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Fitup Tolerances for Mechanized Gas Tungsten Arc Welding Large Diameter Pipe

Study on the influence of fitup tolerances and welding position on weld quality indicates that narrow gap weld joint design is very tolerant of typical variations in the fitup of girth joints

BY P. W. TURNER AND G. D. EICHENBERGER

ABSTRACT. Thirty-two narrow-groove weld joints were welded on 0.36 m (14 in.) diameter, Schedule 80S, AISI 316 stainless steel pipe to evaluate fitup tolerances. Welds were made in both the 2G (pipe oriented vertically) and 5G (pipe oriented horizontally) positions using two levels of root opening and misalignment. These joints were made by the mechanized gas tungsten arc welding process employing an orbiting welding head and a 300 ampere pulsed direct current power supply. The overall effort consisted of a 2^3 factorial experiment with two welds per fitup, plus 16 additional welds to provide further information on fitup conditions.

Measurements of concavity and reinforcement indicated that all 32 welds were well within the permissible limits of Department of Energy standards for nuclear piping and Paragraph NB-4426.2 of the ASME Boiler and Pressure Vessel Code. Also, analysis of the factorial experiment showed that the narrow-groove weld joint design is very tolerant of typical variations in the fitup of girth joints.

Introduction

Problems in implementing mechanized welding technology are associated with joint geometry, alignment and fitup methods, fitting design, and general design and construction practices which are still oriented toward manual welding requirements. Automatic welding requires closer tolerances than does manual welding, and accurate joint preparation and alignment are prerequisites.

Prior work (Ref. 1, 2) at the Idaho National Engineering Laboratory (INEL) resulted in the development of the joint design illustrated in Figs. 1 and 2 for machine welding of thin-wall pipe. This geometry, without a consumable insert, has been prepared and welded satisfactorily on 0.91 m (36 in.) diameter, Schedule 80, AISI 316 stainless steel pipe (Ref. 2) and was also used in the work reported here.

The present study was conducted to examine the influence of fitup tolerances and welding position on weld quality. This work was performed as a two-level factorial experiment to assess main and interaction effects among variables. Later, additional welds were made to acquire qualitative information on fitup conditions that were not within the scope of the factorial experiment.

The maximum value of uniform mismatch was limited to 1.59 mm ($\frac{1}{16}$ in.). This value is twice that allowed by Paragraph NB-4233 of the ASME Boiler and Pressure Vessel Code for aligning components when inside surfaces are inaccessible for fairing. The study does not include joints having misalignment at local points.

Description of Experiment

A 2-level, 3-variable (2^3) factorial experiment was set up to determine the effects of welding position, mismatch, and root opening on the quality of the root bead. Table 1 lists the nominal levels of each variable, and Table 2 shows the eight combinations of fitup and testing conditions used to evaluate the effects of the three variables.

Two joints were welded in each fitup combination, making a total of 16 welds, to satisfy statistical requirements for estimating experimental error. Sixteen additional joints were welded to explore conditions not included in the factorial experiment.

All welding was performed with commercially available equipment. The mechanized head, equipped with a torch oscillator and automatic voltage control, was powered by a 300 ampere (A) direct current power source. The equipment contained programmable quadrant controls and capability for welding in pulsed-power modes including step-pulsed, pulse current, and synchronization of wire feed rate with other pulsing parameters.

The welding coupons were approxi-

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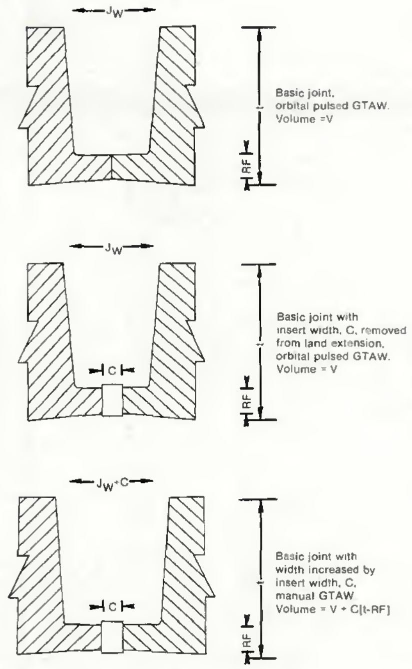

Fig. 1—Evolution of a basic joint geometry with field welding options

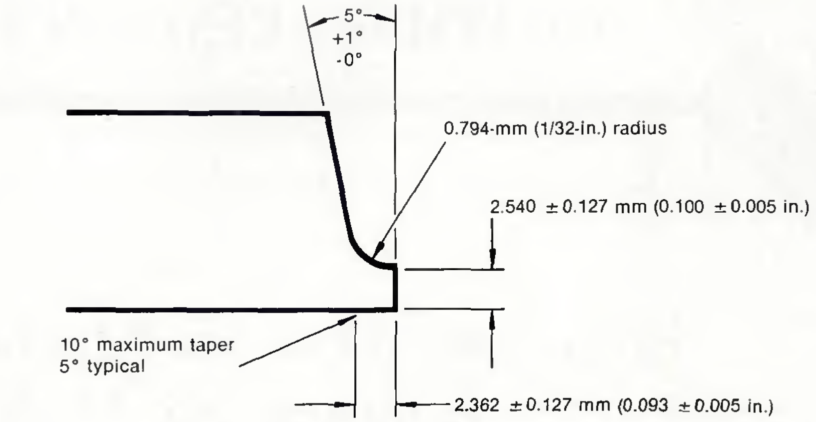

Fig. 2—Details of narrow-groove weld joint geometry

mately 200 mm (8 in.) long sections of 356 mm (14 in.) diameter, Schedule 80S austenitic stainless steel pipe conforming with the requirements of ASTM A-358. The filler metal was 1.14 mm (0.045 in.) diameter ER 316 conforming to AWS A-5.9-69; additional descriptions of backing and shielding gases are given in Table 3.

All end preparations were machined on a lathe. The narrow-groove weld joint geometry shown in Fig. 2 was used. Mismatch or misalignment at the root of the joint was achieved by machining the bore of one member so that, in effect, the diameters of the bore and bevel features were 3.18 mm (⅛ in.) larger than the corresponding diameters of the mating member and then concentrically aligning the members. During welding, the coupons were held by three tack welds about 25 mm (1 in.) long, spaced 120 deg apart on all welds having a root opening. The root openings were measured (midway between the tacks) with a feeler gauge at the center of each section.

The root passes for those welds with root openings greater than zero were made in three sections by welding from one tack to the next, starting at the zero-degree location for 2G position welds and 4 o'clock for 5G position welds. Each joint was welded from the 4 to the 7 o'clock location of the 5G position to obtain specimens for factorial analysis, because it had been previously determined that the tendency toward concavity is greatest at or near the 6 o'clock location. The root opening of each section was measured again just prior to welding, because it was affected by the welding of the previous section. Joints with root openings larger than that of the experimental design (0.79 mm or ⅓2 in.) were rejected and used in exploratory tests. All welds with a zero root opening were tack welded without addition of filler metal and each root pass was welded continuously.

