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AFFECT OF ANGLE OF INCIDENCE ON PLASMAS GENERATED DURING LASER WELDING

by

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Introduction

The work presented in this report is a continuation of studies initiated to generate an understanding of and to characterize laser welding. The work has evolved into research on laser-material-interactions with the overall goal of developing mechanisms for improved control of laser welding.

Previous work (1-3) led to the postulate that a laser supported combustion wave (lscw) was generated during irradiation of a metal surface by a laser. The lscw theory was used to explain enhanced coupling of laser radiation to a surface. Enhanced coupling is the phenomenon whereby more heat is input to a surface, by laser radiation, than can be accounted for by absorption alone.

A lscw is a plasma which is generated when the laser radiation causes breakdown of the gas and material atoms and molecules near the surface. The plasma has a high density and temperature and thus converts the poorly absorbed 1.06 micron laser radiation to blackbody radiation with a broadband wavelength spectrum. The plasma radiation is more readily absorbed because of the large amount of short wavelength radiation which has a higher absorption coefficient.

The possibility that the enhanced coupling is due to increased absorption resulting from reflectivity decreases is probably not valid, at least for aluminum. The absorptance of Al increases by only 2% (4) when the temperature goes from room to melting and by less than 1% when the angle of incidence changes from 0 to 45 degrees (5). These changes, even together, cannot account for theoretical enhanced couplings of up to 50% (6).

The generation of a laser supported combustion wave as opposed to a laser supported detonation wave (lsdw) is more likely because of the laser energies and wavelengths involved. For ND YAG radiation at 1.06 microns, energy densities of 10^9 to 10^{10} watt/cm^2 are needed to initiate laser supported detonation waves (6). These energy densities are beyond the output of our laser system. Thus the creation of a lscw is the most likely explanation for enhanced coupling.

The lscw explanation for enhanced coupling requires that the plasma propagates away from the surface with a subsonic velocity. The velocity will be along the laser axis and the plasma will propagate until the laser energy input is too small to maintain it. The plasma velocity and mass transport limit the maximum plasma temperature to between 10,000 and 25,000 K depending upon the laser intensity. Temperatures in this range are sufficient to provide efficiently absorbed radiation to the material surface.

Previous work has shown that the velocity of the pressure wave generated by the lscw's is subsonic and thus a lscw is generated (1). High speed video and movies (12,000 and 40,000 pictures per second respectively) taken during the same study showed that intense regions of radiation were generated and propagated up the laser axis. This also supports the concept of the generation of lscw's because of the propagation direction. Measured plasma velocities showed subsonic propagation which further supports the lscw theory. The high speed movies also showed that numerous plasmas were generated during each laser pulse which implies variable heat input from the plasma. This and subsequent work (2,3) showed that the plasma ignition was dependent upon material as well as laser power.

All of the previous work was done with the beam normal to the material surface. Since the target vapors are emitted normal to the surface significant photon-metal vapor interactions result. This interaction obscures and/or influences the lscw interaction.

The present work was done to: further verify the existence of lscw's; provide additional measurements of the plasma initiation time; and investigate alternate methods of determining the number of plasmas generated. Correlation between lscw occurrences and the depth of material melted versus laser power were also made.

Experimental

The angle of incidence of the laser beam on the metal substrate was varied during the study. This more clearly shows the existence of lscw's because the vapor plume (emitted normal to the surface) is partially removed from the beam path. Generation of lscw's in both the incident and reflected beams should be possible and observable using photographic techniques and radiation monitors. As the plasma density increases, reflection of the laser beam at the plasma critical density should be detectable in a back reflected position. The plasma critical density is given by the usual expressions:

$$w_p = (4\pi\ ne^2/m)^{1/2},$$

where; w_p = the plasma frequency (in this case the frequency of 1.06 micron laser radiation),
n = the plasma density,
e = the electron charge
and m = the electron mass.

Figure 1 shows a schematic of the plasma/plume boundary and the boundaries of the incident and reflected beams.

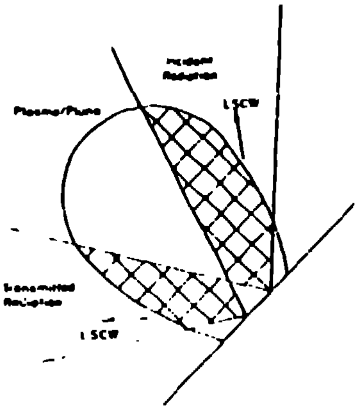

Figure 1. Schematic of the laser-material interaction. The incident beam interacts with material to generate a lscw in both the incident and reflected channels.

