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Nd:YAG Laser Welding Aluminum Alloys

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Nd: YAG LASER WELDING ALUMINUM ALLOYS

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Abstract

Autogenous Nd:YAG laser welding wrought 4047, 1100, 3003, 2219, 5052, 5086, 5456, and 6061 and cast A356 aluminum alloys to cast A356 aluminum alloy in restrained annular weld joints was investigated. The welds were 12.7 mm (0.375 in.) and 9.5 mm (0.375 in.) diameter with approximately 0.30 mm (0.012 in.) penetration. This investigation determined 4047 aluminum alloy to be the optimum alloy for autogenous Nd:YAG laser welding to cast A356 aluminum alloy. This report describes the investigation and its results.

Discussion

Autogenously Nd:YAG laser welding cast A356 and wrought 4047, 1100, 3003, 2219, 5052, 5086, 5456, and 6061 aluminum alloys to cast A356 aluminum alloy in annular weld joints was investigated. The welds were 12.7 mm (0.500 in.) and 9.5 mm (0.375 in.) diameter and approximately 0.30 mm (0.012 in.) penetration.

This investigation determined the following.

- Autogenous Nd:YAG laser welding wrought 4047 to cast A356 and cast A356 to cast A356 aluminum alloys can produce crack free hermetic welds (less than 1 x 10 exp -7 cc/sec with 100% helium at 0.1 MPa, or 1 atm, pressure differential) in restrained annular joints
- The shear strengths of the autogenous Nd:YAG laser welds between wrought 4047 and cast A356 aluminum alloys ranged from 76.38 MPa (13,845 psi) to 108.7 MPa (15,980 psi),
- Autogenous Nd:YAG laser welds between 1100, 3003, 2219, 5052, 5086, 5456, and 6061 aluminum alloys and cast A356 aluminum alloy were cracked and not hermetic.

Introduction

Electronic assembly packaging at the Allied-Signal Inc. Kansas City Plant often requires hermetic sealing to protect the internal electronic components from the potentially detrimental effects of the assembly's external environment such as partial pressure, dust, and/or humidity. Hermetically sealing the assemblies by welding is preferred because it provides a permanent seal and is cost effective. A356 (7% Si - balance Al) aluminum alloy castings are frequently used as the packaging material because they are economical, light weight, and weldable.

Autogenous Nd:YAG laser welding is preferred over gas tungsten arc, plasma arc, electron beam, and CO2 laser welding because Nd:YAG laser welding:

- imparts very low thermal energy input into the weld thereby preventing undesirable heat transfer to the hybrid microcircuits, their substrates, and/or other circuit components,
- imparts very low thermal-mechanical weld stresses during the melting or solidification phases thereby preventing undesirable thermal-mechanical strains in the hybrid microcircuit substrate materials,
- does not utilize electron flow through the part thereby preventing static-charge build-up detrimental to the hybrid microcircuits or their components, and
- couples with the natural surface of aluminum alloys eliminating the need to develop surface coatings to enable the CO2 laser to couple with the aluminum alloys' surfaces.

The literature[1,2] predicts a silicon content above 3% in an aluminum alloy weld, regardless of magnesium or copper content, will result in crack-free welds. Typically, Allied-Signal Kansas City Division autogenously electron beam welds cast A356 (7% Si - 0.3% Mg - balance Al) to 6061, 1100, 3003, or any of the 5000 series aluminum alloys resulting in crack-free hermetic welds. The calculated predicted silicon content in these welds is above 3% which the literature predicts will be a crack insensitive aluminum alloy welding combination.

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However. autogenous Nd:YAG laser welds between cast A356 and 6061-T6 aluminum alloys in 12.7 mm (0.500 in.) and 9.5 mm (0.375 in.) diameter weld joints cracked. perhaps due to the pulsed nature of the Nd:YAG laser welding process. These contradictory results prompted initiating an investigation to evaluate the weldability of cast A356 to a multitude of aluminum alloys by the autogenous Nd:YAG laser welding process.

Experimental Procedure

Material Selection

For this investigation A356. 4047. 1100. 3003. 2219. 5052. 5086. 5456. and 6061 aluminum alloys were selected to be autogenously Nd:YAG laser welded to cast A356 aluminum alloy plate 6.35 mm (0.25 in.) thick. Alloy selection was based on availability and "advertised" weldability. The chemical compositions of the selected alloys are presented in Table 1.

