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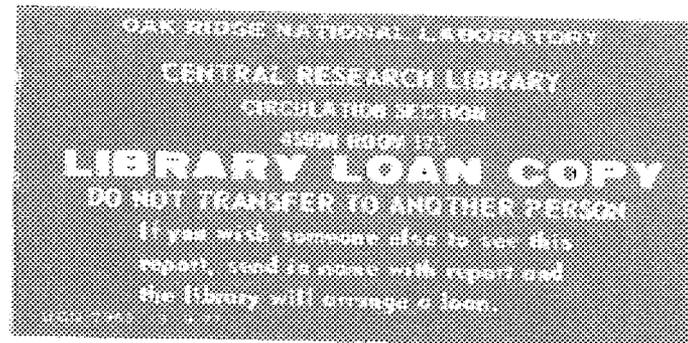
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## Advances in Iridium Alloy Processing in 1987

R. L. Heestand  
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ADVANCES IN IRIDIUM ALLOY PROCESSING IN 1987

R. L. Heestand, E. K. Ohriner, and T. K. Roche

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## ADVANCES IN IRIIDIUM ALLOY PROCESSING IN 1987\*

R. L. Heestand, E. K. Ohriner, and T. K. Roche

### ABSTRACT

A new process for the production of DOP-26 iridium alloy blanks is being evaluated and optimized. The alloy is prepared by electron-beam (EB) melting of Ir-0.3% W powder compacts followed by doping with aluminum and thorium by arc melting. Drop-cast alloy rod segments are EB welded to produce an electrode that is consumable arc melted to produce an ingot for extrusion and subsequent rolling. Initial results showed rejections for ultrasonic indications of alloy blanks produced by this process to be very low. Subsequently, some ingots have exhibited delaminations in the sheet, leading to rejection rates similar to that obtained in the standard process. The increase in delaminations is related to near-surface porosity in the consumable arc-melted ingot. A number of modifications to the arc-melting process and plans for further experimental work are described. In addition, the tensile properties of the DOP-26 iridium alloys have been measured over a range of test temperatures and strain rates. A laboratory evaluation of alternative cleaning procedures indicates that electrolytic dissolution of DOP-26 iridium alloy in an HCl solution is a potential substitute to the KCN process now in use.

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### 1. INTRODUCTION

This report deals with progress made during 1987 in DOP-26 iridium alloy sheet and blank processing, using a new consumable arc-melting, extruding, and rolling procedure. In addition, results of new work on product characterization including recrystallization and mechanical behavior, electrolytic cleaning, and weldability testing of the alloy are reported. The status of product qualification activities, for use in

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nuclear fuel confinement in space power systems, is reviewed. The objectives of the 1987 activities include (1) identification of laboratory capabilities for the new process and problems associated with this process; (2) continuation of process optimization and procedure modifications; (3) work toward resolution of processing problems; (4) initiation of new product characterization; (5) maintenance of blank production capability, including critical staff availability; and (6) coordination of new process qualification efforts.

The new process for production, rather than arc melting and drop casting of small (500-g) ingots for rolling, uses the drop-cast ingots to fabricate an electrode for consumable arc melting into a large (10-kg) ingot.<sup>1</sup> This ingot is extruded to a rectangular bar for rolling to sheet or foil. The new process offers the potential for a significant reduction in unit blank production cost through both improved yields and reduced labor costs. The increase in the number of blanks per ingot leads to a reduction in manufacturing man hours per blank and a decrease in the number of chemical analyses performed. The casting of large ingots, which do not require weld repair and the use of the extrusion process, can increase processing yields through a substantial reduction in laminar defects and ultrasonic indication rejection. The results obtained on the first two ingots processed to blanks showed a substantial decrease in blank rejection rate for ultrasonic-detected defects. However, these low rejection rates obtained initially have not been reproduced with more recently processed ingots. A number of modifications to the process have been made and further modifications are planned to improve the yield of blanks in the new process.

Iridium blanks produced at the Oak Ridge National Laboratory (ORNL) are currently formed at Monsanto Research Corporation, Mound Plant (MP). Pairs of formed cups are loaded with fuel and welded at E. I. DuPont de Nemours & Company, Savannah River Plant (SRP), into a form called clads. Impact testing of the clads, as well as biaxial impact testing of blanks, is performed at Los Alamos National Laboratory (LANL). These four organizations and the U.S. Department of Energy, Office of Special Applications (OSA) are involved in a joint program, which is coordinated by ORNL, to qualify the new process for flight-quality hardware fabrication. Results of that program are summarized in this report.

## 2. BACKGROUND

Demonstration of the new consumable arc-melting and extruding process was initiated in FY 1984. A consumable arc-melted DOP-26 alloy casting (designated AC) was made, cut into two standard process-size ingots, and rolled into sheet using the standard rolling process. Blanks cut from these sheets were found to be essentially free of both ultrasonic- and penetrant-detected defects. In FY 1985, new process development was continued by consumable arc melting two ingots (B1 and B2), extruding to rectangular bar, cutting into billets, and rolling into sheet using a procedure modified for extruded material. Blanks cut from the B1 and B2 sheets were also found to be essentially free of penetrant- and ultrasonic-detected defects, giving a yield of greater than 95% acceptance. A third ingot, designated BR3 and consumable arc melted from virgin B1 and B2 ingots in FY 1985, was later found to be contaminated with molybdenum. Changes were implemented in the recycling practice to avoid use of contaminated scrap. During FY 1986 a virgin ingot, B4, was processed to sheet, and the initial results showed rejection of 6 of 17 blanks for ultrasonic-detected defects.

The materials processed during FY 1987 are discussed in this report and include blanks from XR and ZR batches fabricated using the standard process and blanks from B and C batches processed using the new process. Five consumable arc-melted ingots from B-batch iridium powder and one from C-batch iridium powder were processed to blanks. The chemical analyses of these ingots are listed in Table 1. All are within the specification for DOP-26 iridium alloy, which is also shown. Averages obtained from individual analyses of each of 18 drop-cast ingots of XR and 12 of ZR are also tabulated here.

## 3. FABRICATION OF BLANKS

### 3.1 STANDARD PROCESS BLANKS

Standard process blanks from XR and ZR ingots were fabricated, inspected, and provided to MP during FY 1987. The inspection results are summarized in Table 2. The annealed sheets were ultrasonically inspected

Table 1. Chemical analyses of DOP-26 iridium alloy

Element	Specification	Chemical composition (wt ppm)							
		Consumable arc-melted ingot number <sup>a</sup>						Standard process drop-cast ingot <sup>b</sup>	
		B1	B2	B4	B5	BR6	C1	XR365-XR382	ZR588-ZR599
Al	20-80	42	43	61	54	47	40	47	53
B	<50	<0.1	<0.1	<0.1	<0.1	<1	1	<1	<1
Ca	<50	0.5	<0.1	7	3	1	1	2	2
Cr	<25	5	1	5	3	7	1	7	18
Cu	<50	3	1	20	30	50	10	26	45
Fe	<150	10	1	23	20	35	20	22	58
Mo	<50	10	5	20	<3	7	<1	3	16
Na	<50	0.3	0.3	2	1	10	1	1	1
Ni	<50	3	<0.3	8	<3	12	1	6	15
P	<50	0.1	<0.1	<0.1	<0.3	1	5	<1	1
Rh	<150	<1	<10	<1	<1	<1	<1	<1	2
S	<50	<3	<1	<3	<10	<3	<3	<3	<10
Si	<50	5	1	<3	30	20	10	10	6
Ta	<50	<20	<3	<40	<10	<3	30	15	<5
Th	30-90	54	66	52	66	30	66	71	68
Ti	<50	1	0.3	9	3	3	1	1	<3
W	2000-4000	3200	2600	2900	3300	2800	2800	3100	2900
Zr	<50	<1	<1	<1	<3	<1	<1	<1	<1
Ag		<1	<1	<20	<3	<1	5	<3	<3
Pd		<1	<3	<3	<3	<1	<1	<1	<3
Pt	<400	<10	<5	<5	<3	<3	<3	<3	<5
Ru		5	5	5	<3	10	10	10	3

<sup>a</sup>All analyses from consumable arc-melted ingots are samples from near top surface of the casting, except those for Th that come from the extruded tail.

<sup>b</sup>Average of analyses from individual rolled ingots.

Table 2. Summary of blank yields

Ingot number	Number of ingots	Potential blanks	Defective sheet blanks <sup>a</sup>	Machined blanks	Number of deliverable blanks	Yield	
						From sheet (%)	From blanks (%)
XR	18	108	25	83	68	63	82
ZR	12	72	14	58	39	54	67
B1	1	46	0	42 <sup>b</sup>	42	100	100
B2	1	46	0	39 <sup>c</sup>	39	100	100
B4	1	50	7	43	28	56	65
B5	1	54	7	42	31	57	74
BR6	1						
C1	1						

<sup>a</sup>Manual ultrasonic probe of sheets.

<sup>b</sup>Sheet material equivalent to four blanks was used for tensile test specimens.

<sup>c</sup>Sheet material equivalent to seven blanks was used for mechanical test specimens.

manually (with a hand-held probe) and regions indicating delaminations were avoided during blanking. The yield of deliverable blanks, following all reworking operations for surface defects observed by both visual and dye-penetrant inspection, is shown (Table 2) both from potential blanks in the sheet and from the number of machined blanks. The defects in the standard process blanks are primarily attributable to residual porosity in the casting, which is not removed by electron-beam (EB) repair welding of the ingots. They can also result from flaws introduced during initial hot rolling of the cast structure.

