the pressure pulses to their peak values is due to the elastic precursor wave which travels at a higher velocity than the plastic wave and therefore tends to “break away” from the plastic wave as the pressure pulse propagates through the material. The magnitude of the elastic precursor, the Hugoniot Elastic Limit (HEL) depends on both the dynamic strain rate sensitivity of the material and its static yield strength. For unalloyed aluminum, the HEL has been reported as about  $1 \text{ GPa}$ <sup>3</sup> and  $0.2$  to  $0.6 \text{ GPa}$ <sup>4</sup> whereas several aluminum alloys lie in the range of  $0.1$  to  $0.8 \text{ GPa}$ <sup>4</sup>. The higher value of the elastic precursor for the very thin aluminum specimen ( $\sim 1.3 \text{ GPa}$ ) in Fig. 1 was probably due to the strain rate sensitivity of the material; the magnitude of the precursor would decrease with increasing distance into the material.

The front surface peak pressures have been found to increase approximately linearly with laser power density.<sup>5</sup> For example, power densities of  $1$  and  $3 \times 10^9 \text{ W/cm}^2$  translate into peak pressures of approximately  $20$  and  $60 \text{ GPa}$ , respectively, based on experimental and theoretical results. Thus, in Table I where the laser power density for each experiment is presented, the relative peak pressures for the different experiments vary in approximately the same ratio as the relative peak power densities.

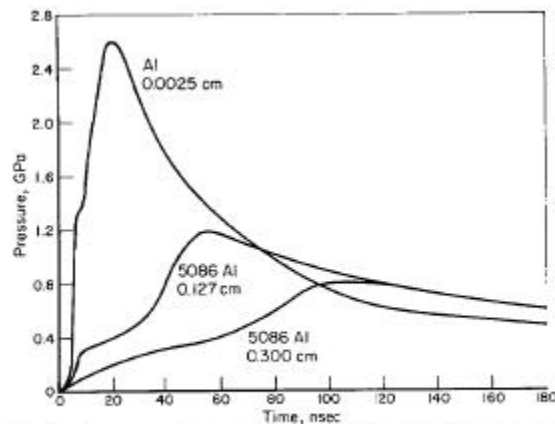


Fig. 1—Pressure wave profiles measured at the back surface of aluminum specimens having the thicknesses indicated by each curve.

## Tensile Test Results

The tensile test results are shown in Table I. Welding significantly reduces the yield and tensile strength of both alloys. In each case, subsequent laser shocking increases the yield strength and in most cases also increases the ultimate strength. It is expected that the small amount of weld zone porosity will not influence the yield strength,<sup>6</sup> but might lower the ultimate strength and ductility a small amount.<sup>6-8</sup> The total elongations and reductions in area maintain acceptable values and did not show any direct correlation with visible porosity in the specimens, and the ultimate strength of the shocked specimens is equivalent to or greater than the welded strength for all specimens.

Duplicate tensile tests were performed only on virgin material. Rather than perform duplicates for each laser irradiation condition, it was expected that any substantial strengthening differences would be evident by comparing individual experimental specimens. This procedure allowed more laser variables to be investigated. Where the larger effects were observed, e.g., greater than 10 pct change, these are presumed to be indications of the effects of the laser conditions used, but smaller differences are probably within the range of scatter due to material and laser radiation variables and in this case relative comparisons can not be made without further experiments.

### 5086-H32 Aluminum

Two different types of laser shock environments and two peak power density levels were investigated in shocking of 5086 aluminum specimens. At the intermediate power density ( $\sim 1 \times 10^9$  W/cm<sup>2</sup>), in one case only one side of the tensile specimen was shocked (No.1) and in the other case the laser beam was split into two approximately equal parts and both surfaces of the specimen were simultaneously shocked (No.2). (The laser emits only a certain amount of total energy. Therefore, for a given pulse duration, the laser spot size required to obtain high power densities or two beams (for the split beam configuration), was necessarily smaller than the spot size used for a single beam, lower energy irradiation (cf. Table I). As can be seen from the data in Table I, the single irradiation on one side (No.1) was not nearly as effective as irradiation on both sides, where the yield strength was raised nearly to the bulk level. When a much higher power density was used ( $\sim 4 \times 10^9$  W/cm<sup>2</sup>), but both sides of the specimen were shocked successively instead of simultaneously, (No.3), the yield strength was increased, but not to the extent attained by simultaneous shocking at a lower energy density. Thus, for in depth hardening, simultaneous shocks gave higher strength than single side shocks.

