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Welding and Mechanical Properties of Cast FAPY (Fe-16 at. % Al-Based) Alloy Slabs

V. K. Sikka, G. M. Goodwin, D. J. Alexander, and C. R. Howell

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WELDING AND MECHANICAL PROPERTIES OF CAST FAPY (Fe-16 at. % Al-BASED) ALLOY SLABS*

V. K. Sikka, G. M. Goodwin, D. J. Alexander, and C. R. Howell

ABSTRACT

This report deals with the welding procedure development and weldment properties of an Fe-16 at. % Al alloy known as FAPY. The welding procedure development was carried out on 12-, 25-, and 51-mm (0.5-, 1-, and 2-in.) -thick plates of the alloy in the as-cast condition. The welds were prepared by using the gas tungsten arc process and filler wire of composition matching the base-metal composition. The preheat temperatures varied from room temperature to 350°C, and the postweld heat treatment (PWHT) was limited only for 1 h at 750°C. The welds were characterized by microstructural analysis and microhardness data. The weldment specimens were machined for Charpy-impact, tensile, and creep properties. The tensile and creep properties of the weldment specimens were essentially the same as that of the base metal. The Charpy-impact properties of the weldment specimens improved with the PWHT and were somewhat lower than previously developed data on the wrought material. Additional work is required on welding of thicker sections, development of PWHT temperatures as a function of section thickness, and mechanical properties.

1. INTRODUCTION

FAPY is an Fe-16 at. % Al-based alloy developed at the Oak Ridge National Laboratory as the highest aluminum-containing alloy with essentially no environmental effect.[1] The chemical composition for FAPY in weight percent is: aluminum = 8.46, chromium = 5.50, zirconium = 0.20, carbon = 0.30, molybdenum = 2.00, yttrium = 0.10, and iron = 83.71. The cast ingots of the alloy can be hot worked by extrusion, forging, and rolling processes. The hot-worked cast structure can be cold worked with intermediate anneals at 800°C. Typical room-temperature ductility of the fine-grained wrought structure is 20 to 25% for this alloy. In contrast to the wrought structure, the ductility of the cast

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structure at room temperature is approximately 1% with a transition temperature of approximately 100 to 150°C, above which ductility values exceed 20%. The alloy has been melted and processed into bar, sheet, and foil. The alloy has also been cast into slabs, step-blocks of varying thicknessess, and shapes. The purpose of this report is to describe the welding response of cast slabs of three different thicknesses of FAPY alloy. Tensile, creep, and Charpy-impact data of the welded plates are also presented.

2. CASTING

For the welding studies, the FAPY alloy was used in the as-cast condition, prepared by vacuum-induction melting, and cast in graphite molds measuring 100 by 150 mm (4 by 6 in.) in length and having thicknesses of 12, 25, and 51 mm (0.5, 1, and 2 in.). All three plates had good as-cast surfaces.

3. WELD PRODUCTION

Weld joints were prepared by sawing as shown in Fig. 1. The included angle of 60° in the double-vee groove geometry was used for all three slab thicknesses and is typical of industrial practice for plate welding.

Weld wire of 3.2 mm (0.125 in.) diam with a matching composition of FAPY alloy was used for all weldments using the manual gas tungsten arc (GTA) process. The joint surfaces and filler wire were cleaned by wire brushing and solvent degreasing with acetone. A summary of the welding parameters is shown in Table 1.

Preheat, when used, was accomplished with an oxyacetylene torch. Interpass temperature was maintained at 350°C minimum. Postweld heat treatment (PWHT), when used, was done immediately following welding in an air furnace followed by free cooling in still air.

Completed weldments were examined for possible defects using liquid-dye penetrant. A summary of the inspection results is shown in Table 2. End sections were removed from each weldment for optical metallography. The macroetched surfaces of the welded slabs are shown in Fig. 2.

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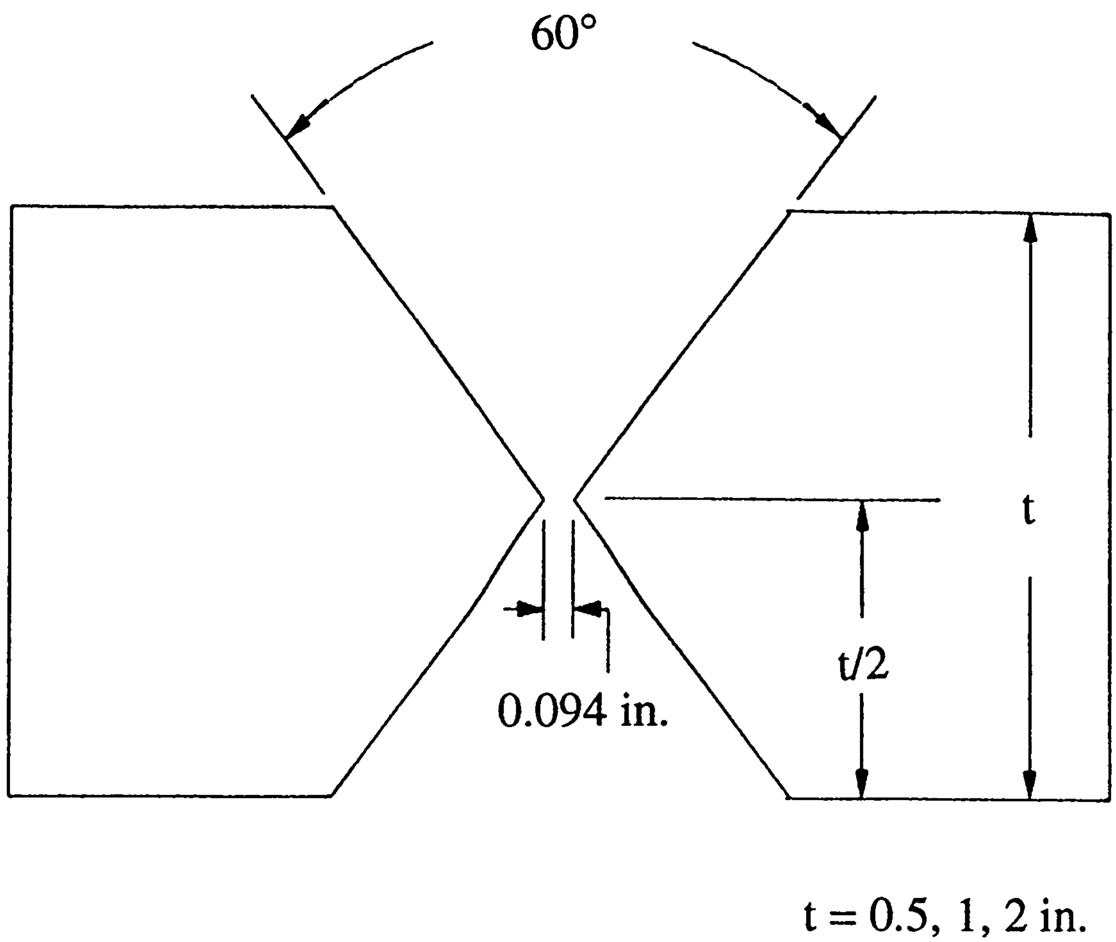

Table 1. Welding parameters for cast FAPY alloy slabs

Process:	Manual gas tungsten arc
Joint geometry:	Double-vee groove, 60° included angle
Base metal:	Cast slabs [100 × 150 × 12, 25, and 51 mm (4 × 6 × 0.5, 1, and 2 in.) thicknesses]
Filler metal:	3.2-mm (0.125 in.) -diam rod, matching composition
Weld current:	100 to 175 A direct current electrode negative
Weld voltage:	10 to 12 V
Torch gas:	Argon, 15 cfh (7.1 L/min)
Backing gas:	Argon, 15 cfh (7.1 L/min)
Approximate number of passes (alternating sides):	12-mm (0.5-in.) slab: 6
	25-mm (1-in.) slab: 25
	51-mm (2-in.) slab: 65

Table 2. Inspection results of cast FAPY alloy slab welds

Temperature, °C		Slab thickness, mm (in.)		
Preheat	Postheat	12 (0.5)	25 (1)	51 (2)
350	750	No cracks	No cracks	No cracks
200	750	--	--	No cracks
20	20	No cracks	Cracks	--