All welds were made with just two passes (including the root pass) using the gas tungsten arc welding (GTAW) process. Filler metal was added on the root pass, and the pipe ends were unrestrained. The welding procedure employed was previously qualified to the ASME Boiler and Pressure Vessel Code, Section IX, on a joint without mismatch or root opening. Nominal welding procedure parameters used for most welds are listed in Table 3.

Some welds in the 2G position had root openings larger than those specified in the experimental design, and some uphill areas of joints in the 5G position had both maximum mismatch and a root opening. For these conditions, the root passes were made with both the weld and low-pulse currents reduced by ten amperes and the wire feed rate increased by 250 mm (10 in.) per minute.

Measurements

To illustrate weld quality and the pro-

Table 1—Nominal Variable Levels

Variable	Levels Low	Levels High
Position	2G	5G
Mismatch, mm	0	1.59
(in.)		(1/16)
Root opening, mm	0	0.79
(in.)		(1/32)

Table 2—Joint Fitup Combinations and Results

Fitup combination No.	Fitup combination 1st weld	Fitup combination 2nd weld	Welding position	Nominal mismatch, mm	Nominal root opening, mm	Concavity or reinforced area, mm² 1st weld	Concavity or reinforced area, mm² 2nd weld	Concavity or reinforced area, mm² Average	C_i[a] mm	C_i[a] in.
1	UG 14(100)−7	UG 4(100)−12	2G	0.00	0.00	0.836	0.279	0.588	0.246	0.010
2	−15	−22	5G	0.00	0.00	−0.372	−0.222	−0.297	−0.131	−0.005
3	−10	−13	2G	1.59	0.00	3.345	3.779	3.562	1.567	0.062
4	−16	−20	5G	1.59	0.00	2.292	2.317	2.304	1.014	0.040
5	−8	−14	2G	0.00	0.79	0.186	−0.031	0.078	0.034	0.001
6	−18	−21	5G	0.00	0.79	−0.838	−0.937	−0.888	−0.391	−0.015
7	−9	−11	2G	1.59	0.79	4.522	3.469	3.996	1.760	0.069
8	−17	−19	5G	1.59	0.79	1.972	2.292	2.132	0.938	0.037
					Totals	11.94	10.95	11.45	5.04	0.199

(a) The areas of the concave and reinforced portions of the root beads are converted to linear values (mm) by multiplying the area by a form factor, 0.44/mm (estimated accuracy ±0.066 mm) determined from measuring concave cross sections. Actually the reinforced zones tend to be triangular in cross section when mismatch is large, i.e., a tiny fillet is formed on the root side of the mismatched joint.

Table 3—Nominal Welding Procedure

Parameter	Setting Pass 1	Setting Pass 2
Arc volts, DC	11.7	11.8
Weld current, A	190	210
High pulse time, s	0.2	–
Low pulse current, A	90	50
Low pulse time, s	0.8	–
Filler metal feed, ipm	80	150
Filler metal upslope, s	4.0	4.0
Filler metal delay, s	1.0	1.0
Filler metal decay, s	0.1	0.1
Carriage speed, ipm	6.0	4.2
Carriage delay, s	2.0	1.2
Carriage travel	Low	Low
Dwell-left, s	–	0.3
Dwell-right, s	–	0.3
Oscillator, cpm	–	99
Synchronization	On	On
Mode	Step pulse	Pulse
Shielding gas (75 He-25 Ar, vol-%), cfh	50	50
Backing gas, (Ar), cfh	10-20	10-20

files of the root bead and fusion zone, one photomacrograph was made of the transverse cross section of each weld at 60 deg from the start on welds made in the 2G position and at 6 o'clock on joints welded in the 5G position. Two types of measurements were made from these photomacrographs.

Measurements Specified by the ASME Code and Department of Energy Nuclear Standards

Measurements of concavity and reinforcement at the root of a weld are referenced to the lower of the inside abutting surfaces and to the higher of the abutting surfaces involved, respectively. The root bead contour or geometry at the mismatched zone between the lower and the higher of the inside abutting surfaces of inaccessible joints is not quantitatively defined in either Department of Energy (DOE) standards for nuclear piping or Code requirements. Nuclear standards do stipulate that permissible concavity has "a uniform radius and blends smoothly with the adjacent base metal."

Both the standards and the Code specify that concavity must not reduce the thickness of the weld below the minimum thickness of the thinner member of the joint. On the other hand, when the joint is accessible, paragraph NB-4732.1 of the Code quantitatively states that any mismatch within allowable tolerance "be faired to at least a 3 to 1 taper over the width of the finished weld or, if necessary, by adding additional weld metal beyond what would otherwise be the edge of the weld." Consequently, in the present work, a method was sought for quantitatively expressing and comparing root geometries of unfaired joints experimentally welded with various fitup conditions.

The concavity or convexity of the fillet at the root of the joint was determined graphically from macrographs of the weld cross section. This measurement was performed by drawing a straight line between the points of intersection of the fusion lines with the inside circumferences of the joint members, and then measuring the maximum deviation of this line from the root bead profile. The data are presented in Table 4.

The concavity or convexity measurement only provides information about the fillet contour at the root of a butt joint that is fully penetrated and has no concavity. Thus, it cannot be compared directly with other data in this experiment. The areal measurement for determining concavity and reinforcement is described in the next section.

Areal Measurements

A method of measurement was needed that would provide sufficient data to quantitatively rate the ability of the welding process and procedure to produce welds on misaligned joints or compare root geometries of welds made on joints having a wide variety of fitups as listed in Table 2. As a consequence, other approaches were used as development tools to analyze effects on root bead penetration and geometry.

Measurements of the areas of zones defined graphically in Fig. 3 were used to analytically show the tendency of fitup variations to cause concavity and reinforcement of the root bead with respect to the lower of the inside abutting surfaces. The areas of these zones were measured from macrographs with a planimeter. These areas can be mathematically related to the conventional expressions of concavity and reinforcement by making the simplifying assumption that the convex and concave contours and geometries are similar but opposite in sign. A form factor was used to express these areas as depth of concavity or height of reinforcement, a dimension more easily visualized and of more practical significance.

