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INVESTIGATION OF HOT CRACKING IN DEEP
PENETRATION ELECTRON BEAM WELDS

William G. Thorvaldson

Fabrication Technology
JOINING RESEARCH AND DEVELOPMENT

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A C K N O W L E D G M E N T S

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INVESTIGATION OF HOT CRACKING IN DEEP PENETRATION ELECTRON BEAM WELDS

William G. Thorvaldson

Abstract. A defect in a deep penetration electron beam weld of 304L stainless steel to 21-6-9 stainless steel has been identified as a centerline hot crack. The study discussed in this report was made to define and to eliminate the cause of cracking. It was determined that

1. The ferrite content of the weld was marginal for the prevention of cracking. With current chemistry specifications, there is no guarantee that sufficient ferrite will be present to prevent hot cracking.
2. Hot cracking can be prevented by drilling a hole in the end of the stem part, thereby reducing the joint restraint.
3. The incidence of weld cracking can be reduced by decreasing either the depth of penetration or the width of the weld.
4. Weld cracking consistently occurred in a portion of the weld that had a concave weld overbead. The concavity was determined to be associated with the beginning of slope-out. By decreasing the rate of slope-out, the depth of concavity was decreased and weld cracking was eliminated.

INTRODUCTION

Fabrication of an assembly at Rocky Flats required the development of a deep penetration electron beam weld for joining a 304L stainless steel stem to a 21-6-9 stainless steel body. The deep penetration weld, which is labeled Weld 1, is shown in Figure 1 along with a lesser penetration weld. The welding schedule developed for Weld 1 is listed in Table 1. Approximately 40 units were welded at these parameters and no defects other than occasional porosity were observed. A seemingly insignificant change was then made in the welding parameters. The reason was to allow the use of a multiple-unit welding fixture in place of the single-unit welding fixture that had been used on the first 40 units.

FIGURE 1. Stem-to-Body Weld Joints.

The large size of the multiple-unit fixture necessitated a decrease in the gun-to-work (G-W) distance from 4 to 2 inches. An increase in the focus current also was required to compensate for the change in the G-W distance, but all other parameters remained constant. Six units were initially welded using the new fixture and the 2-inch G-W distance.

TABLE 1. Initial Weld Schedule for the Stem-to-Body Weld

Parameters	Weld No. 1 (Vertical Weld)
Accelerating Voltage	30 kV
Beam Current	90 mA
Focus Current	4.40 A
Welding Speed	20 in./min
Gun-to-Work Distance	4 in.

Ultrasonic inspection of the deep penetration weld indicated defects in four of the units; subsequent metallographic sectioning revealed the defect to be a centerline crack, one of which is shown in Figure 2. Typical crack sizes, as measured on these units, are given in Figure 3.

Two of the welds were submitted for evaluation by scanning electron microscopy (SEM). As a result of that study, the cracks were identified as centerline hot cracks. The cracks had formed during the final stages of solidification while a small amount of liquid phase was still present in the grain boundaries. This is illustrated by the fracture surface shown in Figure 4.

The objectives of this investigation were to (1) determine the cause of cracking, (2) define the factors that influence weld cracking susceptibility, and (3) eliminate cracking in this weld.

FIGURE 2. Cracked Stem Weld Made at 2-Inch Gun-to-Work Distance (4X)

HOT CRACKING AND FACTORS AFFECTING HOT-CRACKING SUSCEPTIBILITY

The term hot-cracking is used to describe the super-solidus (near solidus temperature) cracking that occurs in welds or castings during solidification. Basically it can be said that cracking occurs when tensile stress from contraction exists in the weld metal, and the weld metal lacks the ductility necessary to accommodate the resultant strain. Hot cracking, then, can be eliminated by either decreasing the strain to which the weld is subjected or by increasing the ductility of the weld metal during solidification. The strain can be decreased by

1. Reducing heat input of the weld.
The extent of heat spread into the workpiece controls the size of the associated strain field. Generally, the narrower the strain field, the less chance there is of cracking in the weld metal. Heat input can be reduced by lowering the beam current

and/or accelerating voltage to the minimum required to meet penetration requirements.