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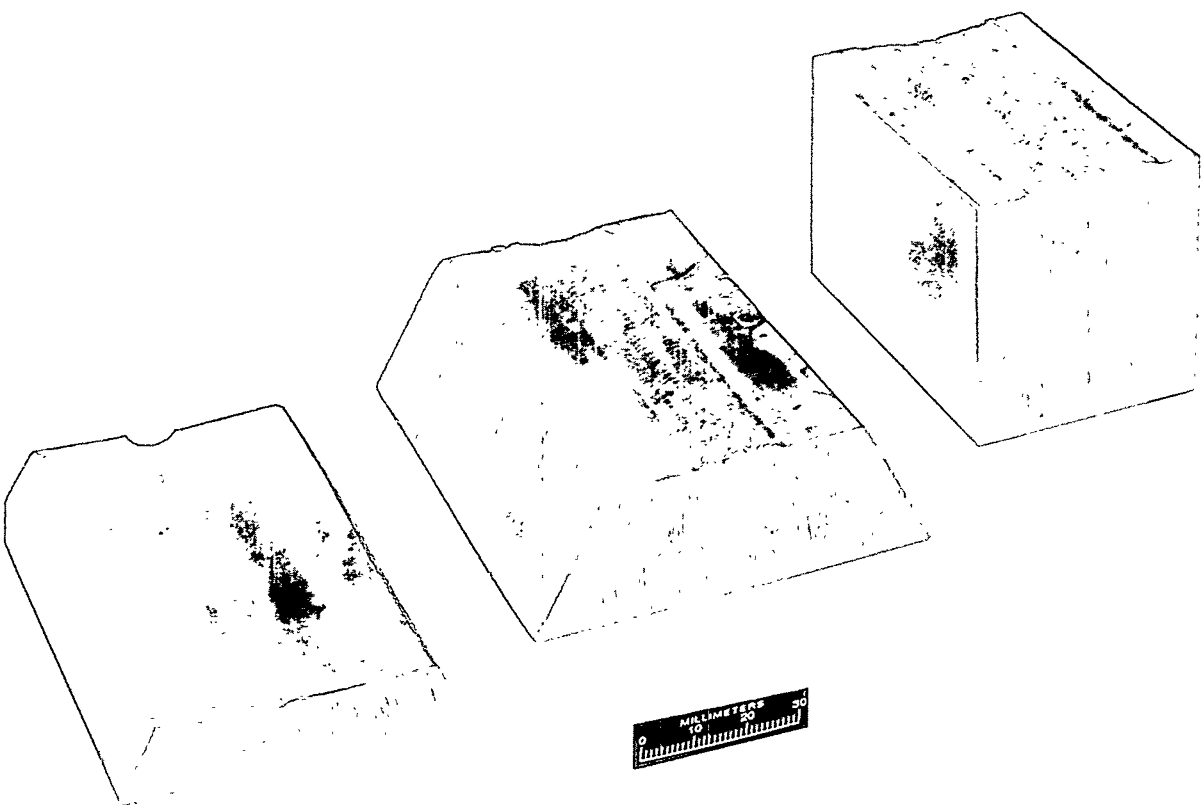

Fig. 2. Macroetched surfaces of gas tungsten arc-processed welds in cast slabs of FAPY alloy.

4. MECHANICAL PROPERTIES

The welded slabs were cut up for mechanical property determinations. The 12-mm (0.5-in.) -thick plates were used for Charpy-impact testing. The 25- and 51-mm (1- and 2-in.) -thick plates were used for tensile and creep properties. The specimen cut-up diagrams for the Charpy, tensile, and creep specimens are shown in Fig. 3.

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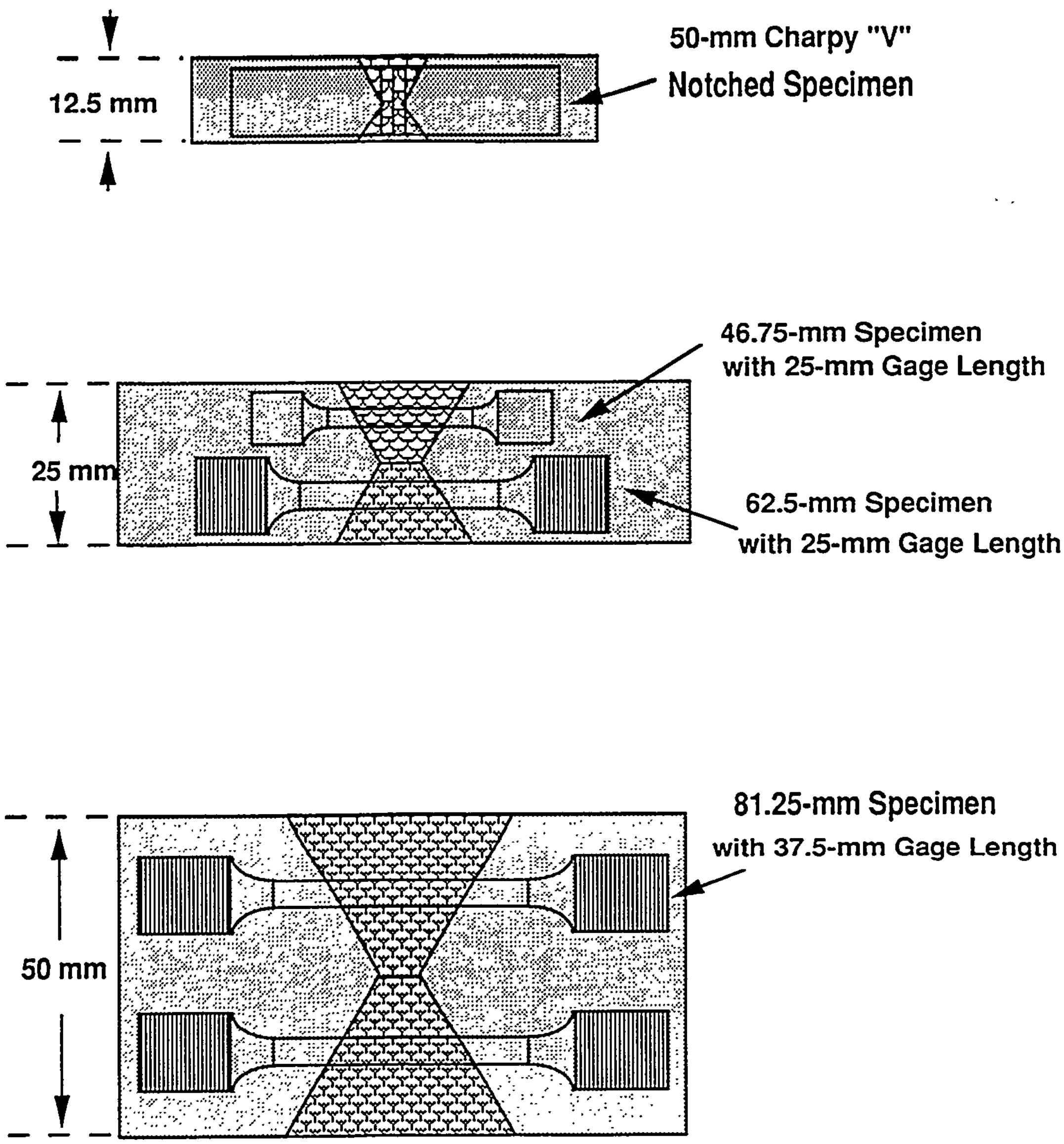

Fig. 3. Schematic showing the location and size of mechanical property specimens machined from welded slabs of FAPY alloy.

4.1 TENSILE PROPERTIES

The tensile data from room temperature to 800°C for the 25- and 51-mm (1- and 2-in.) -thick welded plates are summarized in Table 3. The strength and ductility data of the weldments are plotted and compared with the base-metal data of the cast slabs in Figs. 4 through 7. The following observations can be seen from these figures:

1. The 0.2% yield strength of the weldment specimens is essentially the same as the base-metal values for the entire temperature range. This is true for specimens taken from both the 25- and 51-mm (1- and 2-in.) -thick welded plates.
2. The ultimate tensile strength of the weldment specimens from the 51-mm (2-in.) -thick plate showed lower values than the base metal in the test-temperature range up to 200°C. This is the same temperature region where ductility of both base metal and weldments is low (see Figs. 6 and 7). The observed results in Fig. 5 imply that the weldment specimens from the 51-mm (2-in.) -thick plates are slightly more brittle in this temperature range than base metal or 25-mm (1-in.) -thick plate.
3. The general trend of total elongation and reduction of area of weldments is the same as that for the base metal (see Figs. 6 and 7).

Broken tensile specimens in Fig. 8 show that all failures between room temperature to 800°C were in the weld region.