Table 4—Reinforcement in Welds on Joints With 1.59 mm (1/16 in.) Uniform Mismatch

Weld	Welding position	Root opening mm	Root opening in.	Root bead[a] fillet shape + convexity − concavity mm	Root bead[a] fillet shape + convexity − concavity in.	Macrograph	Taper
UG 14(100)−25	2G	0	0	0.38	0.015	–	–
−9	2G	0.79	0.031	0.20	0.008	Fig. 13	2.1
−13	2G	0	0	0.20	0.008	Fig. 8	2.2
−11	2G	0.76	0.030	0.15	0.006	Fig. 14	2.6
−23	2G	1.22	0.048	0.15	0.006	–	–
−10	2G	0	0	0.10	0.004	Fig. 9	2.2
−28	2G	0.76	0.030	−0.22	0.009	–	–
−26	2G	0	0	−0.25	−0.010	–	–
UG 14(100)−16	5G	0	0	−0.25	−0.010	Fig. 10	2.1
−20	5G	0	0	−0.27	−0.011	–	–
−34	5G	0.81	0.032	−0.27	−0.011	Fig. 15	1.9
−32	5G	0.89	0.035	−0.28	−0.011	–	–
−38	5G	0.86	0.034	−0.34	−0.013	–	–
−36	5G	0.86	0.034	−0.34	−0.013	–	–
−19	5G	0.84	0.033	−0.40	−0.016	–	–
−35	5G	0	0	−0.47	−0.019	–	–
−37	5G	0	0	−0.47	−0.019	–	–
−17	5G	0.84	0.033	−0.55	−0.022	–	–
−31	5G	0.89	0.035	−0.55	−0.022	–	–
−30	5G	0.81	0.032	−0.58	−0.023	–	–

(a) Location: 60 deg from weld start in 2G position and 6 o'clock in 5G position. (Note: None of these welds has either concavity or reinforcement according to requirements of DOE standards for nuclear piping and Par. NB-4426.2, Sec. III, ASME Boiler and Pressure Vessel Code.)

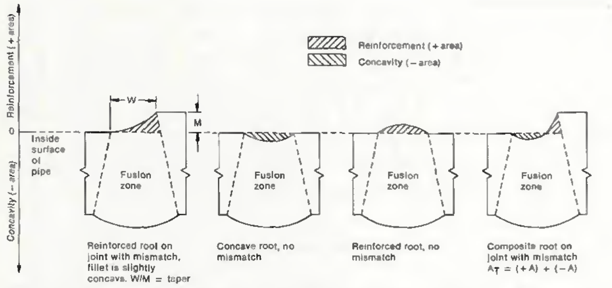

Fig. 3 — Definition of areal measurements relating to concavity and reinforcement tendencies

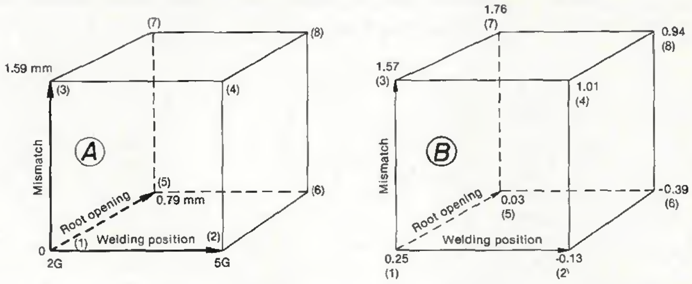

Fig. 4 — Average values in millimeters of C_i for each of 8 trials indicated in parentheses: A — Factorial experiment represented as a cube; numbers in parentheses are fitup combination numbers of Table 1. B — Average concavity/convexity, in millimeters, for each fitup combination

Data Analysis

Table 2 shows data obtained from the replicated 2^3 factorial experiment. The average area of concavity or reinforcement, as defined in Fig. 3, is multiplied by 0.44/mm to produce a conventional expression of concavity or convexity ($\pm C$).

The calculated values of C are listed in Table 2 and also shown at the corners of the cube in Fig. 4. The diagram in Fig. 4 is used to visualize main effects and interactions between variables. Linearity has been assumed in calculations of main and interaction effects.

Main Effects

The effect of one variable on concavity/convexity can be determined by averaging the differences of the values of C for fitup combinations which hold the other two variables constant. For example, to determine the effect of mismatch (E_M), identify the pairs of fitup combinations that vary the mismatch while holding the root opening and welding position constant (1 and 3, 2 and 4, 5 and 7, 6 and 8) and average the differences of the values of C. Thus:

$$\begin{aligned} E_M &= \tfrac{1}{4}\,(C_3 - C_1) + (C_4 - C_2) \\ &\quad + (C_7 - C_5) + (C_8 - C_6) \\ &= 1.38 \text{ mm } (0.054 \text{ in.}) \end{aligned}$$

In a similar manner, estimates of the main effects of welding position (E_P) and root opening (E_G) are determined:

$$\begin{aligned} E_P &= \frac{1}{4}(C_2 - C_1) + (C_4 - C_3) \\ &\quad + (C_6 - C_5) + (C_8 - C_7) = -0.55 \text{ mm} \\ &\qquad (-0.021 \text{ in.}) \end{aligned}$$

$$\begin{aligned} E_G &= \frac{1}{4}(C_5 - C_1) + (C_6 - C_2) \\ &\quad + (C_7 - C_3) + (C_8 - C_4) = -0.09 \text{ mm} \\ &\qquad (-0.004 \text{ in.}) \end{aligned}$$

Thus, it can be seen that mismatch has a powerful and, paradoxically, beneficial influence on shaping the root bead. On the other hand, a change of welding position from 2G to 5G has a strong negative effect. Root opening, within the range tested, has an apparently insignificant effect on the shape or buildup of the root bead.

Interaction of Two Variables

The two-way interaction effects of welding position, root opening, and mismatch were checked to determine if the effect of one is significantly dependent on the presence of each of the other two variables.

The diagram in Fig. 5 was formed by collapsing the diagram of Fig. 4 in the direction of the welding position vector, thus combining corners (1) and (2), (3) and (4), (5) and (6), and (7) and (8). Then the pairs of values were averaged to form a two-way diagram for checking the interdependence of mismatch and root opening (E_{MG}) with welding position held constant. The effect of changing the root opening at zero mismatch is then obtained by subtracting the lower left corner (average of fitups 1 and 2) from the lower right corner (average of fitups 5 and 6) yielding −0.18 − 0.06 = −0.24 mm (−0.009 in.). The effect at 1.59 mm (1/16 in.) mismatch is 1.35 − 1.29 = 0.06 mm (0.002 in.) or practically nil.

The above data show that the effect of root opening on concavity is slightly dependent on the magnitude of mismatch in the joint — that is, the weld with 0.79 mm (1/32 in.) root opening is somewhat less prone to concavity when the joint contains a moderate amount of mismatch. It has already been shown, however, that the main effect of mismatch for preventing concavity is very potent irrespective of interaction effects.