Weld Sample Design

A "BASE" 150 mm (6.00 in.) long. 25 mm (1.00 in.) wide. and 4.8 mm (0.19 in.) thick with three 12.7 mm (0.500 in.) and three 9.5 mm (0.375 in.) diameter by 1.52 mm (0.06 in.) deep counterbored 3.2 mm (0.125 in.) diameter holes was designed. (See Figure 1) Sufficient bases for each of the alloys to be welded were fabricated. Flat disks 12.7 mm (0.500 in.) and 9.5 mm (0.375 in.) diameter 1.52 mm (0.060 in.) thick and flanged disks of the same diameters and thickness with a 0.76 mm (0.030 in.) wide by 0.76 mm (0.030 in.) tall flange were designed and fabricated from each of the alloys to be welded. The dimensions of the disks are shown in Figure 2.

Nd:YAG Laser Welding

Six flat and six flanged disks (12.7 mm and 9.5 mm diameter) from each alloy selected were welded to bases using a Nd:YAG laser welding machine parameters known to produce approximately 0.31 mm (0.012 in.) penetration (Figure 3). Weld preparation consisted of wire brushing the weld joint surfaces with a clean fiberglass brush. followed with an isopropyl alcohol rinse. followed by blow drying with dry nitrogen. The welds were visually examined for weld cracks and if crack-free. were helium leak tested.

Pressure Test Plates

Six "Pressure Test Plates" 100 mm (4.0 in.) square and 4.83 mm (0.19 in.) thick. three each with 9.5 mm (0.375 in.) diameter by 1.52 mm (0.060 in.) deep counterbored 4.57 mm (0.18 in) through holes and three each with 12.7 mm (0.500 in.) diameter by 1.52 mm (0.060 in.) deep counterbored 4.57 mm (0.18 in.) through holes were machined from cast A356 aluminum alloy plate. Eight 6.73 mm (0.265 in.) diameter mounting holes on a 63.5 mm (2.50 in.) bolt circle were drilled into the plates to accommodate the pressure test tooling. See Figure 4 for the pressure test plate design.

A "Vent Tube" configuration with a 12.7 mm (0.500 in.) diameter flat base was designed. See Figure 5 for the vent tube design dimensions.

Based on the results of the disk to base welds. and its availability in wrought form. 4047 aluminum alloy was selected for the disks and vent tubes to be welded into the pressure test plates.

Nd:YAG Laser Beam Welding Pressure Test Plates

Type 4047 aluminum alloy 9.5 mm (0.375 in.) diameter disks and 12.7 mm (0.500 in.) diameter vent tubes were welded to the A356 pressure test plates using the same Nd:YAG laser welding machine parameters used for the disk to base welds. See Figure 3.

Results

Visual and Hermetic Inspection of Disk to Base Welds

Visual inspection by light microscopy of the flat and flanged disk to base welds revealed that the A356 to A356 and the 4047 to A356 aluminum alloy combinations were crack-free and hermetic to 1 x 10 exp -8 cc/sec with 100% helium (He) at 0.1 MPa (1 atm) pressure differential which was the background level of the helium leak tester on the date of the tests. All other alloy combinations cracked during welding. These observations and the helium leak test results for the A356 to A356 and the 4047 to A356 aluminum alloy combination welds are presented in Figure 6. Figures 7 through 14 present the as-welded appearances of the surfaces of the alloy combinations welded.

Metallurgical Evaluation

A representative weld between 4047 and A356 aluminum alloys was cross-sectioned and metallographically examined. The two weld cross-sections measured 0.3175 mm (0.0125 in.) and 0.3175 mm (0.0125 in.) penetration and 1.03 mm (0.041 in.) and 1.19 mm (0.047 in.) width. The weld cross-sections are shown in Figure 15.

Visual Inspection of Pressure Test Plate Welds

Visual inspection of the 4047 aluminum alloy disks and vent tubes welded to the A356 aluminum alloy pressure test plates revealed crack-free welds. The disk and vent tube to pressure test plate welds were helium leak tested followed by pressure testing to failure. Figure 16 presents the reconstructed 4047 aluminum alloy disk to the A356 aluminum alloy pressure test plate weld. Figure 17 presents the reconstructed 4047 aluminum alloy vent tube to the A356 aluminum alloy pressure test plate weld.

Hermetic Testing of Pressure Test Plate Welds

After autogenous Nd:YAG laser welding, the disk and vent tube to pressure test plate welds were hermetic to 1 x 10 exp -9 cc/sec with 100% He at 0.1 MPa (1 atm) pressure differential.