### 3.2 NEW PROCESS BLANKS FROM B1 AND B2 INGOTS

Consumable arc melting of B1 and B2 ingots and extrusion of these ingots to rectangular bar was completed during FY 1985. The rolling of the B1 ingot was completed during FY 1986. The rolling and inspection of the B2 ingot was also completed during FY 1986 except for two sheets that had been held in reserve. One was used to fabricate six oversized blanks [1 mm (0.039 in.) larger diameter]; all were found acceptable in non-destructive evaluation. The second sheet was used for machining of tensile specimens for research purposes. The yield of blanks on both ingots is 100%, as seen in Table 2, with the exception of sheet purposely diverted for research. The number of reworked blanks for B1 and B2 ingots is seven and three, which represent 17 and 8%, respectively, of the deliverable blanks.

### 3.3 PROCESSING OF B4 INGOT

The B4 ingot was processed to blanks during FY 1986. Inspection and rework of this material continued during early FY 1987. The yields of acceptable blanks, shown in Table 2, indicate low yield because of ultrasonic-detected defects. The yields are similar to those obtained in the most recent ZR standard process ingots. Thirteen of 28 deliverable blanks, or 46%, required rework to remove visual or dye-penetrant indications of defects. Near-surface delaminations were observed metallographically in sections from near the tail of the B4 extrusion, corresponding to the top of the ingot. Micrographs of defects in the blanks are shown in Figs. 1 and 2 in the as-polished and etched conditions.

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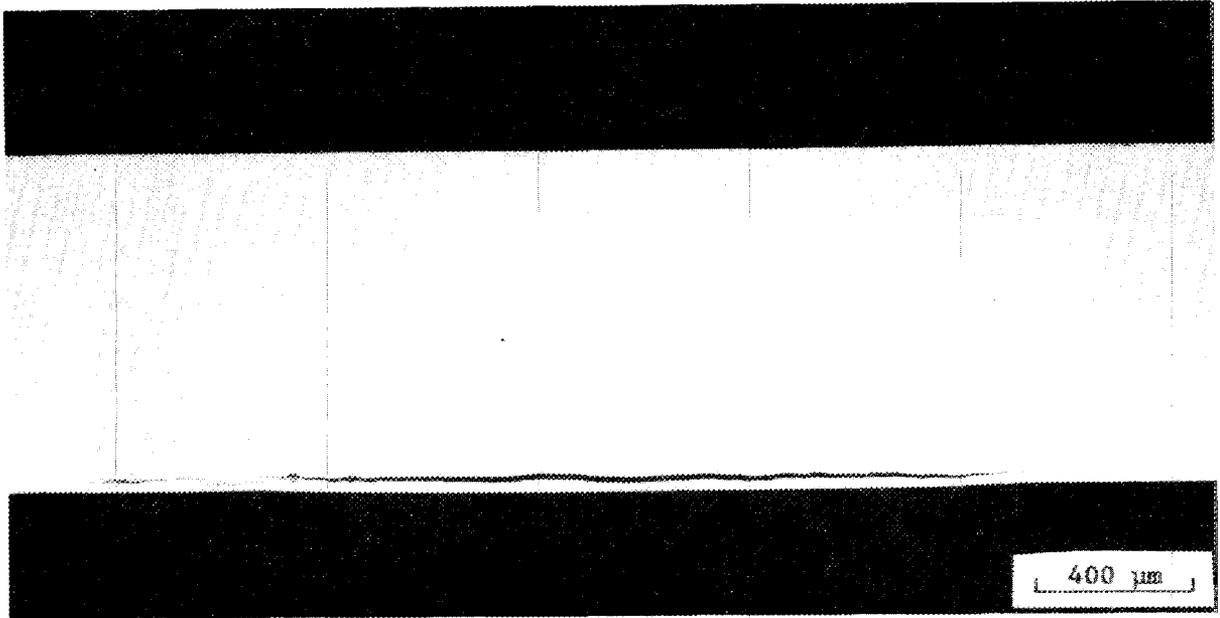


Fig. 1. Near-surface delamination in B4-8 sheet from tail of the extrusion (as polished).

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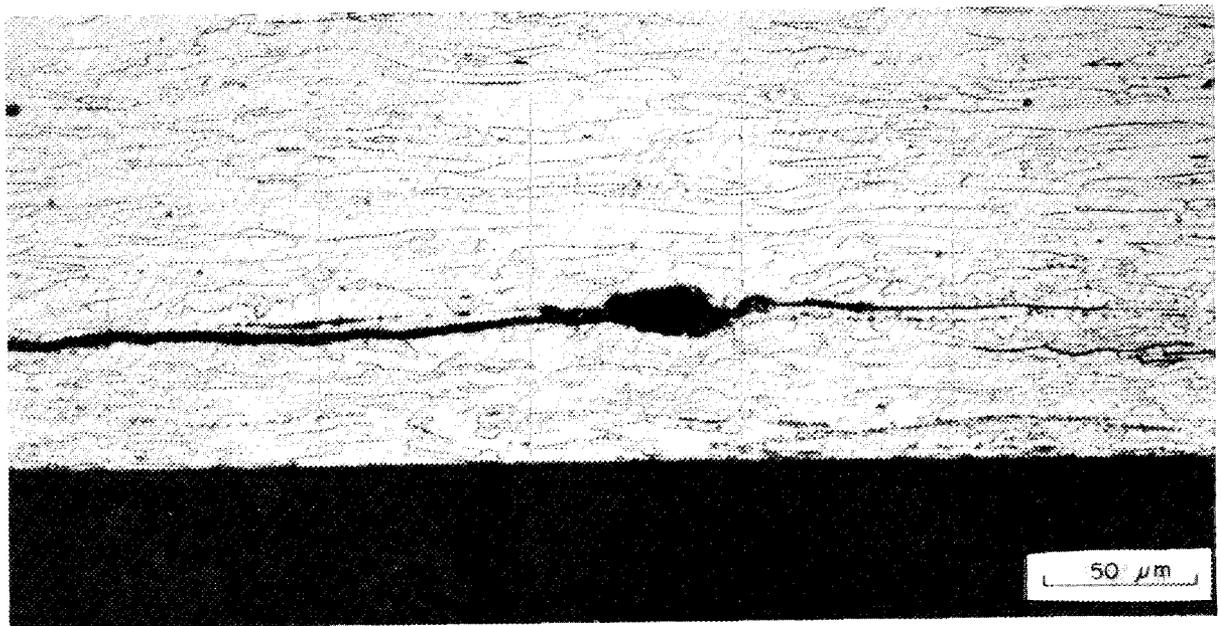


Fig. 2. Near-surface delamination in B4-8 sheet from tail of the extrusion (polished and electrolytically etched).

### 3.4 PROCESSING OF B5 INGOT

Compacts were EB melted to produce 8.8 kg of the Ir-0.3% W alloy. The alloy was doped and drop cast into a 28.6-mm-diam (1.125-in.) mold. An electrode of 11.6 kg (including a connector section) was assembled by EB welding of the drop-cast segments and arc melted in a 51-mm-diam (2-in.) mold. For this ingot, a 30-cm-high (12-in.) copper mold was used as compared to the 25-cm-high (10-in.) crucibles used previously. The mold was machined from a single bar of copper, as compared to a brazed-flange design used in earlier crucibles. This allowed for both a longer ingot and more extensive hot topping (reduced energy input) near the end of the melt.

The B5 ingot was canned in pure molybdenum and extruded in 76-mm (3-in.) tooling at 1250°C. The front 75% of the can was extruded at 6.2 MN (700 ton), at which time the extrusion stopped as a result of an overload of the press. The extruded section was straight and had a uniform cross section. The remaining section was machined to fit the container and subsequently extruded at 1278°C with a running load of 4.5 MN (500 ton).

An investigation into the cause of the partial extrusion of the B5 ingot was conducted. The tail of the initially extruded bar was analyzed for chemical contamination. In the past, abnormally high extrusion loads have been caused by contamination from remelt stock. The chemical analysis showed the material to be within the composition specification. A review was made of the extrusion loads as a function of furnace temperature for four extrusions of molybdenum-canned DOP-26 iridium alloy ingots. The results, shown in Fig. 3, for extrusions B1, B2, B4, and the last quarter of B5 exhibit a well behaved, consistent variation in load with temperature. The K factor is shown on the right hand axis and is calculated as

$$P = KA_0 \ln A_0/A_f ,$$

where

- P = the extrusion load,
- $A_0$  = the cross-sectional area within the extrusion liner,
- $A_f$  = the cross-sectional area of the extrusion.