The differences between shocking on one or two sides can be explained as follows. It has been found that in the 0.3 cm thick specimens, laser shocking produces hardness gradients, with the hardness decreasing with distance into the specimen from the irradiated surface. When this happens, the average

in-depth hardening will be higher when a specimen is shocked from both sides compared to one side. In addition, when a specimen is shocked simultaneously on both sides, the stress waves will meet in the center of the specimen thickness and their individual shock pressures will add together along this plane. (The shock pressures add simply only in the plane where the two shock waves meet. Thereafter, the simple summation is no longer valid, giving too high a value.) The resultant doubling of the stress in the center of the specimen thickness would increase the amount of shock deformation in this region and tend to make the through-thickness distribution of the deformation more uniform. This has been observed in a 2024 aluminum specimen, 0.1 cm thick.<sup>9</sup> Each of these effects would make shocking on two sides more effective than shocking on one side alone.

The microstructures for the different conditions are shown in Fig. 2. The 5086-H32 condition (Fig.2a) shows small subgrains typical of a cold-worked and stress-relieved microstructure. After welding, this substructure has been removed from the HAZ near the weld (Fig.2b), presumably by recovery and recrystallization. After laser shocking, numerous dislocations typical of a shocked microstructure have been introduced (Fig.2c). The laser shocked microstructure shown in Fig.2c represents a single side irradiation equivalent to welded tensile specimen No. 1 in Table 1. Therefore, the dislocation density after shocking on both sides is presumably greater than shown here.

#### 6061-T6 Aluminum

For the 6061-T6 aluminum, all laser shocking experiments were made on two sides simultaneously using the split beam technique. The principal parameters varied in these tests were laser peak power density and laser pulse width. The higher power densities required for irradiations Nos. 5 and 6 necessitated the use of smaller laser beam diameters. Therefore, a 1 cm diam spot size was used and two separate irradiations, overlapping in the weld zone, were required to cover the specimen's gage length. The HAZ was 2.5 cm wide and so extended over the entire 1.5 cm long gage length of the tensile specimens.

Table I shows that laser shocking raised the yield strength about midway between the welded and as received levels. For short pulse durations, the higher power density (No. 5) increased the yield strength about 8 pct more than did the lower power density (No. 4). The long-pulse experiment (No. 6) was designed to have about the same peak power density as the short-pulse irradiation, No. 4, so a comparison of the influence of the pulse length could be made between Nos. 4 and 6. The long pulse gave a 7 pct larger increase in yield strength than the shorter pulse. This suggested a beneficial effect of the longer pulse was anticipated because pressure measurements have shown that for longer laser pulses the pressure amplitude and duration of the shock waves are increased. Appleton and Waddington<sup>10</sup> have shown that the amount of shock hardening depends on pulse length as well as peak pressure at the pressure levels investigated here.