4.2 CREEP PROPERTIES

The creep data on three weldment specimens machined from 25-mm (1-in.) -thick welded plate are summarized in Table 4. The creep-rupture data on the weldment specimens are compared with the previously developed data on as-cast and wrought base-metal specimens in Fig. 9 which shows that although limited in number, the short-term data on weldment specimens match the data on base-metal, as-cast, and wrought specimens. It should be recognized that long-term data are required to further confirm these observations.

4.3 CHARPY-IMPACT TESTS

Full-size Charpy-impact specimens were machined from two welded plates of 12-mm (0.5-in.) thickness. One of the plates contained a weld in the as-welded condition, and the other one was given a PWHT at 750°C for 1 h. The schematic in Fig. 3 shows the orientation of the Charpy specimens. The crack growth was parallel to the welding

Table 3. Tensile properties of weldment specimens machined from the cast-welded 25- and 51-mm (1- and 2-in.) -thick slabs of FAPY alloy

Specimen No.	Test temperature (°C)	Heat-treatment temperature (°C)		Yield strength (MPa)	Tensile strength (MPa)	Total elongation (%)	Reduction of area (%)
		Preheat	Postheat[a]				
1L[b]	23	350	750	70.91	70.91	1.79	0.08
2L[b]	100	350	750	60.31	79.81	22.88	32.53
3L[b]	200	350	750	47.91	75.07	24.32	44.38
4L[b]	400	350	750	41.19	76.78	25.58	42.89
5L[b]	600	350	750	39.26	39.50	46.16	74.71
6L[b]	800	350	750	11.82	12.22	78.24	83.80
11L[c]	23	200	750	65.39	65.39	0.91	0.00
12L[c]	50	200	750	64.43	65.14	1.62	0.40
13L[c]	100	200	750	57.09	73.77	9.20	9.28
14L[c]	200	200	750	45.36	71.94	20.46	50.37
15L[c]	400	200	750	37.04	73.36	26.35	41.20
16L[c]	600	200	750	37.81	38.93	43.74	72.05
17L[c]	800	200	750	--	11.53	64.13	80.37

[a]Time at temperature: 1 h.

[b]Specimen gauge length: 25 mm (1 in.); strain rate: 3.3×10^{-3}/s.

[c]Specimen gauge length: 51 mm (2 in.); strain rate: 2.2×10^{-3}/s.

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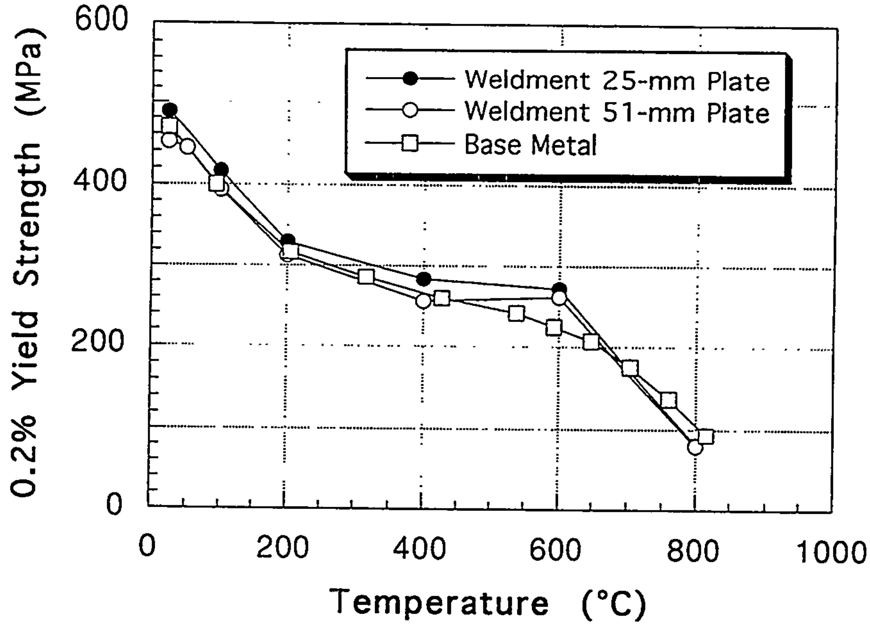

Fig. 4. Comparison of 0.2% yield strength of weldment specimens with base metal of FAPY alloy. The base-metal data are from a previous study on cast slab.

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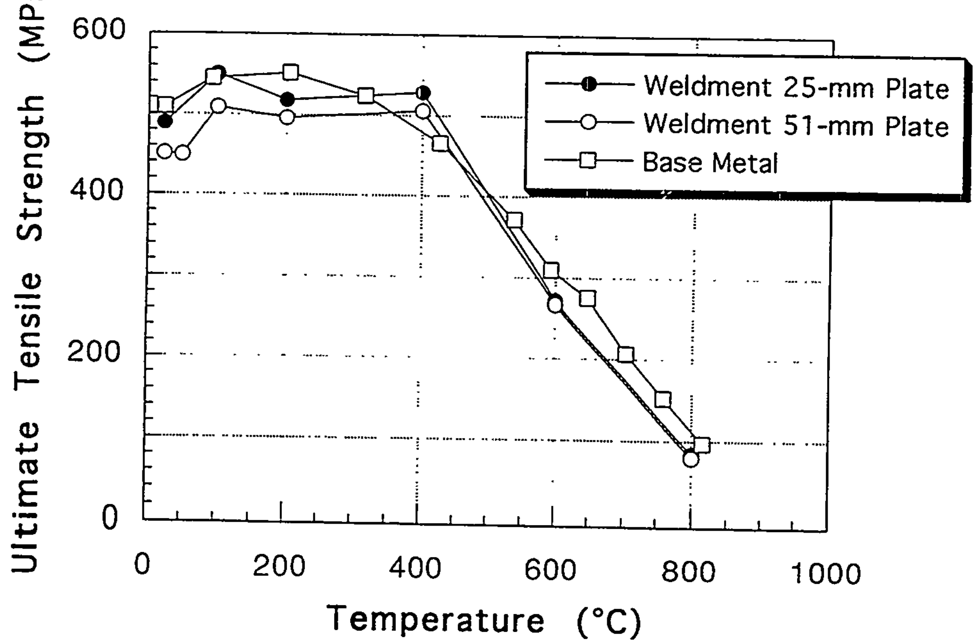

Fig. 5. Comparison of ultimate tensile strength of weldment specimens with base metal of FAPY alloy. The base-metal data are from a previous study on cast slab.

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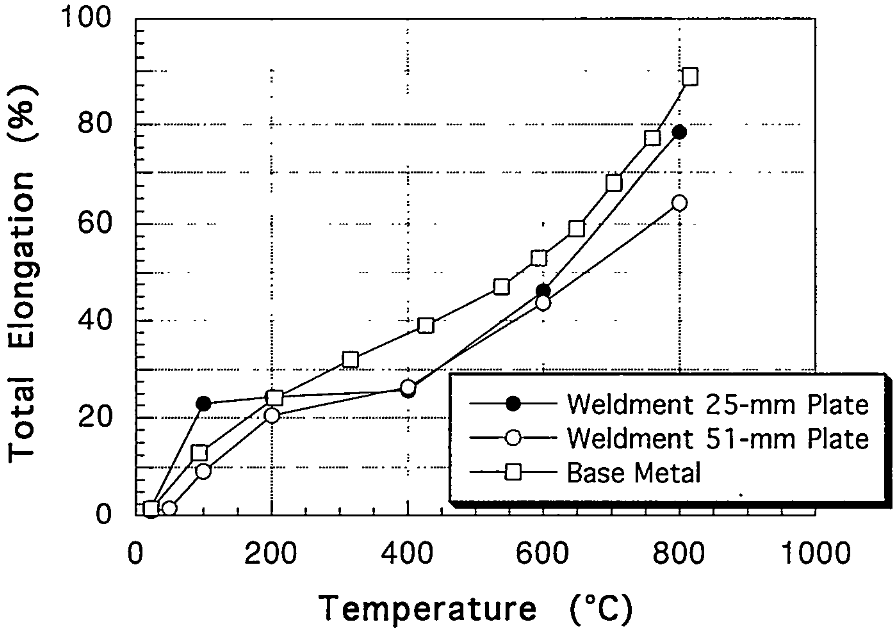

Fig. 6. Comparison of total elongation of weldment specimens with base metal of FAPY alloy. The base-metal data are from a previous study on cast slab.

