Surface Preparation Effects on GTA Weld Shape in JBK-75 Stainless Steel

Wire brushing of weld grooves results in dramatic increases in weld depth of fusion and improved arc behavior

BY R. D. CAMPBELL, C. R. HEIPLE, P. L. STURGILL, A. M. ROBERTSON AND R. JAMSAY

ABSTRACT. The results of a study are reported here on the effects of surface preparation on the shape of autogenous gas tungsten arc (GTA) welds in JBK-75, an austenitic precipitation hardenable stainless steel similar to A286. Minor changes in surface preparation produced substantial changes in the fusion zone shape and welding behavior of this alloy. Increased and more consistent depth of fusion (higher d/w ratios) along with improved arc stability and less arc wander resulted from wire brushing and other abrasive surface preparations, although chemical and machining methods did not produce any increase in depth of fusion. Abrasive treatments roughen the surface, increase the surface area, increase the surface oxide thickness, and entrap oxide. The increased weld d/w ratio is attributed to oxygen added to the weld pool from the surface oxide on the base metal. The added oxygen alters the surface-tension-driven fluid flow pattern in the weld pool. Increased depth of fusion in wire-fed U-groove weld joints also resulted when welding wire with a greater surface oxide thickness was used.

Increasing the amount of wire brushing produced even deeper welds. However, a maximum in depth of fusion was observed with further wire brushing, beyond which weld fusion depth decreased. The decrease in d/w ratio after extensive wire brushing is caused by slag formation produced by oxygen added to the weld pool in excess of the solubility limit. This slag changes the fluid flow and alters the arc. In this case, the benefits of wire brushing are mitigated by the presence of the slag.

R. D. CAMPBELL and A. M. ROBERTSON are with the AWS Precision Joining Center, Wheat Ridge, Colo. P. L. STURGILL and R. JAMSAY are with the Joining Technology Branch and C. R. HEIPLE is with the Materials Technology Branch, EG&G Rocky Flats Plant, Golden, Colo.

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Introduction

Variations in gas tungsten arc (GTA) fusion zone shape have been traced to small differences in residual element content of the materials being welded. Heiple and Roper (Ref. 1) proposed that GTA weld pool shape is determined largely by fluid flow patterns in the weld pool. The dominant force driving weld pool fluid flow, under normal GTA welding conditions, is the weld pool surface tension gradient. This surface tension gradient arises because the surface tension is temperature dependent and there are large temperature gradients on the weld pool surface. Surface active trace elements that segregate to the liquid metal surface lower the surface tension, thereby modifying the surface tension gradient. This in turn changes the fluid flow in the weld pool and thus the fusion zone shape, resulting in narrower, deeper penetrating welds. This model has been described in detail elsewhere (Refs. 1, 2) and used to explain increased weld depth of fusion in austenitic stainless steels when appreciable sulfur, oxygen, selenium or tellurium are present.

Oxygen is known to be surface active in iron and iron-based alloys, and can increase the depth-to-width (d/w) ratio of GTA welds in these metals if it is not combined in stable compounds, such as aluminum oxide. The oxygen can be in the form of oxygen in the shielding gas (Ref. 3), oxygen dissolved in the metal (Ref. 2), or an oxide on the surface of the metal to be welded (Refs. 2, 4, 5). The amount of oxygen required under the proper conditions to produce substantial changes in GTA weld d/w ratio is very small. Heiple and Roper (Ref. 2) showed a 43% increase in d/w ratio with the addition of about 15 ppm oxygen to 304L stainless steel base metal. The amount of oxygen required to produce similar increases in d/w ratio varies for different alloys.

KEY WORDS

GTAW
Surface Preparation
JBK-75 Stainless Steel
Depth of Fusion
Root Penetration
Bead-on-Plate Welds
Arc Spot Welds
Wire Brushing
Oxide Layer
Arc Stability

Background

JBK-75 is a fully austenitic, precipitation hardening stainless steel. It is a modified version of A286, the modifications being directed toward reducing the weld hot cracking tendencies of the alloy

Table 1 — Compositions of JBK-75 Stainless Steels

	Content (wt-%)		
	Chemical and Abrasive Experiments	Machining Experiments	Wire Brushing Experiments
Element	Heat A	Heat B	Heat C
Ni	30.0	29.7	30.8
Cr	14.3	13.9	15.6
Ti	2.0	2.1	2.0
Al	0.17	0.15	0.20
Mo	1.0	1.2	1.0
Mn	0.033	0.021	0.025
C	0.022	0.025	0.018
N	0.0045	0.001	0.0057
P	0.005	0.003	0.009
Si	0.060	0.024	0.052
V	0.23	0.21	0.23
B	0.0015	0.0004	0.0018
S	0.0022	0.004	0.0046
O	0.0021	0.001	0.0044
Fe	Balance	Balance	Balance

Table 2 — Chemical and Abrasive Methods Employed

Chemical Surface Preparations

1. Acid cleaning[a]
   - A. Nitric acid (20 vol-%, room temperature, 6.25 min), distilled water rinse, nitric acid (30 vol-%)/Nitradd®[b] (20 vol-%) (38°C, 6.25 min), distilled water rinse.
   - B. Nitric acid (25 vol-%, room temperature, 6.25 min), distilled water rinse, nitric acid (35 vol-%)/Nitradd®[b] (25 vol-%) (43°C, 6.25 min), distilled water rinse.
   - C. Nitric acid (30 vol-%)/Nitradd®[b] (20 vol-%) (38°C, 6.25 min), distilled water rinse, nitric acid (20 vol-%, room temperature, 6.25 min), distilled water rinse.
   - D. Nitric acid (20 vol-%, room temperature, 6.25 min), distilled water rinse.
2. Acid cleaning followed by solvent cleaning[a]. (Acid cleaning by method 1A above.)
   - A. Vapor degrease in freon (5 min) followed by 1,1,1-trichloroethane (10 min).
   - B. Aqueous clean in detergent (Oakite®, see (a) below for conditions).
   - C. Wipe with isopropyl alcohol.
   - D. Wipe with acetone.
3. Solvent cleaning only
   - A. Vapor degrease in Freon (5 min) followed by 1,1,1-trichloroethane (10 min).
   - B. Aqueous clean in detergent (Oakite®, see [a] below for conditions).

Abrasive Surface Preparations

1. Wire brush using an AISI Type 302 wire brush, in air.[c]
2. Grit blast using 180-grit silica particles, in air.[c]

(a) Prior to acid cleaning, surfaces were degreased in 2 vol-% Oakite® NST aluminum cleaner in distilled water at 55°C for 5 min and rinsed in distilled water.
(b) Nitradd® is a proprietary mixture which, when mixed with nitric acid, partially ionizes to form hydrofluoric acid.
(c) Prior to abrasive preparation, surfaces were degreased and acid cleaned by procedure 1A.

(Refs. 6, 7). This material is welded in production applications at the EG&G Rocky Flats plant. The production components are machined to have a modified single U-groove weld joint. The joint is filled using a multipass GTAW procedure, utilizing JBK-75 welding wire of nominal composition similar to the base metal. The root pass weld is required to fully penetrate and produce consistent root reinforcement.

JBK-75, when GTA welded using argon shielding gas, is often difficult to penetrate and is not very responsive to weld parameter variations from a joint penetration standpoint. This poor welding behavior is further aggravated because the U-groove weld joint is deep, narrow, and asymmetrical. Welds made using this configuration resulted in marginal and inconsistent root penetration. As a result, the shielding gas was changed to 25% argon-75% helium. Welds made with this shielding gas had improved root penetration, but were accompanied by arc instability. Since these welds were controlled by automatic voltage control (AVC), the result was that the torch periodically moved up and out of the narrow weld groove, resulting in incomplete root penetration. Although part of this instability problem is a characteristic of helium shielding gas (Refs. 8, 9), the use of the narrow groove caused the AVC to sense off the sidewalls of the groove, which aggravated the problem. Unfortunately, the weld joint could not be modified, the Ar-He shielding gas was necessary to obtain adequate root penetration, and changing the alloy composition was not an option.

In the course of weld procedure development, improved root penetration and arc stability were noted on wire brushed components. This study was undertaken to verify the effect of wire brushing, to understand the origin of the increased root penetration produced by wire brushing, and to see if other surface treatments would either be more effective or simpler. Most of the experiments involved autogenous GTA welds (bead-on-plate or arc spot) on samples of bar stock. A variety of chemical, abrasive and machining techniques were evaluated. Their effects on surface chemistry, depth of fusion, and voltage-arc length relationships are discussed herein.