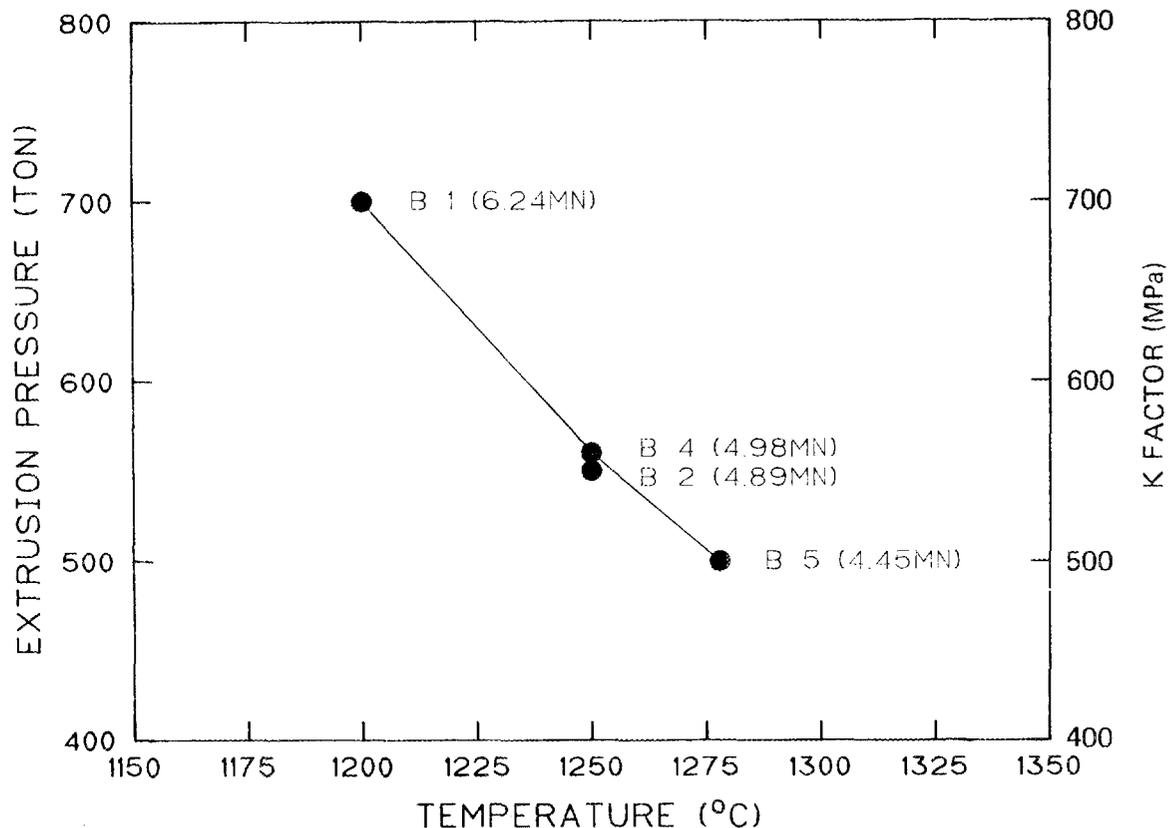


Fig. 3. Extrusion of four DOP-26 iridium alloy ingots (B1, B2, B4, and B5).

The overload during the initial B5 extrusion is believed to be the result of greater than usual ingot chilling because of a slower than normal extrusion. The thermocouples on the billet heating furnace were checked and found to be calibrated properly with the furnace controlling within 5°C of the set temperature.

The extrusion was rolled to 0.89-mm (0.035-in.) sheet using the standard practice and examined with a hand-held ultrasonic probe. Some near-surface delaminations were found similar to those on the B4 sheets. Regions that showed ultrasonic indications of defects were avoided in the layout for blanking. The yields of acceptable blanks are listed in Table 2. The results are similar to those obtained with the B4 ingot.

### 3.5 PROCESSING OF BR6 INGOT

The BR6 ingot was fabricated from recyclable material from B and XR ingots. The material was drop cast in a 228.6-mm-diam (1.125-in.) mold to produce segments that were EB welded to produce an electrode. The electrode broke soon after consumable arc melting began because of a weld failure. The electrode was trimmed to remove regions that were suspected of contamination and cleaned with acid. A replacement section was drop cast and EB welded onto the electrode.

The electrode breakage was found to be the result of transverse cracks in the circumferential welds. To avoid this problem, longitudinal EB welds were made on the repair-welded electrode so that any weld cracks would be in the longitudinal direction. A design for a new welding fixture was prepared to assist in maintaining straightness of future electrodes. The BR6 electrode was arc melted into a 50.8-mm-diam (2-in.) mold to produce a 9.3-kg ingot. This ingot was cut to produce a 178-mm (7-in.) length, as compared to the 127-mm (5-in.) length used previously. The ingot was extruded at 1300°C with a press load of 4.45 to 5.16 MN (500 to 580 ton). The elapsed time from removal of the ingot from the furnace to the completion of the extrusion was 23.5 s. Following cold rolling of nine billets cut from the extrusion, ultrasonic and visual inspections of the sheets were performed. Multiple ultrasonic indications of defects were found in each sheet, and small blisters were found on several sheets. The sheets were blanked; the resultant blanks will receive final inspection in FY 1988.

### 3.6 PROCESSING OF C1 INGOT

A shipment of 19.3 kg of iridium powder for C batch was obtained through Westinghouse Materials Company of Ohio. The chemical analysis of this material performed at the end of FY 1986 show it to be within specification. Approximately 100 g of -325, +400 mesh fractions of the powder was provided to MP for use in frit fabrication for clad-vent sets. The remaining powder were mixed with 0.3 wt % W powder and compacted. Ten kilograms of the compacts were EB melted, alloyed, and fabricated into the C1 electrode of 9.9 kg. The electrode was arc melted into a 50.7-mm-diam (2-in.) mold to produce a 7.67-kg ingot of 180-mm (7-in.) length. The

ingot was canned in molybdenum and extruded at 1300°C with a press load of 4.7 to 4.9 MN (525 to 550 ton) and a total elapsed transfer and extrusion time of 24.5 s. The extrusion of 940-mm (37-in.) length after trimming was cut into nine billets for hot rolling. Each billet was hot rolled to a 7.87-mm-thick (0.200-in.) plate and visually examined after the 1300°C recrystallization treatment. One probable delamination defect was observed at one end of one plate during examination of the cut ends at 30× magnification. Blisters were observed on one side of the C1-4 through C1-7 plates and on both ends of C1-8. The blisters were removed by grinding with tungsten carbide burrs -- a process similar to that used on standard process arc-cast ingots -- prior to continued sheet rolling. Blanking and inspecting of C1 sheets and qualification of C-batch iridium powder is to be completed during FY 1988.

### 3.7 PROCESSING OF D-BATCH AND E-BATCH POWDERS

Approximately 20.1 kg of iridium powder (designated D batch) was received from Engelhard Corporation. During the weighing of the powder for receiving inspection, four out of five jars were noted to contain several lumps of agglomerated powder [up to 6.35-mm diam (0.250-in.)]. These agglomerates are out of specification because all powder is to pass through a 150- $\mu$ m screen (U.S. sieve size 100). Analysis of the powder without agglomerates by spark source mass spectroscopy (SSMS) method shows the composition to be within specification. Samples of the agglomerates analyzed by SSMS separately showed that they are also within specification. Results from quantitative screening averaged 4.1 wt % of the powder in excess of U.S. sieve size 100. Based on these results, the powder was accepted for fabrication of flight-quality hardware. The screened powder was made into master blends, water washed, blended with tungsten to produce the Ir-0.3 wt % W mixture and compacted. The compacts were sintered and EB melting begun. The processing of a D1 ingot and qualification of D batch are to be completed during FY 1988.

Three receipts of iridium powder that weighed about 90 kg (198 lb) total were received and designated E batch. Sampling of the powder for chemical analysis prior to powder acceptance was begun. The fabrication of an E1 ingot and qualification of E-batch iridium are to be completed during FY 1988.

#### 4. PROGRAM TO IMPROVE CONSUMABLE ARC-MELT INGOT QUALITY

At the start of the iridium process improvement program in FY 1985, consumable arc-melts B1 and B2 ingots were extruded, rolled into sheet, and had an acceptance of 100% of the blanks from nondestructive examination. In FY 1986, consumable arc-melt BR3 (a recyclable scrap melt) ingot did not extrude because of strengthening from molybdenum contamination, and consumable arc-melt B4 ingot yielded only 50% blanks because of delamination. At that time, these defects were attributed to arc-spattered material on the side of the melting crucible that was not fused into the ingots. Longer crucibles were then procured to increase melt length and allow a longer section for current tapering (reduction in power) near the top of the crucible. A longer crucible was used for consumable arc-melt B5 ingot in FY 1987 and again the result was only 50% yield of blanks because of delaminations in the rolled sheet. It was proposed that higher amperage be used in melting BR6 ingot. On discovery of similar delaminations in both BR6 and C1 plates, an ad hoc team was convened to determine causes for the delaminations and suggest means to minimize the defects. The consensus of all participants was that the delaminations are associated with surface or subsurface defects in the arc-melted ingots. The defects remained after fabrication into sheets and are not entirely removed during grinding to final thickness.

##### 4.1 METALLOGRAPHY OF ARC-CAST INGOTS

Metallographic examination was performed on the top section of the consumable arc-melted BR6 ingot. A section containing subsurface porosity is shown in Fig. 4. The material, shown in the etched condition, exhibits the same indications of porosity in the as-polished condition. The porosity extends to a depth of about 1.2 mm (0.048 in.). The porosity is in some instances located at a grain boundary; in most cases, the porosity appears to have little effect on the radial growth of the elongated grains. It is not established that this is typical of other ingots or of regions farther from the top of this ingot. Spherical pores at a location about 0.6 mm (0.025 in.) from the surface have been observed in a section near the top of AC ingot, as seen in Fig. 5.