Modulation of the laser radiation to the surface by the plasma will depend upon when the plasma is generated, which channel (incident or reflected) it is generated in, the velocity of the plasma, the boundary between the plasma and the laser beam, and the decay rate of the plasma. For example, assuming the plasma boundary always fills the beam and the plasma is instantly ignited at critical density, expands to the point where the density is subcritical and then is instantly reestablished at critical density a large amount of laser radiation will be reflected and very little light will be transmitted at the angle of reflection. The light reflected in the direction opposite the beam will then be composed of the radiation from the plasma plus the reflected laser radiation. This signal will also show intensity changes which vary at a rate proportional to the velocity of the plasma and the rate at which the plasma critical density is established. The radiation detected at the angle of reflectance, after transmission through the plasma, will be composed of radiation from the plasma only. This analysis assumes that when the plasma departs from critical density the laser radiation is totally absorbed by the plasma.

Another example is, if the plasma does not ignite until after the beam has been incident on the surface for some time. This again assumes that the plasma boundary always fills the beam. After ignition the plasma propagates up the beam absorbing energy until it reaches critical density or the laser radiation can't support it. At critical density the beam will be reflected and the plasma will cool and begin to reabsorb the beam. If it does not reach critical density the plasma will dissipate and a new plasma may or may not be formed. In this case the radiation seen in the direction opposite the beam will consist of that radiated from the plasma and some reflected laser radiation when the plasma becomes critical. The intensity seen at the angle of reflection will be composed of the radiation from the plasma plus the laser radiation transmitted through the plasma and reflected from the metal surface.

The two examples represent simplified cases particularly for laser radiation incident at oblique angles. At oblique angles of incidence the plasma probably only fills the beam area for a short time when the plasma is close to the surface. When the plasma does not fill the beam area some laser radiation will be available for interaction with the surface and the gas behind the plasma. This will result in changes in the intensity of both the radiation seen opposite the beam direction and that seen at the angle of reflection.

The high reflectivity of the metal surface permits sufficient energy in the reflected channel to initiate plasmas. Thus plasmas can be initiated in either/or both of the channels. Energy considerations show that critical density plasmas in either channel result in no intensity variations in the reflected channel. Plasmas with densities less than the critical density in the reflected channel can cause intensity variations, however.

The following results were obtained by varying the angle of incidence of 1.06 micron radiation on commercially pure Al (1100 Al). The laser was a ND YAG system capable of 400 watt average power. The average power used was 350 watt for the radiation monitoring studies and from 50 to 350 watts for the penetration and high speed video studies. For this study the system was operated at 10 pulses/sec with a 0.0078 sec pulse length. All data were taken using one pulse per event and each event was on a fresh surface. The laser pulse shape is shown in the data which follows.

The sample size was 2.5 cm diameter by 0.32 cm thick. The surface finish was left in the as rolled condition and prior to each event the surface was wiped with alcohol. The samples were placed in a fixture which could be rotated about the center of the disks. This allowed several events to be placed on each sample and facilitated machining to the center of each melted spot for melt depth measurements. The fixture also allowed rotation about an axis in the plane of the disk so that the angle of incidence could be easily changed. The angle of incidence was varied from 0 to 45 degrees in steps of 5 degrees.

Interaction of the beam with the plasma was monitored by recording: radiation from the rear of the laser cavity (laser signal); visible radiation from the plasma using a photomultiplier tube (pmt) with an s-20 response (pmt signal); infrared (IR) radiation reflected back up the beam (reflected signal); IR radiation transmitted through the interaction region at the angle of reflection (transmitted signal) and high speed video. All data were recorded on a 4 channel digital oscilloscope at a rate of 5 microsec/data point. The IR detectors were silicon photodiodes with IR pass filters. All radiation was coupled to the detectors using optical fibers. The laser power was monitored several times during a series of events using a calorimeter.

After approximately 10 events the disk was machined to the center of the melted region, polished, etched and the melt depth measured. Figure 2 is a schematic of the detectors, target and plasma orientation.

Results

Figure 3 shows the calculated power density versus the average powers used in this study. The power density was calculated assuming a Gaussian distribution for the beam profile. With no focusing lens the average beam power was measured. An aperature was then placed in the optical path above the calorimeter and closed until the average power was reduced by $1/e^2$. The aperture diameter was then used to calculate the focused spot size from:

$$w_0 = \lambda f/\pi w_1 .$$

where w_0 = the focused spot radius,
w_1 = the radius of the collimated beam incident on the lens,
λ = the wavelength of the radiation
and f the focal length of the lens.

