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PLASMA HEATING EFFECTS DURING LASER WELDING

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Introduction

Laser welding is a relatively low heat input process used in joining precisely machined components with minimum distortion and heat affects to surrounding material. The CO_2 (10.6 μm) and Nd-YAG (1.06 μm) lasers are the primary lasers used for welding in industry today. Average powers range up to 20 kW for CO_2 and 400 W for Nd-YAG with pulse lengths of milliseconds to continuous wave.

Control of the process depends on an understanding of the laser-plasma-material interaction and characterization of the laser beam being used. Inherent plasma formation above the material surface and subsequent modulation of the incident laser radiation directly affect the energy transfer to the target material. The temporal and spatial characteristics of the laser beam affect the available power density incident on the target, which is important in achieving repeatability in the process. Other factors such as surface texture, surface contaminants, surface chemistry, and welding environment affect plasma formation which determines the weld penetration.

This work involves studies of the laser-plasma-material interaction process and particularly the effect of the plasma on the coupling of laser energy to a material during welding. A pulsed Nd-YAG laser was used with maximum average power of 400 W.

Laser Energy Coupling

The coupling of laser energy to a material to produce localized heating for welding is a function of the absorptivity of the material being welded. At the infrared wavelengths of the Nd-YAG and CO_2 lasers many materials are greater than 95% reflective as shown in Figure 1. As the wavelength is decreased to the visible and ultraviolet, absorptivities increase to 50-80%. Plasmas that form above the material surface may reach temperatures of 20,000 deg kelvin /1-2/ and radiate heat to the surface of the target in the visible and ultraviolet range. The amount of short wavelength radiation increases with plasma temperature as shown by the blackbody radiation curves in Figure 2. Hence, energy is transferred to the target material via absorption of the incident laser light and

Plasma Monitoring

Several techniques have been used to monitor plasmas that form during laser welding. /3-4/ Microphones were used to monitor the shock wave that precedes every plasma wave. Photomultiplier tubes were used to monitor the visible light from the plasma itself. Current detectors were used to measure current from the plasma and the target. Infrared detectors were used to monitor the incident laser radiation and the reflected infrared from the target surface and plasma. Many of these signals have been correlated with high speed photography and melt penetration during welding. The signals show plasma initiation, plasma intensity, and the regeneration of plasma waves.

Experimental Results

A composite photograph of a typical high speed film showing plasma formation is in Figure 3. The film speed was 2000 frames per second and each frame contains six pictures of the plasma for a rate of 12,000 pictures per second. Each picture represents an integrated time period of 83 microseconds and each frame 0.5 milliseconds. The pictures correspond with increasing time from right to left with the laser firing at the bright square in the upper photograph. The sample is in a horizontal position at the base of each plasma plume. The photo sequence was taken during a 7.8 ms laser pulse on 1100 aluminum (commercially pure). The plasma initiation time and multiple plasma formation can be noted in the first few frames. Multiple plasmas can be viewed in single pictures travelling up the focal cone which is vertical in the photographs.

Plasma waves initiate at the target surface and propagate into areas of decreasing laser radiation flux as they move up the laser focal cone. These waves absorb, transmit, and reflect the incoming radiation as a function of plasma density. Plasma density has to decrease as the plasma moves into lower energy density regimes in the laser focal cone, where the radiation flux is no longer sufficient to maintain the plasma, resulting in decay. When the plasma decays to the point where incident radiation can pass through the plasma to the target, a new plasma can initiate at the surface and the process repeats. Therefore many plasmas may exist in the laser focal cone at any time. Each one is in a different state of absorption, reflection, or transmission depending on its position in the focal cone.

Figure 4 shows the number of plasmas occurring during a single 7.8 ms laser pulse vs. power for austenitic stainless steel and aluminum alloys. These two materials were chosen as representative of absorptive (stainless steel) and reflective wavelength. A threshold power for plasma regeneration occurs at 100 W for stainless steel and at 300 W for the aluminum alloys.