Pressure Testing of Pressure Test Plate Welds

The 4047 aluminum alloy disk to A356 aluminum alloy disk welds pressure tested to failure failed catastrophically in shear at 12.56 MPA (1846 psig), 10.34 MPa (1520 psig), and 10.18 MPa (1497 psig) for an average burst strength 11.03 MPa (1621 psig). The calculated weld shear strength values are 94.18 MPa (13845 psi) 77.55 MPa (11400 psi), and 76.38 MPa (11228 psi) for an average weld shear strength of 82.7 MPa (12158 psi).

The 4047 aluminum alloy vent tube to A356 aluminum alloy pressure test plates tested to failure failed catastrophically in shear at 9.05 MPa (1330 psig), 10.87 MPa (1598 psig), and 9.12 MPa (1340 psig) for an average burst strength of 9.68 MPa (1423 psig). The calculated weld shear strength values are 90.48 MPa (13300 psi), 108.71 MPa (15980 psi), and 91.16 MPa (13400 psi) for an average weld shear strength of 96.80 MPa (14230 psi).

Summary of Welding Results

- A356 and 4047 Aluminum Alloy Disks to A356 Base Welds Were Crack Free and Hermetic to $1x10^{-9}$ cc/s He
- All the Other Aluminum Alloy Disks to A356 Base Welds Cracked.
- 4047 Disk to A356 Pressure Test Plate Welds Were Hermetic to $1x10^{-9}$ cc/s He. Upon Burst Pressure Testing They Failed Through the Welds as 1621 PSIG, 15.20 PSIG, and 1497 PSIG Burst Pressures. Average - (1621 PSIG).
- 4047 Disk Burst Pressure Test Results Translate into Weld Shear Strengths of 13845 PSI, 11399 PSI, and 11228 PSI. Average - 82.7 13024 PSI.
- 4047 Vent Tube to A356 Pressure Test Plate Welds Were Hermetic to $1x10^{-9}$ cc/s He. Upon Burst Pressure Testing They Failed Through the Welds as 1380 PSIG, 1598 PSIG, and 1340 PSIG Burst Pressures. Average - 1423 PSIG.
- 4047 Vent Tube Burst Pressure Test Plate Welds Translate into Weld Shear Strengths of 13300 PSI, 15980 PSI, and 14230 PSI. Average - 14503 PSI.
- Weld Penetration Was Approximately 0.31 mm (0.012 in.)

Conclusions

Wrought 4047 and cast A356 aluminum alloys can be autogenously Nd:YAG laser welded to cast A356 aluminum alloy to produce crack- free hermetic welds. The optimum choice is 4047 aluminum alloy because it is available in wrought form.

Wrought 4047 aluminum alloy autogenously Nd:YAG laser welded to cast A356 aluminum alloy produced welds with shear strengths equal to the calculated shear strength of wrought 4047 aluminum alloy the same thickness as the weld penetration. The shear strengths were equal to 70% of the actual tensile strength of the 4047 aluminum alloy bar stock used to fabricate the disks and vent tubes.

References

1. W. G. Gates and E. Jimenez. "*Aluminum Alloy Welding and Stress Corrosion Testing*", UNCLASSIFIED, Kansas City Division: BDX-613-2543, April 1981.
2. Aluminum Welding Seminar Technical Papers, The Aluminum Association, 1977.
3. Aluminum. Volume I, American Society for Metals; Metals Park, OH, 1967.
4. "*Welding Kaiser Aluminum*," Kaiser Aluminum and Chemical Sales, Inc., Kaiser Center, Oakland, CA, 1967.

ALUMINUM ALLOY DESIGNATION	CHEMICAL COMPOSITION - % (ALLOYING ELEMENTS ONLY)								
	AL	SI	CU	MN	MG	TI	V	ZR	CR
A356	BAL	6.5/7.5			.25/.45				
4047	BAL	11.0/13.0							
1100	99.6								
3003	BAL		.05/.20	1.5					
2219	BAL		5.8/6.8	.20/.40		.02/.10	.05/.15	.10/.25	
5052	BAL				2.2/2.8				.15/.35
5086	BAL			.2/.7	3.5/4.5				.05/.25
5456	BAL			.5/1.0	4.7/5.5				.05/.20
6061	BAL	.4/.8	.15/.40		.8/1.2				.15/.35