Conventionally, the two-way interactions for mismatch/root opening (E_{MG}),

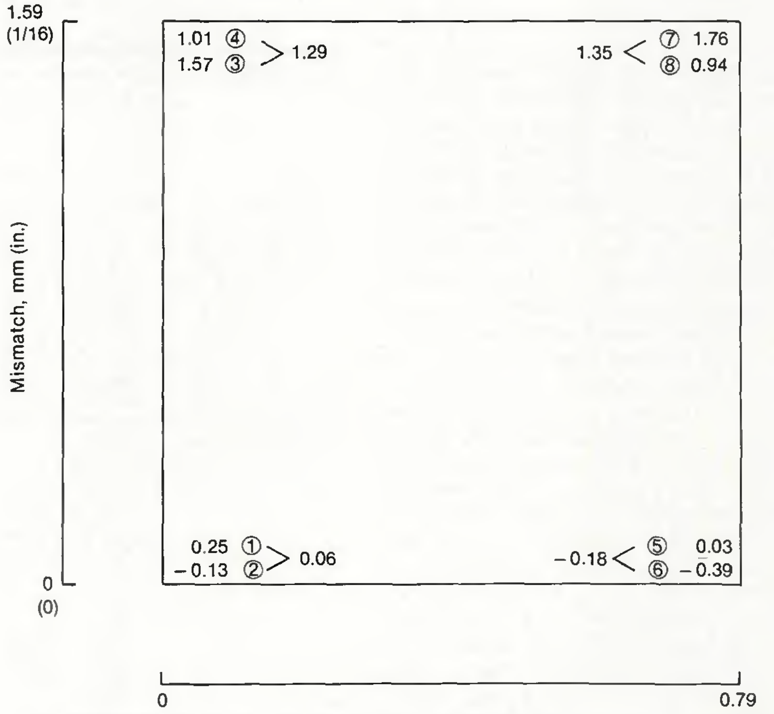

Fig. 5 — Two-factor diagram illustrating mismatch/root-opening interaction effect on root bead shape

Table 5—Effects of Variables on Root Concavity/Reinforcement and 95% Confidence Limits[(a)]

Main effect	Effect ± standard deviation, mm (in.)	95% Confidence interval[(b)] limits, mm (in.)
Position, E_P	−0.55 ± 0.07 (−0.022 ± 0.003)	−0.61 to −0.49 (−0.024 to −0.020)
Mismatch, E_M	1.38 ± 0.07 (0.054 to 0.003)	1.32 to 1.44 (0.052 to 0.056)
Root opening, E_G	−0.09 ± 0.07 (−0.003 ± 0.003)	−0.15 to −0.03 (−0.005 to −0.001)
Two-Factor Interaction Effect		
Position-mismatch, E_{PM}	−0.14 ± 0.07 (−0.006 ± 0.003)	−0.20 to −0.08 (0.008 to −0.004)
Position-root opening, E_{PG}	−0.08 ± 0.07 (−0.003 ± 0.003)	−0.14 to −0.02[a] (−0.005 to −0.001)
Mismatch-root opening, E_{MG}	0.15 ± 0.07 (0.006 ± 0.003)	0.09 to 0.21 (0.004 to 0.008)
Three-factor interaction		
Position-mismatch-root opening, E_{PMG}	0.05 ± 0.07 (−0.002 ± 0.003)	−0.11 to 0.01 (−0.004 to 0.000)

(a) Due to rounding, differences may occur in comparison of English and metric units

(b) Confidence interval for the estimated effect = $\pm t_{5\%(7)} \frac{S_E}{n^{1/2}}$ = ± 0.06 mm (± 0.002 in.)

position/root opening (E_{PG}), and position/mismatch (E_{PM}) are calculated as follows:

$$E_{MG} = \frac{1}{4}(C_1 + C_2 + C_7 + C_8 - C_3 - C_4 - C_5 - C_6) = 0.15 \text{ mm } (0.006 \text{ in.})$$

$$E_{PG} = \frac{1}{4}(C_1 + C_3 + C_6 + C_8 - C_2 - C_4 - C_5 - C_7) = -0.08 \text{ mm } (-0.003 \text{ in.})$$

$$E_{PM} = \frac{1}{4}(C_1 + C_4 + C_5 + C_8 - C_2 - C_3 - C_6 - C_7) = -0.14 \text{ mm } (-0.006 \text{ in.})$$

Three-Factor Interaction

The combined interaction effect of all three variables (position, mismatch, and root opening) is determined as follows:

$$E_{PMG}=\frac{1}{4}(-C_1+C_2+C_3-C_4+C_5-C_6 - C_7 + C_8) = -0.006 \text{ mm } (-0.0002 \text{ in.})$$

Confidence Limits for Effects and Analysis of Variance

The estimated experimental error (standard deviation, σ) for the 8 fitup combinations listed in Table 2 is calculated in the Appendix:

σ = 0.147 mm (0.006 in.)

Also shown in the Appendix is the standard deviation of the main and interaction effects, σ_E:

σ_E = 0.074 mm (0.003 in.)

The 95% confidence limits for the estimated effect (E) are calculated as follows:

$$E = + t_{5\%(7)} \frac{\sigma_E}{n^{1/2}},$$

where $t_{5\%}$ of 7 degrees of freedom is 2.365 from statistical t-tables and n = 8, the number of trials. Thus:

$$E = \pm 2.365 \frac{0.074 \text{ mm}}{2.83}$$

$$= \pm 0.06 \text{ mm } (\pm 0.002 \text{ in.})$$

Table 5 summarizes the results of the factorial experiment. Use of an analysis-of-variance table (Table 7) shows the following:

1. The main effects, welding position and mismatch, were very significant at the 5% level of significance. This level corresponds to a 95% confidence interval.
2. Root openings up to 0.79 mm (1/32 in.) did not significantly affect root bead concavity within the conditions of the experiment.
3. None of the interaction effects was significant at the 95% confidence level of significance.

Metallography

Photomacrographs of root bead profiles of welds for the fitup combinations used in the factorial experiment are presented in Figs. 6 through 15. Photomacrographs are oriented so that the welds are presented in the actual welding position. Two orientations of mismatch are shown for combinations 3 and 7, in Figs. 8 and 9, and 13 and 14, respectively. Tapers, as defined in Fig. 3, are formed at the roots of mismatched joints. Ratios of the tapers are approximately 2:1. Concavity, measured per Department of Energy nuclear piping standards, occurred only on joints not having mismatch.

Root bead geometries for all 32 welds were derived from the areal measurements defined in Fig. 3. The results of regression analyses performed on these data, with mismatch and welding position as parameters, are shown in Fig. 16. Corresponding correlation coefficients (r^2) are indicated with each equation; values near 1 indicate a good fit of the curve with the data whereas values near zero signify scatter of data points and a poor fit.

Joints Without Mismatch

Data for welds made on joints without mismatch are given in Table 6 and are shown in Fig. 17. The curves were fitted by linear regression analyses, and the correlation coefficients (r^2) are listed in Fig. 17.

