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Nd:YAG Laser Welding Experiments

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Abstract

Laser-beam/plume interaction experiments were conducted with a pulsed Nd:YAG laser. A high speed camera was used to study plume growth phenomena and to determine maximum plume velocities. Tests were done on four different metals: Aluminum 1100, Molybdenum, Nickel 200, and Stainless Steel 304. Previous laser welding experiments have indicated that the vapor plume ejected from the irradiated base material significantly attenuates the laser beam energy for Nickel 200 and Stainless Steel 304. To substantiate this observation, the plume was subjected to a cross flow of argon gas. Metallurgical studies showed a significant increase in weld penetration for all materials except for Aluminum. These experiments also indicated that the plume ejects normal to the base material. Thus, the specimen was tilted at different angles in an attempt to reduce laser beam attenuation. Results showed no significant increase in weld depth when the tilt angle was increased. Mass loss measurements were also performed and the experimental data were an order-of-magnitude less than those predicted by a numerical laser welding code.

DISCLAIMER

Introduction

Vaporization in laser welding is an important mechanism that strongly influences the quality of the weld. The amount of vaporization depends primarily on the laser power density and the absorption coefficient of the irradiated material. The vapor plume that is ejected from the irradiated base material contains fine particles of metal. These particles can have a significant influence on laser beam attenuation depending on the size of the particles and their density in the vapor plume. In order to further substantiate this effect, laser welding tests were conducted to study laser-beam/plume interaction. Several laser welding experiments were devised to determine the degree of laser beam attenuation by the vapor plume and to measure the amount of material that is ejected by the plume. These tests involved imposing a cross-flow of argon gas to manipulate the plume and tilting the irradiated base material to direct the plume away from the path of the incident laser beam. Weld depths were measured to determine the extent of laser-beam attenuation. Materials used in these tests included: Aluminum 1100, Nickel 200, Stainless Steel 304, and Molybdenum.

Experimental Apparatus and Procedure

The experiments were performed with a Nd:YAG laser. Each specimen was placed on an x-y platform which was indexed in both directions with a micrometer. The welding parameters for all the tests were 10 pulses per second, 5 msec pulse duration, and 24 Joules per pulse. A high speed video camera was used to study plume growth. The camera was set to record 4000 frames per second. Thus, twenty frames were recorded during a single pulse (5 msec).

Cross-Flow Tests

The experimental setup for the cross flow-tests is shown in Figure 1a. A probe which ejects argon gas was placed at the surface of the specimen approximately 0.64 cm away from the laser weld spot. Preliminary tests were conducted with several velocities of argon. An average velocity of 30 meters per second (70 cubic feet per hour) provided sufficient momentum to manipulate the vapor plume. Aluminum 1100 (AL 1100), Nickel 200 (NI 200), and Stainless Steel 304 (SS 304) metals were used in the cross-flow tests. The dimensions of the specimens are given in Table 1.

Table 1. Dimensions of Specimens.

Material	Length (cm)	Width (cm)	Thickness (cm)
AL 1100	5.08	2.54	0.32
NI 200	5.08	2.54	0.31
SS 304	5.08	2.54	0.19

Angle Tests

Previous laser welding experiments have suggested that the vapor plume is ejected normal to the surface of the specimen. Thus, the specimen was placed at different angles relative to the laser beam to reduce laser-beam attenuation as shown in Figure 1b. Three different angles were used: 0°, 12°, and 26°. The angle tests were conducted on AL 1100, Molybdenum, NI 200, and SS 304 samples. The dimensions of the AL 1100, NI 200, and SS 304 specimens are shown in Table 1. Molybdenum samples had the same dimensions as NI 200.

Mass Loss Measurements

The purpose of this test was to measure the mass of material that was ejected in a vapor plume. Three different materials were used: AL 1100, NI 200, and SS 304. The mass loss results were compared to calculations from the laser welding code WELD2D [1].

A schematic diagram of the experimental setup is shown in Figure 1c. A low velocity cross-flow of argon gas (4 m/sec average velocity) was placed 1.27 cm above the specimen to prevent the vapor plume from depositing metal particles back onto the specimen. Four samples were used for each metal. Three of the samples were irradiated and the fourth was used as a reference. The reference specimen was put through the same surface preparation and cleaning procedures as the other specimens but was not irradiated. The samples were cleaned with alcohol before irradiation and enclosed in individual plastic containers before and after irradiation. The NI 200 and SS 304 specimens were irradiated with 12 pulses and the AL 1100 with 28 laser pulses. Each pulse was incident on a virgin surface location so that spot overlap did not occur. The specimens were weighed before and after each test with a Metler scale accurate to $\pm 1 \mu g$. The specimens were 1.27 cm × 1.27 cm squares with the same thicknesses as shown in Table 1. Their masses were small (1.4 grams for AL 1100, 4.5 grams for NI 200, and 2.5 grams for SS 304) to improve mass measurement accuracy.