TABLE 1. NOMINAL CHEMICAL COMPOSITION OF ALUMINUM ALLOYS WELDED

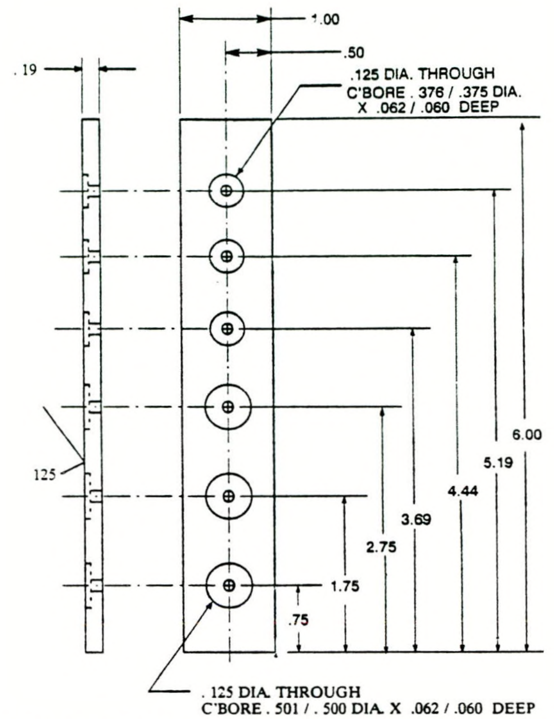


Figure 1. A356 Aluminum Alloy Base

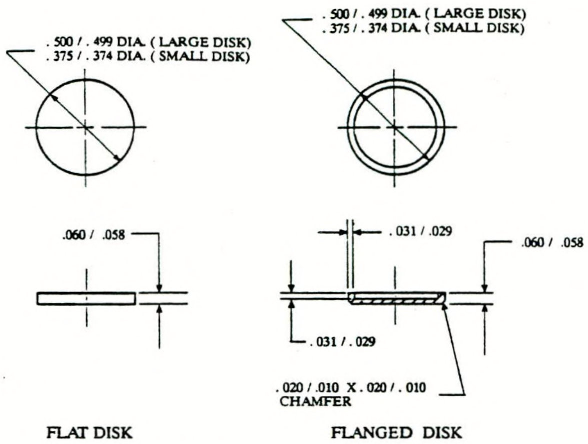


Figure 2. Disks

EQUIPMENT: RAYTHEON SS550 (400 WATTS)
ND:YAG LASER WELDER

PULSE WIDTH LEADING EDGE: .5 MS

PULSE WIDTH TAIL: 3.0 MS

PULSE RATE: 5 HZ (3.5 MS ON/196.5 MS OFF)

RESERVOIR VOLTAGE: 620 VOLTS

LAMP POWER: APPX 5 KW

*ENERGY PER PULSE: APPX. 13 JOULES

FOCUSING CONDITIONS: 150 MM (6 IN.) PLANO-CONVEX CROWN GLASS DEFOCUSED 2.0 MM (.050 IN.) ABOVE SHARP SURFACE FOCUS

GAS SHIELDING: ARGON AT 23.6 L/MIN (50 SCFH) THROUGH A 12.7 MM (.50 IN.) INSIDE DIA. NOZZLE WITH THE NOZZLE OPENING APPX 25 MM (1 IN.) ABOVE THE WELD SURFACE

LASER APERTURE: 1 (MAXIMUM APERTURE SIZE)

WELDING SPEED: 12.9 MM/MIN (0.51 IN./MIN)

*THE ENERGY PER PULSE IS DETERMINED BY USE OF AN ALLIED-SIGNAL KANSAS CITY DIVISION DESIGNED AND FABRICATED ND:YAG LASER ENERGY MONITOR.