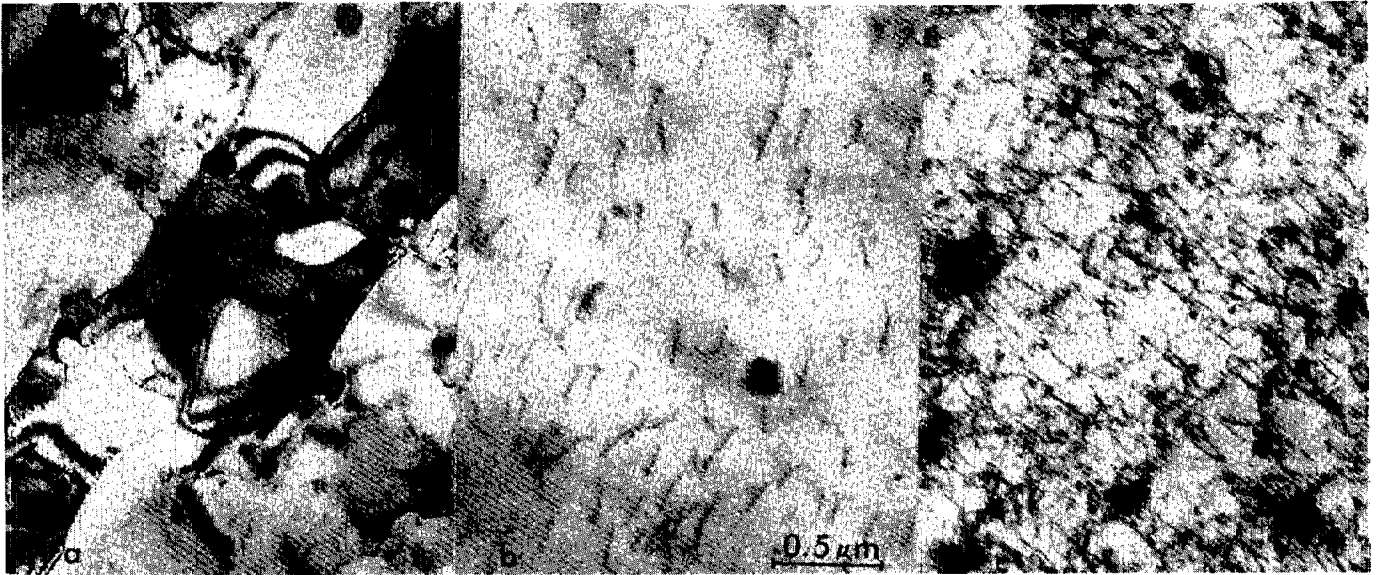


Fig. 2—Microstructure of 5086 aluminum sheet before and after welding and laser shocking (a) Initial condition—5086-H32; (b) After welding—in the heat-affected zone adjacent to the weld zone; (c) After laser shocking (equivalent to No. 1, single side) with a pulse length of 25 ns, power density of  $1.1 \times 10^9$  W/cm<sup>2</sup> and spot diameter of 3 cm—in the heat-affected zone adjacent to the weld zone.