Discussion of Results

Cross-Flow Tests

Photographs of the top view of the weld spots for NI 200 and SS 304 are shown in Figure 2 for different cross-flow velocities and a single laser pulse. The addition of a cross-flow did not change the NI 200 weld bead width but caused the SS 304 weld bead to be wider and rounder in appearance. Comparisons of weld depths for AL 1100, NI 200, and SS 304 are shown in Figure 3 for no cross-flow and a cross-flow of 30 m/sec. The results were for a single pulse and show a significant increase in weld depth for NI 200 and SS 304. However, AL 1100 showed a negligible change in weld depth when a cross-flow was imposed. This implies that the AL 1100 vapor plume causes minimal laser beam attenuation. A summary of weld depth percentage increase with a 30 m/sec cross-flow is given in Table 2.

Table 2. Weld Depth Increase With Cross-Flow.

Material	Range of Weld Depth Increase With 30 m/sec Cross-Flow (percent)
AL 1100	negligible
NI 200	8 to 29
SS 304	16 to 34

Weld depths increased as much as 34 percent and 29 percent for SS 304 and NI 200, respectively, when the plume was manipulated. Thus, SS 304 and NI 200 vapor plumes substantially attenuate the laser beam. Photographs of the SS 304 vapor plume at different times are shown in Figure 4 for no cross-flow and a cross-flow of 30 m/sec. The plume is only visible during the duration of the pulse (5 msec). For no cross-flow, the results show accelerated plume growth (during which time the maximum plume velocity is achieved), then decelerated plume growth, and finally extinguishing of the vapor plume. Imposing a cross-flow significantly reduces the height of the vapor plume.

Maximum plume velocities, with no cross-flow and a single pulse, were calculated from photographs obtained from the high speed video camera and the results are shown in Table 3.

Table 3. Maximum Plume Velocities.

Material	Maximum Plume Velocity (m/sec)
AL 1100	7
NI 200	62
SS 304	33

NI 200 had the highest maximum velocity of the materials tested and AL 1100 had the lowest maximum velocity.

Angle Tests

Weld depths for three different tilt angles are shown in Figure 5 for AL 1100 and Molybdenum, and in Figure 6 for NI 200 and SS 304. The results illustrate no increase in weld depth when the tilt angle was increased from 0^o to 26^o. NI 200 and SS 304 exhibit a decrease in weld depth. But this behavior is inconsistent; other results have shown either minimal increases in weld depth or no change at all. All the results for AL 1100 and Molybdenum showed no change in weld depth. The results for AL 1100 support the hypothesis that the AL 1100 plume does not attenuate the vapor plume as was shown in the cross-flow tests.

The deep craters on the sides of the NI 200 weld pool (Figure 6) were due to the molten metal migrating down the side of the specimen as shown in Figure 7. This occurred for both NI 200 and SS 304. The reason for the inconsistent change in weld depth is evident from the plume photographs in Figure 8 for NI 200 and SS 304. Initially the plume moves normal to the surface and then immediately expands and bends to a vertical direction in the path of the laser beam. Therefore, tilting the specimen does not effectively reduce laser-beam attenuation for NI 200 and SS 304 as compared to imposing a cross-flow. Tilting the specimen does reduce the normal laser beam density (2 percent for 12^o and 10 percent for 26^o) but this was considered negligible.

Mass Loss Measurements

The mass loss results are shown in Table 4. The results in Table 4 show very consistent measurements for each specimen. However, the reference specimen for AL 1100 (AL 4) showed a very large mass loss ($45\mu g$) as compared to the reference specimens for NI 200 and SS 304. This large mass loss for the AL 1100 reference specimen was attributed to the alcohol not completely evaporating. This was evident when the reference specimen (AL 4) was re-weighed and the additional mass loss was 16 μg. The average mass loss per spot for each specimen was calculated by

$$m_{loss} = \frac{\Delta m_{spec.} - \Delta m_{ref.}}{total\ no.\ spots} \tag{1}$$

where $\Delta m_{spec.}$ is the mass loss of the specimen and Δm_{ref} is the mass loss of the reference sample (AL4, NI4, and SS4).

Table 4. Mass Loss Measurements.

Specimen	Mass Loss (μg)
AL 1100:	
AL 1	96
AL 2	93
AL 3	107
AL 4	45
NI 200:	
NI 1	1854
NI 2	1712
NI 3	1736
NI 4	9
SS 304:	
SS 1	2009
SS 2	1981
SS 3	1955
SS 4	-1

The average mass loss for each metal in Table 5 was calculated by summing the mass loss for each specimen (Equation (1)) and dividing by the total number of irradiated specimens (three).

Table 5. Average Mass Loss Per Pulse.

Specimen	Mass Loss (μg)
AL 1100	1.9 ± 0.3
NI 200	146.5 ± 6.3
SS 304	165.2 ± 2.3

It should be mentioned that oxidized material formed around the weld spots and was included in the total mass after irradiation. However, this effect was considered negligible as compared to the total mass loss.

Comparison With Welding Codes

The mass loss results were compared to the laser welding code WELD2D [1]. WELD2D is a two-dimensional pure conduction code that accounts for variable properties, vaporization, and a temperature-dependent absorption coefficient at the surface of the metal. However, WELD2D does not include convection in the weld pool and laser beam attenuation by the vapor plume. The experimental laser parameters (24 J/pulse, 5 msec pulse, 10 pulses/sec, and 1mm beam diameter) were input into WELD2D. A comparison of experimental results and welding code predictions are shown in Table 5.