Figure 5 shows the melt depth vs power for the same materials as Figure 4. The aluminum alloy threshold for melt depth at 310 W corresponds with the increase in plasma activity described in Figure 4. The stainless steel material has a more linear melt depth response with power regardless of the plasma activity shown in Figure 4.

The data for the highly reflective aluminum alloys indicate the plasma radiation is a dominant heating mechanism that increases the melt depth above that expected for absorption of the laser radiation alone. The data for the less reflective stainless steel shows less sensitivity to the plasma formation even though plasmas are created at one third the power required for the aluminum alloys. Although a threshold penetration affect could exist at the 100 W level for stainless steel, the data recorded did not adequately cover this low power regime. The contributions to target heating by plasma radiation and laser light radiation are not as distinct as in the case of the more reflective aluminum alloys.

The two different responses can be caused by different plasma characteristics for the respective materials. The plasma density determines the quantity of laser energy absorbed by the plasma. Increased plasma absorption of laser radiation increases plasma temperature and radiation to the target area. However, the plasma velocity away from the target can also increase with plasma temperature reducing the time a plasma stays near the surface for effective heat transfer. Lower density plasmas may transmit more laser radiation to the target causing absorption at the laser wavelength to be the dominant heating mechanism. These plasma characteristics vary with material composition and atmosphere and determine how the incident laser light is modulated.

Conclusions

From these studies, techniques to monitor the plasma formation during laser welding have been developed. Multiple plasma formation has been observed during a single 7.8 ms pulse from a Nd-YAG laser. Radiant heating by the plasma is the dominant heating mechanism at energy fluxes above the threshold for plasma wave formation for highly reflective materials at the laser wavelength. For materials with higher absorptivity at the laser wavelength the influence of plasma heating appears to be less although measurements of the plasma density, temperature and transmission are required which are the subject of future work.

References

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FIGURE CAPTIONS

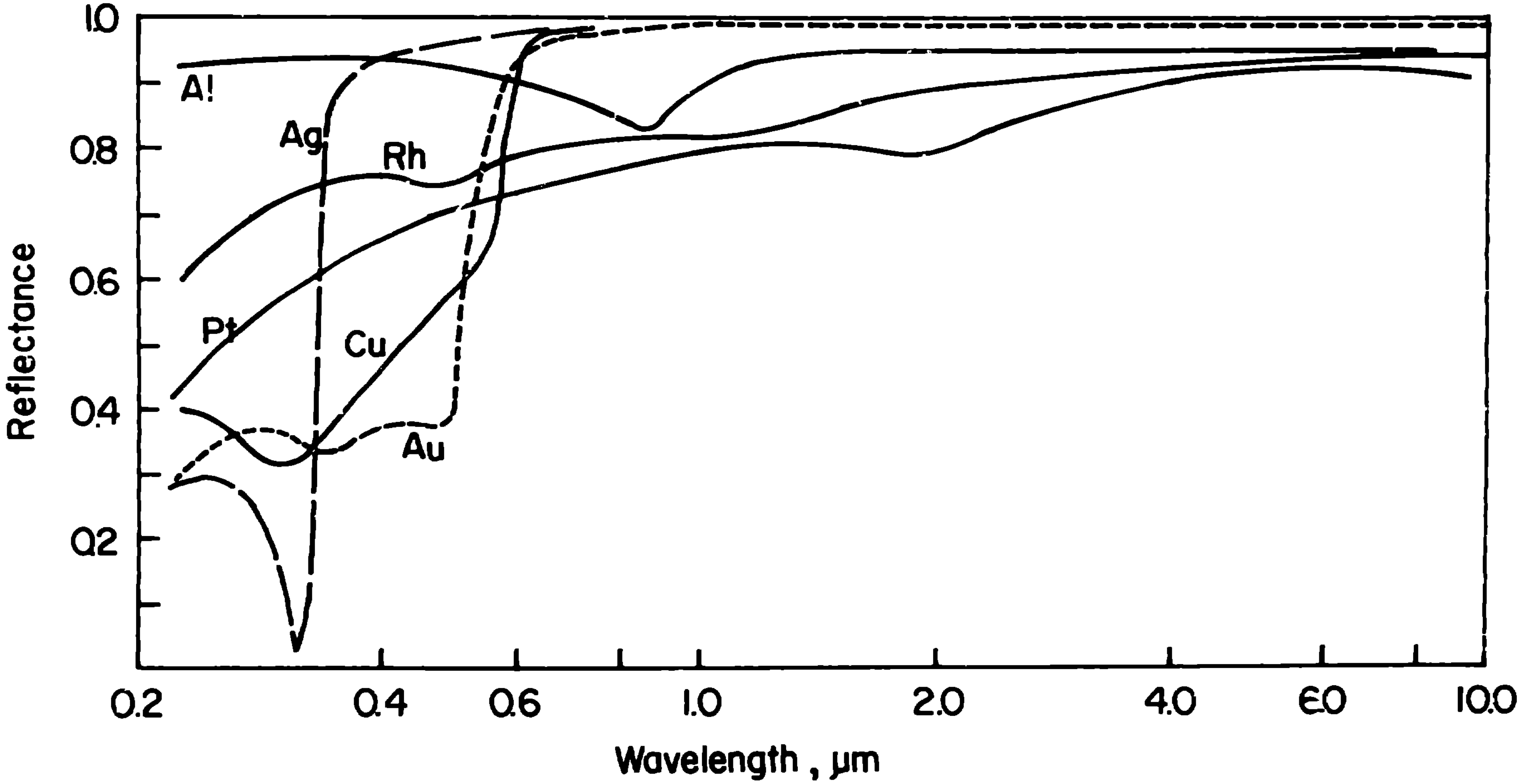
Figure 1. Reflectance versus wavelength for various materials.