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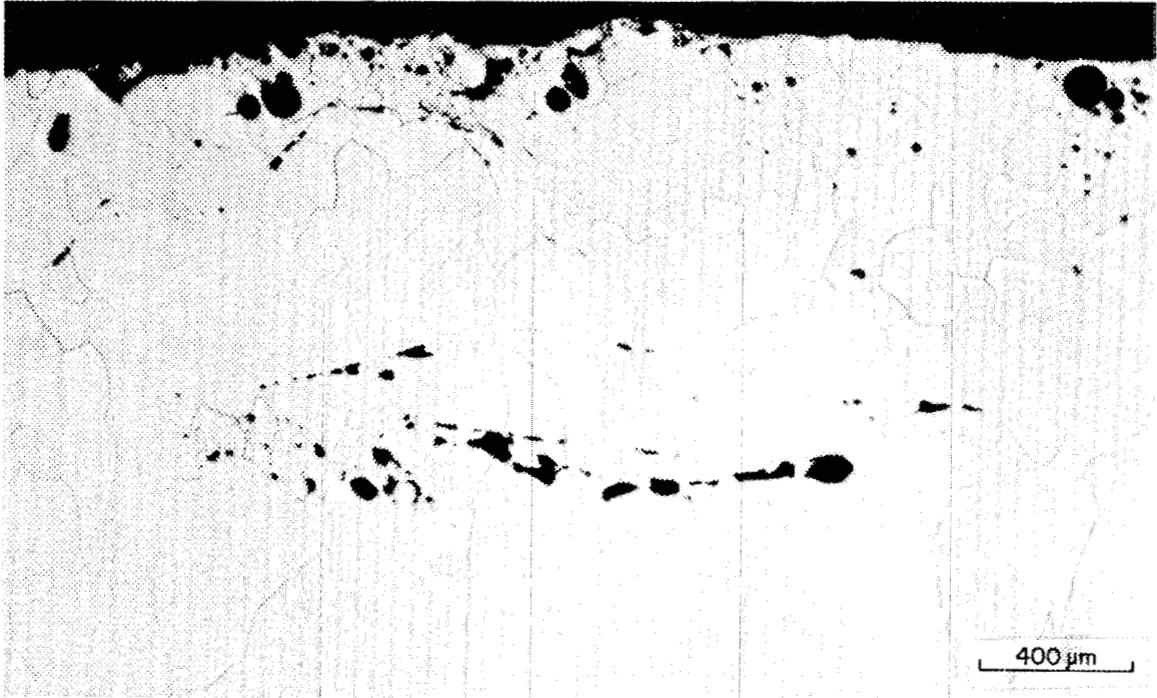


Fig. 4. Transverse section from BR6 ingot. Electrolytically etched.

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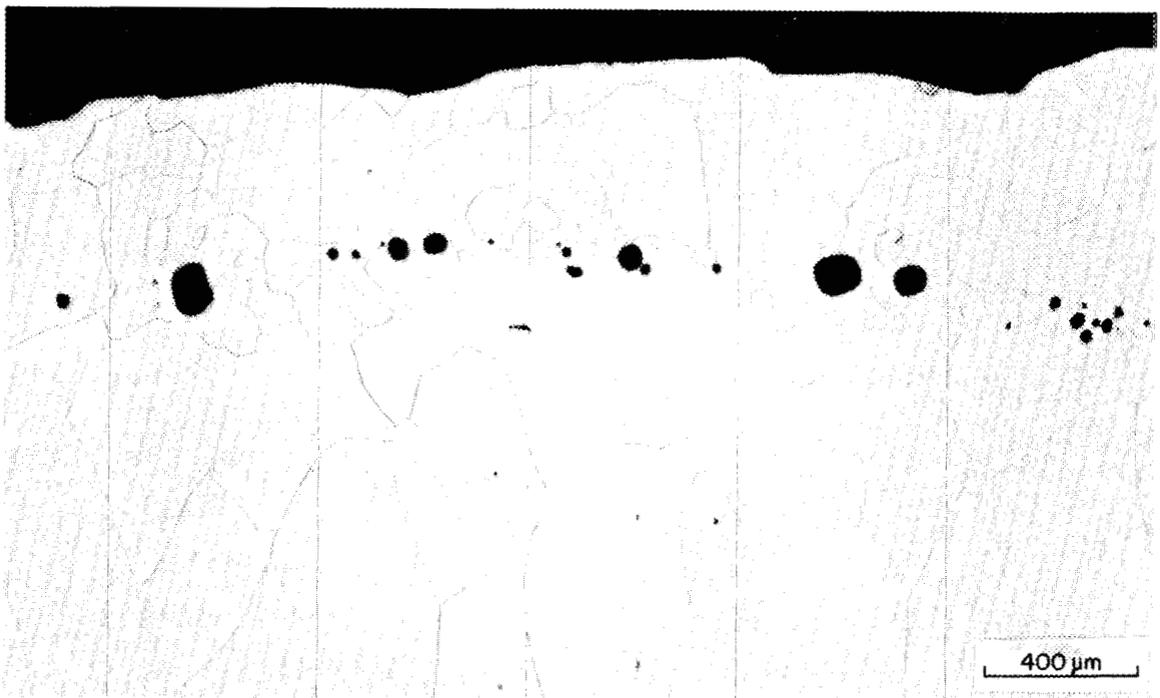


Fig. 5. Transverse section from AC ingot. Electrolytically etched.

## 4.2 CONSUMABLE ARC-MELTING PARAMETERS

To minimize defects that could occur in the ingot, consideration was given to most aspects of arc melting, including electrode condition, mold condition, mold cooling, and melting parameters (e.g., arc current, arc voltage, arc polarity, melt rate, electrode-to-mold gap clearance, and melt chamber atmosphere). Consideration was also given to surface conditioning and nondestructive evaluation of the arc-melted ingot prior to extrusion. An assessment of the relative importance of these parameters in the arc-melting process on ingot surface quality will be made in FY 1988 using melts with both stainless steel and refinable scrap iridium materials.

The arc current and voltage fluctuate during melting. This is related to the release of individual droplets of molten alloy into the gap between the electrode and the molten pool and is inherent to the consumable arc-melting process. The rapid changes in voltage and current and their relation to phenomena occurring in the arc gap have been studied by other researchers.<sup>2</sup> Starting voltage and current measurements have been recorded and melting rates calculated. Table 3 includes this information for six ingots. There is no correlation of average arc current, starting arc voltage, or average melt rate with the delaminations observed in the ground blanks. Instrumentation to continuously monitor and record arc current, arc voltage, and electrode position has been installed on the consumable arc-melting unit to evaluate possible relationships between melting variables and surface quality of the ingots. Measurements are recorded at 0.5-s increments and are available in graphical or tabular form. This instrumentation will be used for experimental stainless steel melts, melting of iridium alloy refinable scrap, and all future iridium alloy melts.

The condition of the mold was also considered as a possible source of defects in the ingots. All molds were made of oxygen-free high-conductivity copper. Molds for B1, B2, and B4 ingots were 25-cm (10-in.) long with a brazed flange. Subsequent melts were made with molds 30-cm (12-in.) long with one-piece construction. The previous use of a crucible for melting of iridium was considered a possible source of improvement in surface quality of the ingots and fewer defects in ground blanks. After

Table 3. Summary of DOP-26 alloy consumable arc melting

Ingot number	Electrode mass (kg)	Melted mass (kg)	Average melt rate (kg/min)	Melting parameters			Crucible	
				Starting potential (V)	Current (A)	Time (min)	Condition	Length (cm)
B1	8.0	6.6	1.8	40	3000	3.6	Used	25
B2	9.0	6.9	1.8	40	3000	3.8	Used	25
B4	8.0	6.6	1.6	34	2900	4.0	New	25
B5	11.6	8.8	2.5	38-40	2600	3.6	New	30
BR6	13.0	9.3	2.5	40	3000	3.7	New	30
C1	11.8	8.6	2.3	40	3000	3.8	Used	30

initial use, the mold retains a thin iridium coating that could affect heat transfer at the molten metal-mold interface. The B1 and B2 ingots with 100% blank yield were melted with a used mold. However, the plate from the C1 ingot (which also employed a used mold) shows indications of defects that are likely to reduce the yield of acceptable blanks. To further evaluate the potential benefit of iridium coating on the mold, it is planned to coat one new mold (EB evaporation of DOP-26 alloy within the mold) and use this mold in the arc melting of a refinable scrap electrode.

The electrode condition has been evaluated as a potential source of defects in the consumable arc-cast ingot. To quantify the variability in voltage drop and degree of resistance heating of the electrode during arc melting of the alloy, resistance measurements were made on an experimental refinable scrap DOP-26 alloy electrode at 25.4-mm (1-in.) intervals. Measurements were made using a constant current of about 11 A. The resistance measurement results listed in Table 4 show maximum deviations from the mean of 4.343  $\mu\Omega$  of +36% and -23%. The regions for which resistance was measured that appeared to contain an above-average amount of welded metal are noted in the table. The mean resistance of these regions is 7% above the overall mean. The effect of these variations in resistance, which may be the result of pores or cracks in the electrode, on the consumable arc-melting process is not known. It is not believed to be large, but this must be confirmed with future melts. The maximum deviation from straightness of this electrode was measured as 0.8 mm (0.031 in.). This is considered to be within acceptable limits. The 28.6-mm (1.125-in.) diam of the electrode used in all previous melts is also be studied. Reducing the diameter of the electrode increases the gap from the electrode to the mold wall and decreases the chance of arcing to the wall. It also increases visibility of the melt to the operator.

Another arc-melting parameter considered is the alignment of the electrode with the mold to maintain a uniform gap to the mold wall. The arc-melting unit was designed for melting ingots of 76-mm (3-in.) diam or greater. The electrode feed mechanism is not capable of maintaining good concentricity of the electrode with the mold. The alignment is considered essential for melting in the 51-mm-diam (2-in.) mold. Initial improvements to concentricity included remachining the molybdenum electrode adapter.