Table 3 — Machining Methods Employed and Resultant Surface Finishes (Including Post-Machining Surface Treatment Conditions)

1. Lathe Turning—63 Microinch Finish
   - A. Machined, acid cleaned
   - B. Machined, wire brushed, acid cleaned
   - C. Machined, acid cleaned, wire brushed
2. Electrical Discharge Machining—83 Microinch Finish
   - A. Machined, acid cleaned
   - B. Machined, wire brushed, acid cleaned
   - C. Machined, acid cleaned, wire brushed
3. Milling—125 Microinch Finish
   - A. Machined, acid cleaned
   - B. Machined, wire brushed, acid cleaned
   - C. Machined, acid cleaned, wire brushed
4. Milling—250 Microinch Finish
   - A. Machined, acid cleaned
   - B. Machined, wire brushed, acid cleaned
   - C. Machined, acid cleaned, wire brushed
5. Milling—500 Microinch Finish
   - A. Machined, acid cleaned
   - B. Machined, wire brushed, acid cleaned
   - C. Machined, acid cleaned, wire brushed

Experimental Procedures

Materials

Three heats of JBK-75 bar stock were utilized in this study, the compositions of which are presented in Table 1. The materials were all produced by the vacuum induction melt/vacuum arc remelt (VIM/VAR) procedure.

Surface Preparation Methods

Numerous surface preparations were evaluated, including chemical and abrasive surface preparations, various ma-

Table 4 — Welding Conditions

	Chemical and Abrasive Experiments			Machining Experiments		Wire Brushing Experiments
Welding Procedures	1	2	3	4	5	6
Welding position	1G flat	1G flat	1G (pipe) horizontal rolled (sample rotated)	1G flat	1G flat	1G flat
Surface welded	flat face	flat face	circumference	flat face	flat face	flat face
Type of weld	bead-on-plate	bead-on-plate	bead-on-plate	spot-on-plate	bead-on-plate	bead-on-plate
Current, A	130	130	150	140	140	130
Travel speed, in./min (mm/s)	2.0 (0.9)	2.0 (0.9)	5.0 (2.1)	—	2.0 (0.9)	2.5 (1.1)
Arc spot weld duration (s)	—	—	—	60	—	—
Voltage, V (automatic voltage control)	10.0	—	8.0	10.4	10.0	10.8
Starting torch position, in. (mm) (torch position locked)	—	0.066 (1.7)	—	—	—	—
Torch shielding gas composition	25% Ar-75% He	25% Ar-75% He	100% Ar	25% Ar-75% He	25% Ar-75% He	25% Ar-75% He

Process: DCEN, Partial penetration GTAW
Electrode: 0.093-in. (2.4-mm) diameter
Tungsten-2% Thoria
10 deg vertex angle
0.031-in. (0.8-mm) truncation diameter
Electrode Extension: 1.250 in. (30.5 mm) from collet
0.375 in. (9.5 mm) from gas nozzle
Torch Position: Vertical
Gas Flow Rate: 22 scfh at 30 psig

chining methods and finishes, and various degrees of wire brushing.

Chemical and Abrasive Surface Preparation Experiments

In the initial experiments, 2-in. (51-mm) diameter, 1-in. (25.4-mm) thick samples of Heat A were prepared by twelve different chemical or abrasive surface treatments to determine which, if any, affected fusion zone shape. The various treatments are detailed in Table 2. Three general types of chemical cleaning were attempted on the steel prior to welding: acid cleaning, acid cleaning followed by solvent cleaning, and solvent cleaning. The two abrasive conditions involved wire brushing in air and grit blasting using 180-grit silica particles transported in air. The abrasive treatments were applied after acid cleaning (*i.e.*, Condition 1A in Table 2) and were followed by a wipe with isopropyl alcohol.

Machining Experiments

The second set of experiments involved a variety of mechanical surface preparations on 6-in. (152.4-mm) diameter, 1-in.-thick samples of Heat B to determine if weld depth of fusion could be improved by surface roughening caused by different machining schedules. Surface roughness was varied by machining the surface via lathe turning, traveling wire electrical discharge (EDM) and different milling schedules. The five surface finishes achieved are listed in Table 3.

For each of the five surface finish conditions, three different treatments were evaluated: 1) the machined samples were acid cleaned (using procedure 1A in Table 2); 2) the machined samples were wire brushed, then acid cleaned; and 3) the machined samples were acid cleaned, then wire brushed (followed by wiping with isopropyl alcohol to remove any residue from the wire brushing). These treatments are identified as Conditions A, B and C, respectively, in Table 3. Thus, 15 different conditions were tested.

Wire Brushing Experiments

The final set of experiments involved varying the amount of wire brushing on the flat surfaces of 2-in.-diameter, 1-in. thick samples of Heat C. These experiments were performed to determine the relationship between the amount of wire brushing, oxide thickness, and weld fusion depth. Samples were first acid cleaned using Procedure 1A (Table 2). Wire brushing was accomplished by holding the sample in a Hardinge head fixture, which rotated the part at 7.1 rpm under the wire brush. The 3-in. (76-mm) diameter, ¼-in. (6.4-mm) thick wire-wheel brush was turning at 1000 rpm. As the brush was lowered, it applied a constant force to the rotating sample. The amount of wire brushing is ex-

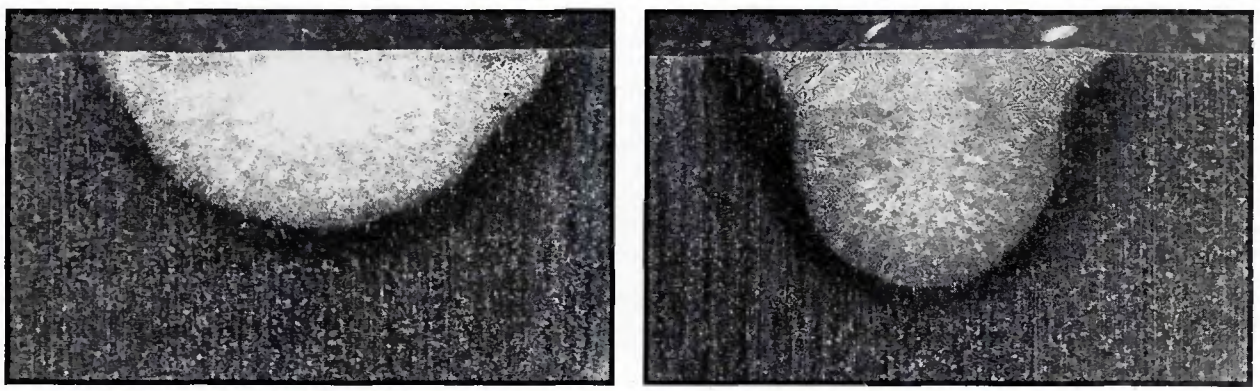


Fig. 1 — Weld cross-sections from welding Procedure 1, 8.75X. Left — Chemical surface preparation (acid cleaned), d/w = 0.41; right— abrasive surface preparation (acid cleaned, then wire brushed), d/w = 0.66.