Figure 3. Nd:YAG Laser Welding Machine Parameters

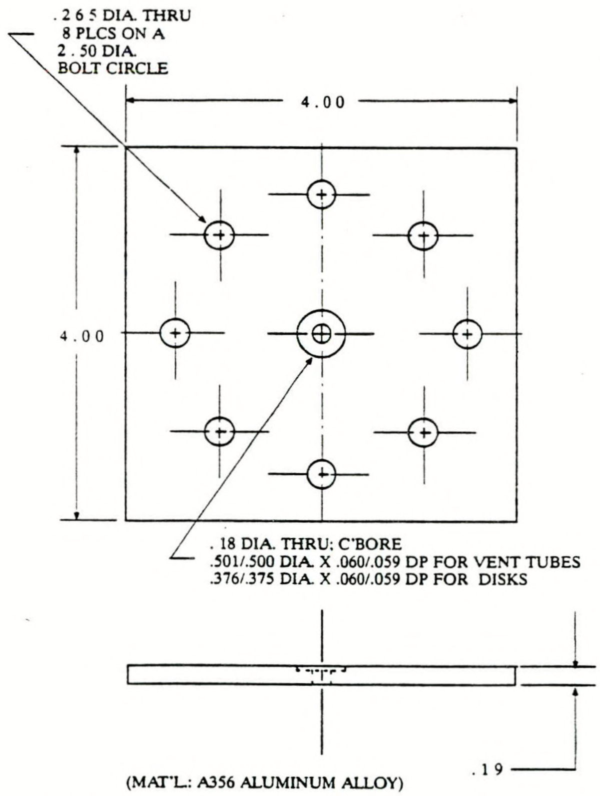


Figure 4. Pressure Test Plate

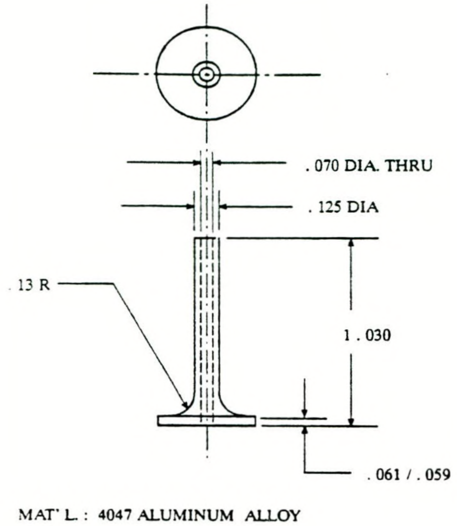
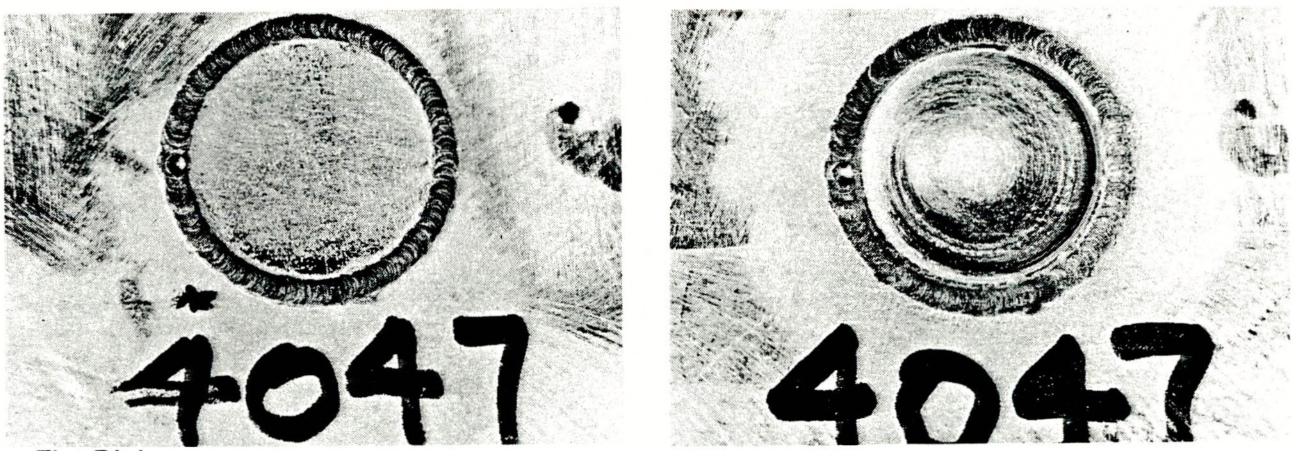


Figure 5. Vent Tube

A356 DISKS - NO CRACKS, HERMETICITY 1 X 10^{-8} CC/SEC HE
4047 DISKS - NO CRACKS, HERMETICITY 1 X 10^{-8} CC/SEC HE
1100 DISKS - ALL WELDS CRACKED
3003 DISKS - ALL WELDS CRACKED
2219 DISKS - ALL WELDS CRACKED
5052 DISKS - ALL WELDS CRACKED
5086 DISKS - ALL WELDS CRACKED
5456 DISKS - ALL WELDS CRACKED
6061 DISKS - ALL WELDS CRACKED

