WELDING RESEARCH

SUPPLEMENT TO THE *WELDING JOURNAL*, APRIL 1990

Sponsored by the American Welding Society and the Welding Research Council

Joint Preparation for Electron Beam Welding Thin Aluminum Alloy 5083

Diamond machining of aluminum joint surfaces significantly reduced porosity

BY J. L. MURPHY, R. A. HUBER AND W. E. LEVER

ABSTRACT. Designs for products require high-quality welds in thin aluminum Alloy 5083 over various underlying materials. These welds must have minimum porosity, no oxide inclusions that can propagate into cracks, no cracks, and generally a smooth outer surface that blends into the base metal. The capability to consistently make good welds over underlying materials and on sealed systems was needed at the Oak Ridge Y-12 Plant[1]. Because porosity in welds in aluminum has been a constant problem, it was of interest to determine how it could be reduced and controlled.

Various methods of joint preparation, which include mechanical and chemical cleaning, have been used in industry to prepare aluminum for welding. Mechanical cleaning of thin aluminum by wire brushing is not preferred because joints are easily damaged. The quality of welds on chemically cleaned joints has not been consistent. Scanning electron micrographs of surfaces cleaned by wire brushing, chemicals or diamond-machining show the latter to have the best finish and, therefore, is least susceptible to retaining water, gases or hydrocarbons.

In unreported work, oxide inclusions and porosity were reduced in gas tungsten arc welds on diamond-machined aluminum Alloy 5083. However, a problem with this welding technique was the venting of heated internal gas in sealed systems while welding. Electron beam welding is attractive because of precise heat input and, since welding occurs in a good vacuum, there are no appreciable internal gases to vent from sealed systems. Therefore, work to evaluate the electron beam process for welding diamond-machined, thin aluminum over developmental materials and to compare porosity in these welds to that in welds on chemically cleaned joints was of interest. Additionally, porosity in welds using 0.38- and 0.76-mm-high (0.015- and 0.03-in.) bosses needed to be compared to determine if more porosity would be removed with the thicker boss since outer surfaces of welds are machined to provide a smooth surface. Sixteen welds were performed as part of a statistically designed experiment on 102-mm (4-in.) diameter and 1.02-mm (0.04-in.) wall thickness aluminum Alloy 5083 cylinders. Welding parameters used with Leybold Heraeus 7.5-kW electron beam machine and R167R gun were based on previous studies that evaluated the effects of parameters on porosity in welds. Porosity was determined by radiography subsequent to machining of weld bosses.

KEY WORDS

Electron Beam Welding
Thin 5083 Aluminum
Joint Preparation
Diamond Machining
Cleaning Methods
Sealed System Venting
Weld Porosity Cause
Weld-Boss Thickness
Statistic Experiment
Reducing Porosity

(1) Operated by Martin Marietta Energy Systems, Inc., for the U.S. Dept. of Energy under contract DE-AC05-840R21400.

J. L. MURPHY and R. A. HUBER are with the Materials Engineering Dept., Development Div., Oak Ridge Y-12 Plant, Oak Ridge, Tenn. W. E. LEVER is with the Mathematical Sciences Section, Engineering Physics and Mathematics Div., Oak Ridge National Laboratory, Oak Ridge, Tenn.

Results of this study showed that high-quality electron beam welds can be made on diamond-machined Alloy 5083 with no damage to the underlying material. Weld-boss thickness did not significantly influence the amount of porosity obtained in this experiment.

Introduction

Many part designs require full-penetration welds in thin aluminum alloys. Porosity in these welds can reduce strength and ductility and have undesirable appearance on machined surfaces. Data from welds on thicker aluminum (6.35 to 9.52 mm/0.25 to 0.37 in.) show that even small-diameter porosity (0.127 mm/0.005 in.) can have an effect on properties (Refs. 1, 2). Since welds must meet specifications that limit number and size of porosity, a welding method, techniques, and a joint preparation that would consistently result in minimum porosity as well as no oxide inclusions or cracks must be used.

The basic cause of porosity in aluminum welds is gas — hydrogen or other gaseous contaminants — entrapped by the freezing weld metal before it has a chance to rise out. The cooling rate of the liquid metal will influence the amount of porosity that is retained in the solid weld metal (Refs. 3–10). The principal reason for porosity is probably the evolution of hydrogen from the reaction between the liquid metal and moisture in the oxide film. Hydrogen is practically insoluble in the solid weld metal and, therefore, will exist as porosity at the time of solidification. Hydrogen may come from water vapor in the atmosphere or from water rinses (when used) and exists as an adsorbed layer on the oxidized metal surface. Hydrogen may also come from hydrocarbons and degreasing solvents (Refs. 3–10).

The oxidized surface on aluminum must be removed for high-quality welding; consequently, joint preparation is extremely important. A surface with a zero weld discontinuity potential is desirable. (Weld discontinuity potential is the amount of porosity that can be expected in a weldment following a given surface treatment.) (Refs. 6, 11).

Aluminum is usually cleaned by solvent degreasing followed by a mechanical method of scraping, filing, grinding, wire brushing, or rubbing with steel wool or by a chemical method using various solutions. These methods of cleaning are expected to remove degreasing solvents that may be adsorbed on the aluminum surface. Precision-machined parts that were cleaned at the Oak Ridge Y-12 Plant in the past by wire brushing or rubbing with steel wool have yielded inconsistent results. Furthermore, joints on thin parts are easily damaged by a mechanical method. Reference 3 states that wire brushing may imbed contaminants in the aluminum. Mechanical wire brushing, scraping or grinding surfaces cannot be relied upon to produce a minimum discontinuity-potential condition (Ref. 11).