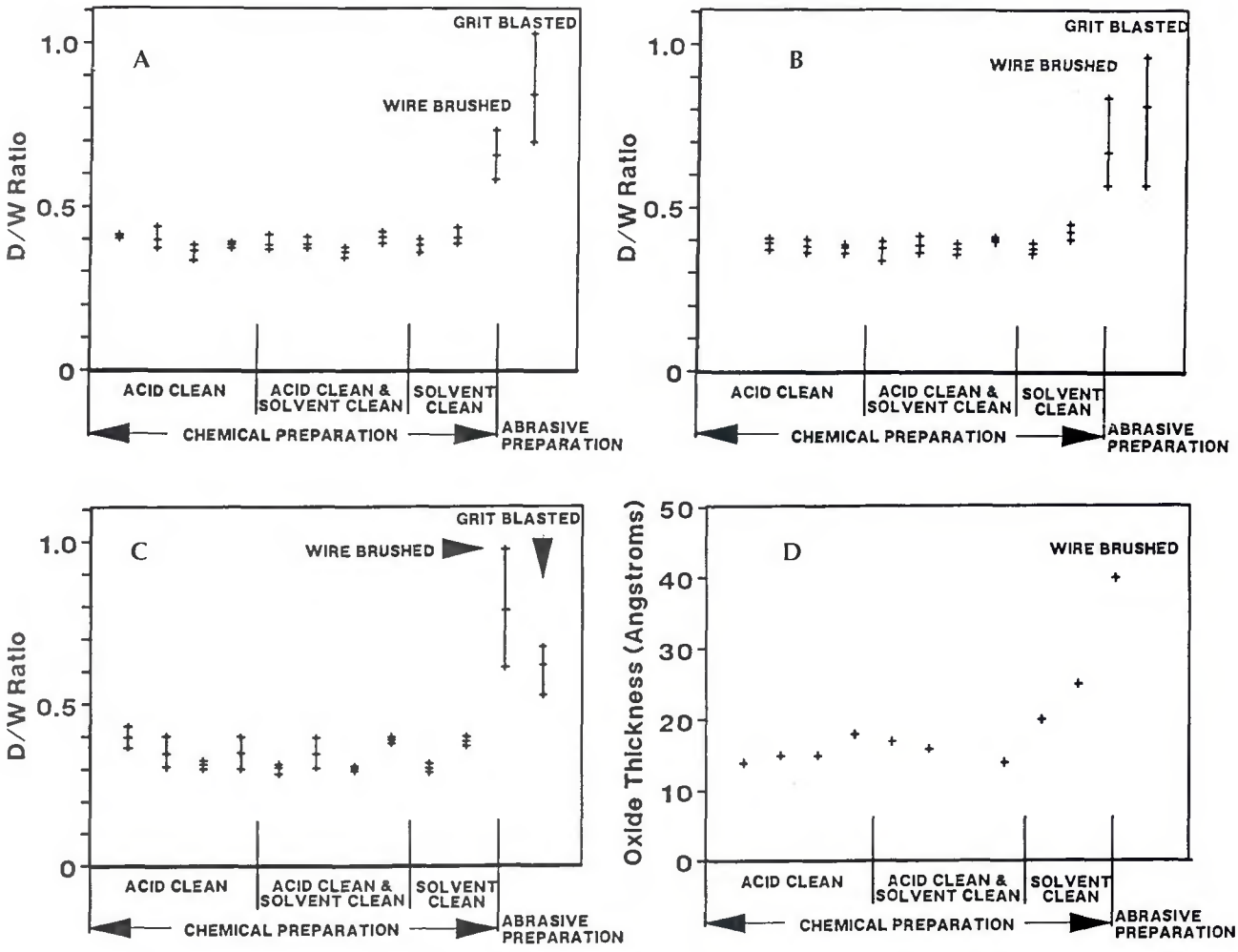


Fig. 2 — Weld d/w ratio for chemical and abrasive surface preparations. A — Welding Procedure 1, arc voltage 10.0 V, Ar-He; B — welding Procedure 2, arc length 0.066 in., Ar-He; C — welding Procedure 3, arc voltage 8.0 V, 100% Ar, circumferential weld; D — surface oxide thickness.

pressed as the number of times (passes) the sample was rotated under the wire brush.

The wire brushes were made of AISI Type 302 stainless steel, with a maximum sulfur content of 0.03% (300 ppm). All brushes were vapor degreased using Procedure 3A in Table 2. Electron microscopy of the wire brushed surfaces indicated that no wire residue was embedded nor trace elements picked up from the brush.

Welding and Metallography

To properly evaluate weld pool fluid flow characteristics and subsequent weld bead geometry, partial-penetration, autogenous (no filler metal) welds were produced utilizing the GTAW process.

Chemical and Abrasive Experiments

For the chemical and abrasive experiments, bead-on-plate welds were produced on both the circumference and flat surfaces of samples of Heat A using welding Procedures 1 through 3 listed in Table 4. Automatic voltage control (AVC) was used with welding Procedures 1 and 3 to maintain a constant arc voltage by adjusting torch height (position) during welding. Torch motion was recorded with a data-acquisition system accurate to 0.001 in. (0.03 mm). Welds were also produced utilizing a fixed arc length of 0.066 in. (1.7 mm) between the tip of the electrode and the top of the sample (Procedure 2). Arc voltages, accurate to 0.01 volt, were recorded with the data-acquisition system.

Procedures 1 through 3 were used to produce one or two welds on samples having each of the twelve surface conditions. Procedures 1 and 2, substituting 100% argon for the argon-helium shielding gas, were also utilized on several of the acid-cleaned and on the wire-brushed samples. Four to eight transverse cross-sections were taken from each weld and fusion zone depth-to-width (d/w) ratios were obtained from these sections.

Machining Experiments

For the machining experiments, both arc spot-on-plate and bead-on-plate welds were produced on the machined faces of samples of Heat B utilizing Procedures 4 and 5 listed in Table 4. These welds were made with automatic voltage control and Ar-He shielding gas.

One arc spot weld was made on each of the 15 surface treatments identified in Table 3. Arc spot weld diameters (widths) were measured prior to metallographic sectioning through each weld centerline, from which the maximum depths of fusion were obtained. The bead-on-plate welds were produced by making continuous (circular) welds across several surface treatments, which allowed evaluation of changes in fusion zone shape with surface condition. Two cross-sections were taken in each of the 15 surface treatment regions to obtain weld fusion zone shapes.

Wire Brushing Experiments

Bead-on-plate welds were produced with argon-helium gas on the samples for the wire-brushing experiments using Procedure 6 listed in Table 4. One weld was made on each flat surface of samples of Heat C, each sample having been prepared with a different amount of wire brushing. At least eight transverse cross-sections were taken from each weld, and reported d/w ratios reflect the nominal values of the individual measurements.

Filler Wire Experiments

A limited number of U-groove joint welds were made with welding wire having different surface oxide-layer thicknesses. The oxide thickness differences usually arose from variations in wire production conditions. Additional tests were performed with wire lightly oxidized by heating in air.

Surface Analysis

The thickness of the oxide layers produced by various surface treatments was measured with a Surface Science Laboratory SSX-100 ESCA spectrometer using electron spectroscopy for chemical analysis (ESCA), more commonly known as x-ray photoelectron spectroscopy. Oxide thickness was measured by depth profiling the surface, and defining the oxide thickness as the ion-etching time at which the oxygen photoelectron peak area dropped to one-half the maximum value. In order to convert the ion-etching time to thickness, the etching rate was taken to be the same as that for SiO_2 on Si. The actual etching rate is likely to be somewhat different, but use of the SiO_2 rate provides a reasonable estimate and, in any event, relative values for the different surface treatments will be correct. It is recognized that oxide thickness measured in this way becomes less reliable as surface roughness increases. The measured oxide thickness on roughened surfaces should be taken as an indication only. Oxide thickness on certain samples was also measured by depth profiling in a PHI 590 Auger spectrometer. The results of these measurements were in agreement with the ESCA results and are included with them.

Results and Discussion

Chemical and Abrasive Experiments

Weld Depth of Fusion

Abrasive surface preparations resulted in significantly greater weld depth of fusion than chemical surface preparations, as illustrated by the fusion zone

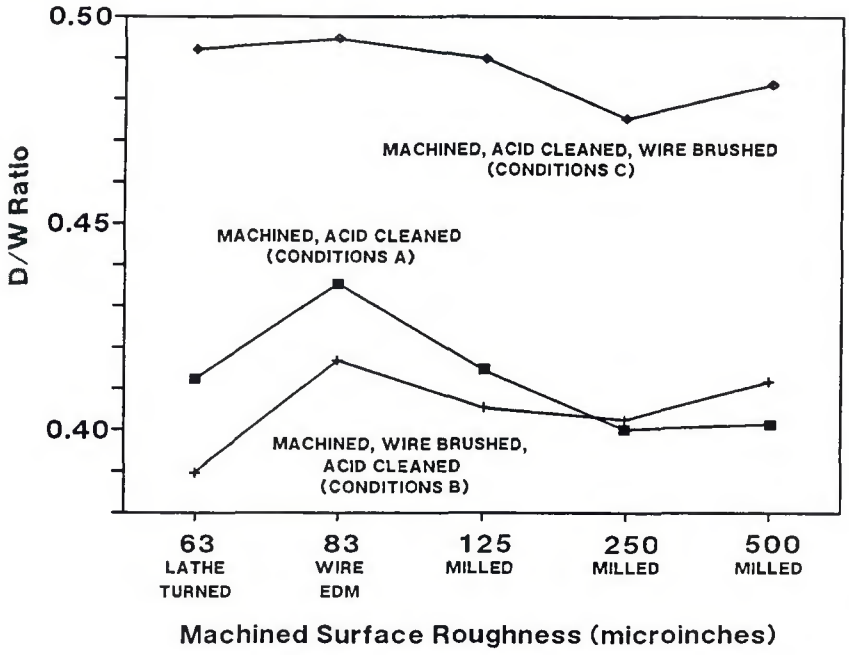


Fig. 3 — Effects of surface finish on arc spot weld d/w ratios (welding Procedure 4).

cross-sections in Fig. 1 (welds produced from Procedure 1 with constant voltage and Ar-He shielding gas). The mean, maximum, and minimum weld d/w ratios for the 12 chemically and abrasively prepared samples produced with welding Procedure 1 are plotted in Fig. 2A. All ten chemical cleaning methods (shown in the same order as listed in Table 2) produced similar fusion zone shapes, with a mean depth-to-width ratio of 0.39. In contrast, the abrasively prepared samples had significantly greater d/w ratios. The wire brushed samples produced a d/w ratio of 0.66, and the grit-blasted samples had an average d/w ratio of 0.85, more than twice that of the chemically cleaned samples.

