Shrinkage of Butt Welds in Stainless Steel Pipe

Development and application of a mathematical model to predict shrinkage

BY E. BRANDON

ABSTRACT. This paper presents a general method for developing the data to predict the shrinkage of cylindrical weldments as a result of girth welding.

Gas tungsten-arc welding was used to butt weld stainless steel rings. The resulting shrinkage values were operated on by a multiple regression analysis technique to produce an equation predicting diametral and axial shrinkage.

Introduction

The many variables associated with welding make it generally difficult to predict the distortion caused by localized heating and cooling. Welding parameters, type and history of materials, and configuration are some of the variables that significantly affect weldment distortion.

For weldments of circular cross sections such as pipe, tubing, and spheres, a knowledge of predicted axial (end-to-end) and diametral shrinkage is essential for accurate design and fabrication. The designer should be aware of the variables that affect distortion and how much distortion to expect.

This investigation develops the data and technique for predicting the axial and diametral shrinkage associated with the girth welding of stainless steel cylinders. The resulting information permits the selection of weld groove dimensions and welding parameters which will result in minimum distortion.

Weldment configurations that fall within the boundary conditions of this experiment include cylinders and spheres 4 in. OD by ¼ and ½ in. wall thickness. However, the value of this study is in the method of applying statistical techniques to predict axial and diametral shrinkage of girth welds in cylinders.

Certain parameters of weld groove size and heat input were selected for each of two thicknesses of material. These independent variables were compared with corresponding shrinkages to determine the likelihood of relationships, using Student's t test.

Using the techniques described herein, groove width was found directly related to shrinkage and heat input inversely related. Shrinkage was minimized by the use of thinner material, narrower grooves and higher heat input. Quantitative results are given.

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Experimental Procedure

Pairs of stainless steel rings were butt welded with zero root opening using specific combinations of controlled parameters. The assembled rings were measured before and after welding, and the shrinkage was determined and prepared statistically. The raw data for each coupon were then averaged and treated using a multiple regression analysis technique.

The design of the experiment was a full factorial of three variables at two and three levels. One weld was made at each of the 18 thickness/groove design/heat input combinations (2 × 3 × 3 = 18). In addition, six replicate welds were made. The test plan is shown in Fig. 1.

Independent Variables

The independent variables of this study were:

X_1, material thickness: ¼, ½ in.
X_2, groove width: 0, 0.075, 0.150 in.
X_3, heat input: 17.72, 23.26, kJ/in. of weld per pass

The method of measuring X_1 and X_2 is given under the heading, "Material."

Note that the data used in this study for heat input are in joules per inch of weld per pass for the filler passes, not the total heat input per joint.

All other factors of this experiment were held as constant as possible to minimize random error and improve the validity of the results for the stated conditions.

Response Variables

The response variables were:

Y_1: change in stack height (axial shrinkage) as a result of the weld filler passes

Y_2: change in diameter (diametral shrinkage) as a result of the weld filler passes

The stack height of the coupons was measured at eight places around the circumference before welding, after the root pass, and after the filler passes. The average differences between the last two measurements were tabulated as axial shrinkage.

The diameter of each of the coupons was measured at four places around the circumference before welding, after the root pass, and after the filler passes. The average differences between the last two measurements were tabulated as diametral shrinkage.

The root passes were made at a heat input necessary to achieve complete penetration. No filler metal was used for the root passes.

Note that only the distortion as a result of the filler passes was used in the analysis; the shrinkage resulting from the root pass is discussed separately under "Discussion."

For purposes of analysis, a quadratic model was used to describe the data. The coefficients were calculated by a multiple regression analysis technique (Ref. 1). By this technique, the main and quadratic effects caused by each independent variable could be assessed. The calculated shrinkage was then found by applying an equation of the form:

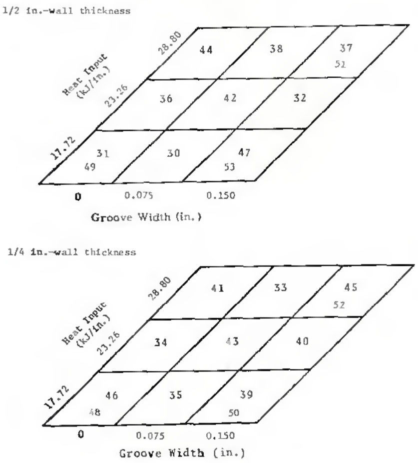

Fig. 1 — Test plan showing the three heat inputs and three groove width parameters used for each thickness. Numbers in cells are weld numbers

$$Y = B_0 + B_1 X_1 + B_2 X_2 + B_3 X_3 + B_4 X_1 X_2 + B_5 X_1 X_3 + B_6 X_2 X_3 + B_7 X_2{}^2 + B_8 X_3{}^2$$

where

Y = calculated shrinkage

B_x = constants determined by regression analysis (B_0, B_1, B_2, etc.)