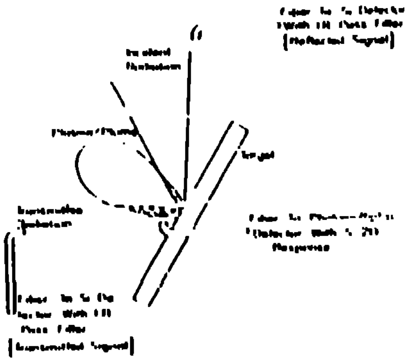

Figure 2. Schematic of the experimental setup. Light reflected back from the plasma is detected as the reflected signal and light transmitted through the plasma is detected as the transmitted signal. The interaction is also monitored by the visible radiation using a PMT.

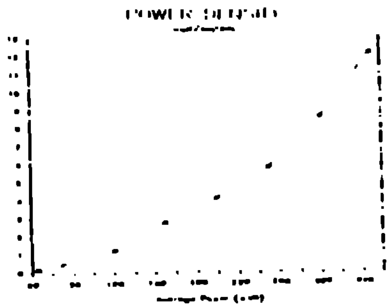

Figure 3. Calculated power density versus average power. The calculated power density is at least 4 orders of magnitude greater than that determined from burn patterns.

Comparison of this data with power densities calculated from burn patterns shows that the present technique yields power densities 4 orders of magnitude higher. Because we have observed sustained burning of the paper used to determine power density from burn patterns we know that there are inaccuracies with that technique also. Power densities determined by burn spots are in the order of 10^5 watt/cm^2. For this work we have elected to use the power density as shown in Fig. 3, recognizing that the true power density is probably several orders of magnitude less. For the data which follows this is not a problem since the power density is calculated from the average power.

Figures 4-9 show the data obtained from the optical radiation detectors for an average power of 350 watt and at angles of incidence of 10, 20, 30, 40, 45, and 0 degrees respectively. Two sets of data are shown for 30 degrees, one of which was obtained with the IR pass filters removed (Fig. 7). This was done to see if there was any major influence of the visible radiation. The filters seem to reduce the amount of signal variations seen in the transmitted signal but do not seem to qualitatively affect the results. In all of these figures, the label "laser" refers to the laser signal, "R" refers to the reflected signal, "T" refers to the transmitted signal and "PMT" refers to the photomultiplier signal as explained above.

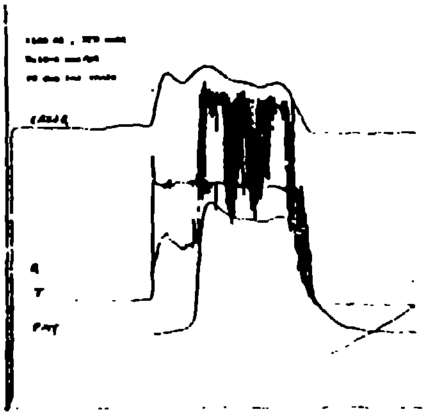

Figure 4. Laser, reflected, transmitted and PMT signals from 1100 Al at 10 degrees. Shows one plasma in R and T at point A and numerous critical density plasmas in the R signal.

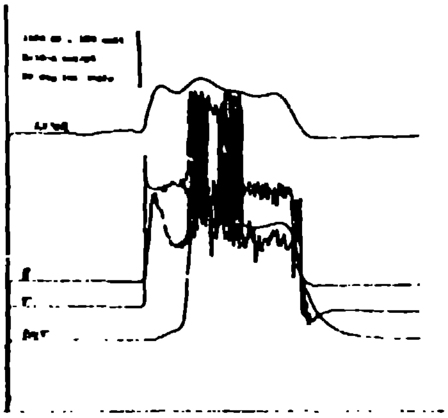

Figure 5. Laser, reflected, transmitted and PMT signals from 1100 Al at 20 degrees. Shows several plasmas in R and T at point A and numerous critical density plasmas in the R signal before and after them.

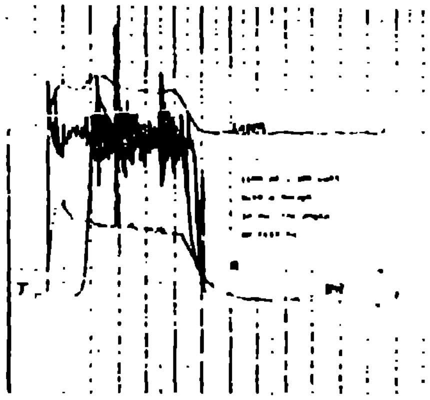

Figure 6. Laser, reflected, transmitted and PMT signals from 1100 Al at 30 degrees with the IR filters in. Shows one plasma in R and T at point A and numerous plasmas in the T signal before and after them.