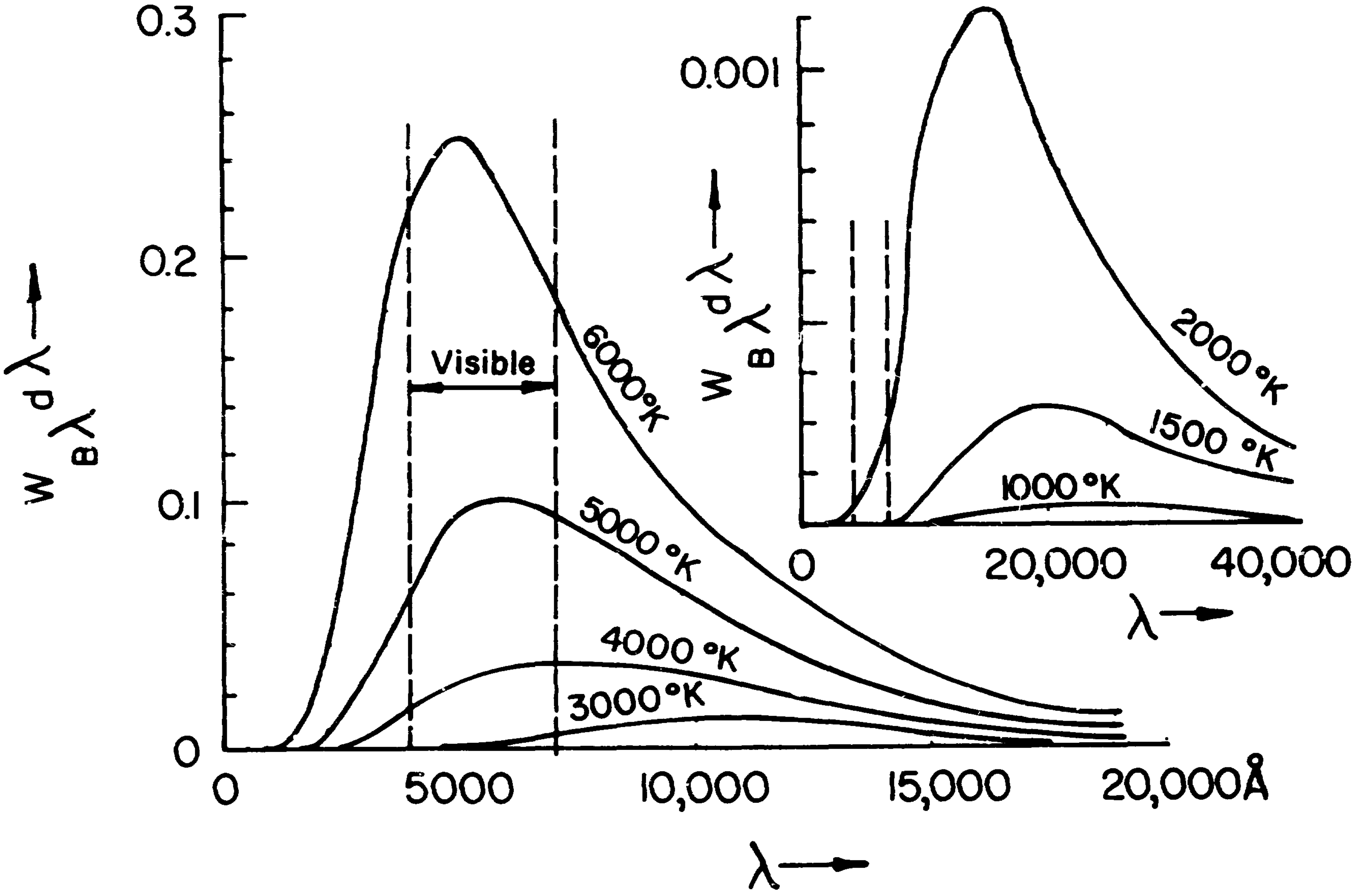
Figure 2. Blackbody spectral irradiance at various temperatures.