Similar fusion zone shapes were produced when a fixed arc length was maintained. Comparison of Fig. 2A and B illustrates that the d/w ratios for the chemically prepared samples were essentially constant regardless of whether a constant voltage (Fig. 2A) or a fixed arc length (Fig. 2B) was maintained. The abrasively prepared samples also had the same weld fusion zone shapes when either constant voltage or fixed arc length were used. The difference in weld fusion zone shape between chemically and abrasively prepared samples was unchanged when Ar-He shielding gas was replaced with 100% argon.

Welds produced on the circumferences using constant voltage and pure argon also produced similar fusion zone shapes (compare Fig. 2C with Fig. 2A and B). These figures illustrate that the increased weld depth of fusion on the

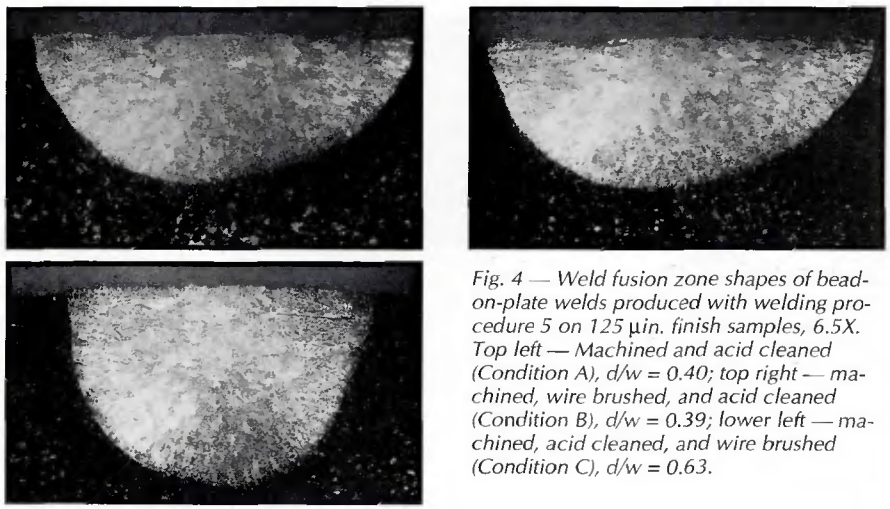


Fig. 4 — Weld fusion zone shapes of bead-on-plate welds produced with welding procedure 5 on 125 μin. finish samples, 6.5X. Top left — Machined and acid cleaned (Condition A), d/w = 0.40; top right — machined, wire brushed, and acid cleaned (Condition B), d/w = 0.39; lower left — machined, acid cleaned, and wire brushed (Condition C), d/w = 0.63.

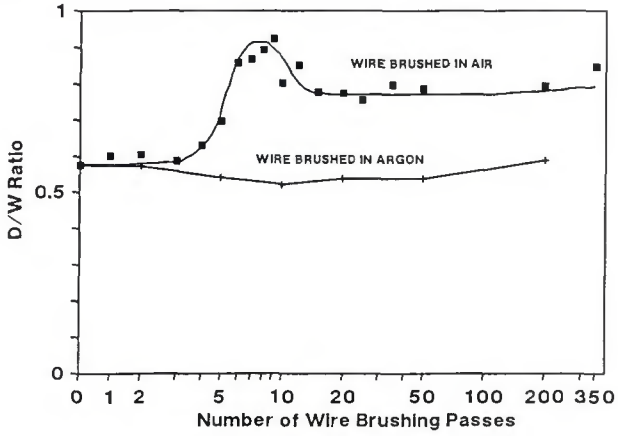


Fig. 5 — Relationship between d/w ratio and amount of wire brushing in air and in argon. Welding Procedure 6, Ar-He.

abrasively prepared samples occurs regardless of voltage/arc-length control techniques or shielding gas composition.

Surface Analysis

The increase in weld depth of fusion was related to base metal surface oxide thickness. As illustrated in Fig. 2D, the measured surface oxide thickness was essentially the same following the various cleaning treatments. However, the oxide thickness was increased substantially by wire brushing, from 14 to 25 Å for chemically prepared surfaces to 40 Å for the wire brushed sample. Wire brushing, in addition, increases the surface area by increasing the surface roughness, and oxide is also folded mechanically into the surface. It is postulated that when a weld is produced on the wire-brushed (or grit-blasted) surface, more oxygen enters the weld pool. Surface tension gradients are altered, and the fluid flow pattern changes to produce a deeper, narrower weld bead.

Changes in Arc Length and Arc Voltage

Changes in arc length at constant arc voltage, and changes in arc voltage at constant arc length, were measured as a function of surface treatment for both shielding gasses. Small differences were observed with surface treatment, but these changes were far too small to account for the observed changes in weld d/w ratio. For example, with the Ar-He shielding gas mixture, the weld d/w ratio increased by nearly 100% on the abrasively treated samples compared with the chemically treated samples. For these conditions, the nominal arc length (at a constant arc voltage of 10.0 V) decreased by only 0.003 in. (0.076 mm) on the abrasively treated samples, compared with the chemically treated samples. Likewise, the nominal arc voltage (at a fixed arc length of 0.066 in.; 1.7 mm) increased by only 0.03 V. Thus, the increase in depth of fusion is not caused simply by a change in arc characteristics.

Torch Motion/Voltage Variation

Overall torch motion during welding on the solvent-cleaned samples and on the abrasively prepared samples was approximately 54% less than on the acid-