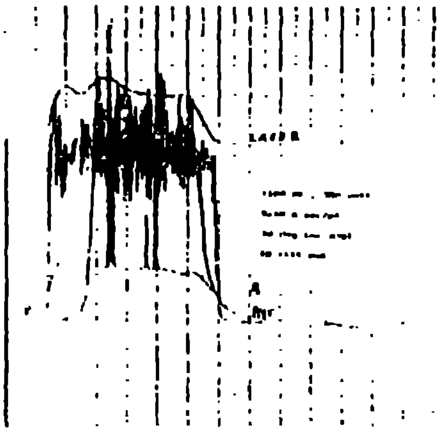

Figure 7. Laser, reflected, transmitted and PMT signals from 1100 Al at 30 degrees with the IR filters out. Shows several plasmas in R and T at points A and numerous plasmas in the T signal before and after them.

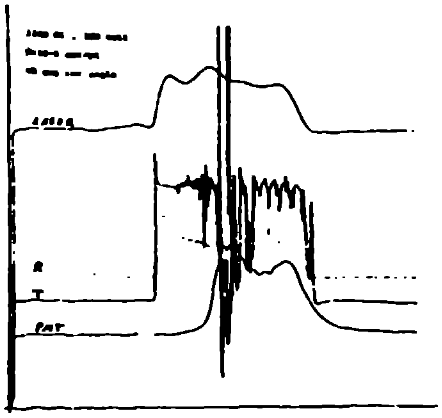

Figure 8. Laser, reflected, transmitted and PMT signals from 1100 Al at 45 degrees. Shows several plasmas in R and T at point A and no plasmas in the T signal before and after them.

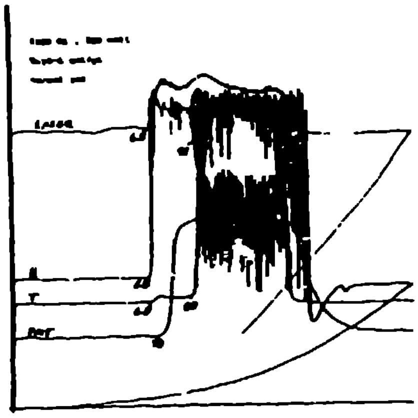

Figure 9. Laser, reflected, transmitted and PMT signals from 1100 Al at normal incidence. Shows numerous critical density plasmas in R and T. Because of position R and T are expected to be the same.

The following observations can be made about the data shown in Fig. 4-9:

1. the transmitted and reflected signals start at the same time as the laser signal;
2. the photomultiplier signal always starts last and
3. the increase in the photomultiplier signal occurs coincident with the major changes in the R and T signals.

Figure 4 shows one plasma formed about half way into the laser pulse (position A). Because the indication is seen in both the R&T signals, a plasma initiation threshold is implied. After the first plasma is initiated, dissipation and regeneration of plasmas at the critical density is indicated by the large amplitude changes and large number of signal variations seen in the reflected signal.

Figure 5 indicates that a critical density plasma is formed immediately, after several regenerations they decay, several other plasmas are formed and decay (A), a critical density plasma is formed again and after several regenerations decays. Approximately three fourths through the pulse no additional plasmas are formed.

Figures 6, 7, and 8 show that only a few critical density plasmas form and quickly die out. The large signal variations seen in the transmitted signals in Fig. 6 and 7 indicate that plasmas are formed in the transmitted channel and absorb the incident radiation but do not reach critical density. Figure 8, on the other hand, shows very little evidence of any plasmas formed other than the 2 or 3 at critical density.

Figure 9 shows the data obtained with the beam at normal incidence. In this case there is no plasma activity until after the PMT signal has been on for a time. For this case, both the reflected and transmitted monitors are set at the same angle and both show essentially the same response, as shown in the figure. This data shows that many critical density plasmas are generated throughout most of the laser pulse.