Chemical cleaning has been routinely used at Y-12 to prepare aluminum Alloy 5083 for electron beam welding (EBW), friction welding (FRW) and gas tungsten arc welding (GTAW). This cleaning process requires that the temperature be closely controlled, as well as cleaning time. Chemical cleaning produces a more reactive surface that will readily combine with gases and water, and chemical reaction products and water can be trapped in etch pits. In many instances, chemically prepared surfaces are characterized by a complex hydrated refractory oxide layer (Ref. 11). Magnesium in aluminum Alloy 5083 will also form hydroxides to provide a source of hydrogen. In unreported work, chemically cleaned (phosphoric, nitric acid and water solution) Alloy 5083 with 1.0-mm (0.04-in.) wall thickness with an additional 0.38-mm boss was welded to meet stringent specifications for porosity using direct current, electrode negative (DCEN) pulsed gas tungsten arc welding. Some welds had excessive porosity (porosity greater than 0.38 mm in diameter and more than 1 per 90 deg of weld length) and oxide stringers that resulted in weld failure under cyclic stress.

The contribution of various surface preparations to weld-discontinuity potential was studied by IIT Research Institute, Chicago, Ill. (Refs. 6, 11). A machined surface was the only one with a zero weld-discontinuity potential. A particular need existed to make machining a part of the welding operation to eliminate postcleaning handling problems. Dry machine cutting produces the best surface for welding, since a freshly machined surface represents the cleanest surface attainable. To avoid contamination, machined surfaces must be stored under controlled environmental conditions.

Diamond machining was first investigated at the Y-12 Plant as a way to achieve the zero-weld-discontinuity potential. Gas tungsten arc welding (DCEN) on joints prepared by diamond machining consistently had less porosity and no evidence of oxide stringers. However, a chronic problem with GTAW on sealed systems with internal parts was an inability to vent heated internal gas, which often caused blowouts in the weldment. Variable gaps existing between the joint and internal parts had great influence on the success of the weld. Electron beam welding was an attractive alternative to GTAW because the vacuum environment both inside and outside the systems would eliminate the pressure differential across the weld. It was desirable to investigate EBW techniques to make autogenous welds over developmental materials. For this work, weld beads were machined to provide a smooth outer surface making a weld boss necessary. Some porosity is machined away with removal of the boss, therefore, increasing the boss thickness could result in welds with decreased porosity.

A statistically designed program was established to evaluate three factors that could contribute to weld quality. These factors were: 1) weld-boss thickness; 2) weld joints prepared by chemical cleaning or diamond machining; and 3) two developmental materials used under the weld. Diamond-machined parts would be dry machined and immediately placed in containers that were evacuated to 760 mm/Hg. This method was used to prevent contamination of the ideally cleaned surface because welding immediately following machining was not practical.

Equipment

The equipment used for the welding development was a Leybold Heraeus EBW machine. The machine has a maximum operating voltage of 150 kV with a maximum beam current of 50 mA, giving a maximum output power of 7.5 kW. Electron guns supplied with the machine include the CL-R167R, CL-R40R and CL-R40A. Welds for this study were made using the CL-R167R gun. Although the chamber is capable of attaining a vacuum of 1×10^{-6} torr, all the welds were made at 5×10^{-5} torr or better.

Welding Development

Joint Geometry

Figure 1 shows details of the cylinders machined from aluminum Alloy 5083-0 pipe. A 0.38- or 0.76-mm weld boss was added, making the total thickness to be welded either 1.38 or 1.76 mm. A chamfer was machined into the root side of the joint to separate the aluminum from the underlying material and to reduce power input that was necessary to melt the joint.

Figure 2 shows details of the developmental materials that were dimensioned to fit inside the aluminum cylinders. A 0.127-mm (0.005-in.) deep groove was added to the outside surface so that, when assembled in the aluminum cylinders, a clearance would exist at the inside surface of the weld joint. This clearance helped to prevent contamination of the weld by the inner material.

Surface Preparation Methods

Methods generally used for cleaning aluminum are shown in Table 1 and include wire brushing, steel wool scrubbing or chemical cleaning. Some of their disadvantages are listed. Diamond machining is being presented as a new method to prepare aluminum for welding.

Aluminum is cleaned to remove oxide and surface contaminants and to minimize

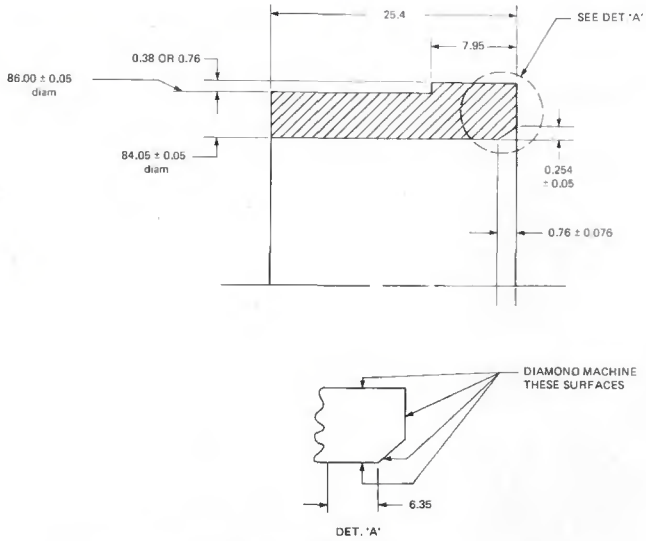

Fig. 1—Details of aluminum cylinders (dimensions in mm).