Figure 6. Results of Flat and Flanged Disk to Base Welds

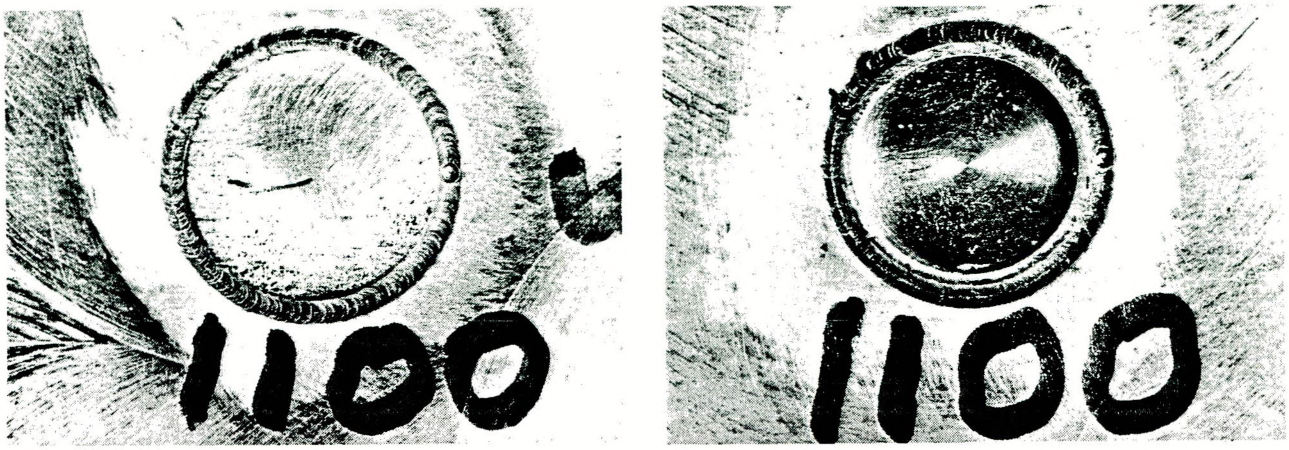


Flat Disk **Flanged Disk**

Figure 7. 4047 to A356 YAG Laser Welds

Flat Disk **Flanged Disk**

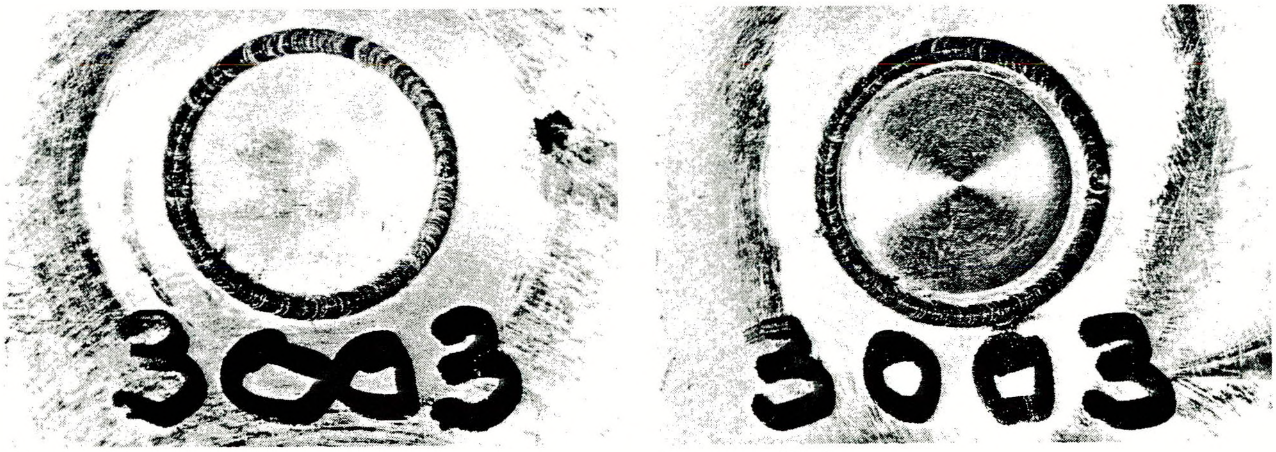
Figure 8. A356 to A356 YAG Laser Welds



Flat Disk

Flanged Disk

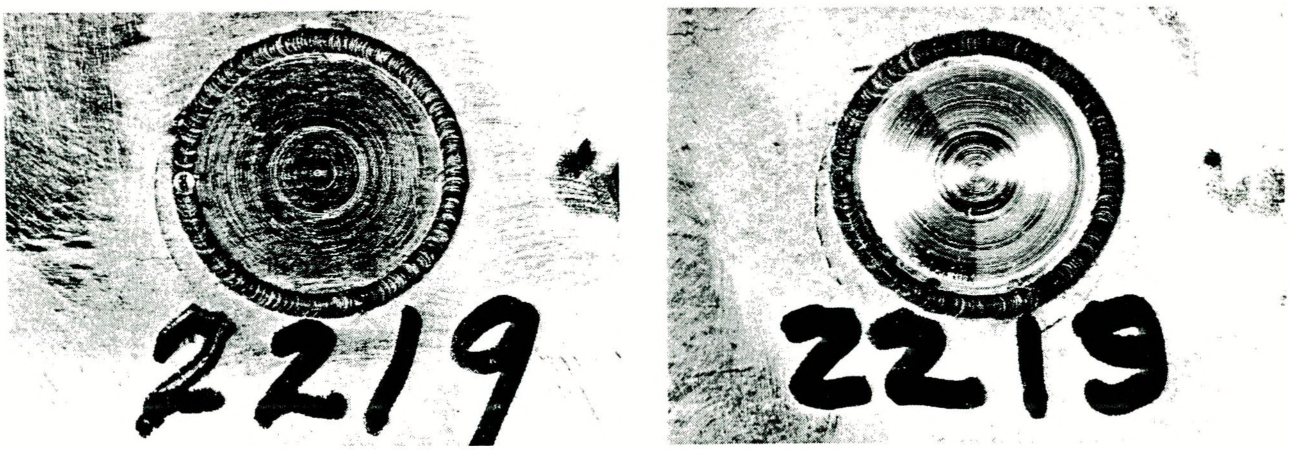
Figure 9. 1100 to A356 YAG Laser Welds