Table 7—Analysis of variance

Source of variance	Sum of squares, mm²	Degrees of freedom	Mean square, mm²	F-ratio
Replicates	6.339	1	6.339	
Main effects				
Position, P	1.182	1	1.182	53.73
Mismatch, M	7.613	1	7.613	346.05
Root opening, G	0.032	1	0.032	1.45
Two-factor interactions				
PM	0.083	1	0.083	3.77
PG	0.025	1	0.025	1.14
MG	0.087	1	0.087	3.95
Three-factor interaction				
PMG	0.011	1	0.011	0.50
Error	$\frac{1}{2}\Sigma d^2$ = 0.173	8	0.022	
Total		16		

Level of significance: 0.05
Critical F-ratio: 5.32

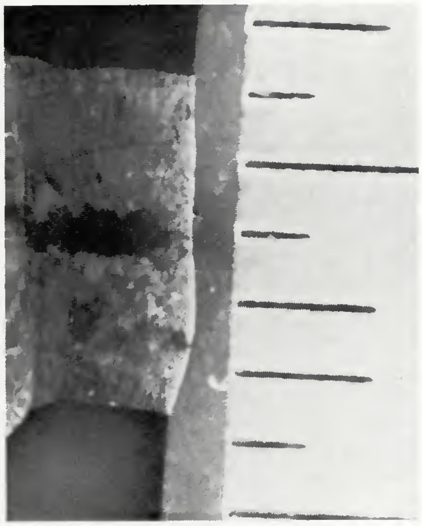

Fig. 6 — Weld UG 14(100)-7, 2G position, zero root opening, zero mismatch. 1 mm scale (reduced 41% on reproduction)

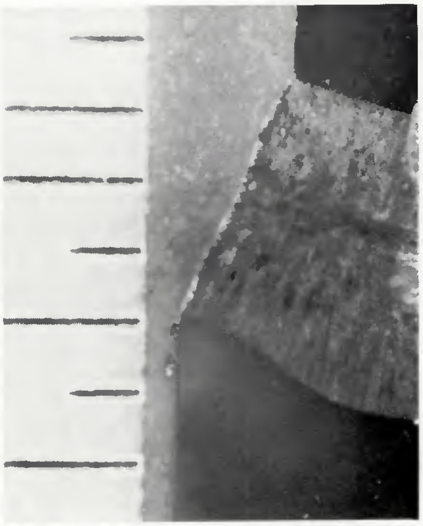

Fig. 9 — Weld UG 14(100)-10, large ID on top, 2G position, zero root opening, 1.59 mm (1/16 in.) mismatch. 1 mm scale (reduced 41% on reproduction)

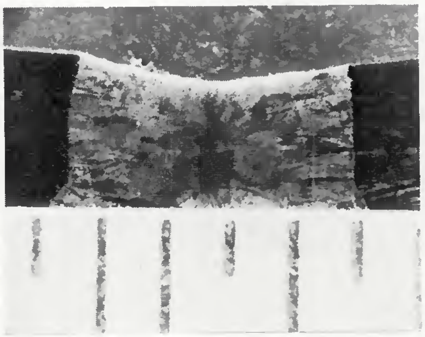

Fig. 12 — Weld UG 14(100)-18, 5G position, 0.79 mm (1/32 in.) root opening, zero mismatch. 1 mm scale (reduced 53% on reproduction)

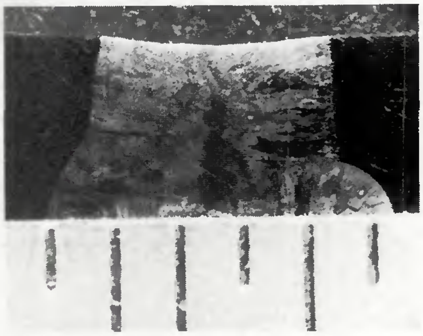

Fig. 7 — Weld UG 14(100)-22, 5G position, zero root opening, zero mismatch. 1 mm scale (reduced 53% on reproduction)

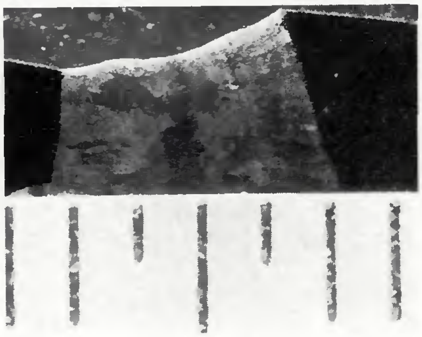

Fig. 10 — Weld UG 14(100)-16, 5G position, zero root opening, 1.59 mm (1/16 in.) mismatch. 1 mm scale (reduced 53% on reproduction)

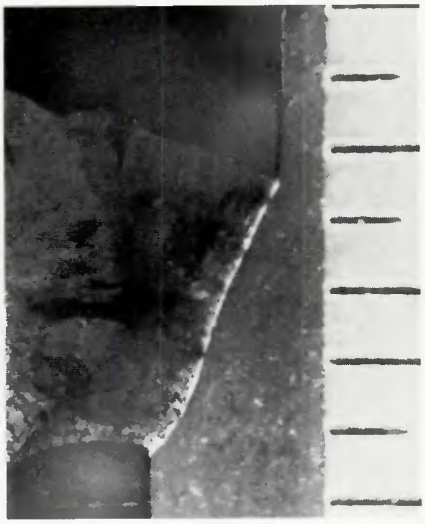

Fig. 13 — Weld UG 14(100)-9, large ID on bottom, 2G position, 0.79 mm (1/32 in.) root opening, 1.59 mm (1/16 in.) mismatch. 1 mm scale (reduced 41% on reproduction)

Fig. 8 — Weld UG 14(100)-13, large ID on bottom, 2G position, zero root opening, 1.59 mm (1/16 in.) mismatch. 1 mm scale (reduced 41% on reproduction)

Fig. 11 — Weld UG 14(100)-14, 2G position, 0.79 mm (1/32 in.) root opening, zero mismatch. 1 mm scale (reduced 41% on reproduction)

Fig. 14 — Weld UG 14(100)-11, large ID on top, 2G position, 0.79 mm (1/32 in.) root opening, 1.59 mm (1/16 in.) mismatch. 1 mm scale (reduced 41% on reproduction)

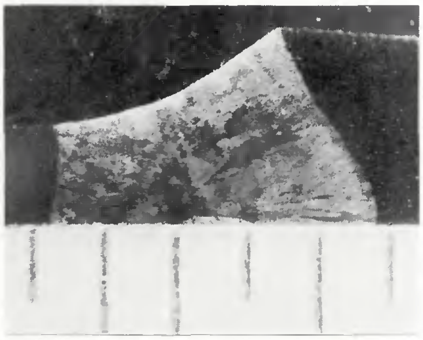

Fig. 15 — Weld UG 14(100)-34, 5G position, 0.79 mm (1/32 in.) root opening, 1.59-mm (1/16 in.) mismatch. 1-mm scale (reduced 53% on reproduction)