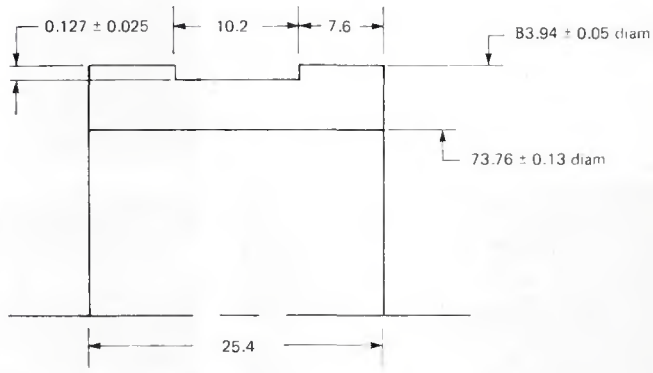

Fig. 2—Dimensions (mm) of inner cylinders.

possible sources for hydrogen to enter the weld pool. Hydrogen must be minimized in aluminum welds since hydrogen is the primary cause of porosity. However, porosity could result from other sources. These sources could include contaminants such as potassium or sodium chloride from a fingerprint left on a joint, or organic contaminants such as oil, grease and waxes. Table 2 shows the most recognized ways that hydrogen is made available. Water from the atmosphere or hydrocarbons is adsorbed on the oxidized metal surface. Magnesium in Alloy 5083 will increase the solubility of hydrogen in aluminum, allowing greater absorption into the pool.

Wire Brushing

Figure 3 shows a scanning electron micrograph (SEM) of a wire-brushed aluminum surface. The rough surface provides more area in comparison to a smoother surface for oxidation and, consequently, for moisture, gases and hydrocarbons to be adsorbed. This figure also shows that the surface can be contaminated with iron from the stainless steel brush. Wire brushing may also damage joints on thin aluminum. Both wire brushing and steel wool scrubbing are dependent on the effectiveness of the person doing the cleaning, and results can vary. Solvents used to degrease aluminum prior to cleaning and as a final wipe after mechanical cleaning may contain hydrocarbons.

Chemical Cleaning

The chemical cleaning solution used at the Y-12 Plant is 81% phosphoric acid, 16% demineralized water and 3% nitric acid, by volume. The solution is maintained at 35°C (95°F) and the weld joint is submerged in the solution for 2 min. Final rinse is in demineralized water. Figure 4 shows an SEM of a chemically cleaned Alloy 5083 surface. Machining marks are still visible, but the surface is pitted. Figure 5 shows the effect on a surface cleaned at 45°C (113°F) for 2 min. Increased temperature causes much heavier attack. Nonuniform etching of the surface is also apparent in Fig. 5, evidently resulting from preferential attack on aluminum. Figures 4 and 5 illustrate the variation in surface condition that can occur with chemical cleaning. These etched and reactive surfaces will trap chemical-reaction products and water in etch pits, which may not be completely removed with the careful rinsing and drying that is necessary subsequent to cleaning. Magnesium and aluminum hydroxides can exist on chemically cleaned parts because of contact with both chemical and rinsing solutions.

Diamond Machining

The advantages of diamond machining include a superior surface finish that pro-

Table 1—Methods of Cleaning Aluminum

Method[a]	Results
Wire brushing	Leaves rough surface that is easily contaminated Can contaminate surface Effectiveness depends on operator Solvents for cleaning may contain hydrocarbons
Steel wool scrubbing	Can contaminate surface Effectiveness depends on operator Slow process Solvents for cleaning may contain hydrocarbons
Chemical cleaning	Reactive surface can trap chemical-reaction products in etch pits which may not be removed with rinsing and water Surfaces are attacked varying degrees depending on cleaning time
Diamond machining	Superior surface finish to provide less metal to be contaminated Surface must be protected from environment

(a) Cathodic cleaning is another possible method—see The cathodic etching technique for automated aluminum tube welding by S. Barhorst in the May 1985 *Welding Journal*.

Table 2—Sources of Hydrogen in Aluminum Welds

1 Water
- At temperatures above 920°F, aluminum reacts with water to produce hydrogen plus Al_2O_3.
- Water vapor may come from ambient atmosphere or from adsorbed or chemically combined layer on the oxidized metal surface (hydrated oxide).