Table 5. Comparison of Mass Loss Measurements to WELD2D.

Specimen	Mass Loss (μg)	
	Experiment	WELD2D
AL 1100	1.9	28.0
NI 200	146.5	1080.0
SS 304	165.2	1911.5

The WELD2D predicted values were approximately an order-of-magnitude greater than the experimental measurements. Part of this difference could be attributed to laser beam attenuation. However, the data indicate that, at least for AL 1100, attenuation is not significant. Therefore, further explanation needs to be sought. Other factors contributing to this large discrepancy could be the absorptivity model in the laser code, plasma shielding, and/or weld pool convection. There is very little data in the literature on absorptivity of vaporizing liquids. Absorptivity experiments were performed with a calorimeter, to validate the model just above the melting temperature. Consistent with the data, when melting occurs the model assumes that the absorptivity decreases suddenly and then increases thereafter. However, at vaporization (boiling) conditions, little is known about the absorptivity. If the absorptivity for the molten metal during rapid vaporization is lower than the liquid value, this would reduce the calculated amount of vaporized material and brings about an improved comparison with the experimental results. The possibility of a plasma at the surface acting as a shield could also contribute to this discrepency. A plasma can also exist in the plume, but because of the low power density ($6.11 \times 10^5 W/cm^2$) and the $1.06\mu m$ laser wavelength it was assumed to be negligible [2]. Earlier spectroscopic measurements by G.R. Hadley and H.C. Peebles of Sandia Laboratories indicated no plasma one millimeter or more above an aluminum surface. Weld pool convection due to surface tension (Marangoni flow) is another possibility. However, preliminary calculations from another welding code that includes this effect have shown a small reduction in mass loss from the values obtained using WELD2D.

Conclusions

Experiments were conducted with a Nd:YAG laser to study laser-beam plume interaction. Cross-flow tests illustrated that the vapor plumes for NI 200 and SS 304 significantly attenuate the laser beam. AL 1100 vapor plumes were shown to have no effect. Results from the angle tests indicated that tilting the specimen did not help to reduce laser-beam attenuation as compared to the cross-flow tests. Photographs of the vapor plume on the tilted specimens show the plume initially ejecting normal to the material and then changing to a vertical direction with an increase in plume width. This behavior caused laser beam attenuation by the plume. Mass loss measurements were approximately an order-of-magnitude less than those predicted by the pure conduction code WELD2D.

These preliminary tests indicate that the vapor plume can have a significant effect on the characteristics of the weld for some materials. Additional laser beam/plume interaction tests are planned to determine if a plasma is present at the surface of the irradiated base material and additional mass loss measurements will be made from these tests.

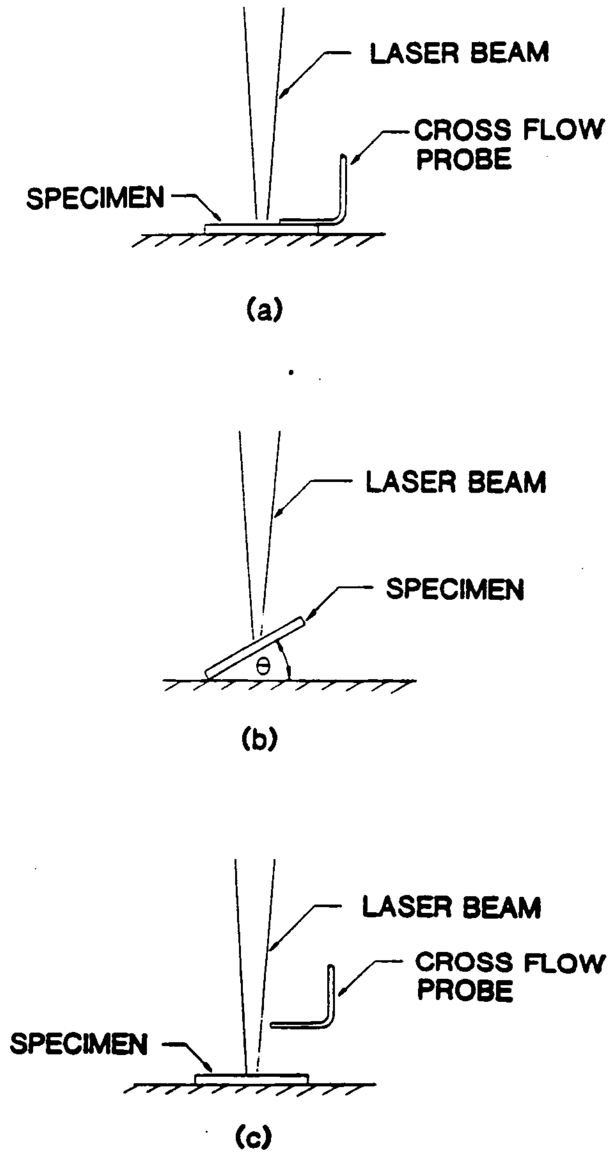

Figure 1: Experimental setups for (a) Cross-flow, (b) Angle, and (c) Mass loss experiments.

