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WPH-6112A Thermal Expansion Test of
PRESS Tubulation

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Summary

We recently performed the WPH-6112A thermal expansion test of the lower portion of the PRESS program tubulation. The objective of the test was to determine whether the tubulation welds could withstand typical stresses from a 1200 °C thermal cycle. Test components failed in two areas: 1) the friction welded Monel to Vanadium tube fitting melted at the dissimilar metal interface and fell against the outer vanadium tube wall causing it to fail and 2) the thin-walled, outer stainless steel tubing failed by cracking at the weld. Both failures were due to irregular occurrences for this system. We feel that the strength of all weldments is adequate to withstand the normal thermal stresses from a 1200 °C cycle without failing prematurely.

Procedure

The WPH-6112A assembly was welded together in a manner similar to that used for typical melt test assemblies, as shown schematically in Figure 1. For this test, the ends were designed so that the inner vanadium tubulation parts would be tensile tested during the heating cycle and so that all loading would be eased during the cooling cycle. The stress conditions during the upward thermal cycle are due to the large mismatch of thermal expansion between austenitic stainless steels and vanadium from room temperature to test temperature and the proximity of high temperature mechanical properties between the two materials, as shown in Table 1. After fabrication, the assembly was thermally cycled from room temperature to 1200 °C and back to room temperature. We inspected the assembly visually for surface defects, radiographically for internal defects and destructively for metallurgical properties.

Discussion

Upon inspection after the thermal cycle, two separate failures were found to have occurred during the test. The approximate location of each failure is shown in Figure 1. Radiographic inspection found a melt failure in the inner vanadium tube fitting and visual inspection found a crack failure in the outer thin wall stainless steel to outer stainless steel fitting laser weld. We sectioned the assembly and sent 1) the cracked area for scanning electron microscopy study of the crack morphology, 2) the remaining weld sections to optical metallography for preparation and 3) the melted portion for sectioning and energy dispersive spectroscopy (EDS).

Melt Failure

Previous work on the vanadium to Monel 400 friction weld had indicated that melting occurred at the dissimilar metal interface at slightly below 1000 °C. Although no tertiary copper-nickel-vanadium phase diagram was found in the literature, some information can be predicted using the appropriate binary phase diagrams. The copper-vanadium phase diagram in Figure 2 shows that copper melts at 1083 °C, but from our previous experience, we know that the addition of nickel into the alloy causes a lower melting point composition to form. At 1200 °C, the nickel-vanadium combination has a low melting point eutectic, shown in Figure 3, that is triggered right in the range of the test temperature and the addition of

copper probably suppresses the melting temperature of the eutectic composition even further.

A cross-section through the alloy formed during melting revealed a eutectic microstructure surrounded by a single phase layer. Figure 4 shows a photomicrograph of these microstructures. The eutectic composition found in EDS is mainly a Monel 400-vanadium mixture. Some iron was found in the alloy, but this probably raised the melting point of the mixture and helped to resolidify the mixture. The single phase layer surrounding the eutectic alloy was found to be composed of mostly stainless steel alloy components.

Crack Failure

Figure 5 shows a low magnification photomicrograph of the crack which occurred fully in the fusion zone of the weld. Figure 6 shows a high magnification photomicrograph of the crack surface. Comparing the crack surface morphology to textbook samples (1), this appears to be a case of creep rupture failure. For creep to occur in the material some tensile loading was required on the stainless steel tubing during the test.

We know that the outer stainless steel tubulation was pinned by the melt failure at one end of the tubing. The other end of the tubing was probably slightly bent due to the off-axis stresses created by solidification of the melt failure and thermal contraction of the tubulation. The slight bending of the tubulation probably caused the sliding surfaces to bind up causing axial loading to be transferred into the stainless steel components. For this scenario to make sense, the stress level to cause tube failure had to be extremely low. Using standard stress calculations (see Figure 7 for high temperature ultimate tensile strength (UTS) of type 316 stainless steel and Equation 1 for calculation), we find that axially loading the thin wall stainless steel tubing to approximately 11 pounds at 1200 °C would cause failure.

$$\begin{aligned}
 \text{Load} &= (\text{UTS}) (\text{Area}) && \text{Eqn. 1} \\
 &= (3000 \text{ psi}) (\pi (0.0625 \text{ in.})^2 - (0.0525 \text{ in.})^2) \\
 &= (3000 \text{ psi}) (0.0036 \text{ in.}^2) \\
 &= 11 \text{ pounds}
 \end{aligned}$$

The loading also would need to be concentrated over a very short length of the tubing because of the high ductility of the material at this temperature. Metallographic cross-sections of the laser weld area, shown in Figure 8-a and b, indicate that the stresses were concentrated at the thinnest section of the fusion zone. Grain boundary coarsening and necking of the specimen were found over a short length of tubing on the order of 0.020 inches. This short gage length over which plastic deformation occurred allowed a stress level above the failure stress to be achieved.