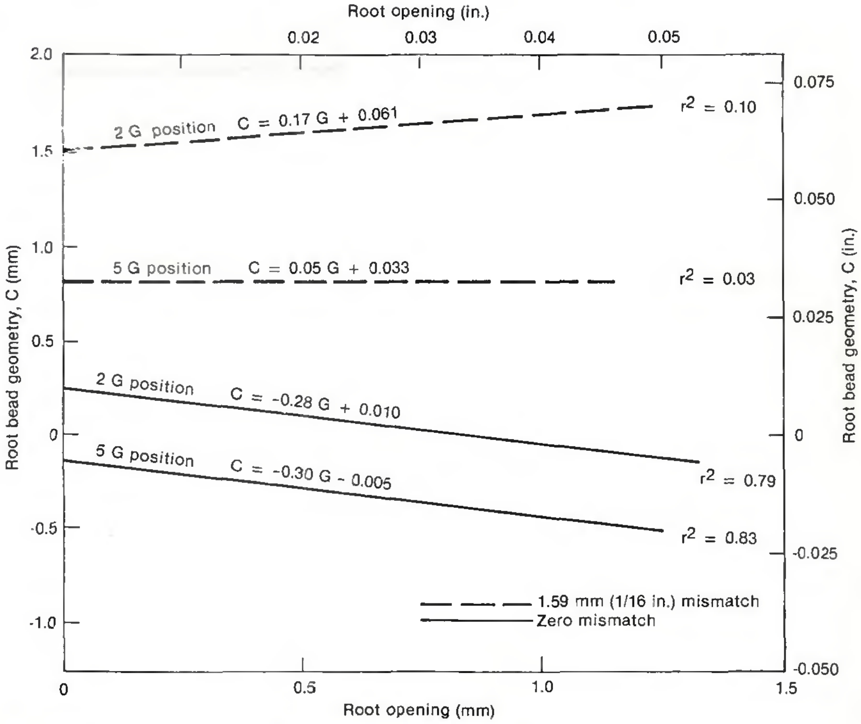

Fig. 16 — Effect of root opening and mismatch on root bead geometry

Joints with Uniform 1.59 mm (1/16 in.) Internal Mismatch

The shape (concavity or convexity) of the fillet formed at the root of mismatched joints for each root opening and welding position is plotted in Fig. 18 and listed in Table 6. Table 4 gives the taper formed at the offset zone and references the photomacrograph of the weld. The equations and correlation coefficients (r^2) in Fig. 18 were determined by linear regression analyses.

Discussion

Mismatch permitted by the ASME Code when inside surfaces are inaccessible is covered in NB-4233. The average uniform inside mismatch is limited to 0.79 mm (1/32 in.), and the maximum mismatch at a point must not exceed 2.38 mm (3/32 in.). A maximum value less than 2.38 mm (3/32 in.) may be used when the smaller mismatch is specified in design.

The 1.59 mm (1/16 in.) value for mismatch used in this study is twice the uniform mismatch allowed by the ASME Code. As a consequence, root bead conditions obtained are conservative except for special situations (e.g., at the point of intersection of longitudinal and girth seams) in which local mismatch may be as high as 2.38 mm (3/32 in.) and still comply with the Code.

The effect of combinations of mismatch and root opening on concavity was used to assess weld quality. Concavity was determined after the root pass and one filler pass were completed. If it is assumed that radial shrinkage resulting from additional passes would decrease concavity somewhat, measurements of concavity are correspondingly more conservative.

The ASME Code requires that the roots of accessible joints with misalignment be faired to a 3:1 taper. Because of this, the shape at the root of an inaccessible joint is of interest. Tapers of welds made in this experiment (see Table 4) on joints having 1.59 mm (1/16 in.) mismatch were approximately 2:1. Assuming the width of the weld at the root remains unchanged, a 0.79 mm (1/32 in.) uniform mismatch, permitted by the Code, would result in a 4:1 taper. Also, these results show that root geometries of the mechanized welds were within the most likely maximum taper (2:1) assumed in an analysis used at the Oak Ridge National Laboratory (Ref. 3) to determine stress indices of girth joints.

At the 7 to 10 o'clock position, melt-thru and hole formation tend to develop when there are moderately wide root openings and large mismatches. Welding in this position is sensitive to melt-thru, because gravity displaces the weld pool to the rear. The arc, without the cushion of the pool and in response to the automatic voltage control mode, has high melting and penetrating efficiency. This condition combined with poor fitup causes excessive melt-thru. Heat input can be reduced to minimize this problem. However, joints with poor fitup can be welded satisfactorily using the downhill mode. In this mode the weld pool cushions the arc and prevents excessive melt-thru.

Concavity was observed only in joints not having mismatch. The degree of concavity was slight, as indicated in Fig. 17, but tends to increase for welds in both welding positions as root openings become larger. Correlation coefficients indicate a good linear relationship

Table 6—Reinforcement in Welds on Joints Without Mismatch

Weld	Welding position	Root opening		Root bead[(a)] − concavity + reinforcement		Macrograph
		mm	in.	mm	in.	
UG 14(100)−7	2G	0	0	0.30	0.012	Fig. 6
−12	2G	0	0	0.15	0.006	–
−8	2G	0.69	0.027	0.10	0.004	–
−14	2G	0.71	0.028	−0.10	−0.004	Fig. 11
−27	2G	1.24	0.049	−0.18	−0.007	–
−24	2G	1.35	0.053	−0.18	−0.007	–
UG 14(100)−22	5G	0	0	−0.15	−0.006	Fig. 7
−15	5G	0	0	−0.20	−0.008	–
−18	5G	0.81	0.032	−0.36	−0.014	Fig. 12
−21	5G	0.81	0.032	−0.36	−0.014	–
−33	5G	1.17	0.046	−0.38	−0.015	–
−29	5G	1.12	0.044	−0.51	−0.020	–

(a) Location: 60 degrees from weld start in 2G position and 6 o'clock in 5G position. (Note: Measurements of concavity and reinforcement were in accordance with requirements of DOE standards for nuclear piping and Paragraph NB-4426.2, Section III, ASME Boiler and Pressure Vessel Code, respectively.)