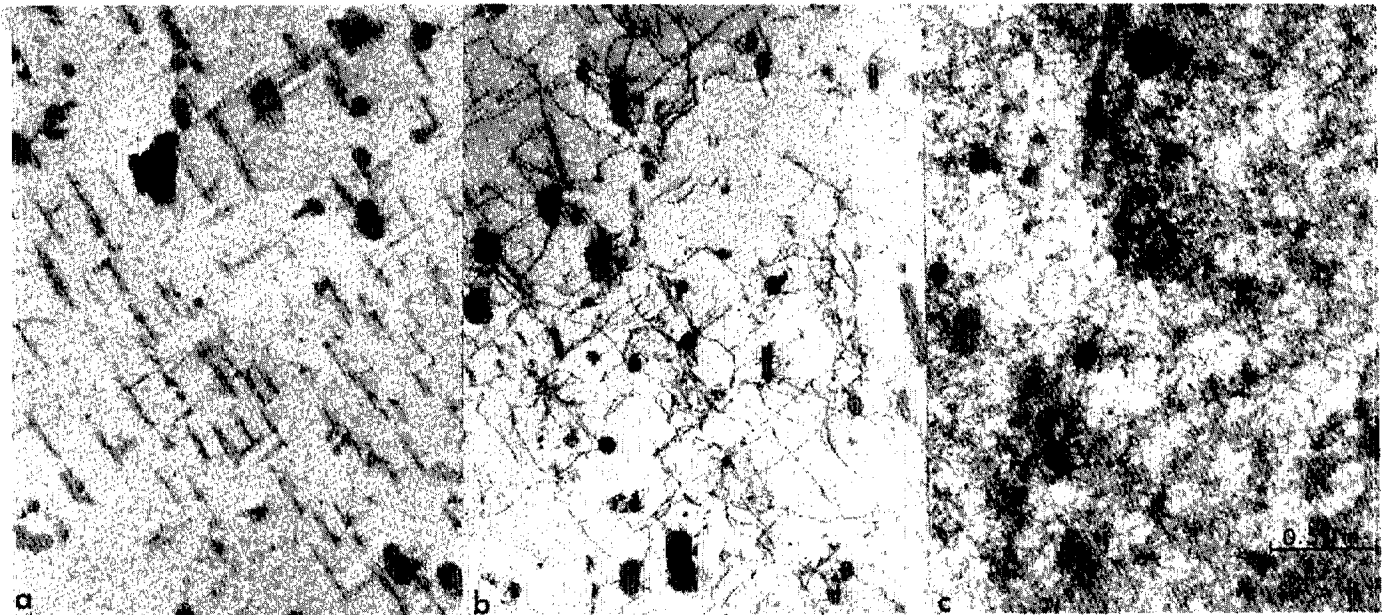


Fig. 3—Microstructure of 6061-T6 aluminum sheet before and after welding and laser shocking (a) Initial microstructure—6061-T6; (b) After welding—in the heat affected zone adjacent to the weld; (c) After laser shocking with a split beam, 25 ns pulse length and a power density of  $1.28 \times 10^9$  W/cm<sup>2</sup> on either surface—in the heat-affected zone adjacent to the weld.

The microstructures for the different conditions of the 6061 aluminum are shown in Fig. 3. The 6061-T6 microstructure shows the lath-like magnesium silicide precipitates and larger, Mn-rich precipitates, but very few dislocations (Fig. 3a). After welding, the lath-like precipitates have disappeared in the HAZ, but dislocations introduced by the shrinkage stresses are present (Fig. 3b). After welding plus laser shocking, equivalent to that received by welded specimen No. 4 (Table I), the thick dislocation tangles expected of shock deformation are present (Fig. 3c). This microstructure is from a region in the center of the specimen, 0.15 cm from both surfaces, indicating that the shock deformation is heavy through the thickness of the specimens.

The average microhardness number of the weld zone was increased approximately 11 pct after laser shocking both sides simultaneously in the short-pulse mode at a power density of nominally  $1.3 \times 10^9 \text{ W/cm}^2$ ; from  $73.7 \pm 2.4 \text{ DPH}$  before shocking to  $81.6 \pm 5.2 \text{ DPH}$  after shocking. (Each of these microhardnesses is an average of over 25 readings taken 0.05 cm apart over the central portion of the weld in the center of the thickness direction, 0.15 cm from both surfaces.) For about the same conditions, the yield strength was increased by 49 pct over the yield strength as welded (No. 4 in Table I). Since the microhardness measurement includes strain hardening, the comparison is usually made between hardness and flow stress at some equivalent strain, e.g., 0.08 tensile strain.<sup>11</sup> A comparison of the flow curves shown in Fig. 4 shows that the difference in flow stress between the welded and welded plus laser shocked conditions at 0.08 strain is about 14 pct.

The hardening through the thickness of specimens shocked simultaneously on both sides was quite uniform, as shown in Fig. 5. The hardness at each depth represents an average of ten indentations along a line within the weld zone at a constant distance from each surface, as shown schematically in Fig. 5.

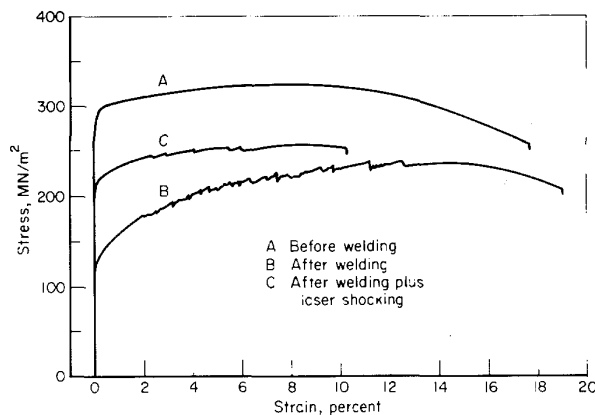


Fig. 4—Stress-strain curves for 6061-T6 comparing the unwelded, welded, and welded plus laser-shocked conditions (Specimen No. 5).