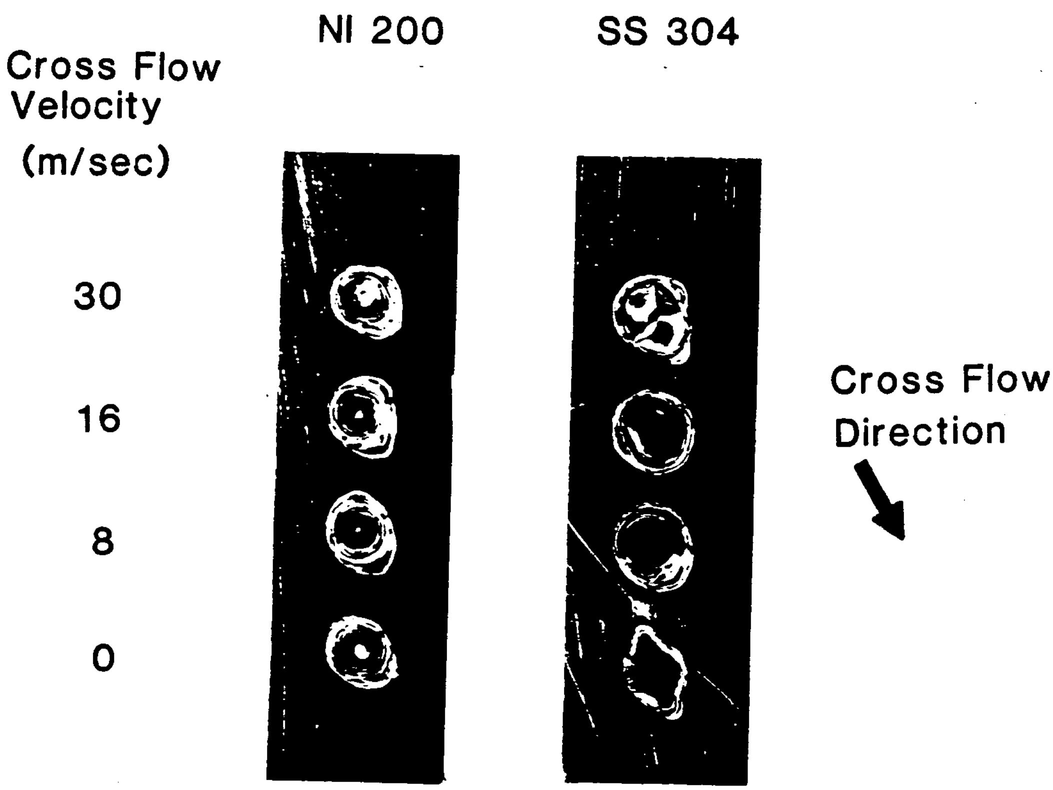

Figure 2: Photographs of top view of weld spots for different cross-flow velocities.