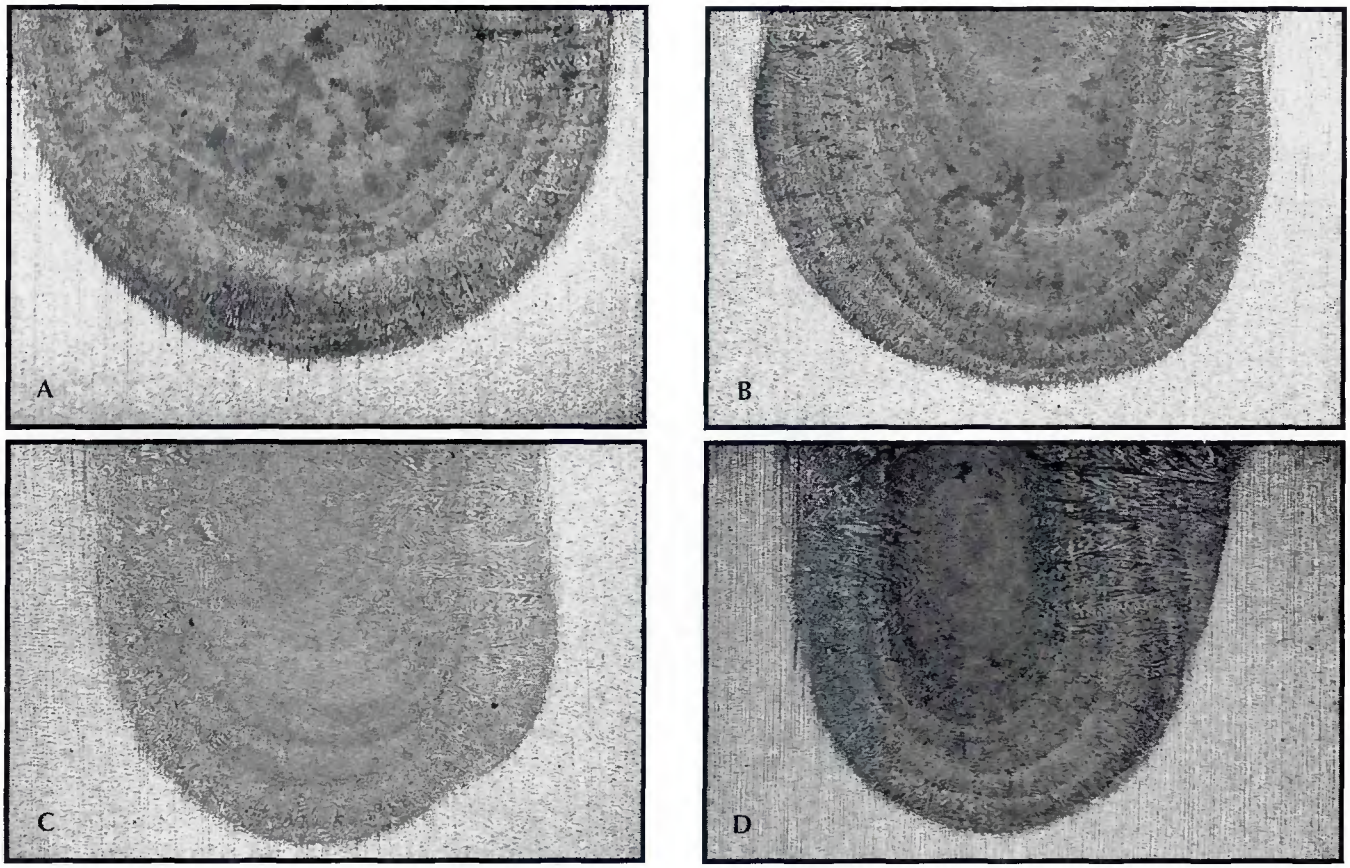


Fig. 6 — Cross-sections of welds on JBK-75 with various levels of wire brushing, 10X. Welding Procedure 6. A — Unbrushed, d/w = 0.58; B — brushed four passes, d/w = 0.63; C — brushed eight passes, d/w = 0.89; D — brushed 50 passes, d/w = 0.79.

cleaned samples (with constant voltage and Ar-He gas). Variations in arc voltage during welding with fixed arc length were also significantly lower for the solvent-cleaned samples and for the abrasively treated samples; by approximately 0.3 volt for the Ar-He gas and 0.1 volt for the argon gas. These smaller variations in both arc voltage and torch motion during welding on the solvent-cleaned samples and on the abrasively treated samples are important, especially considering the deep, narrow U-groove used in production. The wire-brushed, grit-blasted, or solvent-cleaned surfaces produce a more stable welding arc (*i.e.*, less arc wander); thus, the AVC does not sense off the sidewalls. During production welding, this allows the torch to remain in the groove without climbing up and out. The result is deeper and more consistent root penetration.

The composition of the surface oxide after acid cleaning differed from that following abrasive treatment or solvent cleaning. Acid cleaning produces a passivated surface enriched in chromium and titanium compared to surfaces not receiving acid treatment. Abrasive treatment following acid cleaning removes the thin passive oxide and leaves a typical air-oxidized surface. The difference in oxide composition appears responsible for observed changes in arc stability.

Summary: Chemical and Abrasive Experiments

The chemical and abrasive preparation experiments thus showed that abrading the surface dramatically increases weld depth of fusion compared with the ten chemical treatments. This apparently was caused by a thicker oxide combined with increased surface area, which allows more oxygen to enter the weld pool and alter fluid flow characteristics. The increase in depth of fusion was not caused by an increase in heat input from a higher arc voltage or a shorter arc length. Decreased arc stability on acid cleaned surfaces is apparently caused by the passive oxide formed by this treatment.

Machining Experiments

Measurements of the maximum arc spot weld depth of fusion and arc spot weld diameters resulted in the depth-to-width ratio curves illustrated in Fig. 3. Arc spot welds on all machined-plus-acid-cleaned samples (Conditions A) produced d/w ratios ranging from 0.40 to 0.44. On the machined, wire-brushed and acid-cleaned samples (Conditions B) the welds had similar fusion zone shapes, with d/w ratios ranging from 0.39 to 0.42. However, all welds made on the regions which were machined, acid cleaned, then wire brushed (Conditions C) had significantly (19.2%) greater d/w ratios (0.48 to 0.49) than welds made on either of the other two conditions, regardless of machined surface roughness. This was a result both of an average increase in depth of fusion of 8.8% and also an average decrease in weld spot diameter of 8.4%.

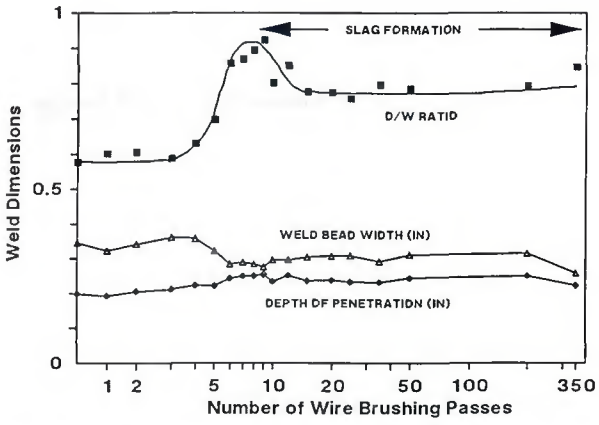


Fig. 7 — Relationship between weld dimensions and amount of wire brushing.

Differences in depth of fusion with surface roughness are minor in comparison to the differences observed when the surface was wire brushed as the final operation prior to welding — Fig. 3. Surface roughness measurements of the wire-brushed samples were similar regardless of whether they were brushed before or after acid cleaning (wire-brushed surfaces were rougher than as-machined surfaces). Therefore, the increase in d/w ratio was caused by the microscopic abrasion produced by wire brushing rather than by macroscopic roughening produced by machining.

Bead-on-plate welds showed similar welding responses. Cross-sections from bead-on-plate welds on the surface with a 125 microinch finish are shown in Fig. 4. The weld fusion zone for the sample which was machined, acid cleaned, and wire brushed (Fig. 4C) is deeper and narrower than for the other two conditions

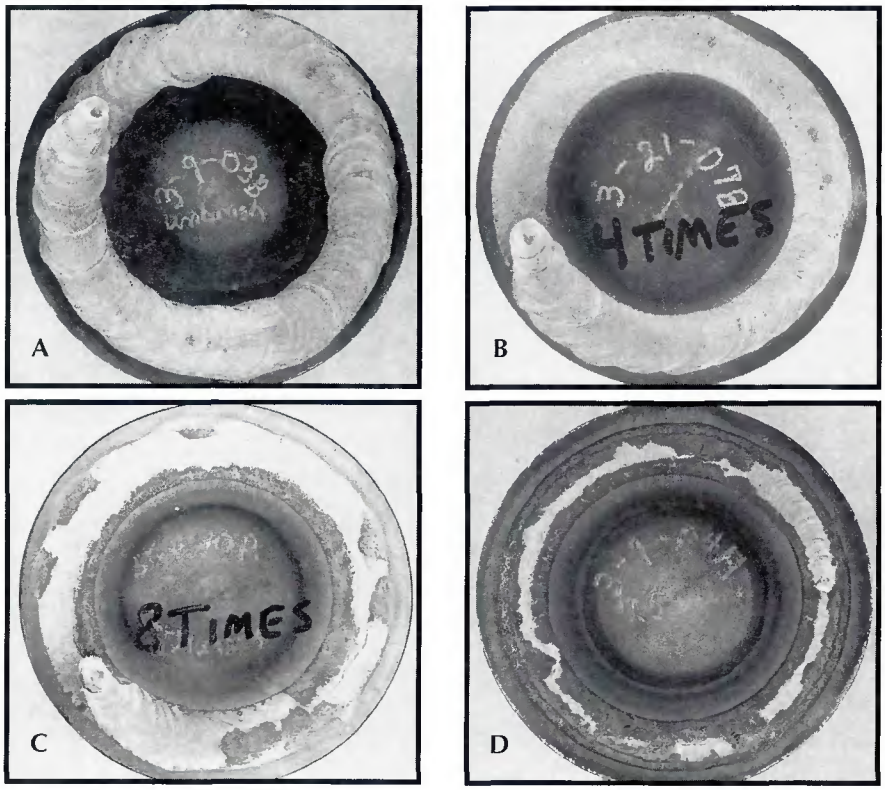


Fig. 8 — Top views of welds on JBK-75 with various levels of wire brushing, 1.3X. Welding Procedure 6. A — Unbrushed; B — brushed 4 passes; C — brushed 8 passes; D — brushed 50 passes.