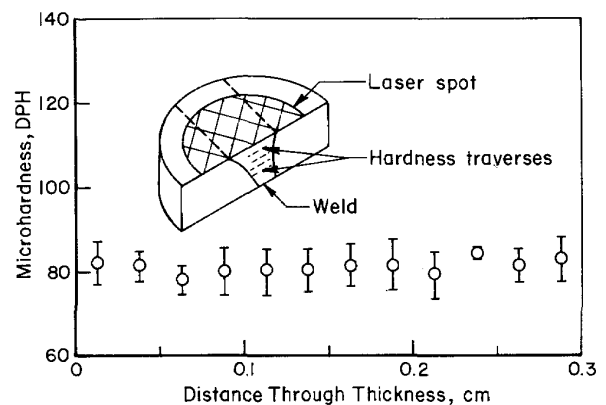


Fig. 5—Hardness variation through the thickness of the weld of a 0.3 cm thick specimen shocked simultaneously on both sides at a power density of  $1.28 \times 10^9 \text{ W/cm}^2$  on each side and a pulse length of 25 ns. The weld zone hardness before shocking was  $73.7 \pm 2.4 \text{ DPH}$ .



The 6061-T6 alloy was also laser shocked in the unwelded condition to determine whether there was any benefit to be gained in shock hardening the bulk material. The results, shown in Table I for an intermediate power density and a short pulse, show no strengthening after laser shocking, although the shock-induced dislocation substructure after shocking was identical to Fig. 3c and showed that a substantial amount of deformation had been produced by laser shocking. A similar lack of strengthening in a peak-aged aluminum alloy after shocking has been observed in 7075-T6.<sup>2</sup> Evidently, precipitation hardening in the T-6 condition is larger than the strain hardening from the shock deformation and masks the latter contribution to strengthening. The overaging or resolution of the precipitates in the HAZ after welding, however, enables the shock deformation to substantially strengthen this region.

### Surface Effects

The laser radiation causes some surface melting. A typical post-radiation surface is shown in Fig. 6. The localized evaporation at the aluminum-quartz interface agitates the melted surface layer considerably, forcing the melt to run over unmelted areas at the edge of the beam (Fig. 6a) and produce an uneven, resolidified surface containing numerous hillocks and holes within the irradiated area itself (Figs. 6b and c). There are also numerous shrinkage cracks which form in the melted layer (marked A in Fig. 6c). These shrinkage cracks extend through the melted layer and in some cases penetrate into the unmelted substrate (Fig. 7). The melted layer varied from 5 to 50  $\mu\text{m}$  in thickness but averaged 10 to 20  $\mu\text{m}$  thick over most of the surface. The degree of porosity within the melted layer also varied from place to place, as compared in Figs. 7a and b. The melted layer on the 5086 aluminum was similar in all respects to the melted layer on the 6061 aluminum shown in Figs. 6 and 7.

This type of surface would have little effect on the tensile strength of ductile alloys such as aluminum, but the fatigue strength would be adversely affected and the melted layer would have to be removed where fatigue was an important consideration. Surface melting can be avoided if an opaque overlay such as black paint or metal foil<sup>12</sup> is placed over the surface of the specimen. In this case, the direct action of the beam occurs at the surface of the opaque overlay, but the shock wave is transmitted into the underlying specimen through the overlay. After removal of the overlay, no cracks are present in the surface of the specimen.