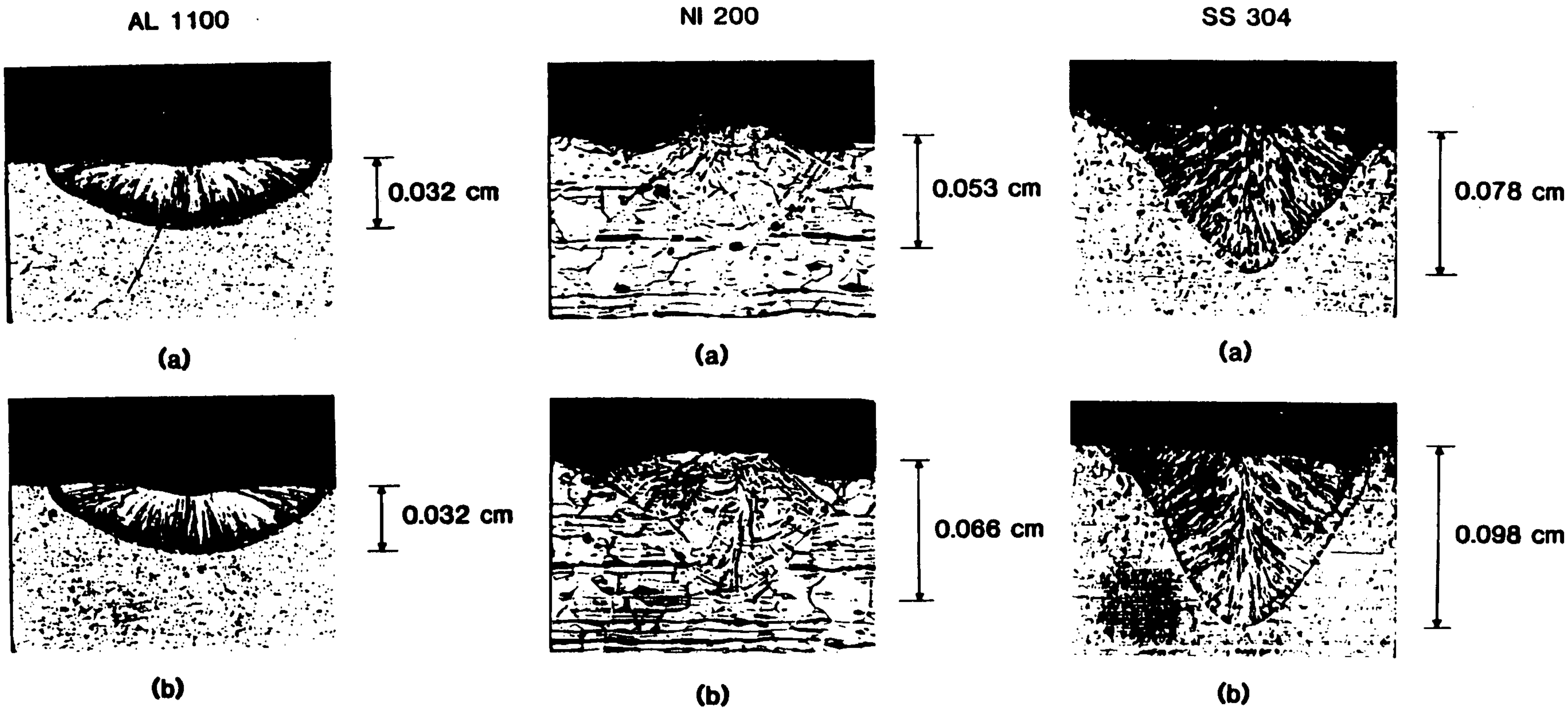

Figure 3: Comparison of weld depths for AL 1100, NI 200, and SS 304 with (a) no cross-flow and (b) 30 m/sec cross-flow.

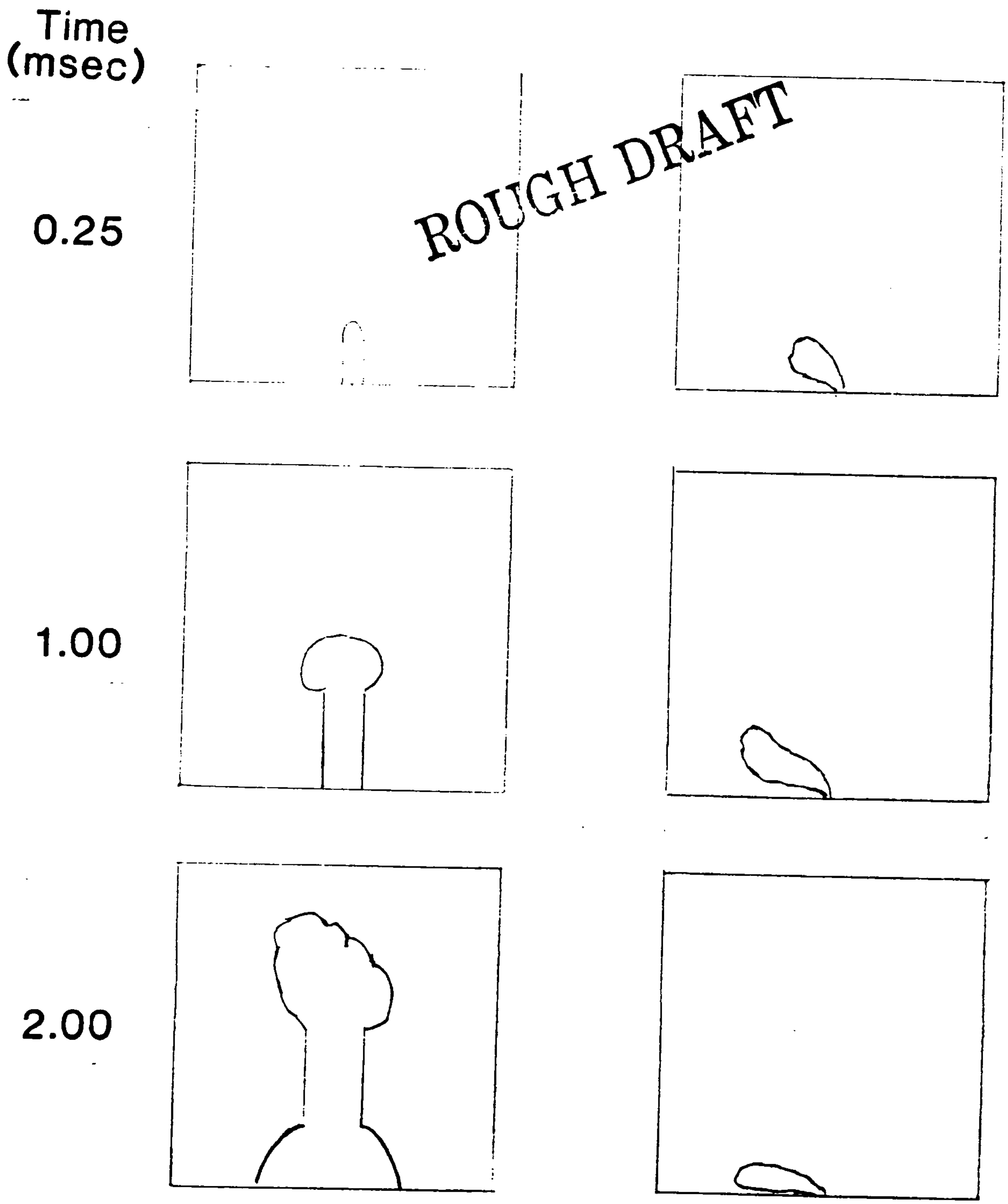

Figure 4: Photographs of SS 304 vapor plume: (a) no cross-flow (b) 30 m/sec cross-flow.