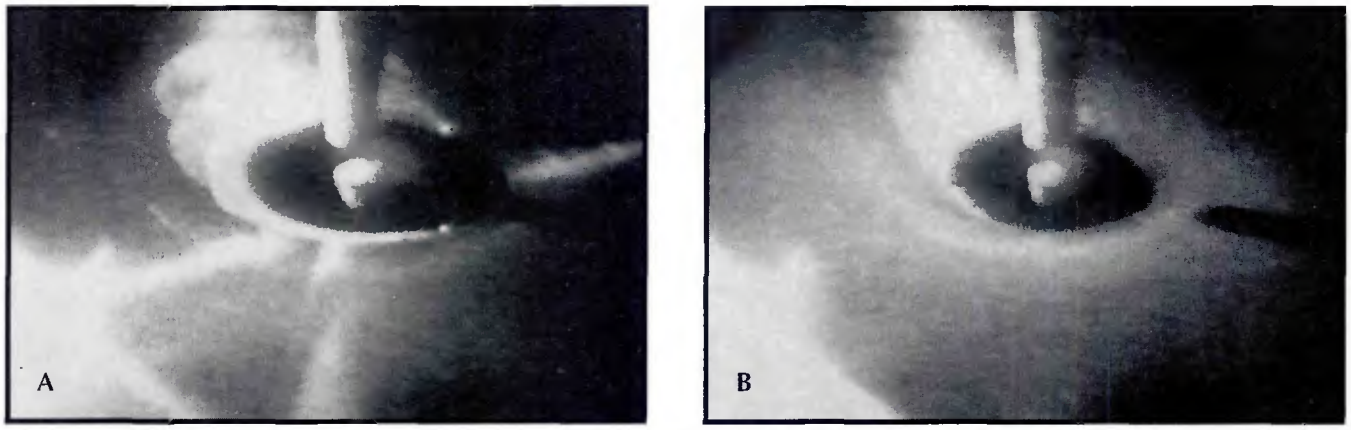


Fig. 9 — Still photographs taken from laser-enhanced video of welds, 4.8X. Arc light is filtered out, revealing only weld pool and electrode tip. A — Weld on acid-cleaned, unbrushed surface; B — weld on surface wire-brushed 2 times.

with the same surface finish — Fig. 4A and B. Depth-to-width ratios increased dramatically, from 0.39 to 0.40 for the samples that were acid cleaned after machining (and wire brushing), compared to 0.63 for the sample that was wire brushed after the cleaning operation.

Depth-to-width ratios on arc spot welds and bead-on-plate welds were similar for Conditions A and B. However, the d/w ratio for Condition C (*i.e.*, wire brushed as the final operation before welding) was significantly greater for the bead-on-plate weld (0.63) compared with the arc spot weld (0.49). This difference is most likely a result of differences between stationary and traveling welds.

One important difference between stationary and traveling welds is that the weld pool surface temperature reached in stationary welds exceeds that in traveling welds (Ref. 10). Trace element effects should therefore be less pronounced in stationary welds because a larger portion of the pool surface is above the temperature range where a positive surface tension temperature coefficient exists (Ref. 11). In addition, for a stationary weld on a material where surface active elements are present largely on the surface of the base metal, a smaller and smaller proportion of surface material is added to the weld pool as it grows. For a traveling weld, the proportion is constant as the weld progresses. Thus, both effects tend to make weld depth of fusion less sensitive to surface condition for a stationary weld compared to a traveling weld. The relative importance of the two effects cannot be determined from the experiments reported here.

Although there is some variation in depth of fusion with machined surface finish, in all cases the samples which had been wire brushed as the final operation prior to welding produced the highest depth-to-width ratios. Wire brushing substantially increases the amount of oxygen on the surface because of increased oxide thickness, increased surface area (from micro-roughness), and mechanical folding of oxide into the surface. This combined increase is much larger than from differences in machined surface finish.

Wire Brushing Experiments

Weld Depth of Fusion/Arc Behavior

Weld d/w ratio was a strong function of the amount of wire brushing. A plot of weld d/w ratio vs. amount of wire brushing is shown in Fig. 5 for welds produced in Ar-He. Similar fusion zone shapes were produced when welded with 100% argon, only with lower d/w ratios. Figure 5 also shows that wire brushing only changes weld fusion zone shape when the wire brushing is performed in air (or, presumably, in some other oxygen-containing atmosphere). Wire brushing in argon had no effect on subsequent fusion zone shape, and welds on all samples wire brushed in argon behaved similarly to those on unbrushed surfaces.

The change in fusion zone shape for wire-brushed samples (in air) compared to unbrushed (acid cleaned) samples is quite dramatic. Weld cross-sections from four conditions are shown in Fig. 6. The increase in d/w ratio is approximately 50% as a result of the optimum brushing condition. The maximum in weld d/w ratio at 6 to 9 wire brushing passes results from both a narrowing and deepening of the weld pool, as illustrated in Figs. 6 and 7. Beyond approximately 12 wire brushing passes, weld fusion zone shapes are constant.

Figure 8, which illustrates the top surfaces of the same four welds shown in Fig. 6, reveals several features. Weld beads become narrower and the shape of the weld bead becomes more uniform, with parallel edges, as the amount of wire brushing is increased. However, slag forms along the edges of the weld with eight or more wire brushing passes, and the amount of slag increases with increasing wire brushing. With 50 wire brushing passes, the slag is continuous along both edges of the weld, as illustrated in Fig. 8D and by the uneven top surface in Fig. 6D.

It should be noted that a portion of the increase in weld d/w ratio with modest amounts of wire brushing results from a change in arc-weld pool behavior. Photographs of welds are shown in Fig. 9 for unbrushed and two-times wire-

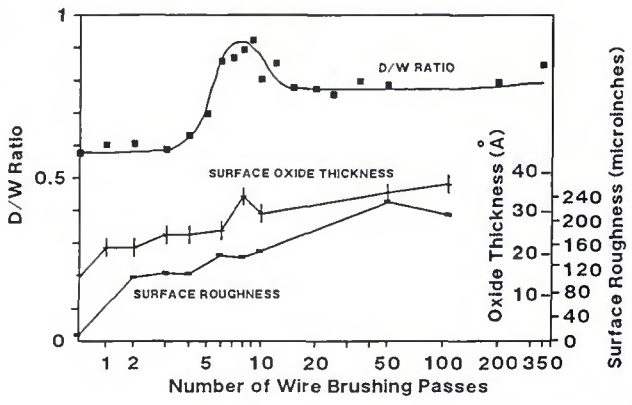


Fig. 10 — Relationship between weld d/w ratio, surface oxide thickness and surface roughness.