Table 4. Absolute resistance over 25.4-mm-long increments from top to bottom of refinable scrap electrode

Increment	Resistance	
	Absolute ( $\mu\Omega$ )	Normalized to mean
1 <sup>a</sup>	4.586	1.056
2	3.473	0.800
3 <sup>a</sup>	4.555	1.049
4	4.590	1.057
5 <sup>a</sup>	4.262	0.981
6	4.275	0.984
7 <sup>a</sup>	5.068	1.167
8 <sup>a</sup>	4.285	0.987
9 <sup>a</sup>	5.110	1.177
10	3.557	0.819
11 <sup>a</sup>	5.803	1.336
12	4.943	1.138
13 <sup>a</sup>	5.898	1.358
14	3.366	0.775
15 <sup>a</sup>	4.197	0.966
16	4.736	1.091
17 <sup>a</sup>	4.225	0.973
18	3.579	0.824
19 <sup>a</sup>	4.393	1.012
20	3.350	0.771
21 <sup>a</sup>	4.208	0.969
22	3.691	0.850
23 <sup>a</sup>	3.732	0.859
Mean	4.343	1.000

<sup>a</sup>These increments were welded more than the others.

The melts performed to date were all made in vacuum starting at about  $7 \times 10^{-3}$  Pa ( $5 \times 10^{-5}$  torr) measured just above the top of the mold. It is reasoned that the low vapor pressure of iridium and the absence of dissolved gases in the alloy, because of extensive EB melting, could result in a less stable arc than that obtained for arc melting of more conventional materials. It is planned to perform arc melting of both stainless steel and a refinable scrap iridium alloy electrode in partial argon atmosphere to obtain improved arc stability.

Consideration has also been given to increasing the diameter of the ingot from 51 to 63.5 mm (2 to 2.5 in.). The existing mold diameter is only marginally of sufficient size for arc melting in general practice. The increased mold diameter would increase the productivity of the arc-melting and extrusion operations and would most importantly increase the gap between the electrode and mold; this would decrease the possibility of side arcing and decrease the sensitivity of electrode alignment. The increase in diameter could be accommodated in the extrusion process using existing equipment.

Consideration must also be given to replacing the arc-melting unit. The electrode alignment mechanism is clearly not adequate for the type of small-diameter castings required for iridium alloy processing. Although modifications are being made to improve the alignment, the design of the electrode drive mechanism is inherently unsuitable for this type of work. The alignment problem in this furnace is compounded by the vibration in the electrode introduced by the vacuum pumps, which are not mechanically isolated from the chamber. The design of the vacuum chamber, with a large number of O-ring joints and seals and large internal surface area, greatly increases the difficulty in maintaining uniform vacuum levels from melt to melt. In addition, arc gap controllers are now available that are superior to those available when the existing unit was constructed.

#### **4.3 SURFACE PREPARATION AND NONDESTRUCTIVE EVALUATION OF CONSUMABLE ARC-MELTED INGOTS**

In addition to improving the surface and subsurface condition of the arc-melted ingot, surface grinding in combination with nondestructive evaluation is another possible means to improve the yield of ground blanks. Grinding of 0.76 mm (0.030 in.) from the radius of the 51-mm-diam (2-in.) ingot will result in a loss of 6% of the weight of iridium. The refinable scrap ingot to be melted in FY 1988 will be subjected to both dye-penetrant and ultrasonic inspection and will also be ground to estimate the amount of material removal needed to eliminate near-surface flaws.

### 5. STRESS-RELIEVING AND RECRYSTALLIZATION STUDIES ON DOP-26 IRIDIUM ALLOY

A study comparing the stress-relieving and recrystallization behavior of standard and new process DOP-26 iridium alloy was performed. This study investigated changes in microstructure and hardness resulting from 1-h heat treatments over the temperature range of 900 to 1500°C. Specimens were taken from standard process B731 sheet and new process B2-3 sheet. The materials differed slightly in their fabrication history in that standard process sheet was stress relieved 1 h at 900°C and new process sheet was stress relieved 1 h at 850°C prior to the heat-treating study.

Results of hardness measurements on the variously heat-treated specimens are plotted in Fig. 6. Standard process material was slightly harder

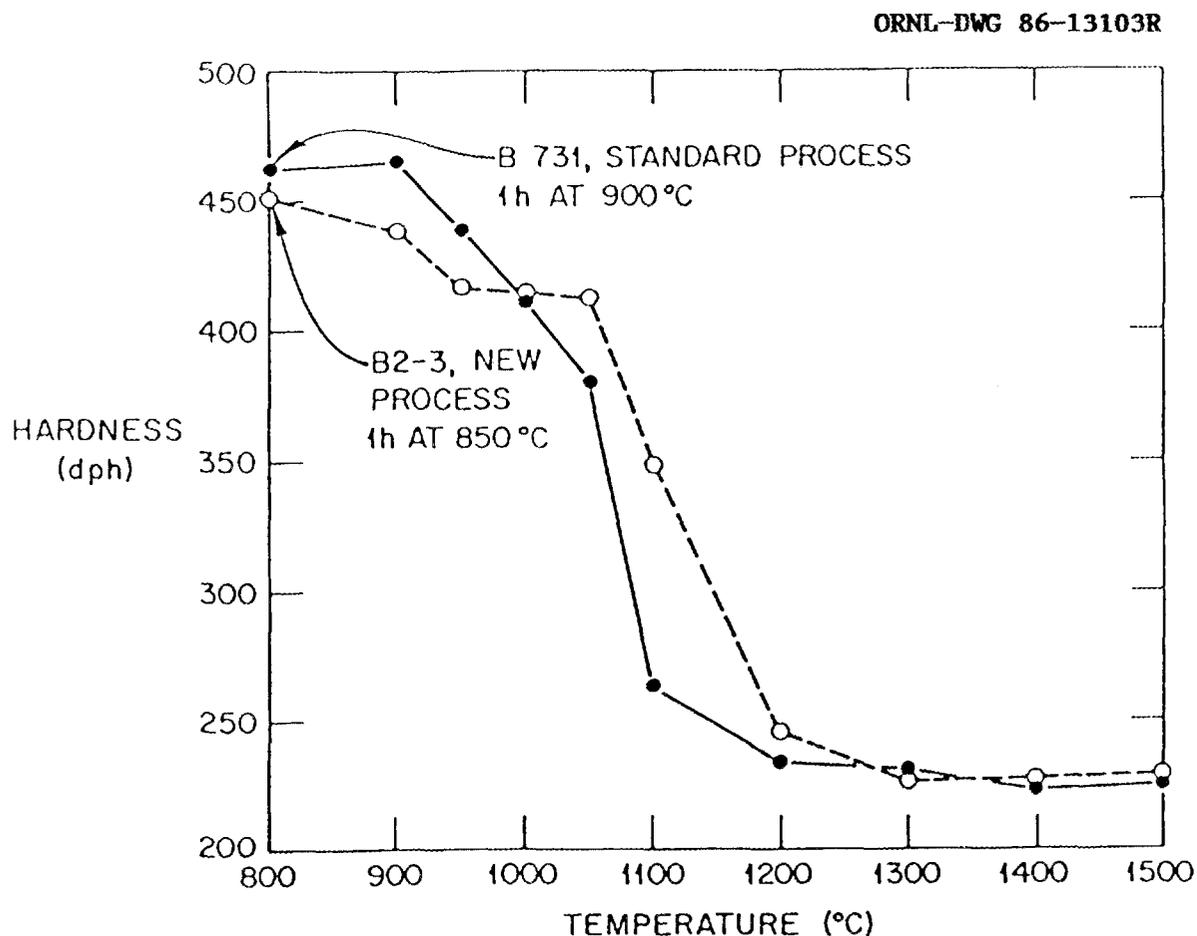


Fig. 6. Effect of 1-h heat treatments on hardness of standard and new process DOP-26 iridium materials.

initially but showed a more rapid decrease in hardness through the temperature range of 900 to 1100°C than new process material. As indicated in Table 5, these results correlated well with the observed microstructures. The microstructure of standard process material retained its fibrous character through a heat-treating temperature of 950°C. Some recrystallization (<5%) was apparent at 1000°C and increased to approximately 95% at 1100°C. New process material showed <5% recrystallization at 1050°C and increased to approximately 25% at 1100°C. Thus, up to 1100°C, the degree of recrystallization of new process material as determined metallographically appears to lag standard process material by about 50°C. At 1200°C, the heat-treating response of new process material still lags that of standard process material, but only slightly.

**Table 5. Effect of 1-h heat treatments on the microstructure of standard and new process DOP-26 iridium materials**

Temperature (°C)	Microstructure, % recrystallization <sup>a</sup>	
	Standard process	New process
	B 731	B2-3
<i>b</i>	<i>c</i>	<i>c</i>
900	<i>c</i>	<i>c</i>
950	<i>c</i>	<i>c</i>
1000	<5	<i>c</i>
1050	~25	<5
1100	~95	~25
1200	100	~95
1300	100	100
1400	100	100
1500	100	100

<sup>a</sup>Visual estimate.

<sup>b</sup>Standard process material stress relieved 1 h at 900°C. New process material stress relieved 1 h at 850°C.

<sup>c</sup>Fibrous.

Material by either process completely recrystallizes at a temperature of 1300°C and above, and the hardness data level off to a fairly constant value of about DPH 225 between 1300 and 1500°C. Some grain coarsening occurs with increasing temperature in this range. This study shows for new process DOP-26 iridium alloy that 1-h heat treatments no higher than about 1000°C will retain a fibrous microstructure. Above this temperature recrystallization begins. Standard process material shows similar behavior but at a slightly lower temperature of 950°C.

## 6. MECHANICAL TESTING OF DOP-26 IRIDIUM ALLOY

The tensile properties of the DOP-26 iridium alloy produced by the new process were measured over a range of both test temperatures and strain rates. The tensile specimens were machined from B2-7 sheet. The specimen dimensions were 0.622-mm (0.0245-in.) thick, 28-mm (0.110-in.) gauge width, and 12.7-mm (0.500-in.) gauge length. The gauge width was decreased from the 3.2-mm (0.125-in.) value used previously to facilitate fracture within the gauge section.