X_1 = wall thickness (normalized)

X_2 = groove width (normalized)

X_3 = heat input (normalized)

Different B_x values resulted for the two types of shrinkage, axial and diametral.

In addition to the calculated shrinkage values, the significant independent variables affecting the two responses were determined using Student's t test. The results of this analysis readily show the significance of the main effects, as well as interactions.

The six replicate welds were used to determine the random error.

Material

Type 304 stainless steel rings were machined from a seamless extrusion, 4 in. OD by 3 in. ID. Mechanical and chemical values are given in Table 1.

The rings were machined to the final dimensions shown in Fig. 2. After machining, the coupons were inspected on a shadowgraph to assure adequate precision of the weld groove dimensions. Linear dimensions of the groove were maintained within 0.005 in. and angular dimensions within 1 degree.

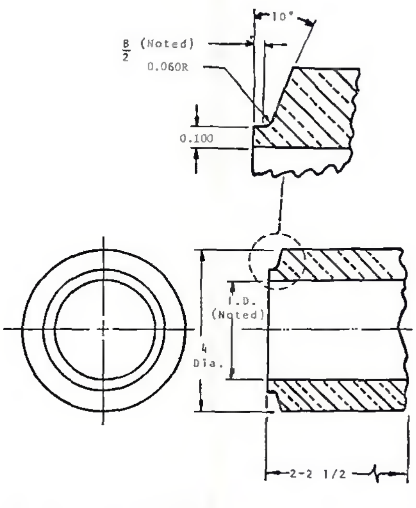

Fig. 2 — One-half of a ring assembly showing joint design used for both 3 and 3½ in. ID rings. For the tightly butted assemblies three values of the groove size parameter B (0, 0.075 and 0.150 in.) were used for each wall thickness

The filler metal was Type 308 stainless steel, 0.030 in. diam.

Welding Procedure

The welding procedure is given in Table 2. The procedure resulted from preliminary welding to develop suitable parameters. The root pass parameters were chosen to produce complete joint penetration of the 0.100 in. thick root face. Greater heat input was required for the B = 0 grooves because of the higher heat sinking capacity of the narrow grooves.

The heat input of the filler passes was chosen such that the low level (17.72 kJ/in.) was the minimum heat that would produce a visually satisfactory weld which exhibited acceptable sidewall fusion, bead contour, and uniformity. The high level (28.80 kJ/in.) was the practical upper limit; greater current caused "burn-through" of the B = 0.150 joints.

Experimental Results

Tabulation of Data

The values of the independent variables and the averages of the corresponding response variables are given in Table 3. The shrinkage values given in Table 3 are due to the filler passes only; shrinkage due to the root pass was calculated separately.

Analysis of Data

The data of Table 3 were used to determine multiple regression equations for Y_1 and Y_2. The two sets of coefficients which resulted are given in Table 4.

As an indicator of degree of correlation between the predicted and actual values, the multiple correlation coefficients were 0.982 for Y_1 and 0.901 for Y_2 (using nine degrees of freedom).

The Student's t test was applied to determine the significance of the variables in affecting the two responses. The results are tabulated in Table 5. Of significance here is the magnitude of the t-statistic. The greater the absolute value of the t-statistic, the more certain that factor is to affect the response.

Table 1 — Mechanical Properties and Chemical Analysis (wt. %) of Type 304 Stainless Steel Rings

U.T.S., ksi	Y.S., ksi	Elong., %	Hardness, Rb	C	Mn	P	S	Si	Ni	Cr	Mo	Cu
82	34.9	59	84/85	0.063	1.8	0.027	0.020	0.46	9.52	18.86	0.35	0.22

A negative t-statistic for the single factors indicates an inverse relationship. As the welding parameter is increased, the response decreases. A product of two factors indicates an interrelationship. A squared single factor simply indicates a second-degree curvilinear relationship between the welding parameter and the response. In this case, the positive or negative sign indicates the direction of curvature.

Groove width was the factor most certain to affect both types of shrinkage. The relationship was direct, i.e., an increase in groove width caused an increase in weldment shrinkage. Heat input was the second ranking significant factor but in an inverse relationship with shrinkage. Wall thickness was also a significant factor affecting axial shrinkage but not diametral shrinkage.

Six replicate welds were made to check the reproducibility (random error) of the experiment. The estimate of random error for axial shrinkage was 0.0045 and for the diametral shrinkage was 0.0018.