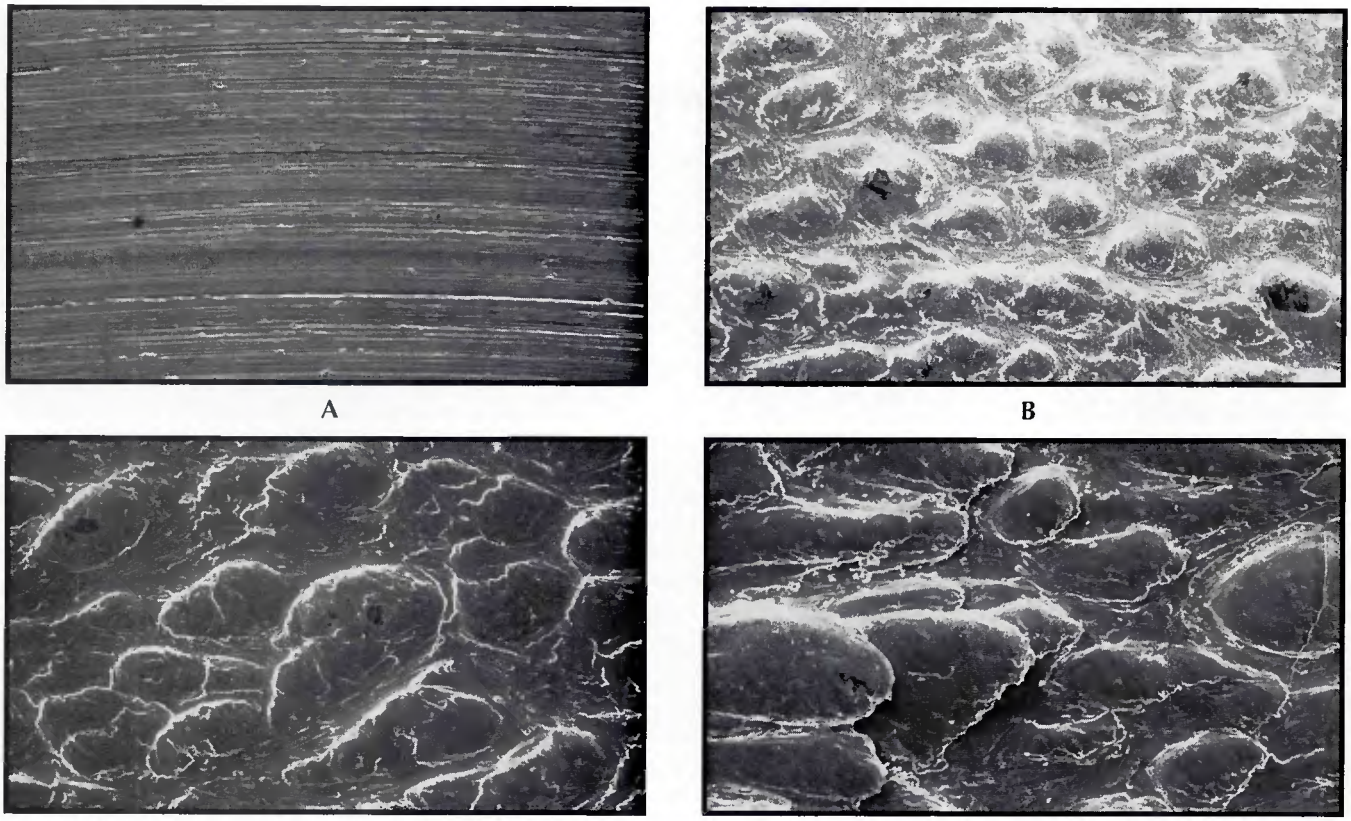


Fig. 11 — Scanning electron micrographs of wire brushed surfaces, 100X. A — Unbrushed; B — brushed four passes; C — brushed eight passes; D — brushed 50 passes.

brushed samples. These still photographs were taken from a videotape made during welding, utilizing a laser-enhanced vision system. A video camera sensed the image of the weld pool, and by appropriate shuttering and synchronization of an ultraviolet laser and camera, the arc light was filtered out so that only the electrode tip and weld pool are seen (a reflection of the electrode tip appears in the center of the weld pool). The photographs in Fig. 9 reveal instantaneous weld pool dimensions, weld pool wander, and overall weld bead width.

The weld pool on the unbrushed sample (Fig. 9A) is wide and wanders in a side-to-side and front-to-back motion. This wander is caused by the arc-weld pool interactions with the base metal surface. The weld pool sweeps out a width approximately 120% of the instantaneous pool width and the resultant weld bead, as measured by transverse cross-sections, is thus wider than the actual pool. The wander produced the irregular weld bead shape illustrated in Figs. 8A and 9A for the unbrushed sample.

On the sample that was brushed two times (Fig. 9B), the pool became narrower — approximately 70% as wide as the weld on the unbrushed sample. The weld bead in this case is the same width as the instantaneous pool width. Weld pool wander also ceased, producing a more desirable welding performance and a uniform weld bead with parallel edges, as evidenced by the weld face appearance in Fig. 8B for a sample brushed four times. Overall vertical torch motion decreased significantly with wire brushing, from 0.017 in. (0.43 mm) for the unbrushed samples to 0.001 to 0.002 in. (0.025 to 0.051 mm) for samples wire brushed five or more passes. The frequency of torch motion was also reduced by 50% on the wire-brushed samples. On heavily brushed surfaces, particles were observed moving along the top surface of the weld pool inward toward the center, as expected from the fluid flow pattern re-

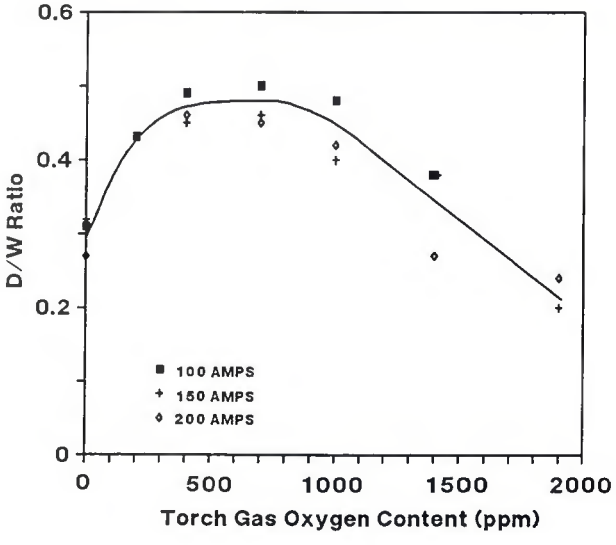
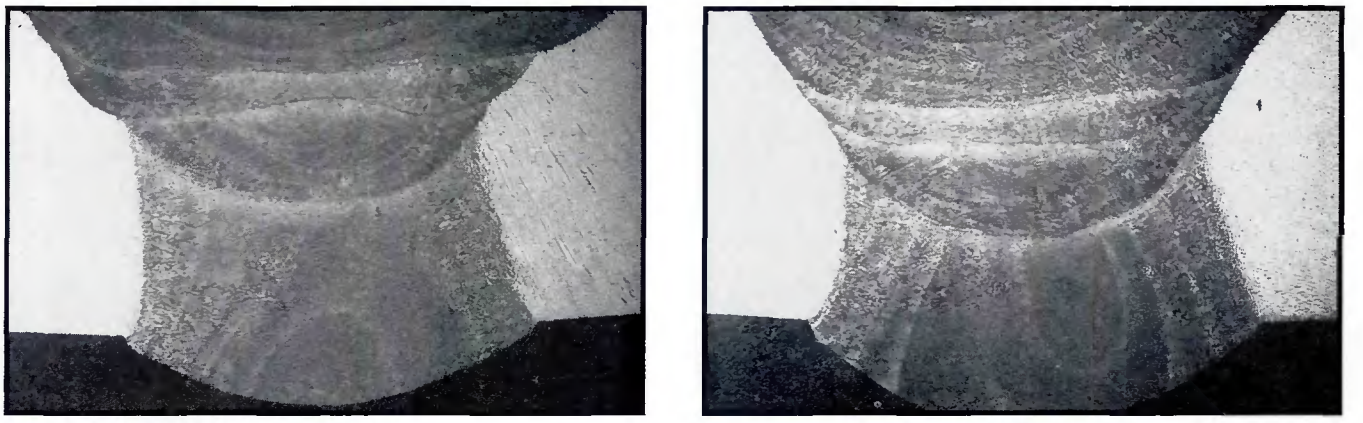


Fig. 12 — Weld d/w ratio vs. shielding gas oxygen content (Ref. 3).



A B

Fig. 13 — Cross-sections of full penetration welds on acid cleaned, unbrushed, JBK-75 base metal using two different spools of JBK-75 welding wire, 8X. The wire was from the same heat, but had different surface oxide thickness. A — Wire oxide thickness 76 Å; B — wire oxide thickness 133 Å.

sponsible for large depth of fusion.

Photographs from the videotape revealed that the wire-brushed surface produced two different qualitative effects. One reduces the width (while increasing the depth) of the weld by surface-tension driven fluid flow. The other increases arc stability and decreases pool wander. The increase in weld bead depth-to-width ratio is a result of both of these. The latter effect has the most significance in terms of improving welds made in grooved joints.

Surface Analysis

Wire brushing results in an increase in surface oxide thickness, as measured by ESCA and Auger depth profiling — Fig. 10. The increased oxide thickness is attributed to local heating under the wire brush. These results are consistent with the results from the chemical and abrasive experiments.

Wire brushing produces a dull, matte finish compared with the bright, shiny surface appearance obtained by acid cleaning. There is also a substantial increase in surface roughness, as illustrated in Fig. 10 and the scanning electron micrographs in Fig. 11. The unbrushed surface reveals the lathe-turned finish while heavy brushing produces extensive surface lapping. Oxidized surfaces have been mechanically folded over themselves, thereby increasing the surface area. Further brushing causes more and more surface to become exposed and folded. Wire brushing in argon produced similar surface roughnesses but caused no change in surface oxide thickness from the unbrushed surface, and resulted in no change in weld depth of fusion — Fig. 5.

The combination of increased oxide thickness, increased surface area, and oxide trapped in surface laps with more wire brushing adds oxygen to the weld pool during welding. This additional oxygen produces inward surface tension driven fluid flow, resulting in increased weld d/w ratios.

Slag Formation

For heavily brushed surfaces (greater than approximately 12 wire brushing passes), the level of oxygen apparently exceeds the solubility limit in the liquid and results in formation of weld slag on the top surface of the weld pool (Fig. 8C and D). ESCA profiling of surface slag revealed it to be nearly all titanium oxide, with minor amounts of chromium, nickel, aluminum and nitrogen. Apparently the presence of extensive slag on the weld pool surface interferes with the arc, as well as the fluid flow patterns necessary for high depth-of-fusion weld pools.This results in the decreased d/w ratios for greater than approximately 12 wire brushing passes, as illustrated in Fig. 7.