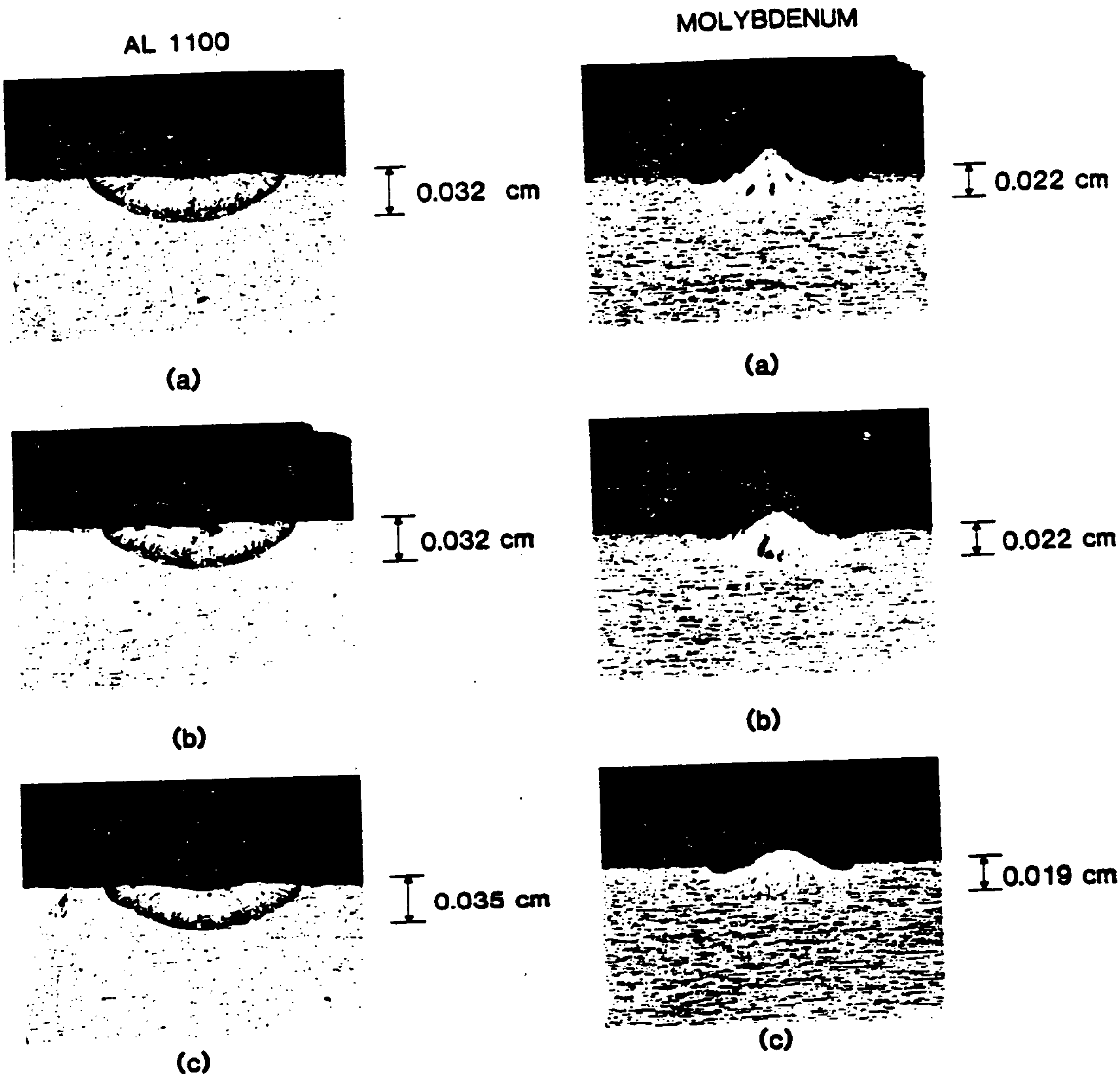

Figure 5: Comparison of AL 1100 and Molybdenum weld depths from angle tests: (a) 0°, (b) 12° (c) 26°.