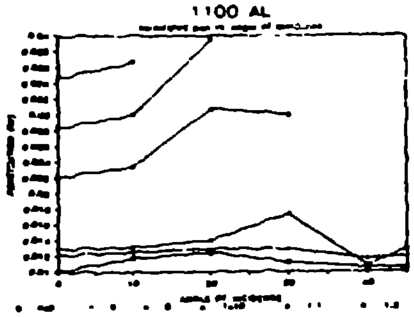

Figure 10. Penetration versus angle of incidence for constant power density. Shows the increase in penetration as the angle changes.

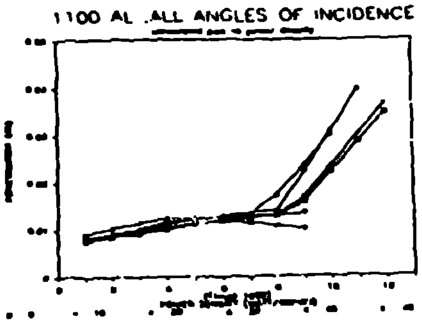

Figure 11. Penetration versus power density for constant angles of incidence. Here again the penetration is shown to increase as the angle increases.

Figures 10, 11 and 12 show that the melt depths obtained at the various powers and angles of incidence. Figure 10 shows that the penetration is constant for the low powers but increases sharply as the power increases. It also shows that there is an increase in penetration as the angle of the incidence increases. Recall from Fig. 5, 6 and 7 that at 20 and 30 degrees there were less critical density plasmas created. Also from Fig. 5, 6 and 7 there were very few critical density plasmas created at 30 degrees which is the angle where the effect first appears at low powers

The data is replotted in Fig. 11 versus power density at constant angles of incidence. This data also displays the increase in penetration as the angle is changed.

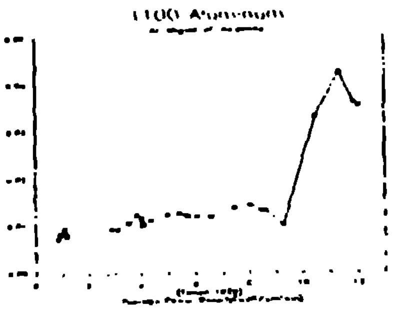

Figure 12. Penetration versus power density for all data. There is an increase in penetration at approximately 300 watts average power.

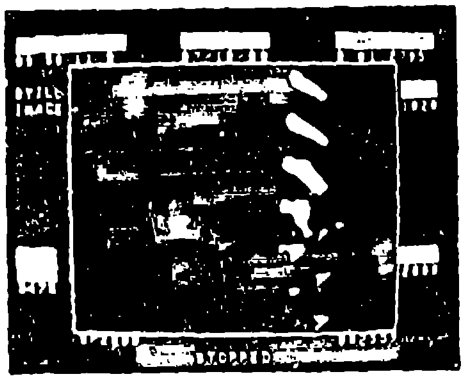

Figure 13. One frame of a high speed video (12,000 pictures/sec). Shows the vapor plume motion and the plasma in the incident channel.

Figure 12 is a graph of the same data but for penetration versus power density. In this figure there is a sharp increase in the penetration at a power density of 9×10^8 which corresponds to about 300 watts average power. This is in agreement with previous work (1) which showed a threshold for Al penetration at approximately 300 watts average power.

Figure 13 shows one frame from the high speed video data. This figure shows the vapor plume normal to the surface and evidence of a plasma in the incident beam channel. Analysis of the video data showed that the plasmas could be seen in the incident channel and occasionally in the reflected beam channel. Identification of a plasma in the reflected channel indicates that sufficient energy is reflected to ignite a plasma. Also seen, in this data, is a precession of the vapor column about the normal to the metal surface. This implies that the vapor emitting surface is moving which is in agreement with the theory that there is motion of the molten pool. The vapor column position is then an indication of the pool motion and position.

Conclusions

This study has shown that lscw's are generated and that they can reach critical density. More critical density plasmas are formed as the angle of incidence approaches the normal. As the angle of incidence is increased the penetration increases. The vapor plume is seen to precess about the surface normal which indicates motion of the molten pool. The penetration increases correlate with fewer critical density plasmas implying that better photon conversion is obtained when the plasma is absorbing and not at the critical density. The radiation monitoring techniques provide data which correlates with penetration and thus are potential monitoring and control methods.

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Mr. R. D. Dixon has a BS in Mathematics and a MS in Physics from The University of South Dakota. He has been an instructor of physics at the University of Wisconsin, Superior; Optical Physicist, Chrysler Corp.; and Research Physicist and Manager, Rockwell International. He is presently a staff member in the Materials Science and Technology Division at the Los Alamos National Laboratory where he is involved with laser and Electron beam Welding Research.

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