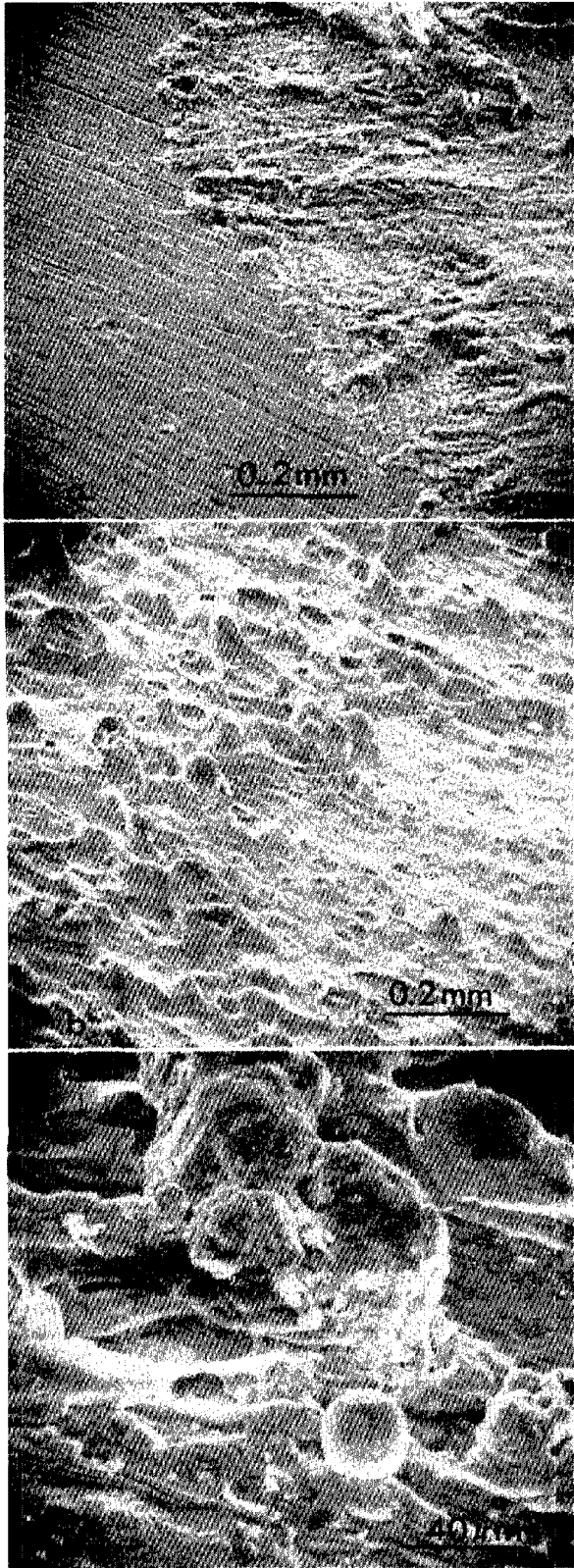


Fig. 6—Surface of 6061-T6 after radiation with a 200 ns pulse at a power density of  $1.38 \times 10^9$  W/cm<sup>2</sup> (a) Appearance of the laser spot on the ground surface; (b) Near center of the laser spot; (c) Detail near the center of (b). Cracks are marked with an A.

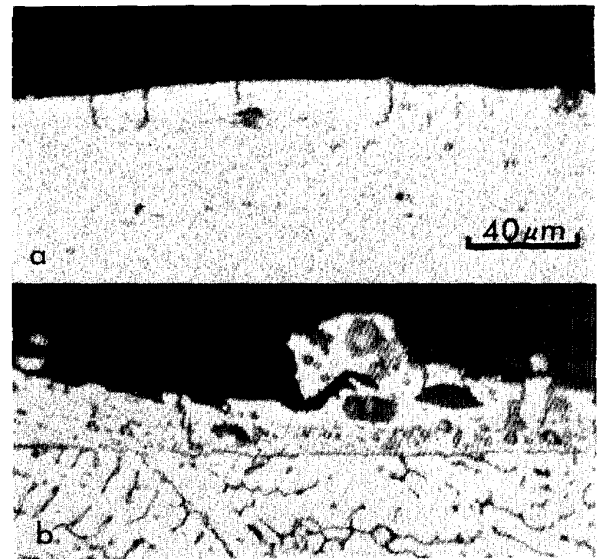


Fig. 7—Cross-section of the melted surface layer formed on welded 6061-T6 aluminum by laser irradiation, quartz overlay, power density  $1.28 \times 10^9$  W/cm<sup>2</sup>, pulse length 25 ns (a) Away from weld zone; (b) At the weld.

## CONCLUSIONS

- 1) Weld zones in both a wrought aluminum alloy, 5086-H32, and an age hardened aluminum alloy, 6061-T6, can be strengthened by laser-induced shocks.
- 2) The yield strength of welded 5086-H32 aluminum can be increased to that of the bulk by laser shocking and the yield strength of welded 6061-T6 can be increased to midway between the welded and bulk yield strengths.
- 3) Increases of 11 pct in DPH numbers were observed after laser shocking on both sides simultaneously at  $1.3 \times 10^9 \text{ W/cm}^2$ . The hardness was uniform through the thickness of a 0.3 cm thick specimen.
- 4) Laser shocking increases dislocation density in the heat affected zones of both alloys.
- 5) Surface melting occurs but is restricted to a thin layer. Shrinkage cracks were formed in the melted layer.

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