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TOPICAL REPORTS

- I. STRUCTURAL CHARACTERIZATION AND BIAXIAL MECHANICAL PROPERTIES OF VACUUM-MELTED TYPE 316 STAINLESS STEEL TUBING
- II. CLADDING WELDABILITY STUDY

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Prepared for the U.S. Atomic Energy Commission
Division of Reactor Development and Technology
Under Contract No. AT(30-1)-4210, Task 3

Submitted to AEC/NY00 in July 1971

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Printed in the United States of America
Available from
National Technical Information Service
Springfield, Virginia 22151
Price: Printed Copy \$3.00; Microfiche \$0.95

REPORT II
CLADDING WELDABILITY STUDY

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SECTION 1

INTRODUCTION

The objective of this study was to evaluate the effects of processing and fabrication variables on the weldability of Type 316 stainless steel fuel pin cladding. The scope of this program was limited to making test welds in different grades of Type 316 stainless steel cladding, with a constant set of weld parameters typical of those used in fuel pin end-closure welding. Originally, the various grades of cladding to be investigated included the following:

1. Air-melted cladding in the solution annealed condition
2. Air-melted cladding with 15 to 20 percent residual cold work
3. Double vacuum-melted cladding in the solution treated condition
4. Double vacuum-melted cladding with 15 to 20 percent residual cold work
5. Air or vacuum-melted cladding that had been planetary swaged

Due to funding limitations and material availability, only materials under (1) and (2) were studied.

A total of 261 test welds were made, using semi-automatic tungsten inert gas welding; the test welds were examined using radiography, helium leak testing, metallography, visual examination, and dimensional inspection. The results obtained during this study indicate that with 0.0015-inch end plug-tube interferences, the annealed material exhibits a 0.9 percent defect rate as compared to a 6.5 percent defect rate with 15 to 20 percent cold worked material. However, with no end plug-tube interference, the annealed material exhibits a 13 percent defect rate as compared to a 0 percent defect rate with 15 to 20 percent cold worked material.

SECTION 2

EXPERIMENTAL SCOPE

Weld test samples were made in four series, as detailed below:

SERIES I   Cladding - Type 316 stainless steel annealed, Heat 20303,
                         Lot 316726

End Plug Tube Fit - 0.0015-inch interference

Number of Welds - 109

SERIES II   Cladding - Type 316 stainless steel annealed, Heat 20303,

End Plug Tube Fit - plug diameter same as tube internal diameter

Number of Welds - 30

SERIES III   Cladding - Type 316 stainless steel 15 to 20 percent Cold
                    Worked, Heat 20303, Lot 321921

End Plug Tube Fit - 0.0015-inch interference

Number of Welds - 92

SERIES IV   Cladding - Type 316 stainless steel 15 to 20 percent Cold
                    Worked, Heat 20303, Lot 321921

End Plug Tube Fit - plug diameter same as tube internal diameter

Number of Welds - 30

The cladding samples were all from heat 20303 (see Table 2-1 for chemistry), and had a 0.300-inch outside diameter with a nominal wall thickness of 0.012 inch. The end plugs were machined from annealed Type 316 stainless steel rod, all from the same heat of material (G-4612). Welding parameters were kept constant in all four series of tests.

The degree of fit between the cladding and end plug was included as a carefully controlled variable in this study because it affects the stress distribution in the weld region. Stresses introduced by inserting the end plugs could be as important as the degree of cold work in the as-received cladding.