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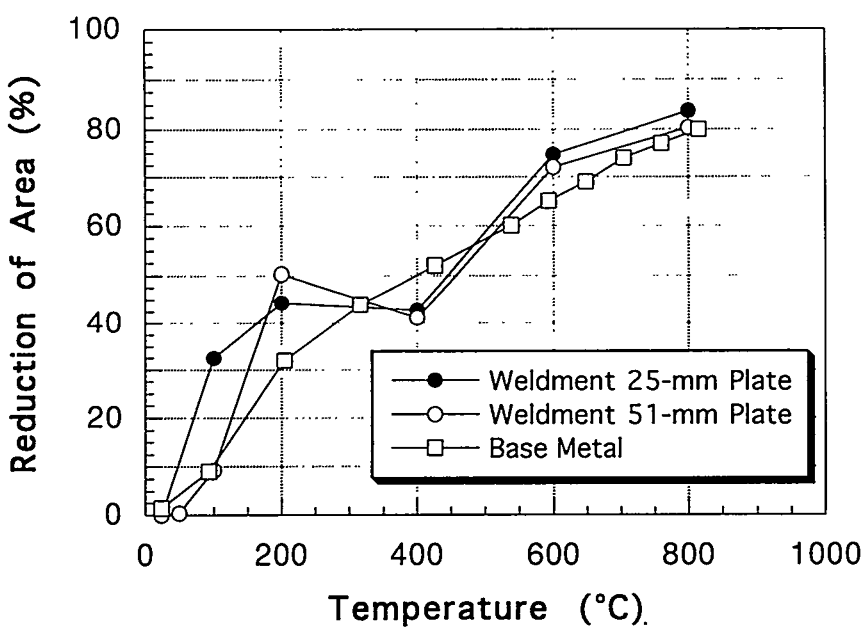

Fig. 7. Comparison of reduction of area of weldment specimens with base metal of FAPY alloy. The base-metal data are from a previous study on cast slab.

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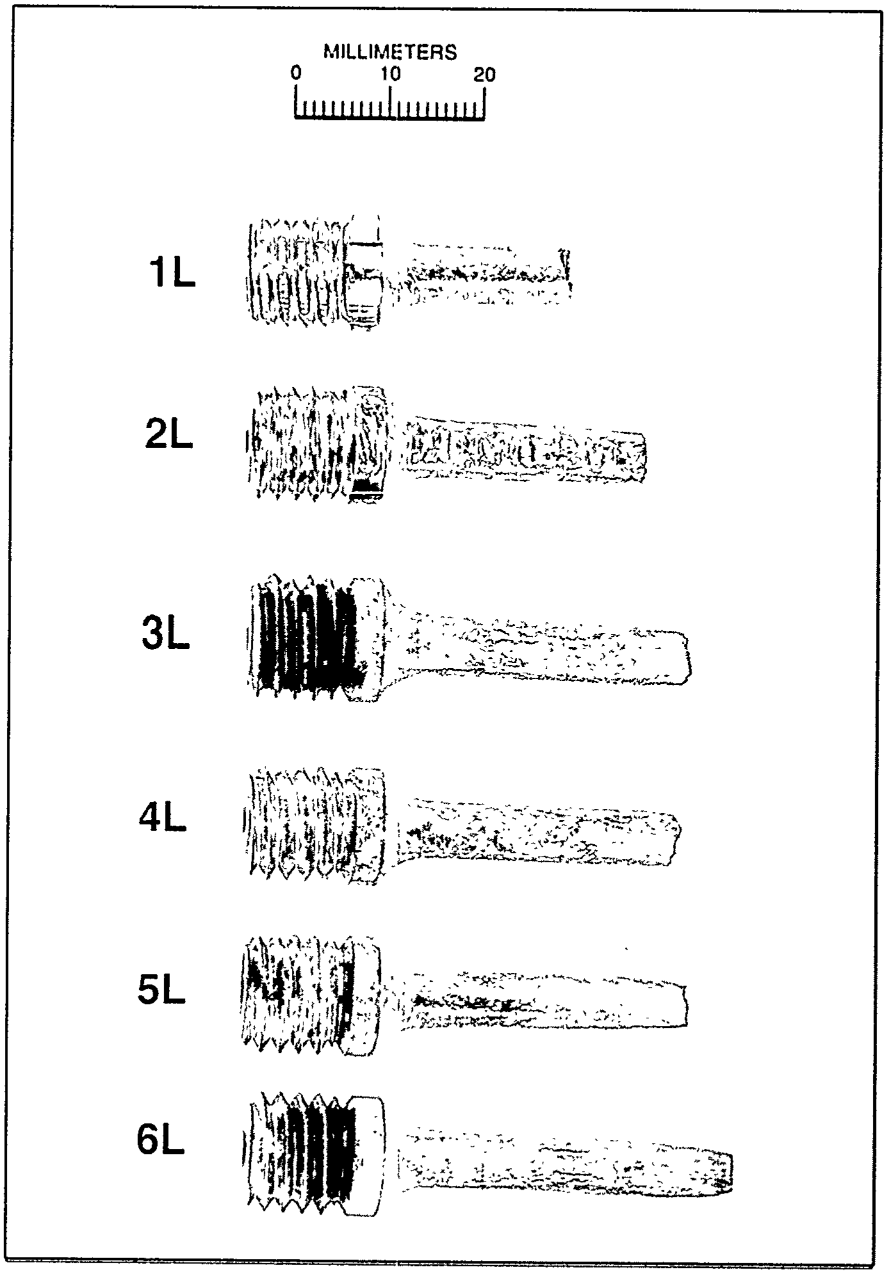

Fig. 8. Weldment specimens from 25-mm (1-in.) -thick slab tensile tested at 25°C (1L), 100°C (2L), 200°C (3L), 400°C (4L), 600°C (5L), and 800°C (6L). Note that the failure, in all cases, is in the weld region.

Table 4. Creep properties of weldment specimens[a] machined from the cast-welded 25-mm (1-in.) -thick slab of FAPY alloy

Test No.	Specimen No.	Test temperature (°C)	Stress (MPa)	Time to rupture (h)	Rupture elongation (%)	Reduction of area (%)
28312	7L	550	207	2.2	19.20	64.94
28321	8L	600	138	2.8	30.38	67.08
28314	9L	650	69	13.6	55.96	75.89
28313	10L	700	20.69	1389.3	48.90	85.90

[a]Weldment prepared with a preheat of 350°C and a postweld heat treatment at 750°C for 1 h.

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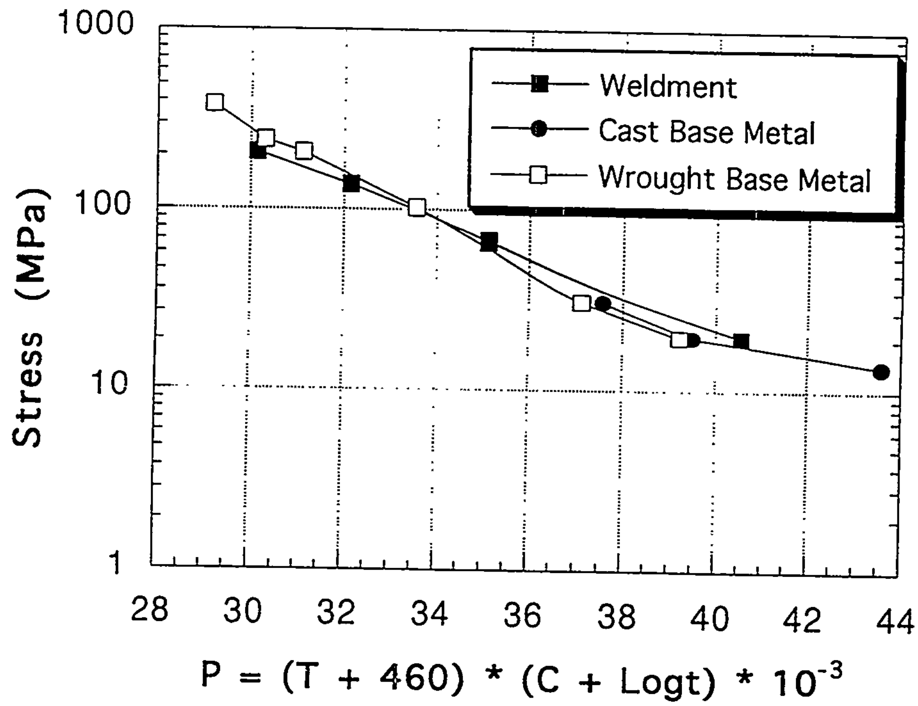

Fig. 9. Comparison of creep-rupture properties of weldment specimens with the as-cast and wrought base-metal specimens.

direction (T-L orientation). The specimens were tested on a 325-J capacity impact tester, and the data are summarized in Table 5. The data, plotted in Fig. 10, were fitted with a hyperbolic tangent function. The lower-shelf energy was fixed at 2 J and the upper-shelf energy was fixed at the value of the test at 400°C for each set of specimens (122 J for the as-welded specimens, 144 J for the postweld heat-treated specimens).