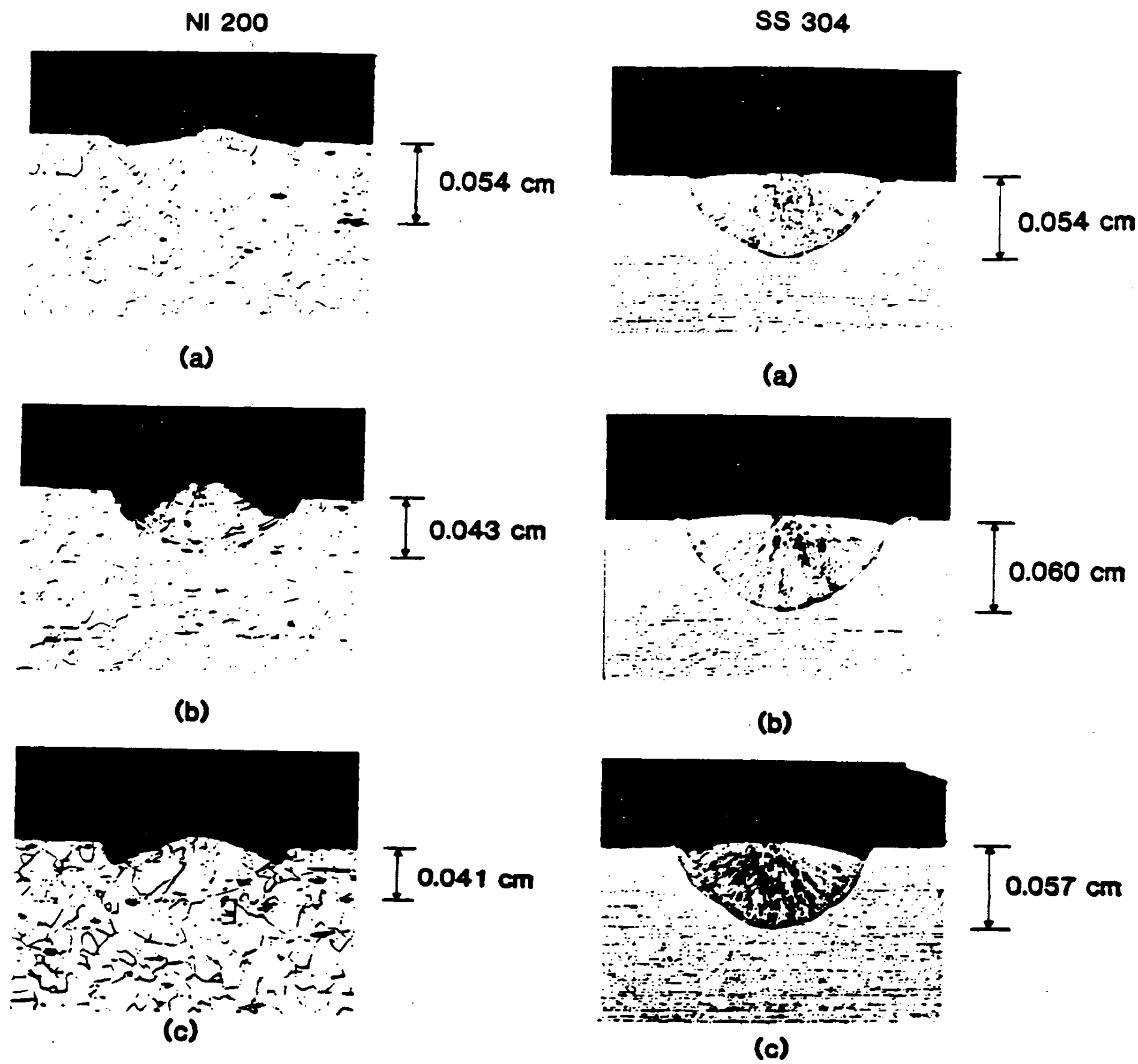

Figure 6: Comparison of NI 200 and SS 304 weld depths from angle tests: (a) 0°, (b) 12°, (c) 26°.