Table 2-1. Heat Analysis of Cladding and End Plug Materials

Element	Cladding (Heat 20303) (w/o)	End Plug Mat. (Heat 9-4612) (w/o)
Cr	17.62	17.31
Ni	13.19	12.50
Mo	2.24	2.62
Mn	1.52	1.80
Si	0.65	0.70
Cu	0.12	0.09
Co	0.11	0.32
N	0.06	- --
C	0.055	0.037
Nb	0.03	- --
Ti	0.015	- --
P	0.018	0.017
S	0.015	0.025
O	<0.001	- --
B	0.003	- --

3.1 SAMPLE PREPARATION

Measurements from both the cladding samples and end plugs were matched to provide the required fit within ± 0.0003 inch. The plugs and tubes were degreased in acetone and assembled in matched pairs. A simple fixture was made to ensure that the plugs were loaded into the tubes without cocking, thereby minimizing the possibility of having an eccentric tube-to-plug fit. Representative samples were measured to determine the amount of tube expansion occurring during the assembly of interference fit samples.

3.2 WELDING

All of the samples were welded with a Miller ESR-150 programmed TIG welding machine. The samples were positioned vertically in a rotating chuck and welded as shown in Figure 2-2. The plexiglass hood around the welding torch and sample was purged with welding grade argon for at least one minute prior to welding. The inside of the tube sample was also purged with argon prior to welding by inserting a drilled copper rod into the sample; the copper rod also acted as a chill. The samples were lightly wire brushed and degreased in acetone immediately prior to loading into the welding chuck. Welding parameters were as follows:

Tube Rotation	19 inch/min = 20 rpm
Electrode	2% thoriated tungsten 0.040 inch diameter, 60 degree tapered end with 0.015 inch flat
Arc Gap	0.015 (+0.0015), set with feeler gage and dial indicator
Torch Purge	99.999 percent purity argon at 12 cfh
Tube Purge	99.999 percent purity argon at 4 cfh

Figure 2-2. End Closure Welding

Electrode Position

Centerline of electrode 0.005-inch
above joint interface

Machine Settings

Hot start with impulse intensity at 35
Straight polarity
28 amps weld current
4-seconds weld time
Slope-out rate 80 for 2.3 seconds
Post flow times 5 seconds

After welding, the samples were visually examined at a five power magnification, and then cleaned by lightly brushing with a stainless steel brush.

3.3 WELD EXAMINATION

All of the sample welds were helium leak tested by evacuating the open ended tube and spraying helium on the external surface. A leak rate of 10^{-8} cc/sec was considered rejectable in this test. After leak testing, each weld was radiographed from four different directions. Film sensitivity levels of better than 2-2T were verified by a radiographic penetrometer and a defect standard. Shape correction blocks, consisting of holes drilled through a stainless steel flat plate, were used to enhance uniform subject density and contrast. Tube wall thinning of approximately 0.001 inch could be detected using these techniques. The rejection criteria for radiography were as follows:

1. Reject all welds showing less than 100 percent penetration
2. Reject all welds containing either cracks, tungsten inclusions, non-metallic inclusions, or porosity
3. Reject all welds exhibiting tube-wall thinning in the joint region.

Representative samples were also metallographically examined and some samples were measured before and after welding to determine dimensional changes in the joint region.

SECTION 4

RESULTS

Two terms used throughout this study may need some clarification: "Tube pull away" refers to a condition that may occur in the heat affected zone of the tube (a section through a sample exhibiting tube pull away would show a pronounced gap between the tube and the plug, as shown in Figure 2-5); "tube wall thinning" refers to thinning of the effective tube wall in the joint region (shown in Figure 2-5).

4.1 SERIES I (ANNEALED CLADDING, 0.0015-INCH INTERFERENCE FIT)

Out of 109 welds in this series only one defect was detected; the defective weld exhibited a clearly visible blow hole. Some of the samples exhibited tube pull away adjacent to the weld, but no tube wall thinning was detected during radiography. Metallographic examination of ten samples did not reveal any tube wall thinning in excess of seven percent of the wall thickness. Measurements of weld penetration are shown in Table 2-2. Representative examples of the metallographic weld sections produced in this study are shown in Figures 2-3, -4, and -5.