Graphs of the predicted shrinkage values of this experiment are given in Figs. 3 and 4.

Each of the plots shows shrinkage as a function of heat input for a particular wall thickness. Each line represents a particular groove width.

Where the lines are relatively horizontal, shrinkage is insensitive to heat input. Where the lines have a substantial slope, shrinkage is strongly affected by heat input. Where the lines are widely separated, shrinkage is strongly affected by groove width.

The t-statistic indicated that groove width and heat input were significant. The effects of these parameters and the combinations at which they are most significant are shown graphically in these plots.

Axial shrinkage (Fig. 3) was strongly and directly affected by groove width. Shrinkage was inversely related to heat input; this effect was especially significant at B = 0.075 and 0.150 inch. Shrinkage was slightly greater with ½-inch material.

Diametral shrinkage (Fig. 4) was inversely related to heat input. The relationship between shrinkage and groove width was not linear, although the lowest shrinkage occurred with the narrowest groove (B = 0). For B = 0.075 and 0.150 in., the regression lines are within one standard deviation. The conclusion is that there is no significant difference in shrinkage in this range of groove width.

The values of shrinkage predicted by the regression equations and the charts of Fig. 3 and 4 should not be considered exact. The variability between the predicted and the observed values can be estimated by the standard deviation of the difference in corresponding values. The standard deviations were:

Axial: σ_Δ = 0.0045

Diametral: σ_Δ = 0.0011

Therefore, 95 % of the observed values would be within 0.009 in. of the predicted values for axial shrink-

Table 2 — Welding Procedure

Process	Automatic gas tungsten arc
Material	Type 304 stainless steel tubing
Configuration	Extruded and machined, 2 and 2½ in. long rings, 4 in. OD × 3 and 3½ in. ID (¼ and ½ in. wall). Single-U butt joint, zero root opening (see Fig. 2)
Position	Horizontal rolled
Filler metal	0.030 in. diam, Type 308 stainless steel, for all except root pass
Electrode	⅛ in. diam, EWTh-2, truncated to 0.030 in. flat end, 10 deg included angle. Changed for each joint
Torch gas	20 cfh argon
Trailing gas	50 cfh argon, shroud covering about ½ the circumference
No. of passes	Determined by heat input and groove size (see below)
Preweld clean	Wire brush and acetone rinse
Part speed	6.5 ipm surface speed (116 seconds per revolution)
Axial force	50 lb, constant throughout welding
Wire speed	See below
Arc voltage	12 V
Arc current per pass:	
Root	220 A (B = 0); 115 A (B = 0.075 and 0.150)
Filler	See below:

Heat input, kJ/in.	Current, A	Wire speed, ipm
low 17.72	160	27
med. 23.26	210	65
high 28.80	260	103

No. of filler passes:

For groove sizes (B in.) of →	0		0.075		0.150	
Wall thicknesses (in.) of →	¼	½	¼	½	¼	½
Heat input: low	3	10	6	12	8	15
med.	2	5	4	7	5	10
high	2	3	2	5	3	6

Table 3 — Variables of Weldment Shrinkage Study

Weld no.	Thickness, in.	Groove width, in.	Heat input, kJ/in.	Experimental Shrinkage Axial, in.	Experimental Shrinkage Diametral, in.
46	¼	0	17.72	0.049	0.011
48			17.72	.048	.010
34			23.26	.043	.014
41			28.80	.049	.009
35	¼	0.075	17.72	.105	.023
43			23.26	.081	.016
33			28.80	.051	.016
39	¼	0.150	17.72	.145	.022
50			17.72	.150	.019
40			23.26	.102	.018
45			28.80	.058	.017
52			28.80	.060	.016
31	½	0	17.72	.080	.014
49			17.72	.089	.018
36			23.26	.062	.014
44			28.80	.047	.012
30	½	0.075	17.72	.121	.019
42			23.26	.096	.016
38			28.80	.082	.016
47	½	0.150	17.72	.188	.020
53			17.72	.177	.017
32			23.26	.152	.016
37			28.80	.134	.014
51			28.80	.131	.016

Table 4 — Values of Regression Analysis

Regression equation:

$$Y = B_0 + B_1X_1 + B_2X_2 + B_3X_3 + B_4X_1X_2 + B_2X_1X_3 + B_6X_2X_3 + B_7X_2^2 + B_8X_3^2$$

Regression coefficients:

	Y_1 Axial shrinkage	Y_2 Diametral shrinkage
B_0	0.08711108	0.01755555
B_1	0.01488888	0
B_2	0.03716666	0.002333333
B_3	−0.02266666	−0.001833333
B_4	0.008333330	−0.001166667
B_5	0.001666656	0.0001666664
B_6	−0.01337500	−0.0002500005
B_7	0.003333347	−0.002833333
B_8	0.003333337	0.0001666664

Independent variables:

X_1 Material thickness		X_2 Groove width		X_3 Heat input	
Real, in.	Normalized	Real, in.	Normalized	Real, kJ/in.	Normalized
		8=0	−1	17.72	−1
¼	−1	=0.075	0	23.26	1
½	1	=0.150	1	28.80	1

Table 5 — Significant Factors Contributing to Responses (Student's t Test Analysis)[a]

Variable	t-statistic
Axial shrinkage	
X_2, groove width	11.809
X_3, heat input	−7.202
X_1, wall thickness	5.794
$X_2 \times X_3$	−3.470
$X_1 \times X_2$	2.648
Diametral shrinkage	
X_2 groove width	4.038
X_3 heat input	−3.173
X_2^2	−2.831

(a) 0.05 level of significance = 2.2622

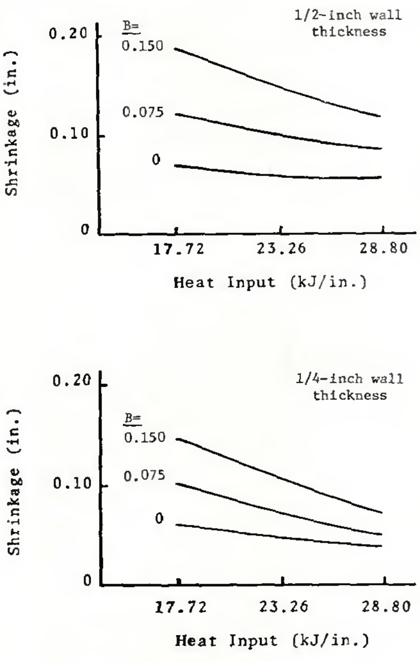

Fig. 3 — Chart of predicted axial shrinkage

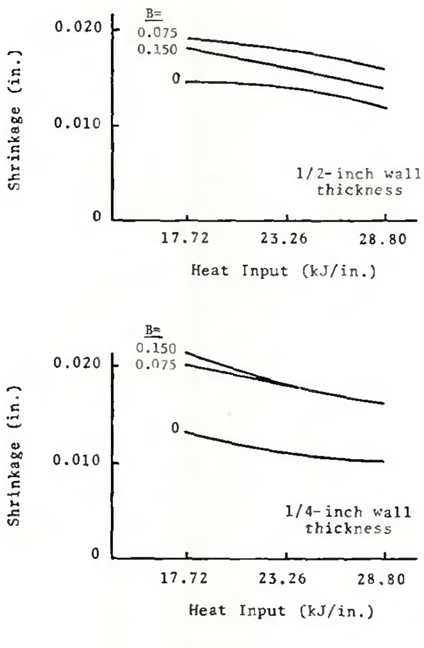

Fig. 4 — Chart of predicted diametral shrinkage

Table 6 — Predicted Minimum and Maximum Shrinkage Values

Direction	Thickness, in.	Groove width, in.	Heat input, kJ/in.	Resulting shrinkage, in.
Axial	¼	0	28.80	min. (0.039
	¼	0.150	17.72	max. (0.145)
	½	0	28.80	min. (0.056)
	½	0.150	17.72	max. (0.189)
Diametral	¼	0	28.80	min. (0.010)
	¼	0.120	17.72	max. (0.021)
	½	0	28.80	min. (0.012)
	½	0.100	17.72	max. (0.020)

age and within 0.002 in. for diametral shrinkage.

The charts show the combinations of primary variables where the minimum and maximum shrinkages occur. The regression equation provides a tool for calculating the amount of shrinkage. Using these two inputs, the predicted minimum and maximum axial and diametral shrinkages resulting from welds made within the boundary limits of this experiment were calculated and are given in Table 6.

The axial shrinkage ranged from 0.039 to 0.189 in. The minimum axial shrinkage occurred at high heat input with a narrow groove. Conversely, the maximum axial shrinkage occurred at low heat input with a wide groove.

The diametral shrinkage ranged from 0.010 to 0.021 in. The combinations of parameters resulting in minimum shrinkage differed, depending on the thickness of material. For both thicknesses, minimum shrinkage occurred at high heat input and maximum shrinkage occurred at low heat input. The net effect of groove width was quadratic, as confirmed by the t-statistic of Table 5. Diametral shrinkage was lower at both narrow and wide groove widths.