The behavior of weld d/w ratio with increasing wire brushing is consistent with previous measurements of the effect of shielding gas oxygen content on weld d/w ratio (Fig. 12) (Ref. 3). Weld d/w ratio passes through a maximum with increasing shielding gas oxygen content, and then declines.

Welding Wire

Similar weld variability has been observed with differences in JBK-75 welding wire surface oxide. Figure 13 reveals the differences in full penetration weld fusion zone shape produced by two spools of wire made from the same heat and lot of material. Each spool of wire was cold-rolled and abrasively cleaned separately, resulting in somewhat different surface oxide thicknesses. The wire with the thicker oxide layer (133 Å) produced deeper, narrower weld pools, which remained down in the groove and resulted in adequate root reinforcement. Wire lightly oxidized by heating in an air furnace also produced improved depth of fusion.

Amount of Oxygen Added

The correlation between increasing oxide thickness and fusion zone shape is good, but the question naturally arises as to whether there is enough oxygen in these thin oxides (particularly on welding wire) to conceivably alter weld pool behavior. For the 0.045-in. (1.1-mm) diameter welding wire, a simple calculation demonstrates that a 70-Å-thick Cr_2O_3 layer on a perfectly smooth cylindrical surface would add about 5 ppm oxygen to the average oxygen content of the wire. However, the actual wire surface is not at all smooth, so that the real surface area is considerably larger than the geometric area calculated assuming a smooth surface. The ratio of the actual surface area to the geometric area is known as the surface roughness factor. The surface roughness factor has been measured by Maeda, *et al.* (Ref. 12), for 304 stainless steel polished to a mirror-like surface with 0.3-μm alumina. They obtained a surface roughness factor of 2.7. Prazak and Eremias (Ref. 13) found a factor of 8.9 for steel, grit blasted with 0.3-mm grit. The roughness of the cold-rolled welding wire is probably similar to the grit-blasted steel, so the actual oxygen contribution from a 70-Å- thick oxide layer is likely to be about 45 ppm. Thus, the magnitude of the oxygen addition from the welding wire is comparable to that known (Ref. 2) to cause substantial changes in weld pool shape.

The contribution of oxygen from

wire-brushed surfaces, particularly in a weld groove, is even larger. Bulk chemical analysis for oxygen was performed on two samples of weld metal from each of several welds with different surface preparations. One sample included the weld face and any slag present, while the other sample did not include the surface. The samples which included the weld face were 0.050 in. (1.3 mm) thick, and all samples contained only weld metal.

For samples wire brushed in air, the oxygen content of the bulk weld metal increased only slightly with increasing amounts of wire brushing (up to only 50 ppm compared with the 44 ppm oxygen base metal composition). However, samples including the weld surface showed substantially higher oxygen content with wire brushing, up to 180 ppm oxygen for the sample wire brushed 35 times. Thus, while some oxygen entered the bulk weld metal, most of the additional oxygen added to the weld pool as a result of wire brushing in air remained on the pool surface.

For samples wire brushed in an argon atmosphere, chemical analysis showed essentially no difference in oxygen content between the bulk weld metal and the samples including the weld face. There was no increase in oxygen with increasing amounts of wire brushing. Thus, brushing in argon does not introduce appreciable oxygen into the surface.

Summary

All the observations are consistent with the addition of oxygen to the weld pool from the welding wire or base metal surface as the cause for changes in weld pool shape. Wire brushing in air increases the oxygen content of the surface and changes fusion zone shape. Wire brushing in argon does not change the surface oxygen content appreciably and does not alter weld fusion zone shape. The dependence of weld d/w ratio on the amount of wire brushing is similar in form to the dependence of weld d/w ratio on oxygen additions to the shielding gas. Various chemical surface cleaning treatments did not change surface oxide thickness significantly and had little effect on fusion zone shape. A simple calculation indicates that enough oxygen is available in the surface oxides to affect weld pool shape. Slag formation on welds over heavily wire-brushed surfaces demonstrates that oxygen is being added to the weld pool. A portion of the improvement in fusion zone shape from wire brushing arises from increased arc stability and reduced pool wander. The lower arc stability on acid cleaned surfaces is apparently caused by the surface oxide, enriched in chromium and titanium formed by this treatment.

Other methods of introducing oxygen increase weld d/w ratio. Silica grit blasting produced increased weld depth of fusion; however, welding behavior was undesirable because of arc instability and excessive pool slag. Possible entrapment of silica in the surface was also a concern. These problems may be correctable with less severe grit blasting. Heat treatment to oxidize the surface also increases depth of fusion.

Finally, it should be noted that GTA weld pool shape in JBK-75 stainless steel appears to be particularly sensitive to oxygen additions. Similar results were obtained on all three heats of JBK-75 in spite of small variations in sulfur, oxygen, aluminum and silicon contents. Limited tests similar to those reported here have been performed on 304L, 316L and 21-6-9 stainless steels. The results were similar to those with JBK-75, but the effects appear to be smaller and more brushing is required to produce any change.

The origin of the high sensitivity of JBK-75 stainless steel fusion zone shape to oxygen is not known. JBK-75 is the only alloy studied that contains Ti and Al above trace levels, which might be responsible for the alloy's high sensitivity to oxygen. Another possibility is indicated by surface tension measurements on iron-silicon alloys in contact with carbon dioxide (Ref. 14). The effect of CO_2 on the surface tension was a strong function of silicon content. For low-silicon alloys, the surface tension dropped sharply when contacted with CO_2. For alloys with more than 1.2% Si, the surface tension increased when contacted with CO_2. The different behavior was attributed to differences in slag formation on the liquid metal surface. Thus, silicon appears to interfere with the ability of oxygen to produce a positive surface tension temperature coefficient on liquid iron. The JBK-75 stainless steel used in the experiments reported here contained only about 0.06% Si, and the 21-6-9 stainless steel used for the shielding gas experiment (Fig. 12) contained only 0.16% Si. Type 304 stainless steel typically contains more than 0.5% Si. Thus, the high sensitivity of JBK-75 to oxygen additions may be related to its unusually low silicon content.

Conclusions

Small changes in the concentration of surface active trace elements in weld pools can have a substantial effect on GTA weld pool shape in high-purity steels. Because the quantity of surface active material required to affect weld pool shape can be so small, it can arise from unexpected sources. Wire brushing, or other abrasive surface treatments (in air), are effective means of increasing GTAW depth of fusion and improving arc stability, at least in JBK-75 stainless steel. Wire brushing alters the surface of JBK-75 by producing a thicker oxide layer than produced by chemical cleaning methods. Wire brushing also roughens the surface, and folds laps of oxide into the surface, thereby increasing the amount of oxide. The oxygen added to the weld pool alters fluid flow and improves depth of fusion (d/w ratio) in accord with the surface tension driven fluid flow model proposed by Heiple and Roper. Acid cleaning of JBK-75 produces an oxide layer enriched in chromium and titanium, which apparently causes significant arc instability and weld pool wander for reasons not at present understood. This thin layer is removed by wire brushing, thereby producing a more stable welding arc.

Increasing the amount of brushing increases the surface roughness and the oxide thickness. This causes weld depth of fusion to increase until the oxygen solubility limit is reached, at which time a slag forms on the surface of the weld pool. This slag affects the fluid flow and reduces weld depth of fusion. The optimum level of wire brushing on flat surfaces occurs between 6 and 9 wire brushing passes. The optimum level will be different in a groove.

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Recommendations Proposed by the PVRC Committee on Review of ASME Nuclear Codes and Standards Approved by the PVRC Steering Committee

WRC Bulletin 370
February 1992

The ASME Board on Nuclear Codes and Standards (BNCS) determined in 1986 that an overall technical review of existing ASME nuclear codes and standards was needed. The decision to initiate this study was reinforced by many factors, but most importantly by the need to capture a pool of knowledge and "lessons learned" from the existing generation of technical experts with codes and standards background.

Project responsibility was placed with the Pressure Vessel Research Council and activity initiated in January 1988. The direction was vested in a Steering Committee which had overview of six subcommittees.

The recommendations provided by nuclear utilities and industry were combined with the independent considerations and recommendations of the PVRC Subcommittees and Steering Committees.

Publication of this document was sponsored by the Steering Committee on the Review of ASME Nuclear Codes and Standards of the Pressure Vessel Research Council. The price of WRC Bulletin 370 is $30.00 per copy, plus $5.00 for U.S. and $10.00 for overseas, postage and handling. Orders should be sent with payment to the Welding Research Council, Room 1301, 345 E. 47th St., New York, NY 10017.