Figure 2-3. Metallographic Section Showing Uniform Weld
(75X)

Figure 2-4. Metallographic Section Showing Preferential
Tube Wall Melting (75X)

Figure 2-5. Metallographic Section Showing Preferential
Tube Wall Melting and Tube Wall Thinning
(75X)

Table 2-2. Metallographic Examination of Series I Samples (Annealed Cladding, 0.0015-inch Interference Fit)				
Tube No. (Met. Lab Ref. in Parentheses)	Minimum Tube Wall Thickness (in.)	Minimum Weld Penetration (% Wall Thick)	Maximum Weld Penetration (% Wall Thick)	Comments
42 (S-236)	0.0120	171	225	Good profile
99 (S-237)	0.0118	171	226	Some tube pull away
45 (S-238)	0.0114	174	192	Good profile
68 (S-239)	0.0120	200	245	Good profile
53 (S-240)	0.0116	141	192	Some tube pull away
A25 (S-231)	0.0120	150	179	Good profile
A23 (S-232)	0.0120	142	187	Some tube pull away
A8 (S-233)	0.0115	140	145	Some tube pull away
A11 (S-234)	0.0113	115	175	Shallow penetration
AS (S-235)	0.0120	175	185	Some tube pull away

Figure 2-3 shows a good weld profile with a uniform weld bead, ample penetration, no tube pull away, and no significant tube wall thinning. The features of the weld shown in Figure 2-4 are similar to those shown in Figure 2-3, except that the weld profile is not as uniform; preferential melting of the tube wall is apparent in Figure 2-4. The weld section shown in Figure 2-5 exhibits tube pull away, tube wall thinning, relatively shallow penetration, and extensive preferential tube-wall melting. All of the welds shown in the three figures were considered to be acceptable, and the variation in weld profile shown in these photographs represents the whole range of weld profiles observed in this examination.

Micrometer measurements of the Series I samples indicated that all of the interference between the plug and the tube was transmitted to the external diameter of the tube. In addition, the weld bead was slightly raised with respect to the surface of the tube; diametral increases at the weld bead were typically 0.003 to 0.004 inch.

4.2 SERIES II (ANNEALED CLADDING, TUBE AND PLUG DIAMETER EQUAL)

A total of 30 welds were made in this test series. All of these welds were acceptable on the basis of visual examination and leak testing. However, radiographic examination indicated that three of the weld samples exhibited unacceptable tube wall thinning. Seven of the weld samples were metallographically examined and the results of this examination are shown in Table 2-3. The measurements obtained during this examination confirmed that tube-wall thinning had occurred in samples attributed with this defect by radiography. In addition, one of the samples that was metallographically examined revealed insufficient weld penetration (Figure 2-6).

Table 2-3. Metallographic Examination of Series II Samples
(Annealed Cladding, No Interference)

Tube No. (Met. Lab. Ref. in Parentheses)	Minimum Tube Wall Thickness (in.)	Minimum Weld Penetration (% Wall Thick)	Maximum Weld Penetration (% Wall Thick)	Comments
D27(a) (S-252)	0.0115	156	163	Tube pull away and thinning
D37(a) (S-253)	0.0112	155	163	Tube pull away and thinning
D8 (S-254)	0.0120	151	185	Tube pull away
D20 (S-255)	0.0115	145	185	Tube pull away
D26 (S-256)	0.0115	148	171	Tube pull away
D25 (S-257)	0.0120	145	185	Tube pull away
D30 (S-258)	0.0120	100	182	Insufficient penetration
(a)Radiography Indicated Tube Wall Thinning				

Micrometer measurements of the Series II samples indicated that diametral increases at the weld bead were typically 0.002 to 0.003 inch.

Figure 2-6. Metallographic Section Showing Poor Penetration and Tube Pull Away (75X)

4.3 SERIES III (COLD WORKED CLADDING, 0.0015-INCH INTERFERENCE FIT)

A total of 92 welds were made in this test series. One of the welds exhibited a blow hole, all other welds were acceptable on the basis of visual examination and leak testing. Radiographic examination indicated that one weld contained a tungsten inclusion and four welds exhibited unacceptable tube wall thinning. Seven of the welds were metallographically examined and the results of this examination are shown in Table 2-4. The measurements obtained during this examination confirmed that tube wall thinning had occurred in samples attributed with this defect by radiography.