The results show that the PWHT does improve the toughness of the material. The ductile-to-brittle transition temperature, defined at an energy level midway between the upper- and lower-shelf energy levels, decreases from 245°C for the as-welded material to 200°C for the material that was given the PWHT, a 45°C improvement. The transition temperature is still quite high however. The upper-shelf energy also improves with heat treatment, increasing from 122 to 144 J. The specimens tested at 400°C showed completely ductile fracture, and they provide a good estimate of the upper-shelf energy, although only one specimen was tested for each material at high enough temperatures to give fully ductile fracture.

Table 5. Charpy-impact energy data on weldment specimens from 12-mm (0.5-in.) -thick plate of FAPY alloy

Test temperature (°C)	Charpy-impact energy			
	As welded		Postweld heat treated[a]	
	J	ft/lb	J	ft/lb
25	2	1.5	2.6	1.9
100	5.4	4.0	5.3	3.9
150	9.5	7.0	9.2	6.8
175	--	--	20.3	15.0
200	20.3	15.0	72.5	53.5
250	71.2	52.5	--	--
300	100.3	74.0	126.1	93.0
400	122.0	90.0	143.7	106.0

[a]Postweld heat treatment at 750°C for 1 h.

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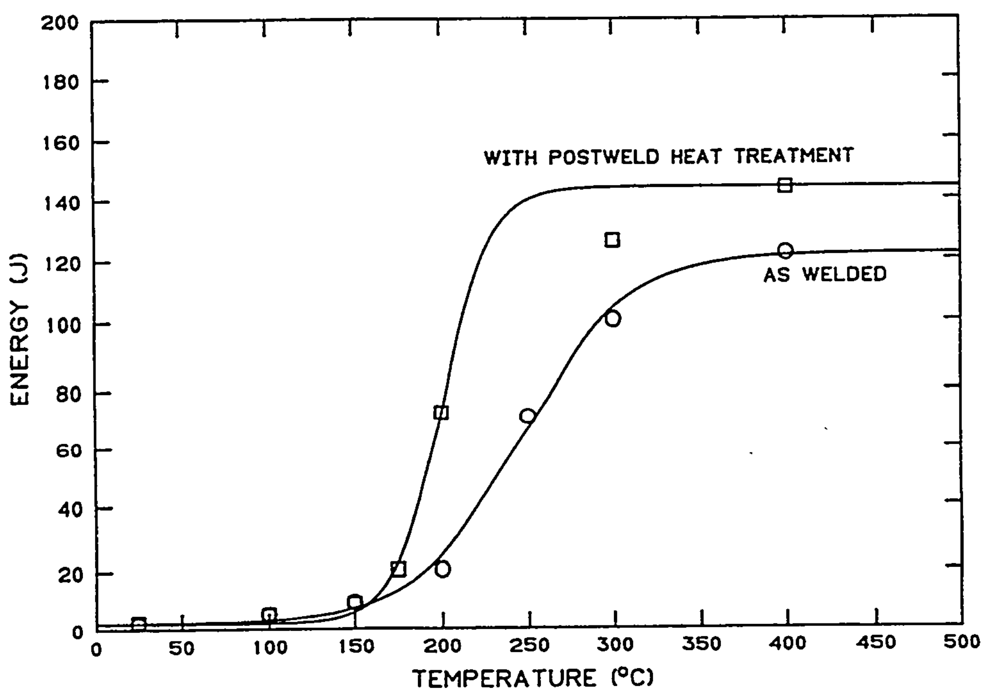

Fig. 10. Plot of Charpy-impact energy of weldment specimens from 12-mm (0.5-in.) -thick cast plate of FAPY alloy. Postweld heat treatment was carried out at 750°C for 1 h.

The Charpy-impact energy data for the weldment specimens are compared with those of the wrought base-metal data in Fig. 11. This figure shows that the transition temperature is approximately 50° higher for the weldment specimens, and the upper-shelf energy is lower by approximately 100 J. The most likely cause for the higher transition temperature for the weldment specimens is their much coarser grain size as opposed to the wrought material.

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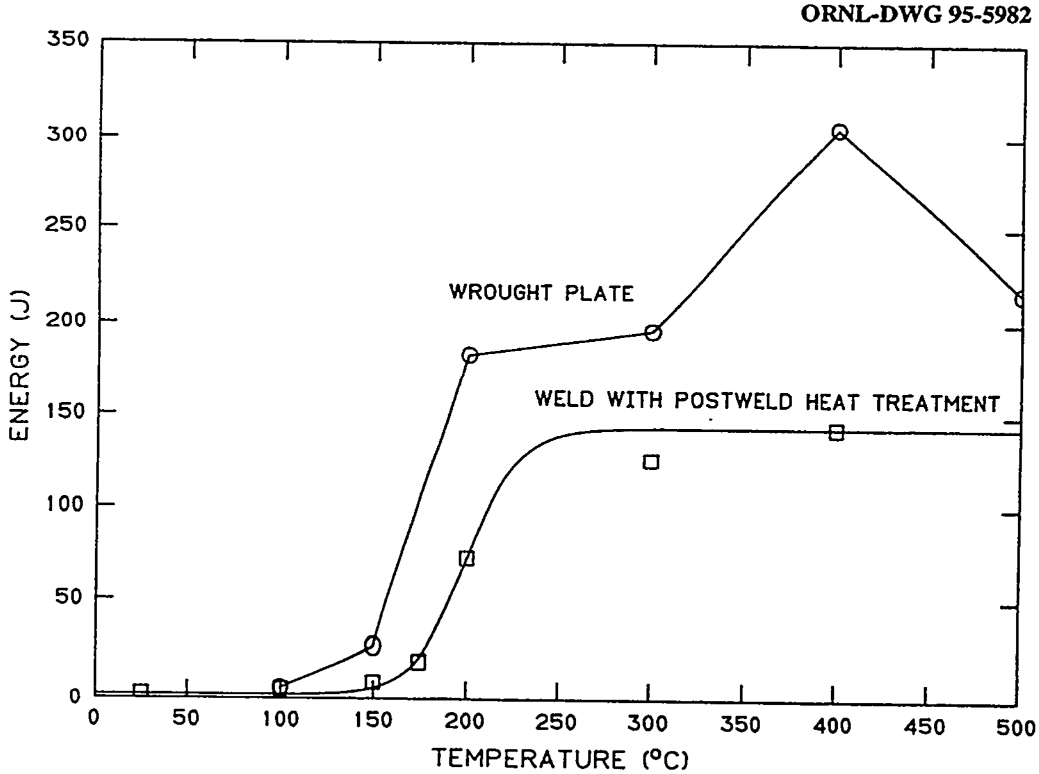

Fig. 11. Comparison of Charpy-impact energy data of weldment specimens with those of base-metal specimens in the wrought condition.

5. MICROSTRUCTURE AND HARDNESS DATA

In addition to the macroetched cross sections, photomicrographs of various regions of the weldment were also taken (see Fig. 2). The sets of micrographs for the base metal, heat-affected zone (HAZ), and weld metal for 12-, 25-, and 51-mm (0.5-, 1-, and 2-in.) -thick plates are presented in Figs. 12 through 17. The photomicrographs of the darker banded regions (see Figs. 14 and 15) in the macroetched sections of the 25- and 51-mm (1- and 2-in.) -thick plates showed them to contain equiaxed grain structure. The general

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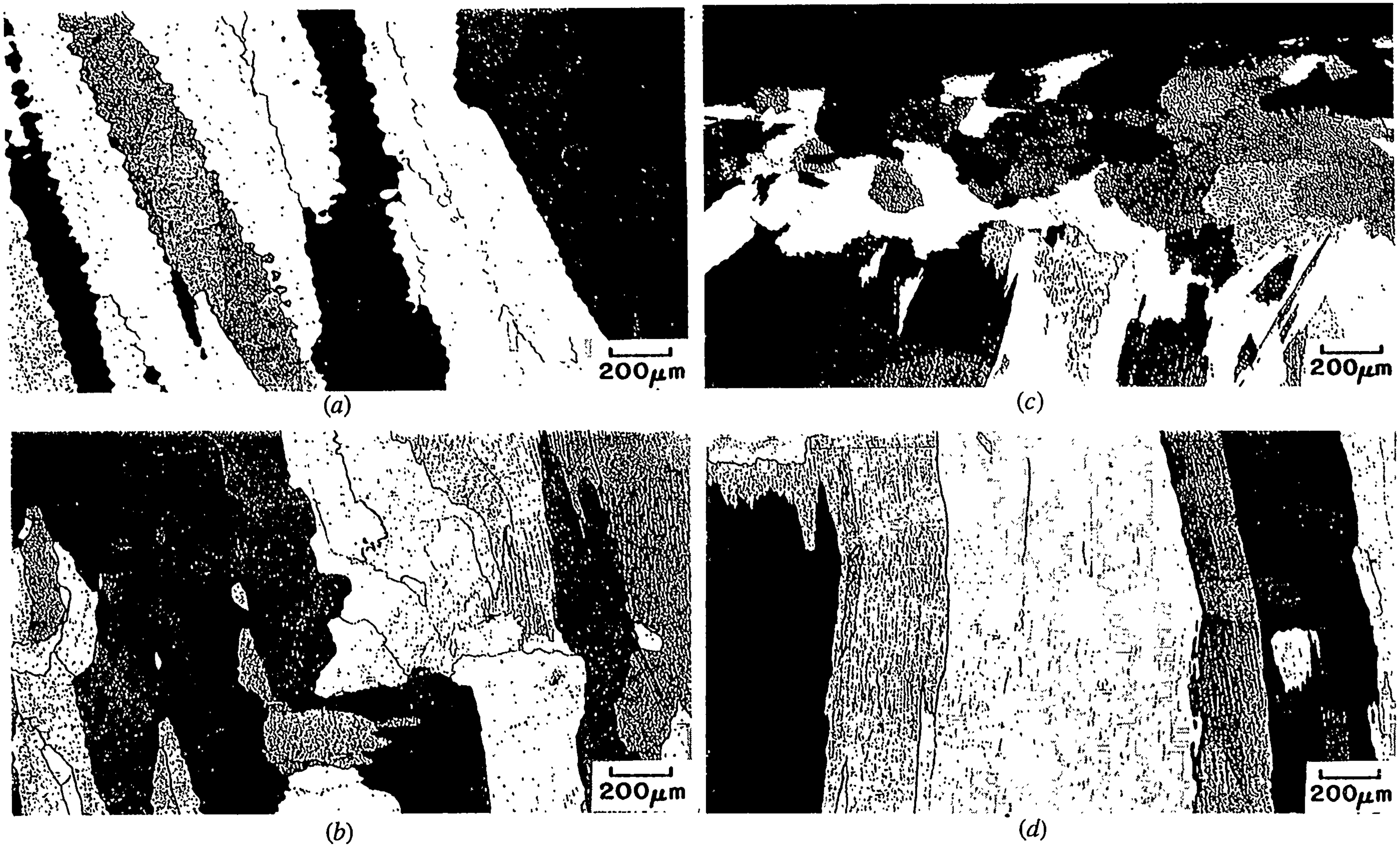

Fig. 12. Optical micrographs of (*a*) base metal, (*b*) heat-affected zone, (*c*) weld top, and (*d*) weld center in 12-mm (0.5-in.) thick welded plate of FAPY alloys. Magnification is 50×.

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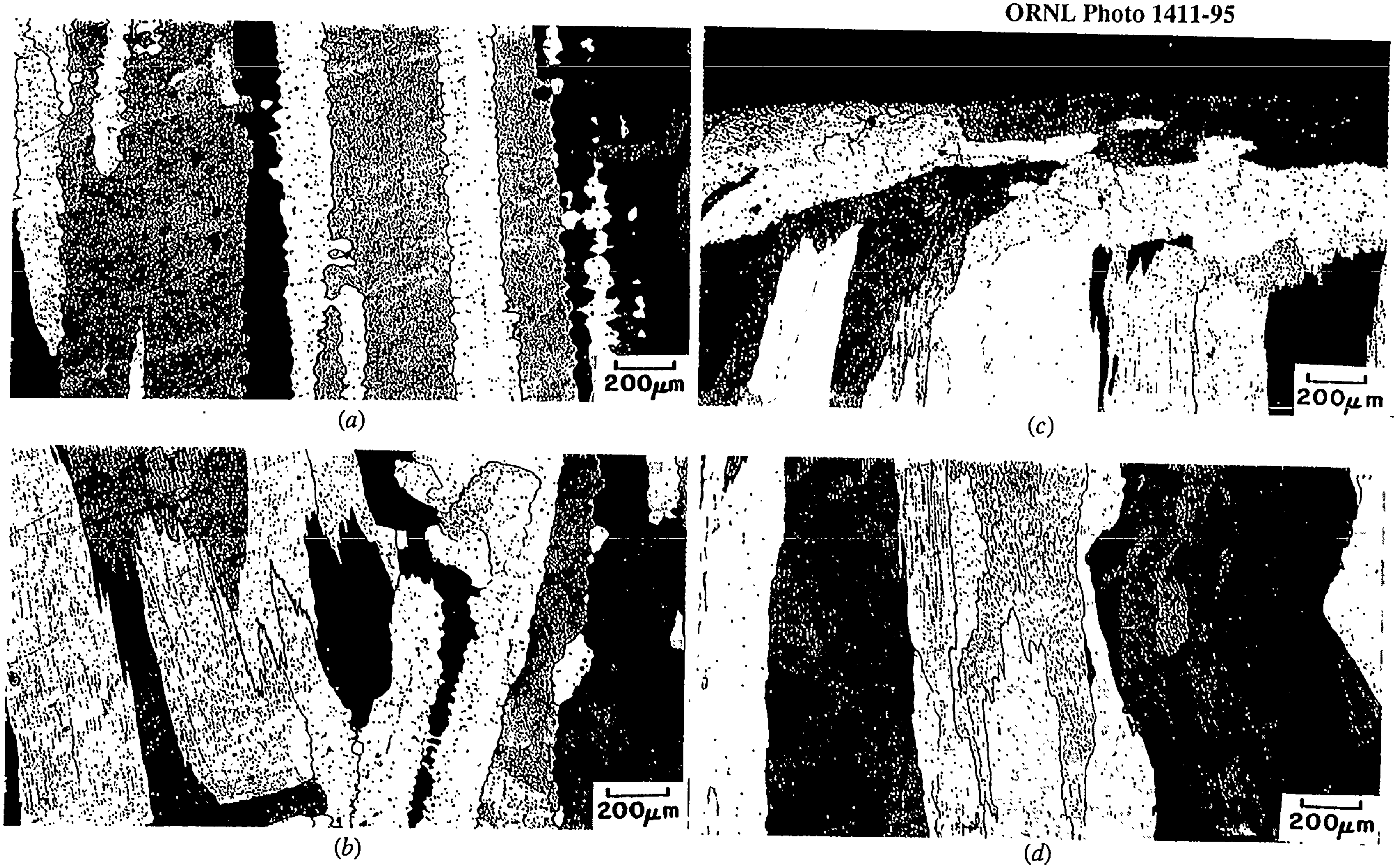

Fig. 13. Optical micrographs of (*a*) base metal, (*b*) heat-affected zone, (*c*) weld top, and (*d*) weld center in 25-mm (1-in.) -thick welded plate of FAPY alloy. Magnification is 50×.

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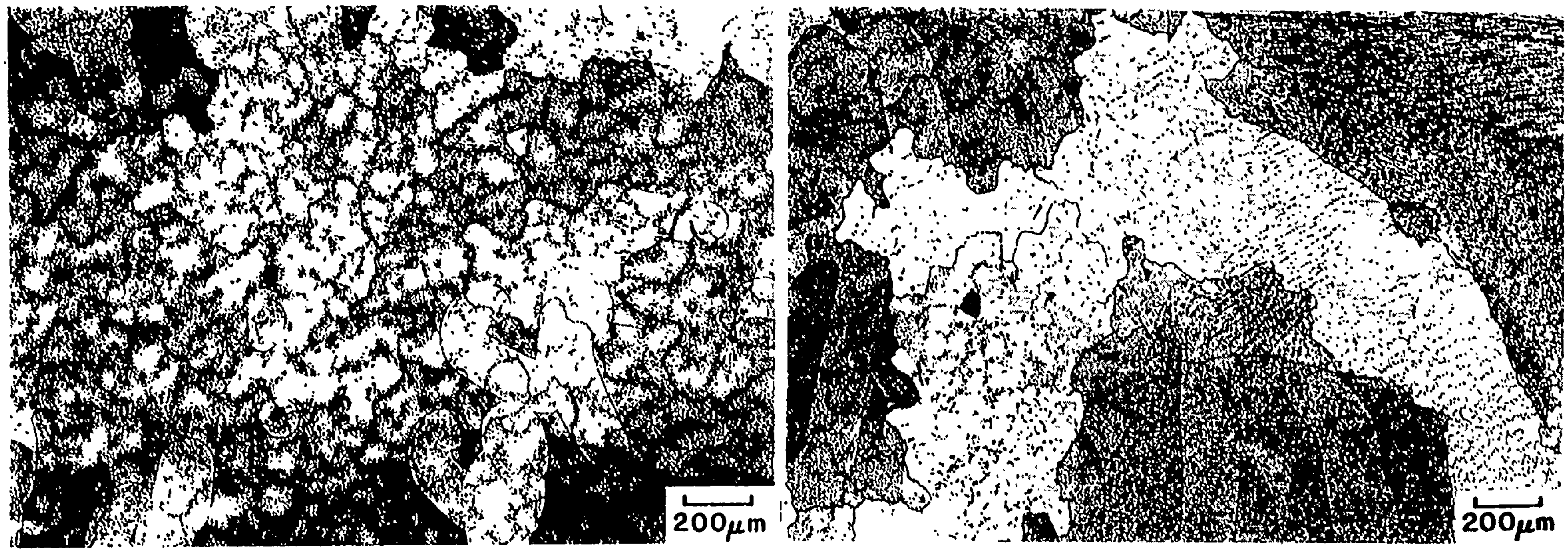

(*a*) (*b*)

Fig. 14. Optical micrographs showing the unusually appearing microstructure in 25-mm (1-in.) -thick plates: (*a*) base metal and (*b*) heat-affected zone in the region of unusual base metal. Magnification is 50×.

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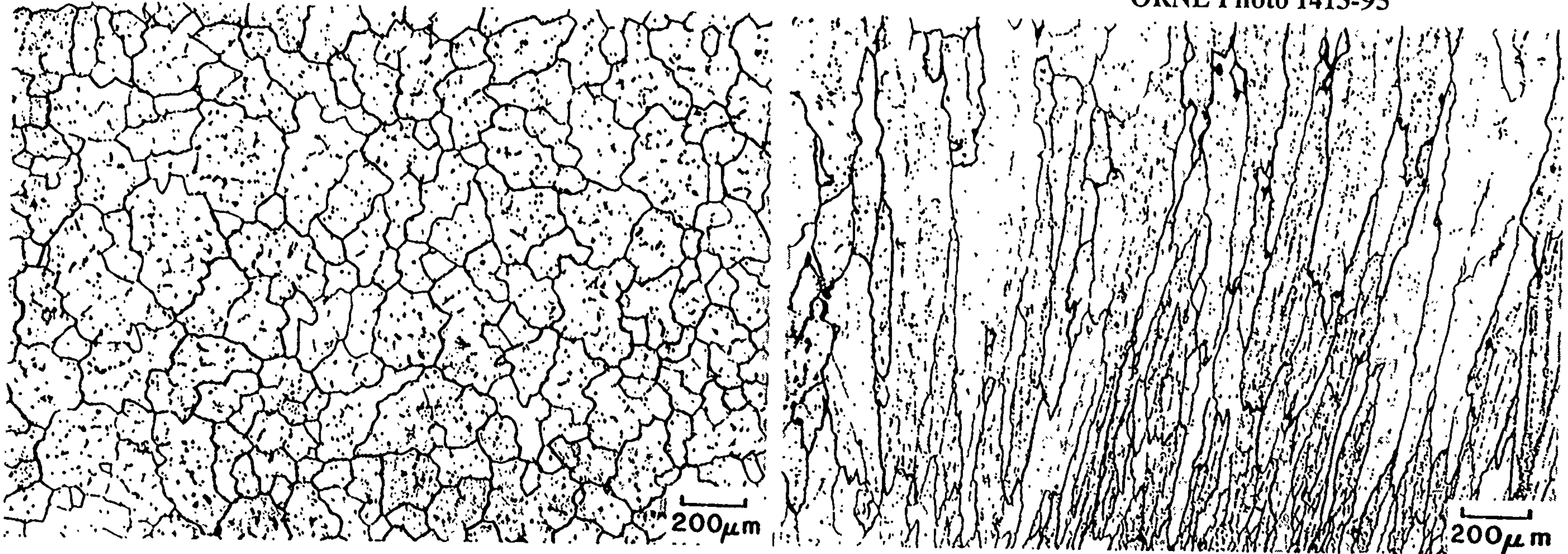

(*a*) (*b*)

Fig. 15. Optical microstructure of 51-mm (2-in.) -thick base-metal plate of FAPY alloy in the as-cast condition: (*a*) near surface and (*b*) near center locations. Magnification is 50×.

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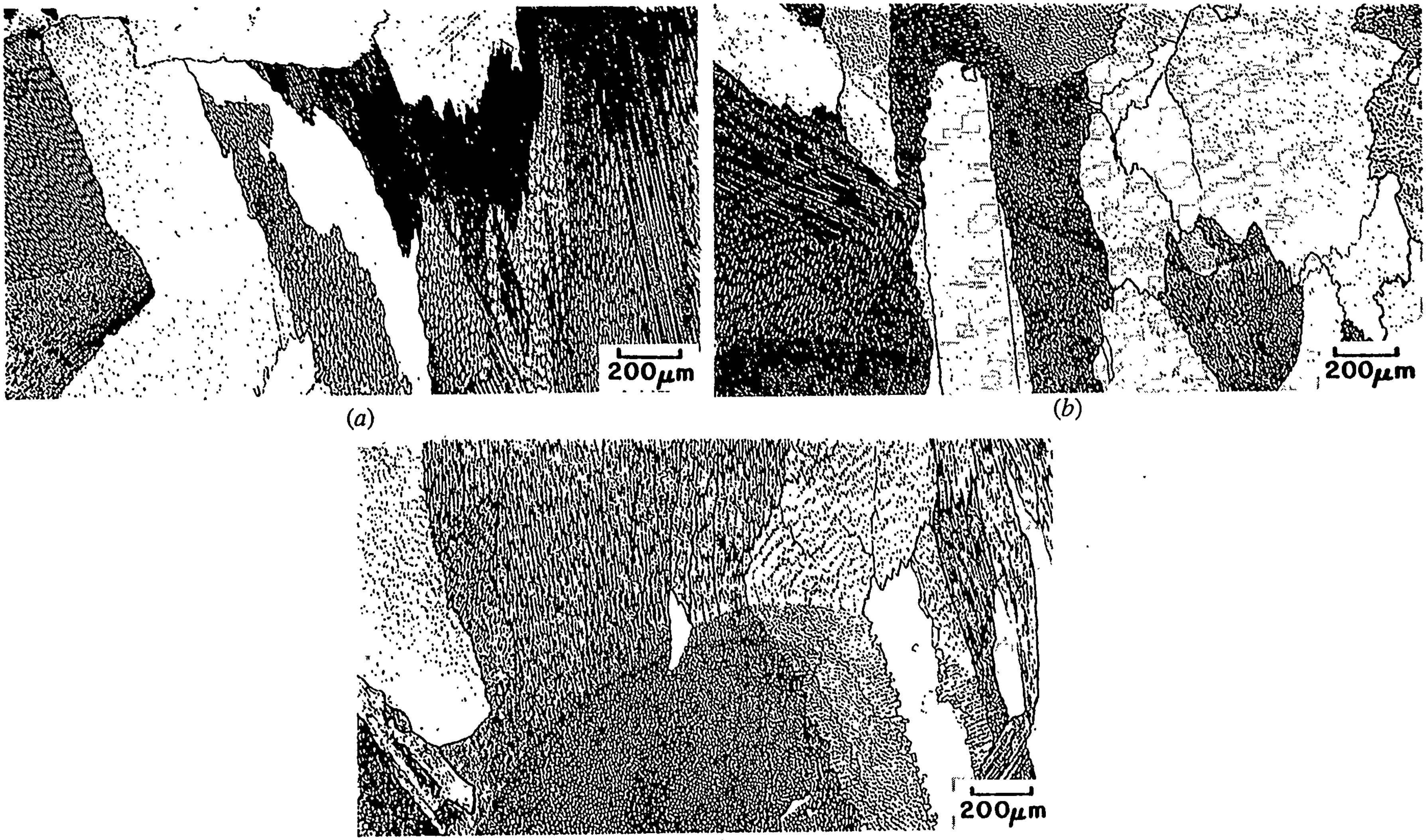

(a) (b) (c)

Fig. 16. Optical microstructures of weld regions in the 51-mm (2-in.) -thick cast plate of FAPY alloy: (*a*) weld crown, (*b*) weld center, and (*c*) weld root. Magnification is 50×.

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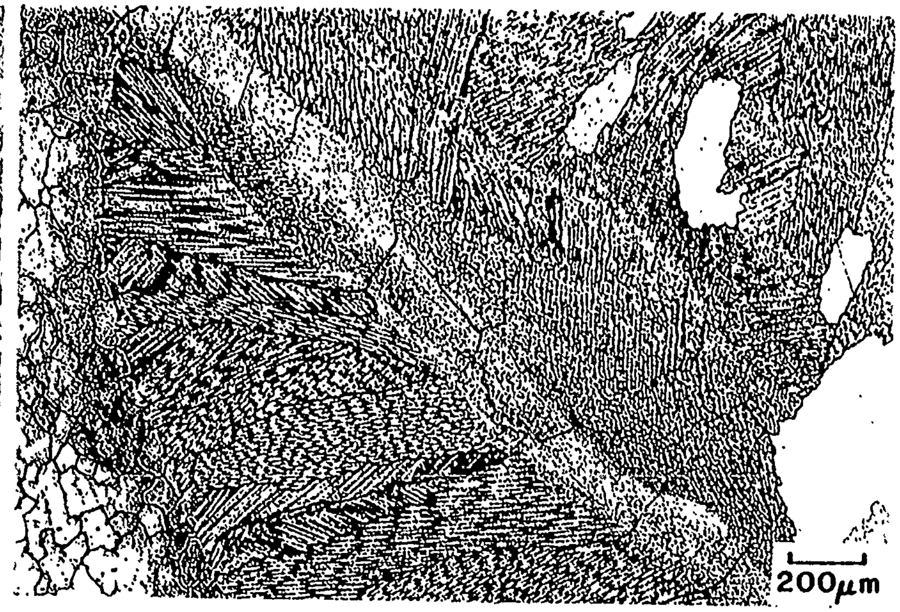
(*a*)



(*b*)

Fig. 17. Optical microstructure of heat-affected regions in the 51-mm (2-in.) -thick cast plate of FAPY alloy: (*a*) near surface and (*b*) near root locations. Magnification is 50×.

observations from the weldment photomicrographs are: (1) the weld metal has a coarse-grained structure similar to the cast base metal, and (2) the region identified as HAZ shows an epitaxial grain growth of the base-metal grains into the weld metal.

The microhardness data of the base-metal, HAZ, and weld-metal regions show that they are essentially the same for plates of a given thickness (see Table 6). However, there is approximately a 10- to 20-dph point increase in hardness of thicker plates as opposed to a 12-mm (0.5-in.) -thick plate. This is probably due to the greater number of passes, thus more thermomechanical cycles, which the thicker plate experiences. Although different in appearance, the banded region of the 25-mm (1-in.) -thick plate has hardness very similar to the base- and weld-metal regions.

Table 6. Microhardness of base, weld, and heat-affected zone of welds in 12-, 25-, and 51-mm (0.5-, 1-, and 2-in.) -thick welded plates in the as-cast condition

Plate thickness (mm)	Microhardness (dph)			
	Base metal	Weld metal	Heat-affected zone	Base metal and heat-affected zone in unusual area
12	223 ± 4	227 ± 5	223 ± 7	--
25	238 ± 4	237 ± 6	243 ± 3	246 ± 6
51	233 ± 10	252 ± 7	238 ± 4	240 ± 11

6. DISCUSSION

The vacuum-induction-melted and as-cast plates of 12, 25, and 51 mm (0.5, 1, 2 in.) thicknesses were successfully welded using the GTA process. All of the welds used a filler wire of base-metal composition. The 12-mm (0.5-in.) -thick plate could be welded without preheat. However, 25 mm (1 in.) and thicker sections require preheat to make crack-free welds. The preheat temperature for the FAPY alloy can be as low as 200°C, which is no different than that required for many ferritic steels. In addition to preheat, a PWHT of 750°C is highly desirable for lowering the transition temperature and increasing the upper-shelf energy during Charpy-impact testing.

The microstructure of the starting plates was coarse due to being in the as-cast condition. For the thinner plate of 12 mm (0.5 in.) thickness, the grain structure was primarily columnar. However, for the plates of 25 and 51 mm (1 and 2 in.) thicknesses, some equiaxed structure was also present in addition to the columnar structure. The weld region also showed a coarse-grained microstructure similar to the cast structure of the base metal. Epitaxial growth of base-metal grains into the weld region was observed. No distinct transition in microstructure was observed from the base- to the weld-metal regions. This observation was confirmed by noting essentially the same microhardness values for base-metal, HAZ, and the weld-metal region. The uniformity in microstructure and microhardness was also confirmed by the failure of the tensile specimens in the middle of the gage section, which normally happens for a material of uniform properties.

The similarity in microstructure and microhardness of the base and weld metals yielded tensile properties of the weldment specimens to match the base-metal properties. A similar match was also observed for the creep-rupture properties. It is important to note that although the properties of the weldment specimens matched the base-metal properties in the as-cast condition, the ductility values for FAPY alloy are low at temperatures ≤ 100°C.

An unusual event of cracking was observed in this weldment section of the 51-mm (2-in.) -thick plate during the etching process to reveal its macrostructure. The acid-etching process is known to produce hydrogen, and it is this hydrogen that is believed to have caused the cracking. This cracking was observed only in the 51-mm (2-in.) -thick plate and not in the plates of 12 and 25 mm (0.5 and 1 in.) thicknesses. Since the hydrogen-related cracking typically requires the combination of stress and the presence of hydrogen, it is believed that a PWHT of 750°C was not adequate to relieve the welding stresses for the 51-mm (2-in.) -thick plate. However, the same PWHT must have been adequate for the thinner sections, which had lower welding stresses to start with because of their thinner sections. Thus, it is believed that a higher preheat or PWHT temperature than 750°C may be required for section sizes of ≥ 51 mm (2 in.). Additional work is required to establish the preheat and/or PWHT requirements as a function of section thickness for the FAPY alloy.

7. SUMMARY AND CONCLUSIONS

The as-cast plates of 12-, 25-, and 51-mm (0.5-, 1-, and 3.2-in.) thicknesses of FAPY alloy were welded using the GTA process and a 3.2-mm (0.125-in.) -diam filler wire of matching composition. Welds were made without any preheat and with preheats of 200 and 350°C. Crack-free welds could be prepared in 12-mm (0.5-in.) -thick plates without preheat. However, the thicker plates required a preheat for crack-free welds, and a temperature of 200°C was acceptable up to plate thickness of 51 mm (2 in.). The preheat temperature for thicker sections may be higher and needs to be determined. The PWHT at 750°C for 1 h was found to lower the transition temperature and increase the upper-shelf energy during Charpy-impact testing of the 12-mm (0.5-in.) -thick welded plate. Thus, all the other weldment properties were determined in the postweld heat-treated condition. Tensile and creep properties of the weldment specimens matched the properties of the base metal. These results were explained on the basis that the microstructure and microhardness of the weld region were similar to the base metal.

Major conclusions from this study include:

1. The cast plates of the FAPY alloy can be welded by a commonly used GTA process. A filler wire of composition matching the base metal is acceptable. No preheat is required for plates of 12 mm (0.5 in.) thickness. Plates of ≥ 25 mm (1 in.) thickness require a preheat of at least 200°C. A PWHT at 750°C for 1 h is desirable to improve the Charpy-impact properties and to reduce the suceptibility of the weld to hydrogen-related cracking. A PWHT temperature of higher than 750°C is probably required to eliminate the hydrogen-related cracking in the 51-mm (2-in.) -thick welds. However, a correlation of PWHT as a function of section thickness needs to be developed.
2. Tensile and creep properties of the weldment specimens matched that of the base metal. These results are explained on the basis that the microhardness and microstructure of the welds are very similar to the base metal.

8. FUTURE WORK

Additional work is required on welding of thicker sections of the FAPY alloy:

1. Prepare welds in a section thickness greater than 51 mm (2 in.), and determine the PWHT temperatures to eliminate hydrogen-related cracking. Macroetching solution can be used to determine the presence of hydrogen-related cracking.
2. Determine the effect of PWHT temperature on Charpy-impact properties. Use these data to select the optimum temperature for the best combination of transition temperature and upper-shelf energy.
3. Determine additional weldment creep tests to obtain data for rupture times exceeding 1000 h.

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