Tensile tests were conducted at temperatures of 600 to 1100°C at a conventional displacement rate of 1.3 mm (0.05 in.) per minute, which corresponds to a strain rate of  $1.67 \times 10^{-3}$ /s. The material was tested in both a stress-relieved condition (1 h at 1025°C) and in a recrystallized condition (1 h at 1300°C). Representative microstructures are shown in Figs. 7 and 8. All tests were performed with the tensile axis in the rolling direction. No reinforcing pads were used and all fractures occurred within the gauge section. The results of single tests for each condition are listed in Table 6 and plotted in Figs. 9 and 10. The tensile and yield stresses decrease with increasing temperature for both stress-relieved and recrystallized materials. The rate of decrease in strength with temperature is substantially less at temperatures of 900 to 1100°C than at lower temperatures. The tensile elongation increases with increasing temperature for recrystallized material. The tensile elongation of stress-relieved material is much lower and shows only slight variation with test temperatures.

Tensile tests were performed at a higher strain rate on stress-relieved material at 925°C, which is the cup-forming temperature. The

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Fig. 7. Microstructure of DOP-26 iridium alloy sheet stress relieved at 1000°C for 1 h. The material is from the B2 ingot fabricated using the new process, with prior anneal of 1 h at 850°C. Longitudinal section. Electrolytically etched.

Y-206166



Fig. 8. Microstructure of DOP-26 iridium alloy sheet recrystallized at 1300°C for 1 h. The material is from the B2 ingot fabricated using the new process, with prior anneal of 1 h at 850°C. Longitudinal section. Electrolytically etched.

Table 6. Elevated temperature tensile data for DOP-26 iridium alloy at strain rate of  $1.67 \times 10^{-3}/s$

(Specimens from B2-7 sheet)

Specimen number	Temperature (°C)	Strength (MPa)		Elongation (%)
		0.2% Yield	Ultimate	
<i>Stress-relieved condition at 1025°C for 1 h</i>				
1	600	733	801	11.7
5	650	705	752	9.1
9	700	641	710	9.2
11	800	606	673	8.0
14	900	512	638	7.5
18	1000	546	577	6.2
19	1100	524	556	7.6
<i>Recrystallized condition at 1300°C for 1 h</i>				
3	600	182	475	24.7
4	650	190	450	36.5
8	700	117	410	41.8
12	800	102	357	38.9
13	900	93	319	43.3
16	1000	94	270	44.0
21	1100	82	259	47.4

tests were conducted at 508 mm (20 in.) per minute, which correspond to a strain rate of  $6.67 \times 10^{-1}/s$ , using material stress relieved at 1025°C for 1 h. No reinforcing pads were used on the grip section. Tensile strength and elongation measurements are shown in Table 7 for both parallel and transverse orientation to the rolling direction. The transverse ductility is significantly lower. The measured ultimate tensile strengths and tensile elongations obtained for the parallel test specimens are slightly greater than those obtained at the lower strain rate of  $1.67 \times 10^{-3}/s$  as shown in Figs. 9 and 10.

Tensile impact tests were performed at 980°C and 61 m/s (200 ft/s) corresponding to a strain rate of approximately  $4.8 \times 10^3/s$ . The test samples were oriented parallel to the rolling direction and recrystallized at 1500°C for 19 h prior to testing. Reinforcing pads were used on the

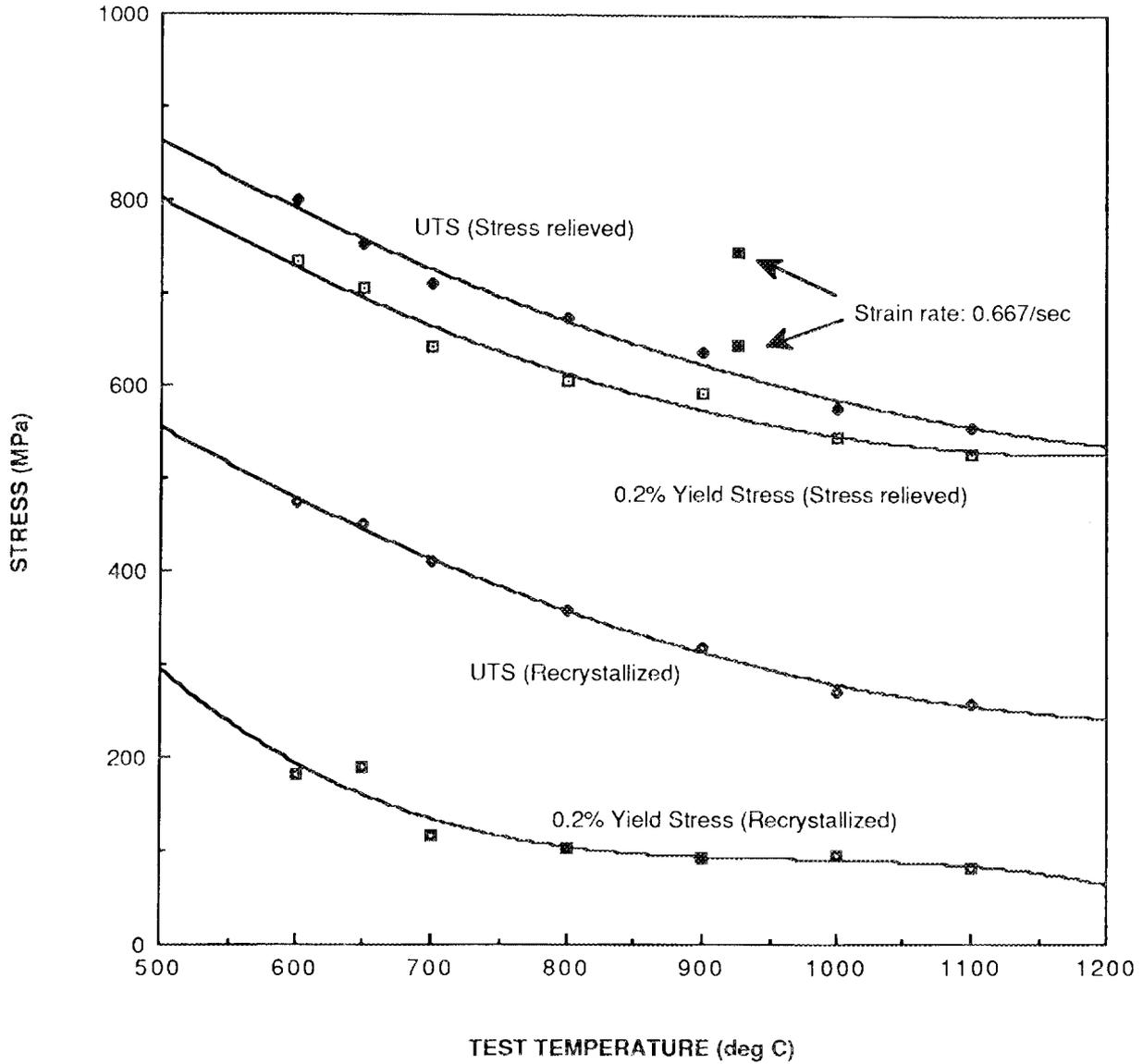


Fig. 9. The temperature dependence of the ultimate tensile strength (UTS) and 0.2% offset yield strength of DOP-26 iridium alloy. Tests performed at  $1.67 \times 10^{-3}/s$  strain rate except where noted.