Micrometer measurements of the Series III samples indicated that diametral increases at the weld bead were typically 0.002 to 0.004 inch.

4.4 SERIES IV (COLD WORKED CLADDING, TUBE AND PLUG DIAMETER EQUAL)

Out of the total of 30 welds made in this test series no defects were observed by any of the inspection techniques employed. Five of the samples were metallographically examined and the results of this examination are shown in Table 2-5. Micrometer measurements of the Series IV samples indicated that diametral increases at the weld bead were typically 0.002 to 0.003 inch.

Table 2-4. Metallographic Examination of Series III Samples
(Cold Worked Cladding, 0.0015-inch Interference Fit)

Tube No. (Met. Lab. Ref. in Parentheses)	Minimum Tube Wall Thickness (in.)	Minimum Weld Penetration (% Wall Thick)	Maximum Weld Penetration (% Wall Thick)	Comments
B71(a) (S-260)	0.0116	118	145	Tube wall thinning
B19(a) (S-261)	0.0112	126	156	Tube wall thinning
B67 (S-262)	0.0120	156	207	Good profile
B59 (S-263)	0.0115	207	230	Good profile
B97 (S-264)	0.0116	163	174	Tube pull away
B114 (S-265)	0.0116	178	194	Tube pull away
B113 (S-266)	0.0116	141	171	Tube pull away
(a)Radiography indicated tube wall thinning				

Table 2-5. Metallographic Examination of Series IV Samples
(Cold Worked Cladding, No Interference)

Tube No. (Met. Lab. Ref. in Parentheses)	Minimum Tube Wall Thickness (in.)	Minimum Weld Penetration (% Wall Thick)	Maximum Weld Penetration (% Wall Thick)	Comments
B20 (S-244)	0.0120	159	237	Tube pull away
B85 (s-245)	0.0116	200	215	Good profile
B35 (S-246)	0.0116	171	192	Good profile
B34 (S-247)	0.0116	178	192	Good profile
B36 (S-248)	0.0116	178	197	Tube pull away

SECTION 5

DISCUSSION OF RESULTS

The defect occurrences observed in this study are summarized below:

SERIES I (Annealed Cladding, 0.0015 inch interference fit)

1 blowhole. Defect rate - 0.9 percent

SERIES II (Annealed Cladding, tube and plug diameter equal)

3 joints exhibiting tube wall thinning (detected by radiography)

1 joint exhibiting insufficient penetration

Defect rate - 13 percent

SERIES III (Cold Worked Cladding, 0.0015 inch interference fit)

1 blowhole

1 tungsten inclusion

4 joints exhibiting tube wall thinning (detected by radiography)

Defect rate - 6.5 percent

SERIES IV (Cold Worked Cladding, tube and plug diameter equal)

No defects

Defect rate - 0 percent

Comparing the results from Series I and III on a purely empirical basis indicates that annealed cladding exhibits a lower defect frequency rate than cold worked cladding. The opposite is indicated if the results from Series II and IV are compared on a purely empirical basis. Comparing the results from Series I and II indicates that with annealed cladding, a lack of interference between the end plug and tube increased the defect frequency rate; without interference, the weld penetration tended to be less and tube wall thinning was apparent on weld radiographs. Comparing the results from Series III and IV indicates that with cold worked cladding, a lack of interference between the end plug and the tube may decrease the defect frequency rate.

To provide an explanation for these results requires a knowledge of the mechanism by which degree of fit and degree of residual cold work affect the welding operation. The factors affecting tube wall thinning appear to be particularly important in the interpretation of these results. Before the effect of residual cold work on tube wall thinning can be discussed, a knowledge of the stress-strain distributions occurring during end closure welding is required.