Figure 3. High speed photography of a 7.8 ms Nd-YAG laser pulse on 1100 Aluminum. Time increases from top right to left. Each picture represents 83 μs in time. Sample is horizontal at the base of each plasma plume. Only the first 5.5 ms are shown.

Figure 4. The number of observed plasma waves vs power during a single 7.8 ms pulse. Target materials were 304 stainless steel and aluminum alloys.

Figure 5. Melt depth vs power for a single 7.8 ms pulse for the same materials as Figure 3.


1.0
0.8
0.6
0.4
0.2
Reflectance
Al
Ag
Rh
Pt
Cu
Au
0.2
0.4
0.6
1.0
2.0
4.0
6.0
10.0
Wavelength , µm



0.3
0.2
0.1
0
$w_B d\lambda_B$ →
Visible
6000°K
5000 °K
4000 °K
3000°K
0
5000
10,000
15,000
20,000Å
λ →
0.001
$w_B d\lambda_B$ →
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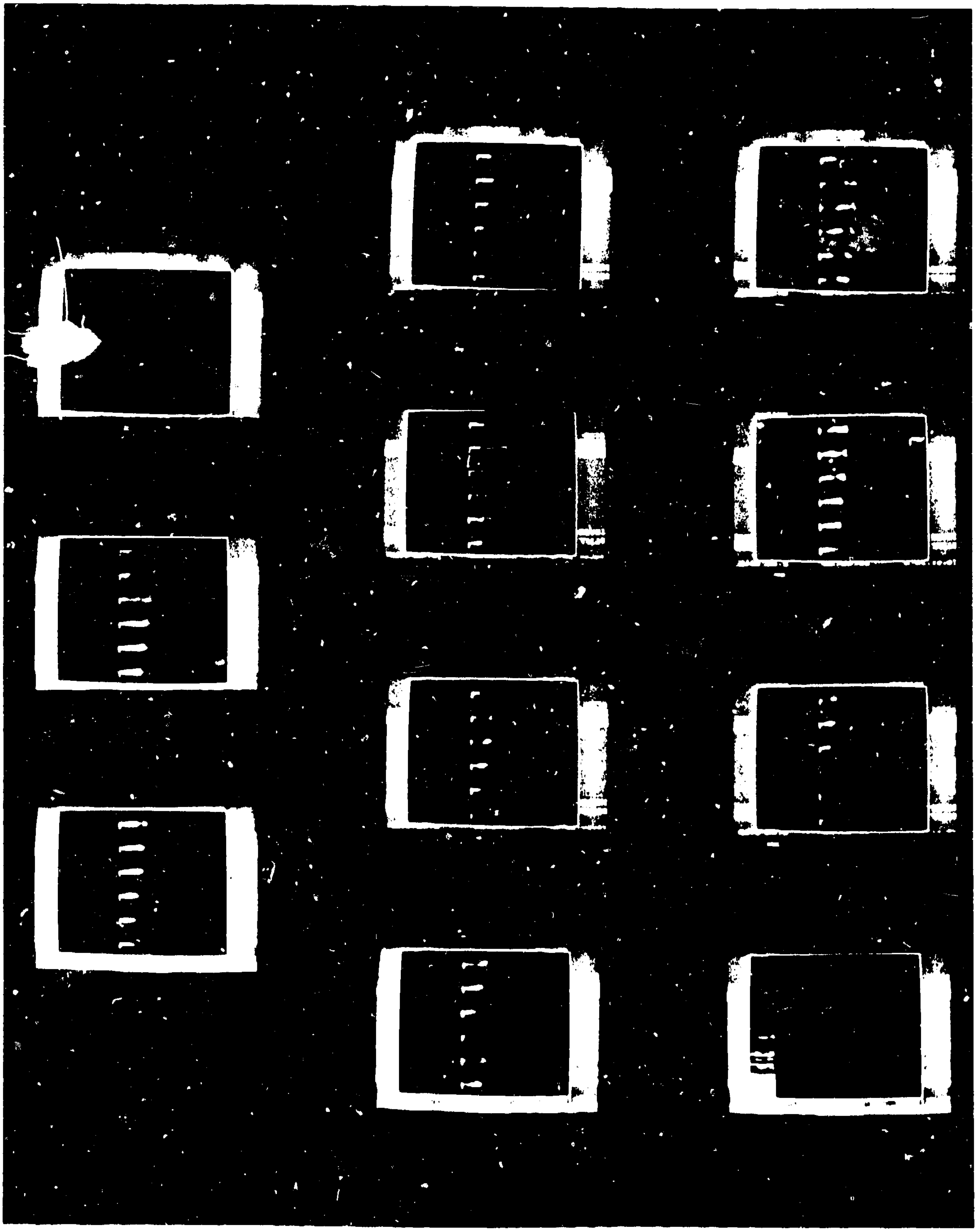