Discussion

The validity of the regression equations derived in this experiment was tested by welding four coupons at intermediate parameters. The resulting experimental values of shrinkage were compared with those predicted by the regression equations. The standard deviation of the difference between the predicted and the experimental values (estimate of error) was calculated as a measure of correlation. Those values are as follows:

$\hat{\sigma}$ (axial) = 0.0029

$\hat{\sigma}$ (diametral) = 0.0006

The above values can be compared with the standard deviation of the raw data from the validity test about the regression line (standard error of estimate). Those values were:

σ (axial) = 0.0109

σ (diametral) = 0.0020

The validity test data are well within one standard deviation of the regression line. Therefore, the equations are assumed to be valid.

Shrinkage due to the root pass was ignored in the preceding analysis. The total weldment shrinkage would be calculated by summing the root pass shrinkage and the shrinkage due to the filler passes. In this investigation, the root pass caused an average axial shrinkage of 0.015 in. and a diametral shrinkage of 0.006. Shrinkage due to the filler passes can be determined by reference to Figures 3 and 4 or by the regression equation given in Table 4. Thus cylinders of ¼ in. wall and 0 groove width welded at 28.80 kJ/in. would show total axial shrinkage of 0.054 in. and diametral shrinkage of 0.016 in.

Summary and Conclusions

An experiment was designed and conducted to develop the data necessary to quantify the shrinkage resulting from the girth welding of stainless steel rings. The independent variables were wall thickness of the rings (¼ and ½ in.), weld groove width (0, 0.075, and 0.150 in. — see Fig. 2), and welding heat input (17.72, 23.26, and 28.80 kJ/in.). The measured responses were axial (end-to-end) shrinkage and diametral shrinkage.

A multiple regression analysis technique was applied to the experimental data to produce a quadratic equation to predict, within certain boundary conditions, the two types of shrinkage.

The reproducibility of the experiment was checked by evaluating the results of six pairs of replicate welds. Good correlation was found; the replicate values of shrinkage were within one standard deviation of the predicted values.

The validity of the regression equations derived in this experiment was tested by welding four coupons at intermediate parameters. The check data were within one standard deviation of the predicted values.

Reference

1. N. R. Draper and H. Smith, *Applied Regression Analysis*, John Wiley and Sons, Inc., New York, 1966.

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Standard Procedures for Calibrating Magnetic Instruments To Measure the Delta Ferrite Content Of Austenitic Stainless Steel Weld Metal, AWS A4.274

Ferrite is useful in preventing or minimizing cracking and fissuring in austenitic stainless steel weld metals. In a few special situations, it can be detrimental to corrosion resistance and to mechanical properties if it transforms to sigma phase due to exposure to temperatures above 900 F (480 C). Within a weld pad, the ferrite content is variable, and it is even more so from pad to pad or when the welding conditions are changed.

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WRC Bulletin No. 194 May 1974

"Fatigue Behavior of Pressure-Vessel Steels"

by J. M. Barsom

The regulations governing the design of pressure vessels are based on experience gained over many operational years and have evolved, primarily, to prevent failure under static load conditions. This design philosophy has been successful in ensuring adequate service behavior because pressure vessels are not usually subjected to large numbers of load fluctuations during their expected service life. However, the need to effectively utilize materials and to provide the utmost in safety and reliability has made it imperative to determine the fatigue behavior of these structures.

The fatigue life of structural components is determined by the initiation of cracks and their propagation to critical dimensions. This report presents fatigue-crack-initiation and fatigue-crack-propagation data for pressure-vessel steels operating in a benign environment and at temperatures below the creep region.

Data obtained by testing pressure vessels and pressure-vessel components, and the results of surveys of pressure-vessel failures are discussed. It is concluded that the probability of fatigue failure of properly designed and fabricated pressure vessels is very low and that the most effective approach to keep this probability low is to minimize the magnitude of the stress (strain) concentration factors. This can be accomplished through proper design of details and through proper fabrication.

This paper was prepared for the Pressure Vessel Research Committee of the Welding Research Council. The price of WRC Bulletin 194 is $4.50. Orders should be sent to the Welding Research Council, 345 East 47th Street, New York, N.Y. 10017.

WRC Bulletin No. 196 July 1974

"Electron Beam Welding"
by M. M. Schwartz

The first WRC-sponsored interpretive report on electron-beam welding, published as *WRC Bulletin 100* in 1964, covered the early pioneering stages of the process and the men who refined theories, described their principles and finally built laboratory equipment. In addition, the authors covered the materials (steel and aluminum), the limited applications and the equipment which were available during the process's growing infancy.

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