2. Reducing joint restraint.
Restraint is the resistance of the workpiece to the expansion and contraction of the weld metal. The higher the degree of restraint, the more likely the weld is to crack. Restraint is a function of the rigidity of the workpiece. Although design considerations limit the changes that can be effected in this joint, one method suggested by Sandia Livermore Laboratory to reduce restraint was to drill a hole into the stem end prior to welding. Experiments that demonstrate the effectiveness of this approach are discussed later in the report.

A second means of reducing weld susceptibility to hot cracking is to increase weld ductility. This can be accomplished by

FIGURE 3. Measured Crack Sizes

FIGURE 4. Fracture Surface as Revealed by Scanning Electron Microscopy (1100X)

1. Minimizing sulphur and phosphorous contents.

The low ductility of the weld is generally attributed to the presence of intergranular liquid films during solidification. These liquid films result from low-melting-point compounds, which are formed by impurities such as sulphur and phosphorous. The sulphur and phosphorous contents must therefore be kept at a minimum. It has also been reported that an interdendritic eutectic can form between austenite and what is thought to be M_6N in nitrogen steels.¹ Obviously there is no control over formation of this eutectic in the high-nitrogen 21-6-9 stainless steel.

2. Ensure the presence of delta ferrite in the weld metal.

The effectiveness of small amounts of delta ferrite (approximately 3 to 8 FN*) in preventing hot cracking of austenitic stainless steel weldments has been well documented.²⁻⁴ The latest theory explaining the effect of ferrite in reducing hot cracking is based on the following assumption: Ferrite reduces the amount of liquid film present when cooling through the critical solidification range.^{2,5} Ferrite content in the weld is primarily a function of the material chemistry. For proper ferrite content within the alloy, a specific balance must be maintained between elements that stabilize the delta ferrite and those elements that stabilize the austenitic phase.

DISCUSSION OF EXPERIMENTAL RESULTS

Ferrite Content

Ferrite content of the welds can be predicted from the material chemistries by

*FN = ferrite number.

use of the appropriate constitution diagram. The DeLong diagram⁶ is used for 304L; the Hull diagram⁷ is reportedly the best available for predicting ferrite in 21-6-9.³ The predicted ferrite contents for the many combinations of 304L and 21-6-9 chemistries that were welded in this study are listed in Table 2. The table also lists measured ferrite contents that were slightly higher than values predicted by the constitution diagrams. Measurements were made with a Magne Gage as recommended by the Welding Research Council.⁸ The ferrite contents of all of the welds must be considered as being marginal from a crack prevention standpoint. With the current chemistry specifications for 304L and 21-6-9, there is no guarantee that sufficient ferrite will be present in the weld metal to prevent cracking.

TABLE 2. Ferrite Contents of Stem-to-Body Welds

Component	Material Control Number	Predicted Ferrite (FN*)	Measured Ferrite (FN)
Stem	103387	3	4
Body	104687	3	
Stem	103380	3	3
Body	105309	0	
Stem	103371	1	2
Body	105309	0	
Stem	103290	2	3
Body	105309	0	
Stem	103369	0.5	None
Body	105308	0	available for measurement

*FN = ferrite number.

Joint Restraint

The beneficial effect of reducing the joint restraint was demonstrated in an experiment in which a hole was drilled in the stem end prior to welding. This is depicted in Figure 5. Nine units representing three levels of joint restraint (solid stem, 0.093-inch-diameter hole, and 0.250-inch-diameter hole) were welded at parameters selected to produce a wider than normal weld. This was done for assurance that conditions for cracking were favorable.

The order of welding was chosen to eliminate the effects of welding-equipment variables. Results of the experiment are summarized in Table 3. Units with solid stems and those with the 0.093-inch-diameter hole were all subject to weld cracking. None of the units with the 0.250-inch-diameter hole cracked. One unit each from the three groups was sectioned; these are shown in Figures 6-8. Evidently the minimum hole diameter necessary to prevent cracking is greater than 0.093 inch and perhaps less than 0.250 inch. The critical diameter can of course be decreased by increasing ferrite content or by decreasing the heat input of the weld.

FIGURE 5. Location of Hole Drilled in Stem End to Reduce Joint Restraint

The experimental results were further verified by welding 16 more units that had the 0.250-inch-drilled stem. None of these 16 welds cracked.