Prior to welding with an interference fit between plug and tube, there is a hoop stress imposed on the tube. This stress is superimposed on any resi-

dual stress in the tube resulting from cold work. With no interference between plug and tube, only the residual stress due to cold working has to be considered. When an arc is established at the joint, several reactions happen simultaneously:

1. Any residual hoop stresses in the tube are relieved as soon as the molten pool is formed
2. The tube tends to pull away from the plug as the residual hoop stress (from plug insertion and cold deformation) is relieved.
3. The tube and plug both expand in the joint region as a result of the arc heating; the stress-strain distribution at the joint due to thermal expansion is dependent on the position of the molten pool with respect to the joint line, the relative mass of the tube and plug, the efficiency of the copper chill, the heat conduction between the tube and plug, and the size of the molten pool.
4. The gas inside the tube expands and escapes around the unsealed joint interface.

As the weld pool progresses around the circumferential joint, parts of the joint region expand while other parts tend to contract. Axial contraction (transverse to the weld) can produce a stress in the partially completed joint; the side of the joint containing the solidified weld will contract and tend to misalign the end plug with respect to the longitudinal axis of the tube. This contraction will also tend to pull tube material into the weld pool. The gas inside the tube is continually expanding, and as the joint solidifies this gas pressure tends to blow out the last part of the weld pool.

As the completed weld solidifies and shrinks, a compressive hoop stress is developed at the center of the weld, and a tensile hoop stress is developed in the heat affected zone of the tube. Simultaneously, axial contraction is pulling the tube and plug into the joint. However, at the last part of the weld, the plug and tube are restrained by the previously solidified and cooler weld metal. Consequently, any strain resulting from this axial contraction will tend to be concentrated in the tube wall adjacent to the last part of the weld. If this part of the tube is molten, or very hot with respect to the surrounding material, tube wall thinning occurs (see diagrammatic explanation in Figure 2-7).

It appears that uniformity of the weld bead would be an important factor in determining the frequency of tube wall thinning. If an assymetric weld bead is formed (similar to that shown in Figure 2-6) the axial contraction is more likely to cause tube-wall thinning than in a symmetrical weld (similar to that shown in Figure 2-4). Assuming that this hypothesis is valid, one must consider the factors affecting the symmetry of the weld bead and how residual cold work or plug-tube interference affect weld symmetry. Poor heat conduction between the tube and plug or the tube and

and 0.000 (± 0.0003) inch. In actual production it is unlikely that the degree of fit could be as closely controlled because each tube-plug pair would have to be individually matched. Typical tolerances on a production basis would be end plug diameter ± 0.0005 inch. A typical nominal interference fit would be 0.0007 inch, and with accumulation of tolerances this fit could actually vary from 0.0014 inch to 0.0000 inch interference. This range of fit almost covers the range of both degrees of fit used in this study. Therefore, the results from Series I and II (annealed cladding) could be realistically grouped together and compared to the results from Series III and IV (cold worked cladding). As shown below, the resultant comparison provides an indication of the relative defect frequency rates between annealed and cold worked cladding on a production basis:

SERIES I & II	- Total Welds	139
	Total Defects	5
	Defect Rate	3.6%
SERIES III & IV	- Total Welds	122
	Total Defects	6
	Defect Rate	4.9%

On the basis of this comparison there appears to be no major difference between the weldability of annealed and cold worked cladding.

Cold worked cladding welding trials, performed under AEC Contract AT(30-1)-3791,^[1] have indicated that when tube wall thinning exceeds 50 percent of the tube wall thickness there is a tendency for microfissures to form in the weld metal. The tube wall thinning observed in the present work was approximately 10 to 15 percent of the tube wall thickness and no microfissuring was observed in any of the samples examined.

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^[1] R. C. DeKlever, W. R. Jacoby, R. K. McGeary, "Welding Stainless Steel Fuel Element End Plug Closures," WARD-3791-44, February 1970.