Flat Disk

Flanged Disk

Figure 10. 3003 to A356 YAG Laser Welds



Flat Disk

Flanged Disk

Figure 11. 2219 Flanged Disk to A356 YAG Laser Welds

Flat Disk

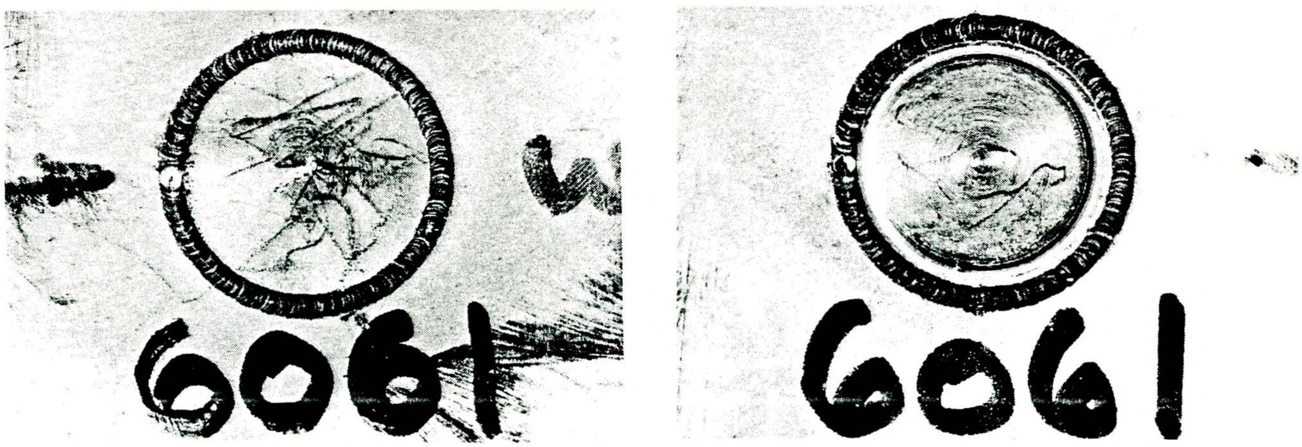
Flanged Disk

Figure 12. 5052 to A356 YAG Laser Welds

Flat Disk

Flanged Disk

Figure 13. 5456 to A356 YAG Laser Welds



Flat Disk

Flanged Disk