2 Contaminated surface from grease or other hydrocarbons.

3 Oxide film
- This film consists of a thin layer of moisture, greases, dirt or adsorbed gas.

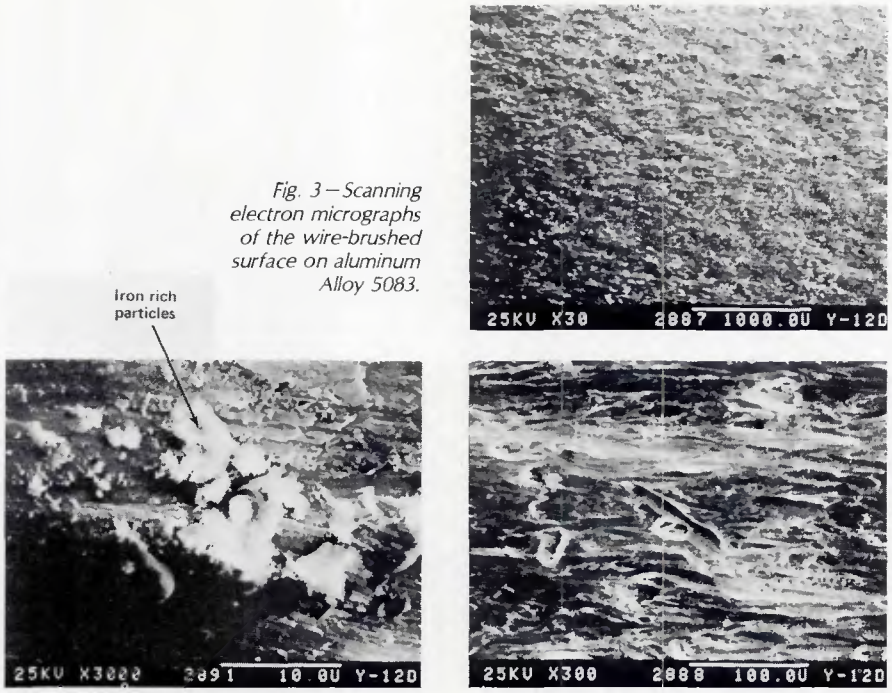

Fig. 3 — Scanning electron micrographs of the wire-brushed surface on aluminum Alloy 5083.

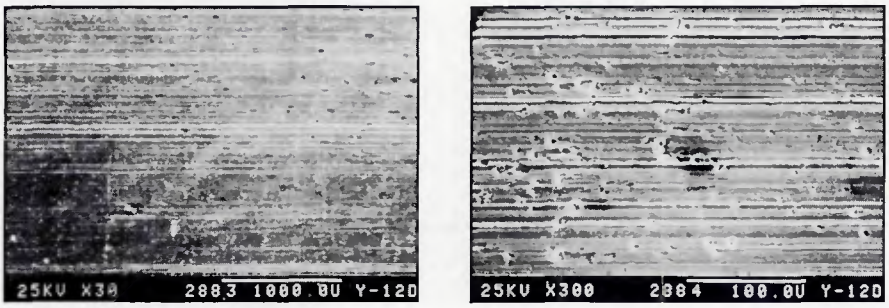

Fig. 4 — Scanning electron micrographs of the chemically cleaned surface on aluminum Alloy 5083 after 2 min at 36 °C.

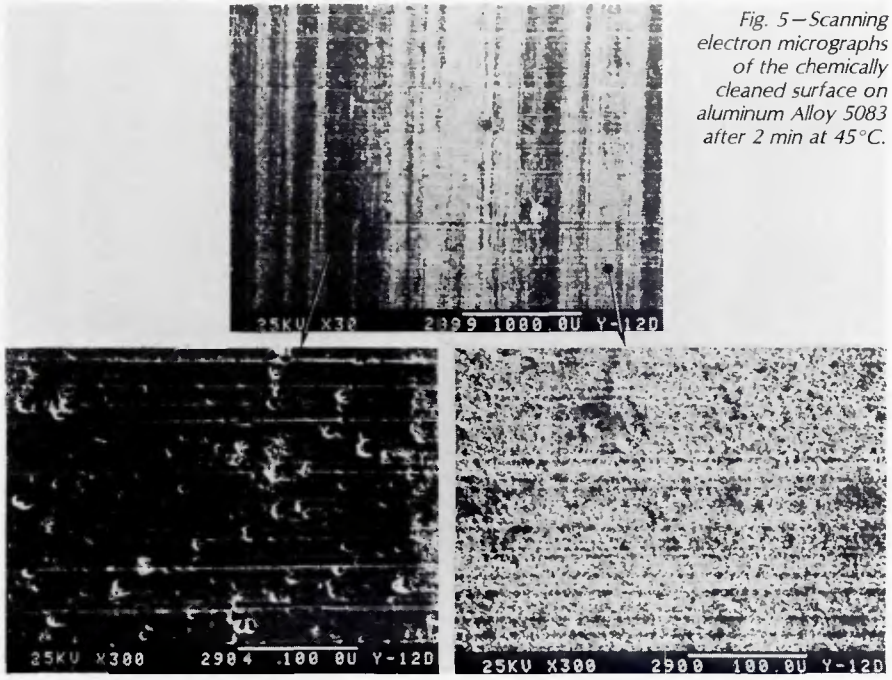

Fig. 5 — Scanning electron micrographs of the chemically cleaned surface on aluminum Alloy 5083 after 2 min at 45 °C.

vides less surface area to be contaminated and no further rinsing or cleaning of this surface is necessary. Figure 6 shows an SEM of a diamond-machined surface. The microgrooves are caused by inclusions that are caught and dragged by the diamond tool.

Results from studies using electron spectroscopy for chemical analysis (ESCA) show that subsequent to diamond machining, the oxide film initially grows very rapidly to a calculated thickness of 10 to 12 Å. The amount of oxide on an aluminum surface can be taken as proportional to the intensity of the oxygen and aluminum photoelectron peaks if the film is not too thick in comparison to the mean inelastic electron attenuation lengths. Figure 7 shows that this thickness stays constant up to a relative humidity of approximately 50%, and the protective oxide film results in a minimal effect from the humidity. At room temperature, no surface reaction apparently occurs, but moisture is adsorbed on the surface along with gases (oxygen, carbon dioxide and carbon monoxide) and hydrocarbons. As the relative humidity exceeds 50% moisture, adsorption increases. No surface morphological changes were seen as a result of environmental exposure.