Heat Input of the Weld

Two conditions determined as being necessary but not sufficient for weld cracking were deep-weld penetration and a wide fusion zone. The fusion zone shown in Figure 2 is representative of welds that were borderline from a cracking standpoint. They were borderline because cracking occurred in only 60% of these units. Units welded with approximately the same penetration but with a wider weld (Figure 6) were 100% subject to weld cracking. Reducing the weld width as shown in Figure 9 completely eliminated weld cracking. Conversely, the weld penetration was decreased, and even with a very wide weld, no cracking occurred (Figure 10). These results indicate that weld cracking can be minimized by proper choice of welding parameters.

TABLE 3. Results of Joint Restraint Experiment

Unit Number	Stem Counterbore (in. dia)	Weld Cracking
27535	none	yes
27541	none	yes
27542	none	yes
27536	0.093	yes
27533	0.093	yes
27540	0.093	yes
27537	0.250	no
27538	0.250	no
27539	0.250	no

FIGURE 6. Weld Cracking in Unit 27525 (Solid stem, 4X)

FIGURE 7. Welding Cracking in Unit 27536 (Drilled
0.093-inch diameter hole in stem, 4X)

FIGURE 8. Unit 27537 (Stem drilled to 0.250-inch diameter, no cracking, 4X)

FIGURE 9. Narrow Deep Penetration Weld, No Cracking (4X)

FIGURE 10. Wide Weld With Shallow Penetration and No Cracking (4X)

Crack Location

It was observed that the crack occurred consistently in the same location of the weld relative to the weld start position. Figure 11 shows the welding sequence as accurately determined by data acquisition. In addition, Figure 11 indicates the crack location relative to this sequence. The welding sequence includes sloping in the weld for approximately 95 degrees of part rotation, full weld power for 421 degrees, and weld slope-out for 170 degrees. Hot cracking of the weld, as shown in Figure 11, always occurred in the vicinity of 100-180 degrees from the weld start location. Concavity of the weld overhead also was a characteristic of this region. From the consistent location of the crack, it was surmised that cracking was associated with a particular step in the welding sequence. Figure 11 shows that

FIGURE 11. Welding Sequence and Crack Location.

LEGEND

- +++++ — Slope-In
- — Weld
- ooooo — Slope-Out

the cracks occurred just beyond the point where slope-in ended or just prior to where slope-out began. Either function could be associated with weld cracking. Also, the cracked region of the weld was approximately opposite the weld start, which is a region of maximum joint gap. It was speculated that weld cracking could be related to the joint gap. This would increase the strain to which the weld is subjected.

A series of experimental welds was made on stem-body assemblies to determine the relationship between welding sequence and cracking. The computer-based data acquisition system was used to accurately determine the weld sequence, and the cracks were located by ultrasonic inspection.

Initially, welds were made with the normal welding procedure to verify the weld sequence shown in Figure 11. Weld times were then increased so that the weld lengths were increased by 124 and by 226 degrees of part rotation. Slope-in and slope-out times remained constant. The effect of these changes on overbead concavity and crack location is shown in Figure 12. It is obvious from Figure 12 that cracking is not a function of either the weld start or the weld slope-in, but cracking is associated with the slope-out condition. By actual observation of the welding process, it was determined that concavity of the weld bead (approximately 0.25-inch in length) trails immediately behind the electron beam. When slope-out begins, the concavity is solidified in place. It is in this region of the weld that cracking occurs.

Since the weld concavity and cracking were associated with the slope-out condition, it was theorized that by minimizing the rate of slope-out (increasing

the slope-out time), cracking could be eliminated. Two units were welded at the minimum slope-out rate obtainable. This resulted in welds having less concavity and no weld cracking. Three additional units were welded at the same parameters to verify the results. Again, no cracking was detected. The results indicate that a high level of stress exists in the concave section of the weld, and that this stress can be decreased to an acceptable level by decreasing the slope-out rate.

CONCLUSIONS

Weld cracking in the stem-to-body weld can be effectively eliminated by (1) counterboring the stem to reduce constraint, (2) by proper selection of welding parameters, or (3) by decreasing the slope-out rate of the weld. Since it has been demonstrated that each of these methods was singly effective in preventing weld cracking, the combined effect will provide more than adequate assurance against weld cracking.

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FIGURE 12. Effect of Weld Sequencing on Concavity and Crack Location

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