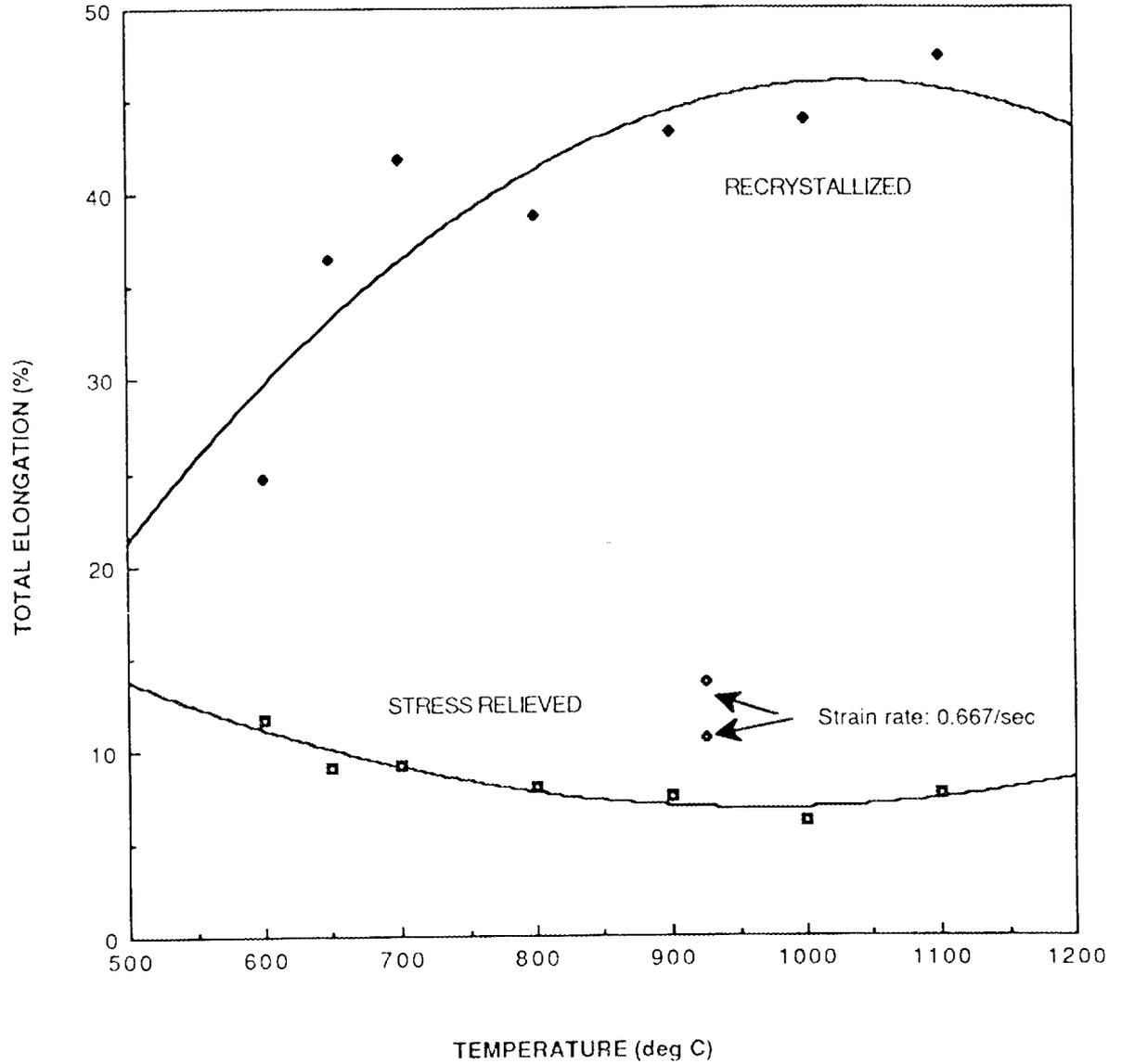


Fig. 10. The temperature dependence of the tensile elongation of DOP-26 iridium alloy. Tests performed at  $1.67 \times 10^{-3}/s$  strain rate except where noted.

**Table 7. Tensile data for DOP-26 iridium alloy  
at 925°C and a strain rate of  $6.67 \times 10^{-1}$ /s**

(Specimens from B2-7 sheet)

Specimen number	Ultimate tensile strength	Elongation (%)	Orientation to rolling direction
2	745	10.6	0° (parallel)
15	645	13.6	0° (parallel)
22	628	8.1	90° (transverse)
23	692	9.6	90° (transverse)

grip at the impact end of each specimen. Two specimens were tested and both fractured in the gauge section with elongation of 23.0 and 24.5%. These values are well above the 13.5% minimum needed to qualify an iridium powder batch for production. In addition to these tests of B2-7 material, tensile impact tests were also performed on samples from sheets B5-1 and B5-3 using the same conditions. The measured elongations are 13.6 and 19.8%, respectively.

## 7. CLEANING OF GROUND BLANKS

The procedure for cleaning of DOP-26 iridium alloy blanks involves an electrolytic dissolution of the surface in a saturated potassium cyanide solution. Potassium cyanide is highly toxic and requires careful handling by trained personnel. During FY 1987, a new formal procedure has been prepared for the use of KCN in connection with the cleaning of iridium. Safety, emergency preparedness, environmental, and operating training procedures are specified.

Alternatives to KCN cleaning have been considered and some limited experimental work performed. In the event that KCN usage is no longer permitted for reasons of personnel safety, these studies would form the basis for the development of new cleaning procedures. The current cleaning process uses a KCN solution (130 g/L) with stainless steel electrodes operated at 9 V. The alternating current is of the order of 200 A and approximately 100 mg is removed during the 5-min cleaning.

The results obtained in laboratory-scale dissolution experiments are listed in Table 8. The initial weight loss results for HCl solutions were superior to those of H<sub>2</sub>SO<sub>4</sub>. Additional HCl experiments were performed with both varying acid concentration and current levels. The metal removal rate increases with increasing current and decreasing HCl concentration for the range of 50 to 12.5% by volume. The measured removal rates for HCl solutions studied are lower than for KCN but are well within a useful range. Micrographs of the ground and cleaned surfaces are shown in Figs. 11 and 12 for an iridium blank cleaned with HCl solution and another blank cleaned with KCN solution. The specific weight losses on the two samples are 1.9 mg/cm<sup>2</sup> for the HCl-cleaned blank and 2.0 mg/cm<sup>2</sup> for the KCN-cleaned blank. This may account for the apparent lower degree of surface roughness on the HCl-cleaned sample. With further development, HCl cleaning of the DOP-26 iridium alloy could prove a viable alternative to KCN cleaning.

**Table 8. Experimental study of alternative cleaning solutions**

Aqueous solution	Concentrated volume (%)	Time (min)	Current (A)	Weight loss (mg)	Specific weight-loss rate (mg/cm <sup>2</sup> min)
H <sub>2</sub> SO <sub>4</sub>	25	178	2.0	55.6	0.013
HCl	25	33	4.5	62.8	0.079
HCl	25	20	10	70.3	0.118
HCl	25	20	20	85.9	0.181
HCl	25	20	10	83.7	0.175
HCl	12.5	20	10	52.0	0.095
KCN (typical)	50	5	200	100	0.4

Note: All results are shown for half-immersed iridium blanks except for KCN aqueous solution, which is for full immersion.

## 8. WELDABILITY TESTING OF DOP-26 IRIDIUM ALLOY

DOP-26 iridium alloy blanks are drawn to cups and pairs of cups containing isotopic fuel and arc welded to produce clads. Hot cracking of the alloy during gas tungsten arc welding (GTAW) has caused rejection of

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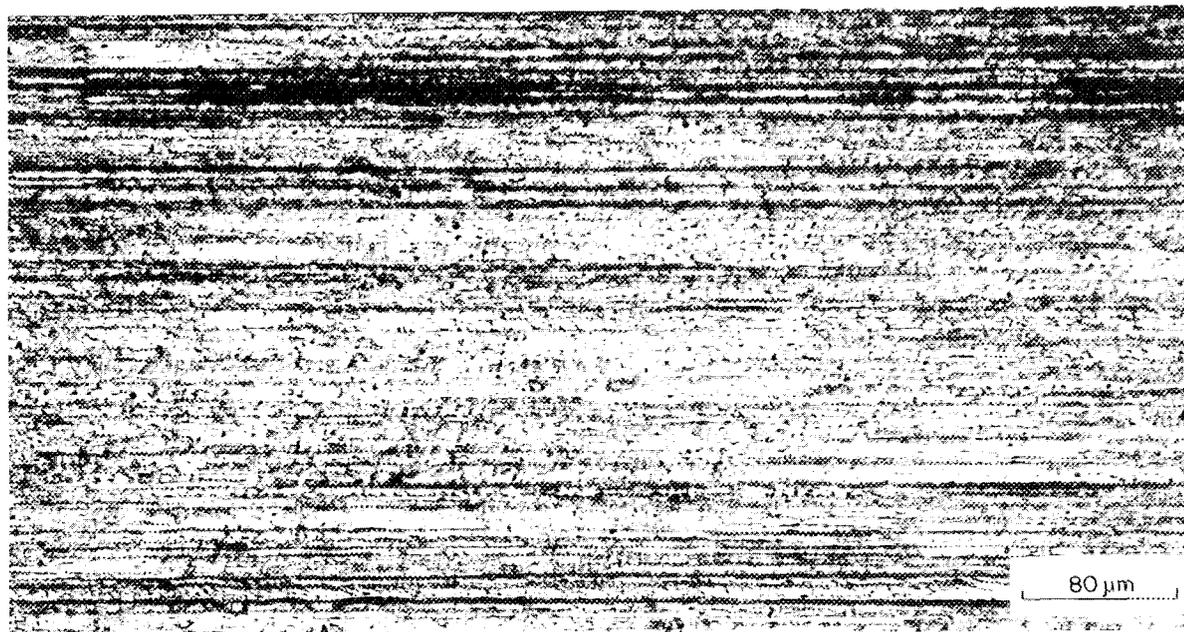


Fig. 11. Ground surface of DOP-26 iridium alloy electrolytically cleaned in 12.5 vol % aqueous solution HCl at 10 A.

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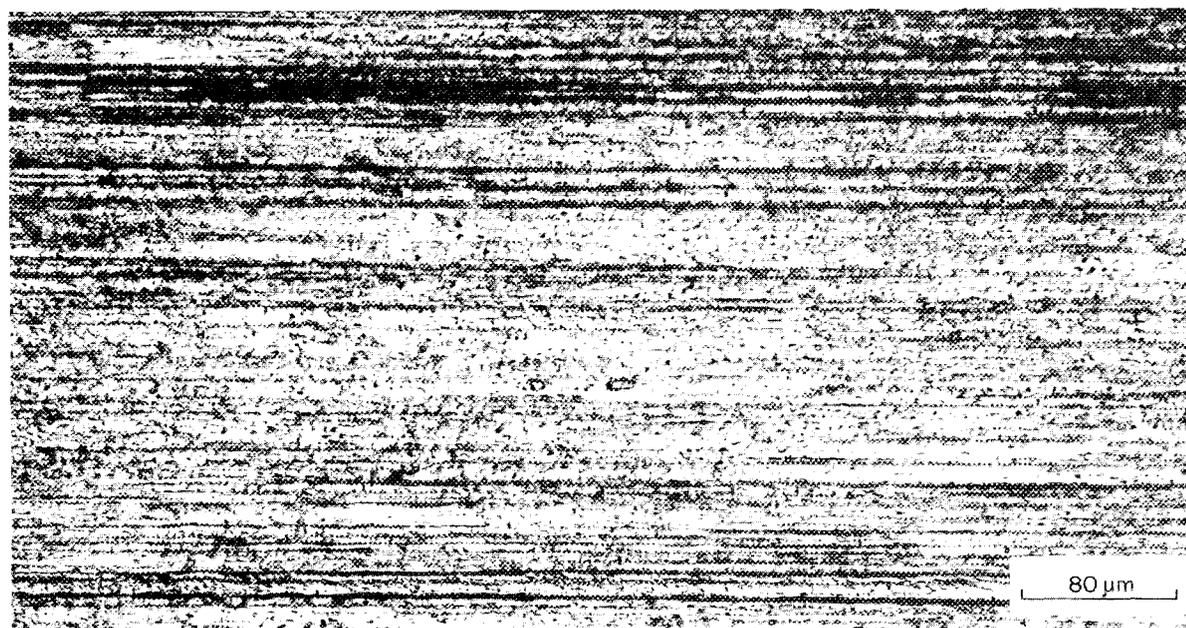