The cylinders used in this investigation and illustrated in Fig. 1 were rough machined using conventional techniques. Approximately 0.0254 mm of material was left on each surface to be diamond machined. Diamond machining was performed at 500 to 600 rpm with 0.0051 to 0.0127 mm of material being removed in each cut for a total of one or two cuts to achieve the desired surface finish. A diamond tool can be reused if it is not chipped. A chipped tool occurs by dragging a hard inclusion from the part. A mirror surface will not be produced with a chipped diamond. Cutting was performed dry with no lubricants added. Diamond machined surfaces are improved with lubricants, but the use of lubricants can add contaminants, which are generally undesirable for welds. Hundreds of machined parts are possible with the same diamond tool. The diamond-machined cylinders were placed in a container, evacuated to approximately 760 mm/Hg, and stored until they were removed for welding.

GTA Welding

A double-pass GTA welding procedure developed in a separate study used DCEN pulsed current with helium shielding at a welding speed of 4.2 mm/s (10 in./min). Welding current for the first pass was pulsed, 128 A for 0.038 s and 50 A for 0.025 s, at 16 pulses/s. High current for the second pass was 109 A. The joint geometry shown in Fig. 1 had a 0.38-mm (0.015-in.) boss. The backing material, however, had no groove machined on

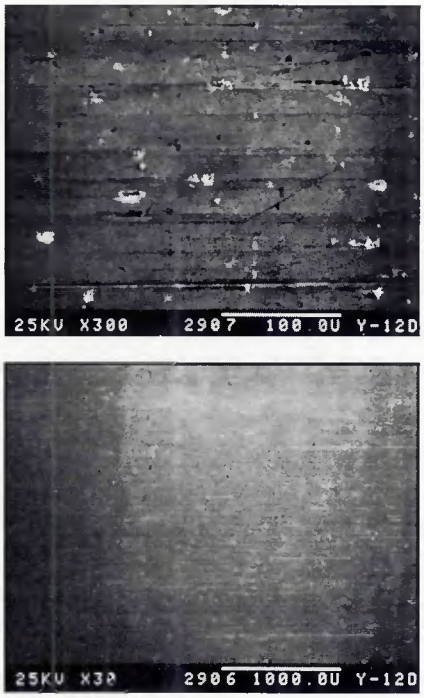

Fig. 6 — Scanning electron micrographs of the diamond-machined surface on aluminum Alloy 5083.

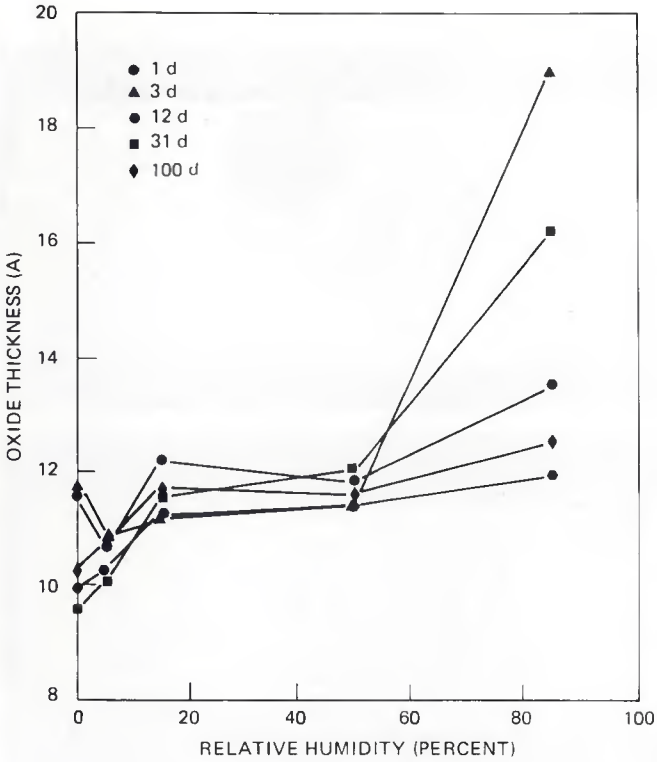

Fig. 7 — Aluminum oxide thickness on diamond-machined surfaces exposed to various relative humidities for five exposure periods.

the outer surface because the arc welding process is not as likely, compared to the EB process, to dilute backing material into the weld.

Porosity and oxide inclusions (folds) are shown in cross-sections (Fig. 8) of GTA welds on chemically cleaned joints. Welds on diamond-machined joints typically had less porosity and no evidence of oxide inclusions.

The major difficulty encountered with arc welding of sealed systems was the inability to control heated internal gases, which caused weld blowouts. Vent grooves machined in the weld joints were helpful, but not entirely corrective because the gas expansion due to heating was faster than the gas escaping through the vents.

EB Welding Parameter Development

The EBW process was desirable for sealed systems because weld blowouts are not a problem in the vacuum environment. Air is pumped from the inside of the systems through vent grooves that are machined in the joint faces. The grooves are typically 0.254 mm (0.01 in.) wide and 0.127 mm (0.005 in.) deep and spaced every 12.7 mm (0.5 in.).

Optimized EBW parameters evolved over the years from experimental welding of numerous aluminum cylinders. A high-kilovolt EB that would produce a high depth-to-width ratio weld would also melt backing material and create weld defects. For this reason, 45 kV was selected for the accelerating voltage since the beam is still stable at this setting and there was less tendency to penetrate the backing material. The GTA process, where welds are created by heat conduction rather than by vaporization as is typical of the EB process, was simulated. To further encourage welding in the conduction mode, the EB was defocused (plus 20 mA) from a sharp setting at the surface of the part to produce a wider weld fusion zone.