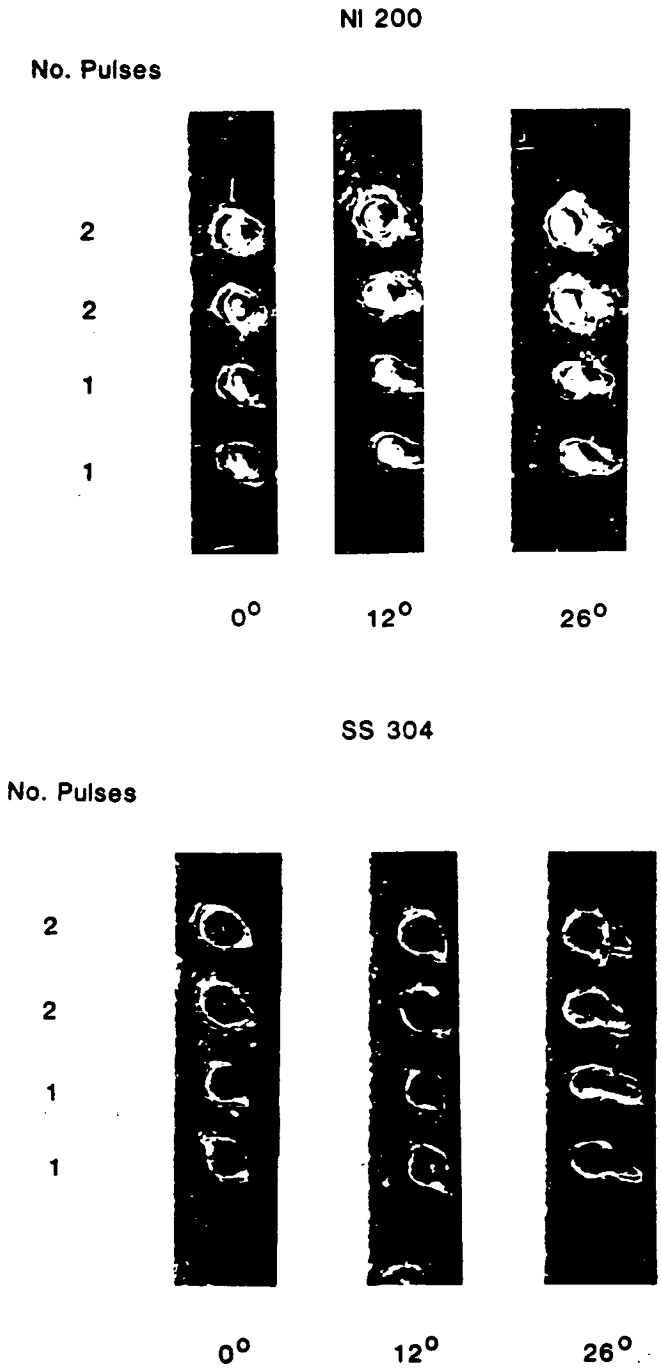

Figure 7: Top-view photographs of NI 200 and SS 304 weld spots for different tilt angles and pulses.

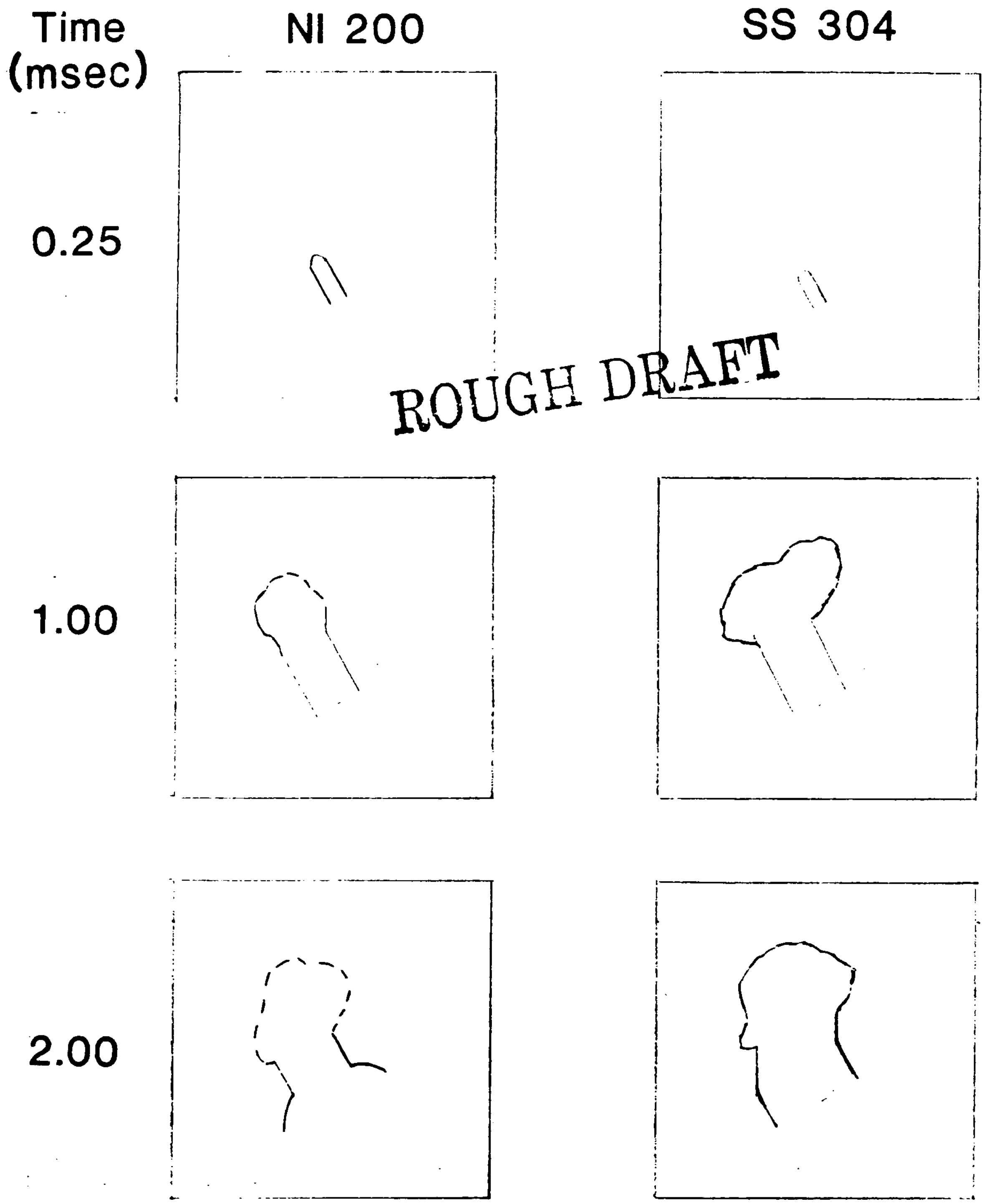

Figure 8: Plume photographs for a 26° tilt angle: (a) NI 200 (b) SS 304.

Acknowledgement

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