Fig. 12. Ground surface of DOP-26 iridium alloy electrolytically cleaned in aqueous KCN solution at 200 A.

significant numbers of welded clads. The hot cracking has been attributed to formation of a thorium-enriched molten material at grain boundaries in advance of the molten pool.<sup>3</sup>

A new hot-cracking test<sup>4</sup> (designated Sigmajig) has the potential to quantitatively differentiate the hot cracking tendency of DOP-26 iridium alloy made from various iridium powder batches. The test has been successfully applied to 12 heats of austenitic stainless steel and to other materials including Nb-1% Zr alloy, which has a liquidus temperature of about 2450°C, similar to that of iridium. The test requires application of a transverse stress ( $\sigma$ ) to a sheet specimen, followed by autogenous gas tungsten arc welding. As the preapplied stress is increased from specimen to specimen, cracking eventually occurs. The test yields threshold stress values at the onset of cracking and, therefore, provides quantitative indices unavailable from other tests.

Initial tests were completed to demonstrate the feasibility of applying the Sigmajig hot-cracking test to iridium alloys. All tests were performed in a large vacuum-pumped and inert-gas-purged chamber in high purity 75% helium-25% argon mixture. Four standard 51-mm-diam (2-in.) blanks of new process material (AC-2) were tested in the stress-relieved condition; stresses were determined using the relationship

$$\sigma = \frac{p}{44.0 t} ,$$

where stress of  $\sigma$  in MPa is a function of load of  $p$  in newtons and thickness of  $t$  in millimeters. To establish welding parameters, the first blank was welded using standard conditions for fueled clads: viz. 83 A, 12.7-mm/s (30-in./min) travel, and 0.88-mm (0.035-in.) arc length. As had been anticipated, the resultant weld had incomplete penetration, a result of the conductivity difference between actual clad welding and the Sigmajig fixture setup. Additional welds were then made on the same blank at 110, 130, and finally 120 A, which resulted in a weld width of about 3 mm (0.120 in.).

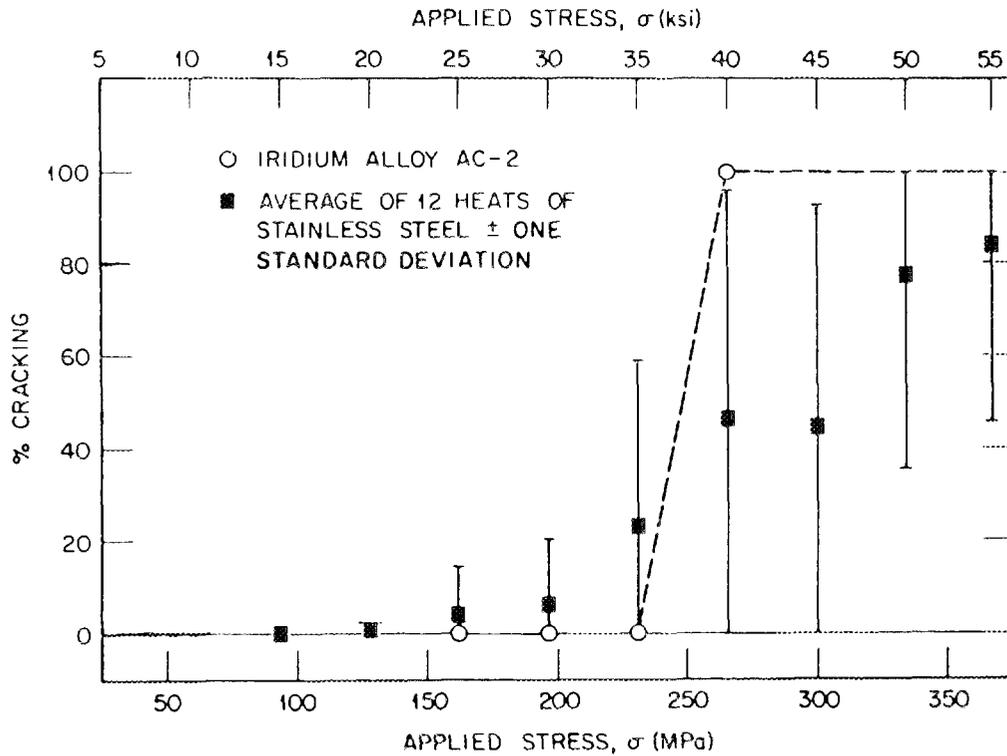


Fig. 13. Cracking response of DOP-26 iridium alloy (AC-2 sheet) compared with commercial stainless steel.

The remaining three blanks were tested at 120 A, at stresses ranging from 172 to 276 MPa (25 to 40 ksi). The data are plotted in Fig. 13, which shows a comparison to averages for 12 heats of commercial types 304 and 316 stainless steels. The threshold cracking stress,  $\sigma_{\min}$ , is seen to be approximately 241 MPa (35 ksi).

These results demonstrate that it is feasible to evaluate the hot-cracking tendency of DOP-26 iridium alloy using the Sigmajig test. Sheet-to-sheet variations in hot-cracking response, which the alloy might exhibit, could be determined and procedures developed to minimize hot cracking of the welded capsules. Additional testing of recrystallized material would provide a more direct comparison with the welding of fueled clad-vent sets at SRP, which uses cups in a recrystallized condition.

## 9. QUALIFICATION OF THE CONSUMABLE ARC-MELTING, EXTRUDING, AND ROLLING PROCESS FOR BLANK PRODUCTION

The qualification of the new process for DOP-26 iridium alloy sheet and blank production for flight-quality hardware is based upon a three-phase technical program. Phase I involved production of new process and standard process DOP-26 iridium alloy blanks at ORNL, evaluation of the relative formability of the blanks from each of two processes by MP, evaluation of the relative weldability of the two materials at SRP, and evaluation of the relative ductility in high-strain-rate biaxial tension testing at LANL. The forming study showed formability without delaminations and EB weldability equivalent to the standard process blanks.<sup>5</sup> The gas tungsten arc weldability of the new process DOP-26 iridium alloy cups was found to be superior to that of standard process cups in tests by SRP with under bead cracking reduced by 44%.<sup>6</sup> The ductility of new process blanks in high-strain-rate biaxial tension at LANL was found to be greater than standard process blanks.<sup>7</sup> Phase II of the program, including impact testing of eight simulated UO<sub>2</sub>-fueled clads has been delayed. LANL wants to conduct two tests and to hold the remaining six clads for tests yet to be defined.

The third phase of the program involves impact testing of plutonia-fueled clads with new process iridium cladding. Phase III was only partially completed in FY 1987. ORNL shipped 30 new process blanks to MP, which were inspected and forwarded to LANL for grid application prior to PuO<sub>2</sub>-fueled-clad fabrication. Grids were applied at LANL, and the blanks were returned to MP for forming. Forming has not been initiated at MP, but plans are to complete the forming in fiscal year 1988 for shipment to SRP. SRP has estimated that fabrication of plutonia-fueled clads and compatibility tests cannot be started for at least two years.

## 10. SUMMARY

The yield of acceptable new process iridium alloy blanks for two most recent ingots has decreased, as compared to the first two ingots, which were extruded and processed to blanks. A number of variables known to be

important in the arc-melting process have been evaluated with no convincing correlation found between these process variable and yield of blanks. Thus, a series of experimental melts using both stainless steel and refinable iridium scrap have been planned that, combined with new equipment for continuously recording melt current and voltage and electrode feed, should lead to an optimized melt process and improved yields.

The tensile properties of DOP-26 iridium alloy have been evaluated in both recrystallized and stress-relieved conditions. Tensile ductility increases over the temperature range of 600 to 1100°C for recrystallized material only. The tensile ductility of stress-relieved material is relatively insensitive to both test temperature and strain rate.

On the basis of laboratory studies, it may be possible to substitute HCl in the electrolytic cleaning step if safety considerations eliminate the use of KCN cleaning. Further development and evaluation would be required.

## 11. ACKNOWLEDGMENTS

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## 12. REFERENCES

1. R. L. Heestand, G. L. Copeland, and M. M. Martin, *A Consumable Arc-Melting, Extruding, and Rolling Process for Iridium Sheet*, ORNL-6270 (1986).

2. F. J. Zanner and L. A. Bertram, "Behavior of Sustained High-Current Arcs on Molten Alloy Electrodes During Vacuum Consumable Arc Remelting," *IEEE Trans. Plasma Sci.* PS-11(3), 223-32 (September 1983).
3. W. R. Kanne, Jr. "Welding Iridium Heat Source Capsules for Space Missions," *Weld. J.* 62(8), 17-22 (August 1983).
4. G. M. Goodwin, "Development of a New Hot-Cracking Test - The Sigmajig," *Weld. J.* 66(2), 33-s-38-s (1987).
5. M. A. Forrest, J. R. McDougal, and R. W. Saylor, *General Purpose Heat Source (GPHS) