WELDING AND WELDABILITY OF THORIUM-DOPED IRIDIUM ALLOYS

S. A. David, E. K. Ohriner, and J. F. King

Metals and Ceramics Division
Oak Ridge National Laboratory
Oak Ridge, TN 37830

Abstract

Ir-0.3%W alloys doped with thorium are currently used as post-impact containment material for radioactive fuel in thermoelectric generators that provide stable electrical power for a variety of outer planetary space exploration missions. Welding and weldability of a series of alloys was investigated using arc and laser welding processes. Some of these alloys are prone to severe hot-cracking during welding. Weldability of these alloys was characterized using Sigmajig weldability test. Hot-cracking is influenced to a great extent by the fusion zone microstructure and composition. Thorium content and welding atmosphere were found to be very critical. The weld cracking behavior in these alloys can be controlled by modifying the fusion zone microstructure. Fusion zone microstructure was found to be controlled by welding process, process parameters, and the weld pool shape.

The paper will discuss in detail the inter-relationship between the process-microstructure and weldability of iridium alloys.

Introduction

An Ir-0.3% W alloy doped with about 60 wt-ppm Th is currently used as post-impact containment material for radioactive fuel in thermoelectric generators that provide stable electrical power for a variety of outer planetary missions.[1] Iridium alloys were chosen for this application because of their high melting point, good high temperature strength, oxidation resistance, and compatibility with oxide fuel forms and carbon insulation materials. Thorium is added as a grain boundary strengthener, segregating strongly to the grain boundaries and inhibiting intergranular fracture.

Two promising iridium alloys containing 200 wt-ppm Th (DOP-14) and 60 wt-ppm Th and 50 wt-ppm Al (DOP-26) respectively, were developed at ORNL. Of these two alloys, DOP-26 in thin sheet form is the alloy of choice for cladding the radioisotopic fuel. The closure weld on the fueled clad is performed by gas-tungsten-arc (GTA) welding. One of the major concerns in welding of iridium alloys is its weldability. Weldability is a complicated property, however, and not easily defined. One of the important considerations of weldability is the ability of the material to avoid hot cracking during weld fabrication. Preliminary weldability screening tests have shown that some of the iridium alloys are subject to severe hot cracking during welding.[(2-4)]

Hot cracking during welding has been studied experimentally.[(5-8)] Different manifestations of hot cracking during welding are (1) solidification cracking; (2) liquation cracking in the heat affected zone (HAZ); (3) a combination of the above two; and (4) elevated temperature (subsolidus) cracking during heat treatment of welds. Of these various manifestations, iridium alloys commonly experience solidification cracking in the fusion zone (FZ). Solidification cracking in the fusion zone often occurs during later stages of solidification when the strains resulting from thermal and solidification contraction exceed the ductility of the partially solidified metal. Solidification cracking has been known to be favored by the factors that decrease the solid-solid contact area during the last stages of solidification. Two of the most important factors are low-melting segregates including non-equilibrium eutectic and grain size. Low-melting segregates at the grain boundaries may exist as a liquid film to a temperature well below the equilibrium solidus and reduce the grain boundary contact area to a minimum.[(9)] Also, the coarser the grain structure, the less the grain boundary contact areas for a given amount of non-equilibrium liquid. Hence, coarse grained fusion zone structures are generally more prone to solidification cracking than fine-grained material. Although several tests have been developed to determine the hot-cracking tendency of metals and alloys.[(10-11)] One test that is used currently to qualify the weldability of thin sheets of iridium alloys is the Sigmajig test.[(12-13)] This test ranks materials by quantitatively measuring the threshold stress (σ_o) above which cracking in the fusion zone occurs.

Weldability of iridium alloys has been found to be a strong function of alloy composition, grain structure of the fusion zone, and the welding atmosphere. The paper will discuss in detail the inter-relationship between the process microstructure and weldability of iridium alloys.

Welding of DOP-14 Alloy

Thin sheets of alloy Ir-0.3% W containing 200 wt-ppm Th are prone to severe hot cracking during both arc welding and electron beam (EB) welding.[(2-3)] Figure 1 shows macrostructures and transverse microstructures of an autogenous bead-on-plate weld. The microstructure was observed to be very coarse and is typical of arc welds made on high temperature alloys. In particular, along the centerline of the weld, one or two grains often span the thickness of the sample. Also the grains are oriented such that grain boundaries are normal to the thermal and solidification shrinkage stress axes. The cracking predominantly follows the centerline of the weld and is intergranular in nature. Extensive characterization of the crack surface using scanning electron microscopy (SEM) revealed segregation of Th and the presence of eutectic patches (Ir-Ir_5 Th) on the grain boundaries (Figure 2) indicating the cracks to be hot cracks. Efforts to overcome the hot-cracking problem through refinement of the fusion zone microstructure using arc oscillation and pulsed arc welding process were not fruitful. However, welds without hot cracking were successfully made with a continuous wave multikilowatt CO_2 laser system.(3) Typical microstructures of the DOP-14 laser weld are shown in Figure 3. Refinement in the fusion zone is attributable to the pool shape and epitaxial growth of the partially melted base metal grains.(3) Due to the circular or elliptical nature of the weld pool during laser welding at low to moderate welding speeds, most of the grains that grow epitaxially from the base metal continue to grow normal to the solid-liquid interface with no single grain experiencing a favored growth for an extended period. Since the base metal has a very fine grain structure, many grains from the fusion line survive to reach the centerline of the weld, leading to a refined grain structure in the FZ. This refinement in grain structure improves the hot-cracking resistance of the alloy as discussed previously. In addition, the successful application of the laser welding process to weld DOP-14 results from the highly concentrated heat source and the selection of weld process parameters to control weld heat input.

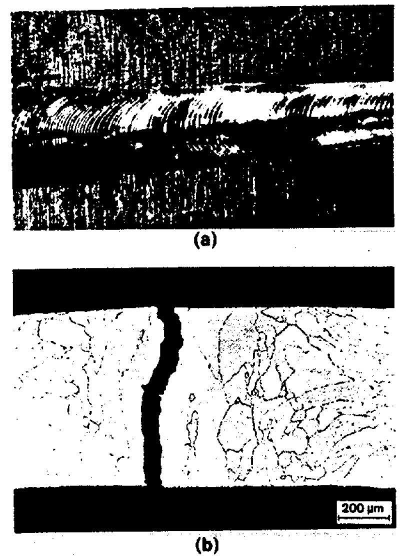

Figure 1 Autogenous bead-on-plate Gas Tungsten Arc Weld of Ir-O.3% W – 200 ppm Th. Welding Speed 21.5 mm/s. (a) Macrostructure (b) Transverse Microstructure

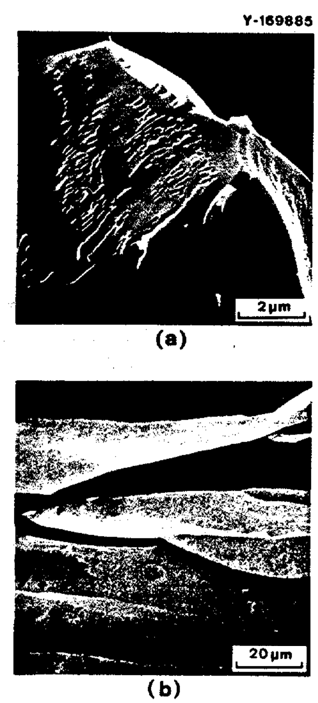

Figure 2 Scanning Electron Micrographs of weld crack (a) Eutectic Patches on the surface of the fractured arc weld (b) Absence of eutectic patches on the surface of the fractured laser weld by high-velocity impact testing.

<u>Welding of DOP-26</u>

This alloy containing 0.3 wt. % W, 60 wt-ppm Th and 50 wt-ppm Al (DOP-26) can be successfully welded by both GTA and laser welding processes. Although the weldability of DOP-26 is much superior to that of DOP-14 alloy, the existence of coarse unfavorable FZ structure of DOP-26 GTA welds can severely reduce the ductility and impact strength of the weld. In addition, the hot cracking sensitivity and the quality of the DOP-26 alloy welds have been found to be a strong function of thorium content and the welding atmosphere. Therefore it is critical to ensure that the fusion zone grain structure is fine enough to provide resistance to hot-cracking and the required weld ductility.

Refinement in the FZ grain structure in DOP-26 alloy weld has been achieved by using arc oscillations during GTA welding or by laser welding process. Figures 4, 5, and 6 show

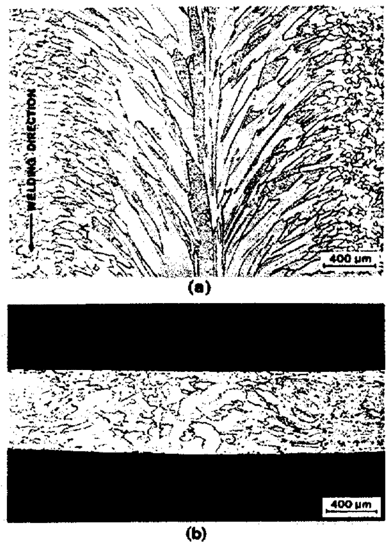

Figure 3 Fusion zone microstructure of DOP-14 laser weld. Welding speed 12.5 mm/s. (a) top surface (b) transverse section

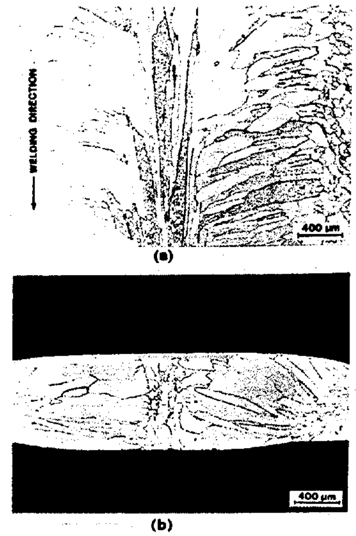

Figure 4 Fusion zone microstructure of DOP-26 arc weld without arc oscillation. Welding speed 12.5 mm/s. (a) top surface (b) transverse section

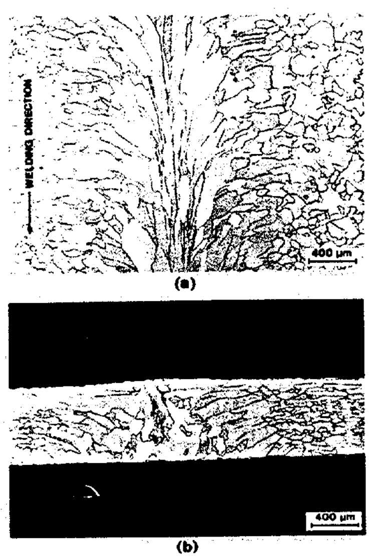

Figure 5 Fusion zone microstructure of DOP-26 arc weld with 375 cycles/s arc oscillation. Welding speed 12.5 mm/s. (a) top surface (b) transverse section

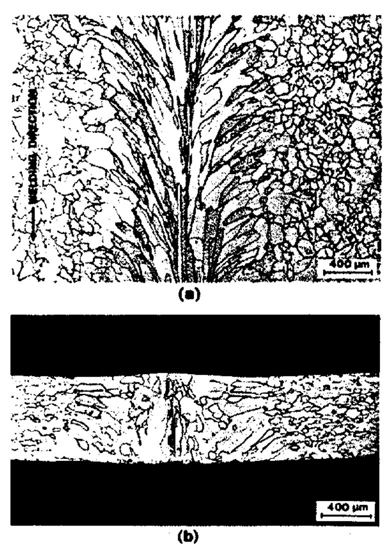

Figure 6 Fusion zone microstructure of DOP-26 laser weld. Welding speed 8.3 mm/s. (a) top surface (b) transverse section

microstructures of arc welds made without and with arc oscillations and laser welding process respectively.[3] Arc oscillations were introduced during welding using a magnetic arc oscillator. Arc oscillations both in the direction of welding (longitudinal) and normal to the welding direction (transverse) were evaluated using a constant amplitude and dwell time. Of the two directions, transverse oscillations at a frequency of 375 cycles/min were found to be effective. A number of factors may contribute to the refinement in this structure due to arc oscillations. When arc oscillation is employed, both the shapes of the weld pool and the instantaneous growth rate at the trailing edge of the weld pool can be made to vary with time. Also the direction and magnitude of the temperature gradients may be altered periodically as the heat source is oscillated, leading to variations in the growth direction and weld pool solidification conditions. The refinement in the fusion zone grain structure of the alloy DOP-26 laser welds was mainly due to the circular or elliptical pool shape obtained during laser welding at low or moderate welding speeds.

The effect of thorium content on the weldability of DOP-26 was evaluated using Sigmajig test. The hot-cracking behavior for a series of sheet materials intentionally alloyed with varying amounts of thorium is shown in Figure 7 for varying applied threshold stress. The threshold stress decreases from 170 MPa at the 37-ppm thorium level to half that value at 94-ppm thorium. Although the resistance to cracking decreases substantially at the higher thorium level, it is important to realize that the material does have some degree of resistance to hot-cracking at the highest thorium level in the alloy investigated. This decrease in the threshold stress at higher levels of thorium can be attributed to increased levels of low melting eutectic available to wet the grain boundaries and cause cracking. The results also confirm an earlier study conducted by David et al.[14] The iridium alloy DOP-26 containing 2000 to 4000-ppm W, 30 to 90 ppm Th, and 20 to 80 ppm Al by wt used for the current space missions contains optimum amounts of the alloying elements to give good grain boundary strength and hot-cracking resistance.

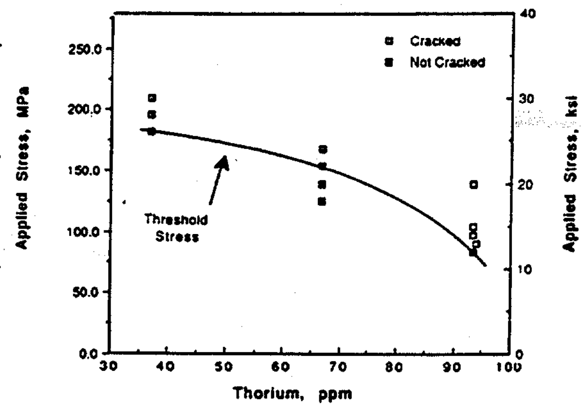

Figure 7 Materials produced with Controlled Variations in Thorium Content from Identical Melt Stock show Decreased Threshold Cracking Stress with Increased Thorium Content.

The effect of welding atmosphere on the hot-cracking sensitivity of the alloy DOP-26 was evaluated by conducting Sigmajig test in controlled atmosphere containing oxygen and moisture. Both oxygen and moisture were found to have no effect on the hot cracking behavior of the alloy DOP-26. However, the presence of oxygen had a major effect on the weld geometry. Welds made with high-oxygen content were found to have much wider weld beads. This is mainly due to the nature of fluid flow within the weld pool. Impurities in the weld metal such as oxygen and sulfur are often surface active in that they alter the surface tension and the temperature coefficient of surface tension, dV/dT, of the liquid metal, the remelting direction of convective flow in the weld pool, and the shape of the weld pool.[15-17] For the iridium alloy weld pool with oxygen on its surface, it appears that the convective flow is outward (dV/dT in-ve); thus increasing the width of the weld pool.[18]

Welding of Iridium Alloy Hardware

Welds of iridium alloy cladding over fuel pellets are performed by automated GTA welding. The weld is performed in an atmosphere of helium using He-25% Ar as a shielding gas.[19] Initial difficulties with weld cracking in the underbead region of the weld taper zone at the end of the weld caused reduced yields to unacceptable levels. The use of a four-pole magnetic oscillator was found to substantially reduce the incidence of weld cracking[20]. These methods were use satisfactorily during the 1980's to produce hardware for Galileo and Ulysses spacecraft.

A number of improvements in both materials and welding methods were made for use with the Cassini spacecraft launched in 1997. The production methods for the iridium alloy for the cladding were improved to increase yield and to eliminate potential sources of defects in the material.[21] The effect of the processing changes on weldability were evaluated using a laboratory test in which repeated short weld passes are made over an existing weld bead to promote cracking, and the number and total lengths of the cracks are measured using fluorescent dye penetrant inspection. The results of this test showed improved weldability with reduced susceptibility to cracking for the new process material.[22]

Changes in the welding process and in particular the weld set-up were made in order to improve process yields from welding. These changes included separate assembly of iridium cups into snap-in chucks, precision weld start location, and synchronous rotation of upper and lower chucks under controlled load which permitted elimination of the tack welding process used previously.[23] The welding process yield for 319 capsules produced for Cassini is 97.8% . The total yield of welded capsules for Cassini was 88.7% as compared to 72.7% for the earlier production runs.[24]

Acknowledgement

This research is supported by the Office of Space and Defense Power Systems at the Oak Ridge National Laboratory, managed by Lockheed Martin Energy Research Corporation for the U.S. Department of Energy, under contract DE-AC05-96OR22464. The authors wish to thank Dr. William J. Barnett of that office for useful technical discussions.

References

1. C.T. Liu and H. Inouye, "Development and Characterization of an Improved Ir-0.3 W Alloy for Space Radioisotopic Heat Sources" (Report ORNL-5290, Oak Ridge National Laboratory, 1977).

2. S.A. David and C.T. Liu, Metals Technology, 7 (1980), 102.

3. S.A. David and C.T. Liu, Weld. J., 61 (5) (1982), 157-s.

4. E.K. Ohriner, G.M. Goodwin, and D.A. Frederick, "Weldability of DOP-26 Iridium Alloy: Effects of Welding Gas and Alloy Composition," Ninth Symposium on Space Nuclear Power Systems, ed. M.S. El-Genk and M.D. Hoover, New York: American Institute of Physics, 1992), 164-170.

5. P.O. Puzak, W.R. Apblett, and W.S. Pellini, Weld. J., 35 (1) (1956), 96-s.

6. W.R. Apblett and W.S. Pellini, Weld. J., 33 (2) (1954), 83-s.

7. J.C. Borland, British Weld. J., 7 (1960), 558.

8. F.C. Hull, Weld. J., 46 (9) (1967), 399-s.

9. C. S. Smith, Transactions of the American Institute of Mining and Metallurgical Engineers, 175, p. 15, 1948.

10. R.D. Stout and WD. Doty, "Weldability of Steels," Welding Research Council, New York, N.Y.

11. J.J. Bagi, R.P. Meister, and M.D. Randall, "Weldment Evaluation Methods," DMIC 244, 1968.

12. G.M. Goodwin, Weld. J., 77(2), 33-s, 1987.

13. S.A. David, M.L. Santella, and G.M. Goodwin, North American Welding Research Seminar, Columbus, Ohio: Edison Welding Institute.

14. S.A. David and J.J. Woodhouse, Weld. J., 66(5), p. 129s, 1987.

15. C.R. Heiple and J.R. Roper, Weld. J., 61, 97s, 1982.

16. C.R. Heiple and J.R. Roper, Trends in Welding Research, Ed. By S.A. David, 1982 (ASM Materials Park, OH), p. 489.

17. A.J. Paul and T. DebRoy, Metall. Trans. B, 19, p. 851, 1988.

18. S.A. David and J.M. Vitek, Intl. Mater. Rev., 34, 5, p. 213, 1989.

19. W. R. Kanne, Jr., "Welding Iridium Heat Source Capsules for Space Missions," Weld. J. 62 (8), (1983) 17-22.

20. J. D. Scarbrough and C. E. Burgan, "Reducing Hot-Short Cracking in Iridium GTA Welds Using Four-Pole Oscillation," Weld. J. 63 (6), (1984) 54-56.

21. E. K. Ohriner, "Processing and Properties of Iridium Alloys for Space Power Applications," Tungsten and Refractory Metals - 1994, ed. A. Bose and R. J. Dowding, Metals Powder Industry Federation, Princeton, NJ, (1994) 605-611.

22. W. R. Kanne, Jr., "Weldability of General Purpose Heat Source New Process Iridium," (Report DP-1748, Westinghouse Savannah River Laboratory, Aiken, SC) May 1987.

23. E. A. Franco-Ferreira and T. G. George, "Cassini Mission to Saturn Relies on Flaw-Free GTA Welds," Weld. J, 75, (4) (1996) 69-75.

24. E. A. Franco-Ferreira et.al, "Long Life Radioisotope Power Sources Encapsulated in Platinum Metal Alloys, Platinum Metals Rev., 41, (4) (1997) 154-163