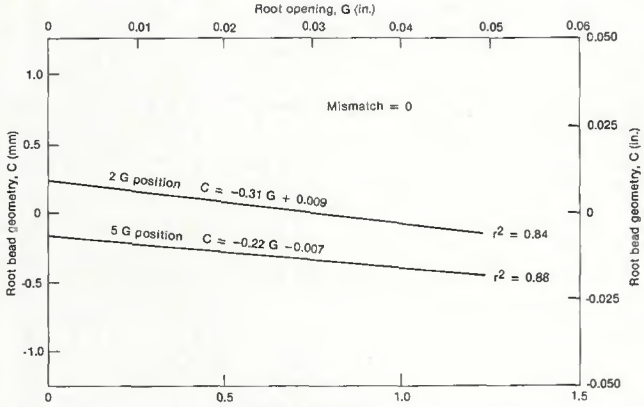

Fig. 17—*Effect of root opening on root bead concavity for joints without mismatch*

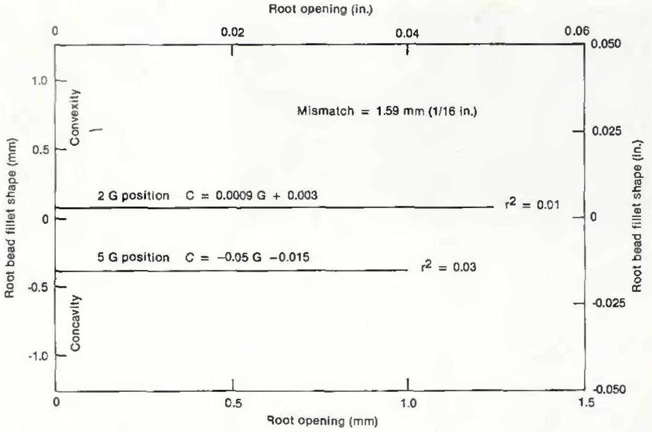

Fig. 18—*Effect of root opening on root bead shape for joints having 1.59 mm (1/16 in.) uniform internal mismatch*

between root opening and root bead geometry.

The corresponding curves and equations derived from areal measurements and shown in Fig. 16 are in good agreement with those in Fig. 17 acquired by direct measurement. Results in Fig. 16 show that root beads will be flush within about 0.25 mm (0.010 in.) for root openings up to 0.79 mm (1/32 in.) with the tendency toward concavity being in welds made in the 5G position.

Ironically, the propensity toward concavity with increase in root opening disappears when mismatch occurs in the joint. In fact, the upper curves in Fig. 16 show that root reinforcing power increases as root opening becomes larger. A wide root opening apparently provides better access for the arc which then can fuse the inner mismatch zone more efficiently. This material provides filler metal to supplement the wire that is fed into the root opening synchronously with the welding current high pulse.

The contour of the fillet formed at the root of mismatched joints is relatively independent of root opening. Linear correlation coefficients for the graphical data in Fig. 18 reveal considerable scatter. However, it is the relative positions of the two curves that are of interest. The 2G fillets are relatively flush, while the 5G fillets are slightly concave.

This effect becomes visually apparent when comparing weld cross sections in Figs. 8 and 14 with those in Figs. 10 and 15, respectively. Also, the influence of mismatch orientation in the 2G position has a slight effect on the contour of the fillet. When the lower member is smaller in diameter than the upper member, it supports the root pass and there is a smoother transition at the toe of the fillet. The smooth transition at a large obtuse angle is, of course, conducive to lower stress intensity. This effect, caused by a difference in mismatch orientation in 2G joints, is evident in a comparison of welds shown in Figs. 8 and 13 with those in Figs. 9 and 14.

Results of the factorial experiment (Table 5) indicate all effects (main and interaction), except welding position and mismatch are comparable in magnitude to the standard deviation of each effect. This suggests that effects other than mismatch and welding position are not very significant. An analysis of variance (Table 7) confirms that only mismatch and welding position have significant effects, 1.37 and −0.56 mm (0.054 and −0.022 in.), respectively, on the geometry at the weld root. The interaction effects of mismatch/root opening and position/mismatch could be significant at the 10% level.

The 95% confidence limits for the main effect of mismatch show that concavity should not occur when there is mismatch and that reinforcement as a result of mismatch alone could be as high as 1.45 mm (0.057 in.). Actually, concavity did not occur in welds on joints with mismatch, and reinforcement higher than 1.45 mm (0.057 in.) tended to occur mainly in the 2G welding position; this, as can be seen in Fig. 16, is not prone to concavity irrespective of mismatch and root opening of the magnitudes used in the factorial experiment.

The effect of position on concavity at the 6 o'clock 5G position is well known. Results in Table 5 confirm that welding in the 5G position is more risky than welding in the 2G position. When there is a choice of the two positions, the 2G position should be chosen unless there is moderately high uniform mismatch; in this case, welds in either position are not likely to contain root concavity.

The use of areal measurements converted by a form factor to represent either concavity or reinforcement provided a continuous analytical expression for measuring the susceptibility of the narrow-groove joint geometry to fitup conditions. Concavity and reinforcement, including the weld metal zone between the inner surfaces of mismatched members, are accounted for by the equations in Fig. 16 for all fitup conditions. The narrow-groove weld joint design, compared to a number of conventional joints having relatively thin root faces and wide groove angles, is tolerant of moderate variations in fitup, particularly root opening.

Mismatch stresses in girth joints are proportional to mismatch and inversely proportional to wall thickness. For example, the axial bending stress caused by pressure at a mismatched zone is:

$$\sigma_{ab} = + \frac{3}{2} \cdot \frac{PD_o}{2t} \cdot \frac{M}{t}$$

where P = internal pressure; D_o = outside diameter; t = wall thickness; M = mismatch.

Table 8—Calculation Data

Fitup combination	C, mm			(Difference)^2 mm^2
	1st weld	2nd weld	Difference	
1	0.368	0.123	0.245	0.060
2	−0.164	−0.097	−0.067	0.004
3	1.472	1.663	−0.191	0.036
4	1.008	1.019	−0.011	0.000
5	0.082	−0.014	0.096	0.009
6	−0.369	−0.412	0.043	0.002
7	1.990	1.526	0.464	0.215
8	0.868	1.008	−0.140	0.020
				0.346

This relationship shows that mismatch obviously penalizes design, and for this reason mismatch should be avoided. On the other hand, Fig. 16 shows that mismatch is beneficial in preventing root bead concavity. This benefit occurs, because the innermost edge of the mismatched joint provides filler metal for the weld root.

All 32 welds met the requirements of DOE standards for nuclear piping and paragraph NB-4426.2, Section III of the ASME Code. Welds in joints without mismatch tend to be slightly concave at the 6 o'clock 5G position, as defined in Fig. 3. This condition is evidently preferred instead of large root-reinforcement, in certain sectors of the nondestructive testing community (Ref. 4). In any event, all measurements were well within the allowable values for concavity and reinforcement at the root of welds made in the 2G and 5G positions on joints having a practical range of mismatch and root opening.

Conclusion

The experimental work and its results were reviewed to provide an overall perspective and draw conclusions therefrom. This study covered two separate considerations. The first was related to overall quality and conformance to standards. It resulted in a mathematical description of the area of each reinforced or concave zone to show the reinforcing tendency of the narrow-groove welds used.

The second consideration was to detail the effects of varying mismatch in combination with welding position and joint geometry (root opening). Cross-section-areal measurements and their mathematical description were needed. This was because the zone between the two inner mismatched surfaces is not explicitly and quantitatively defined by either the ASME Code or DOE standards for nuclear piping.

Conclusions and related recommendations drawn from this work are as follows:

1. Joints welded in the 5G position are more susceptible to concavity than those welded in the 2G position. Consequently, when there is a choice of position, the 2G position provides the least risk of defects due to concavity.

2. Concavity of joints welded in the 5G position has a tendency to occur in the lower quadrant of joints free of mismatch. This tendency is proportional to root opening. However, the magnitudes of concavity observed for the range of root openings studied were well within the requirements for nuclear piping.

3. Moderate root openings up to 0.79 mm (1/32 in.) do not cause concavity in the 2G position.

4. Joints with mismatch are not prone to concavity in either the 2G or 5G welding positions for the magnitudes of root opening used in this experiment.

5. Small fillets are formed at the root of mismatched joints. By nuclear standards the roots of these welds would be neither concave nor reinforced. However, the face of the fillet itself varies from slightly concave to flush. The as-welded tapers formed by the fillets were about 2:1 when mismatch was 1.59 mm (1/16 in.). Based on these results, joints having allowable ASME Code uniform mismatch of 0.79 mm (1/32 in.) should have tapers of approximately 4:1.

6. The main effects of mismatch and welding position on root bead reinforcement and concavity, respectively, were significant at the 95% confidence interval. The main effect of root opening and the two- and three-way interactions of the three factors (mismatch, root opening, and welding position) were not significant at the 5% level of significance (95% confidence interval).

7. Using negative values to represent concavity and positive values to relate to fused material above the lower inside surface of a mismatch joint, the 95% confidence intervals relating to effects of mismatch and welding position are as follows: welding position, P, is −0.61 to −0.49 mm (−0.024 to −0.020 in.); mismatch, M, is 1.32 to 1.44 mm (0.052 to 0.057 in.)

These values indicate that a moderate amount of mismatch is very effective in reducing concavity. Also, as known from practice, the tendency toward concavity is much more pronounced at the 6 o'clock 5G position than elsewhere, as well as in the 2G position. The powerful effect of mismatch toward preventing concavity is due to the edge of the mismatched member melting in much the same manner as a consumable insert, thus becoming a gap filler.

8. Levels of root opening greater than 0.81 mm (0.032 in.) were examined in a limited experiment to acquire qualitative information with respect to welding position and mismatch. Results indicated the uphill portion of the 5G position is sensitive to melt-thru and hole formation at moderately large gaps and mismatch conditions. However, using nominal welding procedure parameters, root openings up to 1.14 mm (0.045 in.) with 1.59 mm (0.062-in.) mismatch were welded on the corresponding downhill side of the joint (2 to 5 o'clock) without defects. These observations show that downhill welding is more tolerant of poor fitup conditions than the uphill technique when using automatic voltage control of the welding head. More work should be done to define the tolerances of welding variables for the uphill and downhill mechanized welding techniques.

9. Two types of mismatch that can occur in joints in the 2G welding position are illustrated in Figs. 8 and 13 and in Figs. 9 and 14. The orientation in Figs. 8 and 13 should be avoided in piping subjected to cyclical loading because of the tendency for high stress concentration at the toe of the fillet. Additional experimental studies of welds made in these two orientations are needed to quantitatively express root geometry in terms of stress intensity.

10. The undefined zone between two mismatched surfaces can be expressed quantitatively along with reinforcement and concavity stipulated by ASME Code and DOE nuclear standards by using a form factor to relate the zone to reinforcement. This method can be used to compare the reinforcing propensities of different joint designs. The shape of this zone needs to be defined in terms which are related to the inspection process.

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References

1. Key, J. F., Turner, P. W., Hood, D. W., and Keiser, D. D. 1980. Joint geometry influence on mechanized pipe welding. *Welding Journal* 59(5): 24-32.

2. Eichenberger, G. D., and Turner, P. W. 1978 (April). *Tooling for mechanized welding of large diameter pipe.* TREE 1258.

3. Unpublished Oak Ridge National Laboratory report on stress indices for girth-welded pipe joints.

4. Minton, W. C., and Wenk, S. A. 1977. The influence of materials and welding processes on UT of weldments. AWS 58th Annual Meeting, Philadelphia, Pennsylvania, April 25-28.

5. Wu, S. M. 1964. An analysis of rail steel bar welds by two-level factorial design. *Welding Journal* 43(4): 179-s to 183-s.

Appendix: Calculation of Estimated Experimental Error (Ref. 5)

Calculation of Variance and Standard Deviation

See Table 8. Estimated variance is:

$$\sigma^2 = \frac{\Sigma(C - C)^2}{(d.f.)} = \frac{\Sigma d^2}{2} \frac{1}{(d.f.)} = \frac{0.346}{2} \cdot \frac{1}{8}$$

$\sigma^2 = 0.022 \text{ mm}^2$

Estimated Standard Deviation, $\sigma =$

$(\sigma^2)^{1/2} = 0.147$ mm (0.006 in.)

Calculation of Variance of Effects

(a) Effects (main or interaction) =

$$\frac{1}{8}\sum_{i=1}^{16}(C_i)$$

(b) Variance of effects:

$$V_{(\mathrm{effects})} = V\left[(1/8)\sum_{i=1}^{16}(C_i)\right]$$

Then:

$$V_{(\mathrm{effects})} = (16/64)\,V\,(C_i) = \tfrac{1}{4}\,\sigma^2$$

$$= (1/4)0.022\ \mathrm{mm}^2 = 0.0055\ \mathrm{mm}^2\ (8 \times 10^{-6}\ \mathrm{in.}^2)$$

(c) Estimated standard deviation of an effect:

$$\sigma_E = (1/4\ \sigma^2)^{1/2} = \frac{1}{2}\sigma$$

$$= 0.074\ \mathrm{mm}\ (0.003\ \mathrm{in.})$$

WRC Bulletin 273
December, 1981

Design Implications of Recent Advances in Elevated Temperature Bounding Techniques

by J. S. Porowski, W. J. O'Donnell and M. Badlani

Recent advances in bounding (*i.e.*, limiting) techniques and simplified methods of analysis for components operated in the creep regime are used herein to obtain some very useful design guides. Damage mechanisms are determined for a wide range of dimensionless design parameters, operating pressure and cyclic thermal conditions, and material properties.

Publication of this report was sponsored by the Subcommittee on Elevated Temperature Design of the Pressure Vessel Research Committee of the Welding Research Council.

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WRC Bulletin 274
January, 1982

International Benchmark Project on Simplified Methods for Elevated Temperature Design and Analysis: Problem II—The Saclay Fluctuating Sodium Level Experiment; Comparison of Analytical and Experimental Results; Problem III—The Oak Ridge Nozzle to Sphere Attachment

by H. Kraus

Problem II. Recently, experimental results became available on the second benchmark problem on simplified methods for elevated temperature design and analysis: the Saclay fluctuating sodium level experiment. These are compared to previously published numerical and analytical results in WRC Bulletin 258, May 1980.

Problem III. The Oak Ridge Nozzle to Sphere Attachment is analyzed by finite element computer programs and by approximate analytical techniques. The methods are described and the results obtained by each are compared. No experimental data are available.

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