Welds made at speeds up to 33.8 mm/s (80 in./min) had excessive porosity. Some unreported data indicated that porosity tended to decrease with a decrease in welding speed. In a separate study, porosity decreased with speed for GTA welds. The welding speed of 4.2 mm/s, used for the EBW process, was also se-

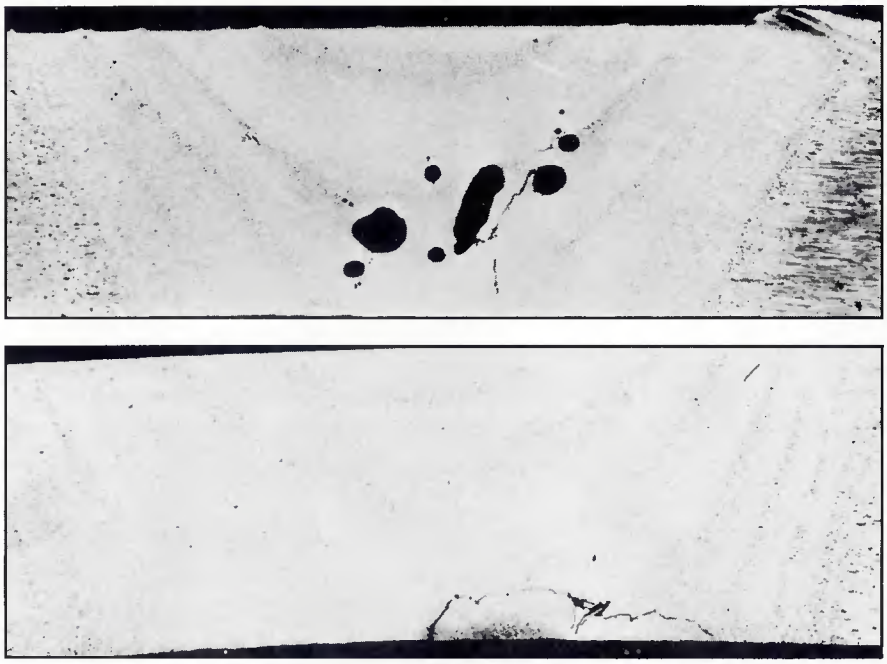

Fig. 8 — Cross-sections from GTAW on chemically cleaned Aluminum Alloy 5083 showing defects (weld boss removed). 50X.

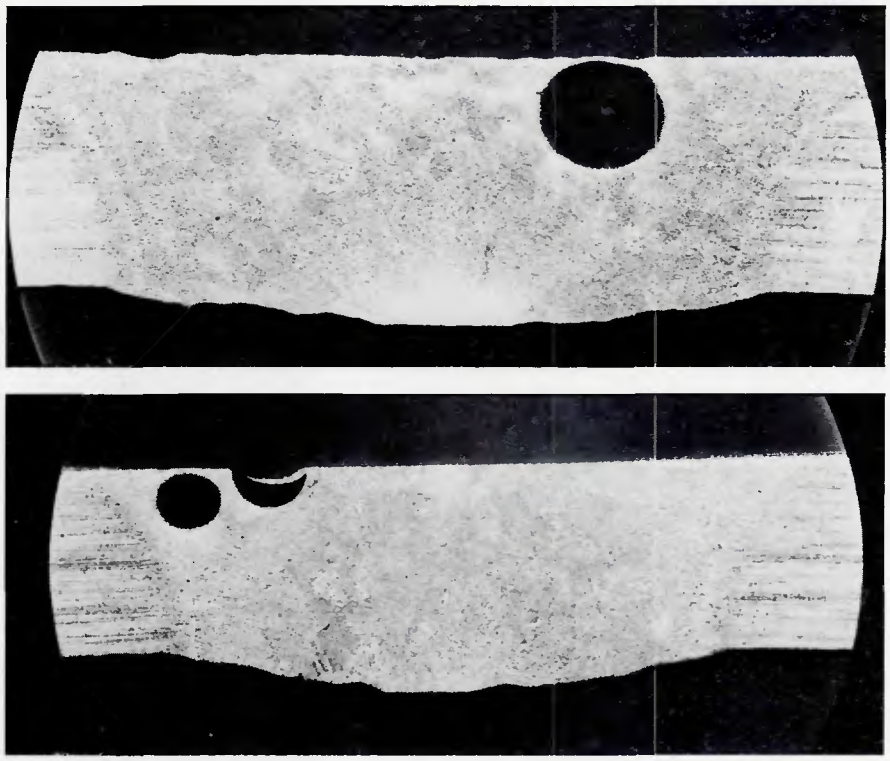

Fig. 9 — Cross-sections from EB weld on chemically cleaned joints in Aluminum Alloy 5083 showing porosity (weld boss removed). 35X.

Table 3—Radiographic Inspection Results Data from Statistically Designed Experiment to Evaluate Weld Boss Thickness, Weld Joint Preparation and Two Types of Inner Material

Run Number	Weld Boss Thickness (mm)	Weld Joint Preparation[a]	Inner Cylinder Type[b]	Radiographic Inspection Results: Number of Pores (pore diameter, mm)
1	0.76	DM	A	2 (0.38)
2	0.76	CC	A	<0.25
3	0.76	CC	B	1 (0.76) 2 (0.38) 2 (0.25)
4	0.38	CC	A	2 (0.51) 2 (0.38) 4 (0.25)
5	0.76	CC	A	1 (0.76) 3 (0.64) 1 (0.38) 2 (0.25)
6	0.38	DM	B	<0.25
7	0.38	DM	A	1 (0.38)
8	0.38	CC	A	1 (0.64) 2 (0.51) 10 (0.38) 13 (0.25)
9	0.76	CC	B	4 (0.51) 1 (0.38) 5 (0.25)
10	0.38	CC	B	4 (0.51) 14 (0.38) 15 (0.25)
11	0.38	DM	A	2 (0.25) 2 (0.38)
12	0.38	DM	B	2 (0.38) 2 (0.25)
13	0.38	CC	B	1 (0.76) 1 (0.64) 1 (0.51) 12 (0.38) 8 (0.25)
14	0.76	DM	B	2 (0.38)
15	0.76	DM	A	4 (0.38) 1 (0.30)
16	0.76	DM	B	<0.25

(a) DM is abbreviation for diamond machined using no coolant. CC is abbreviation for chemically cleaned using a mixture of phosphoric acid (240 mL), water (80 mL), and nitric acid (15 mL).
(b) Inner cylinder types A and B refer to two types of developmental materials.

lected based on the observation that GTA welds made at this speed had less porosity than EB welds made at the faster speed. Beam current was 6.6 mA for the first pass and 7.0 mA for the second pass. The first pass does not fully penetrate the joint. The second pass penetrates the joint, forms the convex root surface, and reduces porosity created by the first pass.

Figure 9 shows cross-sections from EB welds on chemically cleaned joints. In the top section, the pore is approximately 0.51 mm (0.02 in.) in diameter, and in the bottom section, the two pores would count as one having an equivalent diameter of 1.0 mm (0.04 in.) in radiographic inspection. These welds have an approximate depth-to-width ratio of 0.33:1, which is very similar to the GTA weld shown in Fig. 8. In Fig. 10, a view of part of a machined weld surface shows random unacceptable porosity.

Figure 11 shows a typical EB weld on diamond-machined Alloy 5083. The thickness of this weld exceeds that of the base metal by approximately 0.13 mm (0.005 in.) because the groove in the backing material and the diametral clearance, where available, allows weld reinforcement. Figure 12 shows a typical convex root surface of an EB weld. This smooth surface is not easily obtainable on an aluminum-magnesium alloy, and results from carefully selected welding parameters.

The Statistical Experiment

The purpose of the statistical experiment was to compare weld quality primarily based on the amount of porosity in the welds. The experimental plan was in the form of a three-factor, two-level, factorial design with each of the eight design points being replicated once. The three factors were weld-boss thickness (0.38 and 0.76 mm), the cleaning method (diamond machined and chemically cleaned), and two types of materials under the welds. The statistical analysis of the data was accomplished by characterizing porosity as spherical pores with the equivalent diameters that are listed in Table 3. The data in Table 3 were obtained from radiographic inspection results after the machining operation that removed the weld bosses. The basic response variable used in the statistical analysis was the total volume of all pores in the weld. Table 4 shows the number of pores in a weld and the total equivalent volume of the pores. Welds on diamond-machined joints had an average of 2.25 pores per weld, while welds on chemically cleaned joints had an average of 14 pores per weld.

The only interaction between factors that exhibited a statistically significant effect on the experimental results was the weld joint cleaning method. The average total equivalent pore volume resulting from chemical cleaning was 0.49 mm^3

Fig. 10 — Typical surface porosity, subsequent to removal of weld boss, from EB weld on chemically cleaned Aluminum Alloy 5083. 7X.

Fig. 11 — Cross-section from EB weld on 1.0-mm-thick diamond-machined Aluminum Alloy 5083 (weld boss removed). 35X.

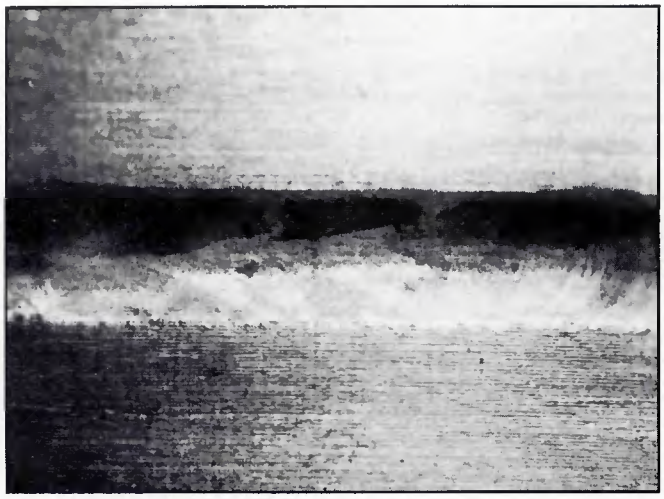

Fig. 12 — Typical convex root surface of EB weld on Aluminum Alloy 5083. 10X.

versus 0.05 mm^3 for the diamond machining — Table 5.

Figure 13 gives 95% confidence limits for the average cleaning method responses. All statistical tests were conducted at the 5% level of significance.