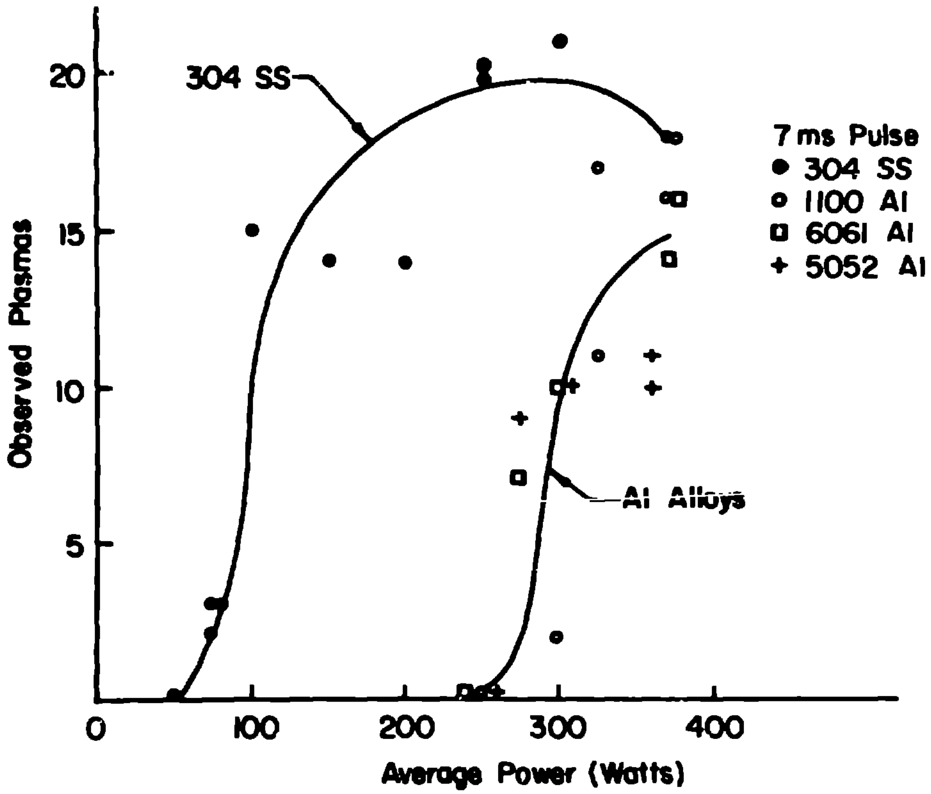
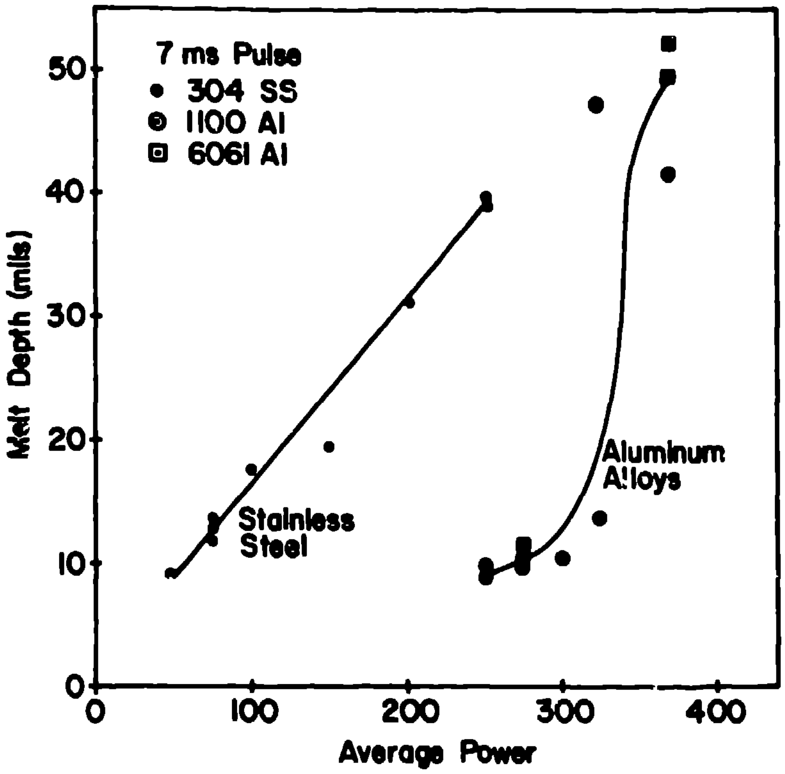
1500 °K
1000 °K
0
20,000
40,000
λ →




304 SS
Al Alloys
7 ms Pulse
● 304 SS
○ 1100 Al
□ 6061 Al
+ 5052 Al
Observed Plasmas
20
15
10
5
0
100
200
300
400
Average Power (Watts)


7 ms Pulse
● 304 SS
⊙ 1100 Al
▣ 6061 Al
Melt Depth (mils)
0
10
20
30
40
50
0
100
200
300
400
Average Power
Stainless Steel
Aluminum Alloys