Vanadium Welds

Two vanadium welds were tested in tension during the thermal cycle from ambient to 1200 °C. The welds joined the inner vanadium tubing to the friction weld (FW) fitting and the FW fitting to the inner vanadium tube fitting. Both welds handled the tensile loading without signs of mechanical deformation. The thermal cycle did cause a great deal of grain growth in the base materials, but had little effect on the weld fusion zone material. A metallographic cross-section of the inner vanadium

tubing to the FW fitting laser weld is shown in Figure 9. A metallographic cross-section of the inner vanadium tube fitting to the friction weld (FW) fitting laser weld is shown in Figure 10.

Acknowledgments

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References

1. Mills, Kathleen, ed., Metals Handbook, 9th Edition, Volume 8, ASM International, Metals Park, OH (1987), p.354.

Table 1. Physical and Mechanical Properties of Vanadium and Type 21-6-9 Stainless Steel

Commercially Pure Vanadium

Temperature (°C)	CTE (10E-6/°C) ^a	P. H. ^b	E (psiX10E6) ^b	UTS (ksi) ^b	YS (ksi) ^b
20	9.4	0.38	19.3	36.3	29.0
100	9.6	0.38	19.0		
200	9.9	0.38	18.7	34.2 (c)	24.1 (c)
300	10.1	0.38	18.3		
400	10.4	0.38	18.1	38.2 (c)	23.8 (c)
500	10.8	0.38	17.7	32.8 (c)	21.8 (c)
600	11.1	0.38	17.4	28.4	17.1
700	11.5	0.38	17.1	17.5	10.1
800	12.0	0.38	17.0	11.8	7.7
900	12.4	0.38	16.9	10.5	7.0
1000	12.9	0.38	16.6	8.2	4.5

Type 21-6-9 Stainless Steel

Temperature (°C)	CTE (10E-6/°C) ^a	P. R. ^d	E (psiX10E6) ^d	UTS (ksi) ^d	YS (ksi) ^e
20	16.6	0.31	28.9	111	49.9
100	17.3	0.31	27.7	100	
200	18.2	0.30	26.1	91	31.2
300	19.0	0.29	24.8	85	25.4
400	19.8	0.29	23.7	80	20.2
500	20.6			74	21.8
600	21.4			66	20.7
700	22.2			54	19.4
800	22.9			35	17.1
900	23.7				11.2
1000	24.4				6.2

a - Personal Communication with T. Quick

b - DOE document (COO-4540-1) Vanadium Property Assessment Reports

c - Gallegos, G., Mechanical Properties of Vanadium, LLNL Report UCID 20726

d - Armco Product Data Bulletin, Nitronic 40, Report S-2

e - Kassner, M., Mechanical Properties of Type 21-6-9 Stainless Steel, LLNL Report UCID 19597

Figure 1. Tubulation configuration for thermal expansion test (WPH-6112A). This schematic shows the approximate configuration of tubulation parts. Note the locations of the two failure areas. The melt failure slumped onto the wall of the inner vanadium tube fitting causing a reaction. The laser weld failure covered approximately 15% of the weld circumference.

Figure 2. Vanadium-copper phase diagram. Pure copper melts at 1083 °C. (Reference: J. F. Smith, Ed., Phase Diagrams of Binary Vanadium Alloys, ASM International, Metals Park, OH (1989), p. 65.)

Figure 3. Vanadium-nickel phase diagram. Low melting eutectic occurs at 1202 °C. (Reference: J. F. Smith, Ed., Phase Diagrams of Binary Vanadium Alloys, ASM International, Metals Park, OH (1989), p. 168.)

Figure 4. Photomicrograph of melt failure microstructure after resolidification. Inner structure consists of vanadium and Monel 400 eutectic structure. Nickel and vanadium have a similar structure in binary alloy form. In this case, copper has replaced some of the nickel in the alloy. The outer surface layer consists mainly of stainless steel constituents.

Figure 5. Low magnification scanning electron photomicrograph of stainless steel laser weld crack. The crack propagated for approximately 15% of the weld circumference.

Figure 6. High magnification scanning electron photomicrograph of crack surface shown in Figure 5. This surface looks typical of high temperature creep rupture failure.

Figure 7. Stress-strain curves for type 316 stainless steel. The thin wall tubing used in this test was made from 316 stainless steel. The peak test temperature was very close to 2200 °F. (Reference: Wolf, J., ed., Aerospace Materials Handbook, Volume 2, Belfour Stulen, Inc. (1988), p. 29.)

(a)

(b)

Figure 8. Photomicrographs of cross-sections of the stainless steel laser weld. These photomicrographs show the high degree of localized plastic deformation in the weld fusion zone. Figure 8-a shows a highly necked region of the weld with some grain boundary coarsening associated with creep. Figure 8-b shows grain boundary coarsening, new twinning along some grain boundaries and two areas where creep rupture appears to have started to occur.

Figure 9. Photomicrograph of a cross-section of the inner vanadium tubing to friction weld fitting laser weld. The weld shows no evidence of plastic deformation. Grain growth and recrystallization have occurred in both base materials. Material impurities appear to have been pushed to the weld centerline during solidification as grain growth in this area has been greatly suppressed.

Figure 10. Photomicrograph of a cross-section of the inner vanadium tube fitting to friction weld fitting laser weld. The weld shows no evidence of plastic deformation. Grain growth and recrystallization have occurred in both base materials.

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