Conclusions

Diamond machining of aluminum Alloy 5083 is presented as an alternate method to prepare joints for welding. The experiment conducted in this work shows that diamond matching of weld joints on aluminum is a statistically significant factor to reduce porosity in welds. A disadvantage of the method may be that parts must be welded within a limited time period following machining, or stored in a controlled environment that includes vacuum or controlled humidity. Subsequent experiments will determine safe exposure

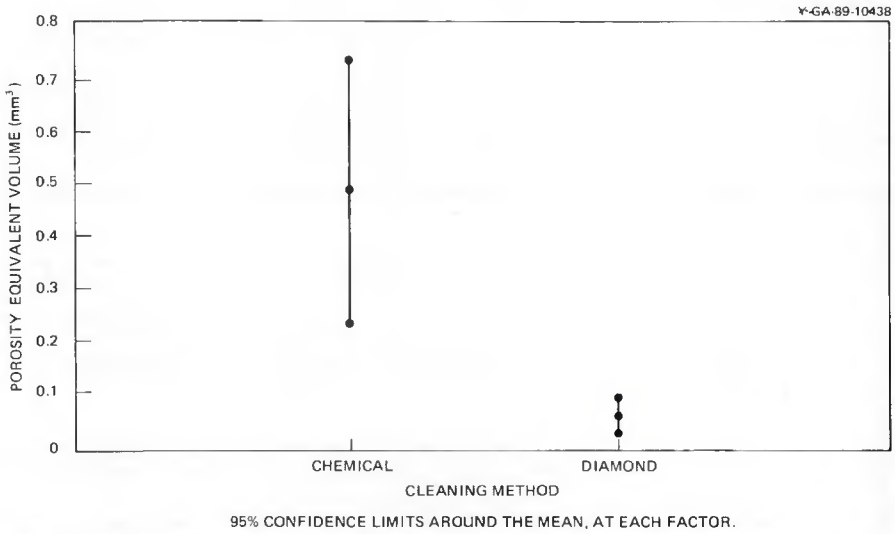

Fig. 13 — Comparison of 95% confidence limits to porosity for data from welds on chemically cleaned and diamond-machined cylinders.

Table 4—Equivalent Volume, Number and Maximum Diameter of Pores from Experiment to Evaluate Weld Boss Thickness, Weld Joint Preparation and Two Types of Inner Material

Run	Weld Boss Thickness (mm)	Weld Joint Preparation[a]	Inner Cylinder Type[b]	Equivalent Volume of All Pores (mm^3)	Number of Pores	Maximum Diameter of Pores (mm)
1	0.76	DM	A	0.0575	2	0.38
2	0.76	CC	A	0.0	0	0.00
3	0.76	CC	B	0.3037	5	0.76
4	0.38	CC	A	0.2291	8	0.51
5	0.76	CC	A	0.6867	7	0.76
6	0.38	DM	B	0.0	0	0.00
7	0.38	DM	A	0.0287	1	0.38
8	0.38	CC	A	0.6698	26	0.64
9	0.76	CC	B	0.3475	10	0.51
10	0.38	CC	B	0.8028	33	0.51
11	0.38	DM	A	0.0738	4	0.38
12	0.38	DM	B	0.0738	4	0.38
13	0.38	CC	B	0.8468	23	0.76
14	0.76	DM	B	0.0575	2	0.38
15	0.76	DM	A	0.1291	5	0.38
16	0.76	DM	B	0.0	0	0.00

(a) DM is abbreviation for diamond machined. CC is abbreviation for chemically cleaned.
(b) Inner cylinder types A and B refer to two types of developmental materials.

Table 5—Mean Effect Summary of Porosity from Statistically Designed Experiment to Evaluate Weld Boss Thickness, Weld Joint Preparation and Type of Inner Material

Parameter	Level[a]	Volume (mm^3)[b] Mean	Standard Deviation
Boss	0.38 mm	0.34	0.368
thickness	0.76 mm	0.20	0.238
Weld joint	CC	0.49	0.307
preparation	DM	0.05	0.043
Inner	Type A	0.23	0.283
cylinder	Type B	0.30	0.347

(a) DM is abbreviation for diamond machined. CC is abbreviation for chemically cleaned.
(b) Mean volume is the sum of all pore volume divided by the total in each parameter group.

time of parts to the atmosphere following machining. Also, special machines and diamond tools are necessary. Lathes or turning machines must be equipped with pneumatic slides and spindles to prevent vibration from deteriorating the mirror finish.

The surfaces of chemically cleaned and diamond-machined parts had approximately the same oxide thickness. Two major differences of the chemically cleaned surfaces were the remaining residue and the topography, or roughness, of the surfaces. Wire-brushed surfaces had the most damage.

The statistical experiment showed diamond machining of weld joints on aluminum Alloy 5083 was significant for reducing porosity in welds. The two boss heights evaluated, or the two underlying materials, did not significantly influence the amount or size of porosity.

Acknowledgments

The authors thank S. C. Bieniek for typing the manuscript; B. G. Cross for producing the experimental welds; H. L. Richards for the electron spectroscopy for chemical analysis examinations; W. L. Bolinger for the scanning electron microscopy examinations; personnel in the Machinability, Metrology and G-3 Support Dept. for preparing the diamond-machined parts; and L. D. Frye, a former Martin Marietta Energy Systems, Inc., employee, for developing the GTA welding procedure. Appreciation is extended to the Oak Ridge Y-12 Plant Development Div. and the Oak Ridge National Laboratory Engineering Physics and Mathematics Div. for their support and permission to publish this work. The developments described in this paper were sponsored by the U. S. Dept. of Energy under contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

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