Figure 14. 6061 to A356 YAG Laser Welds

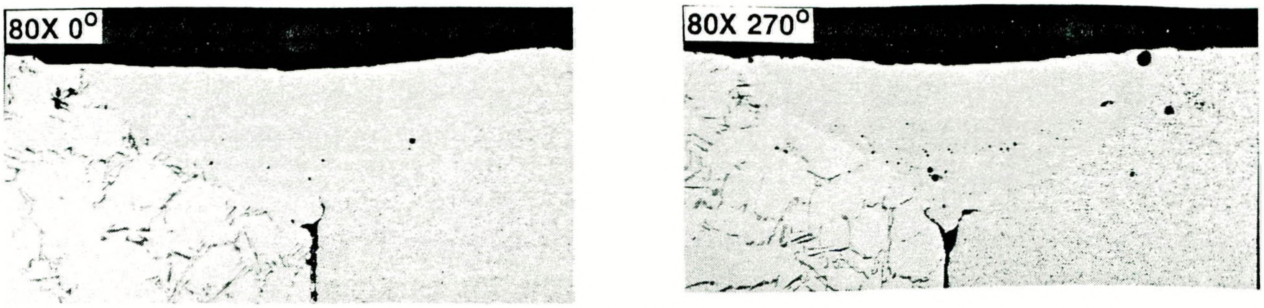


Figure 15. Cross-Sections of 4047 to A356 YAG Laser Welds 80X and Unetched

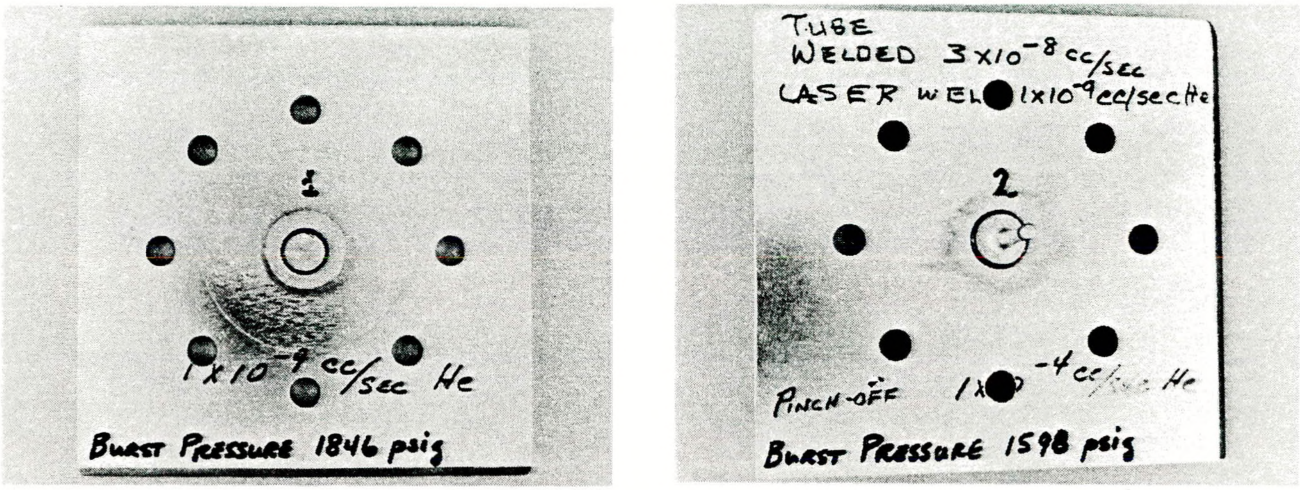


Figure 16. 4047 to A356 Pressure Test Plate Welds

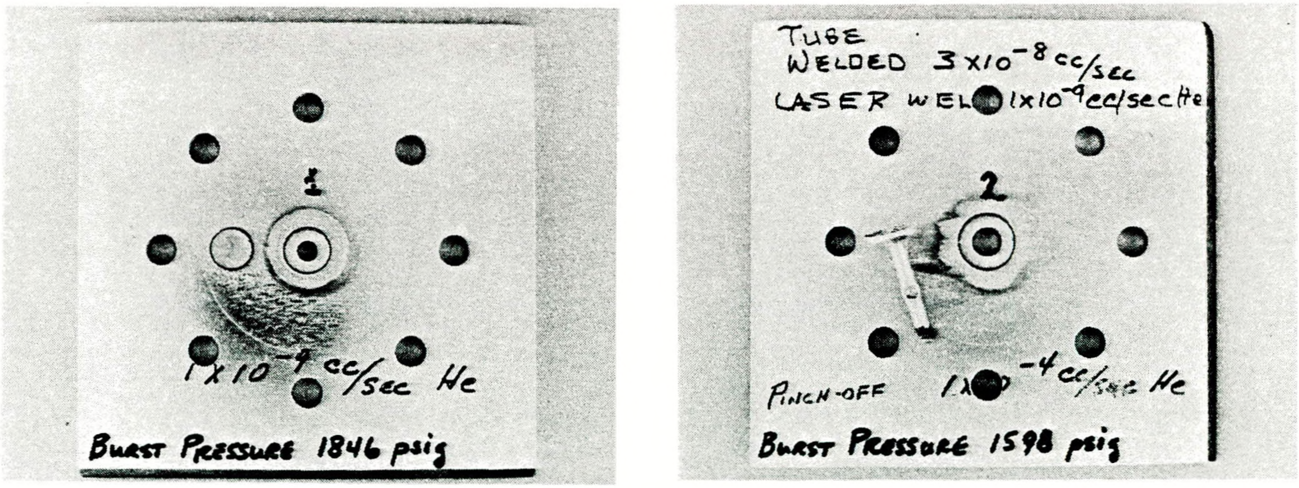


Figure 17. 4047 to A356 Pressure Test Plate Welds After Pressure Testing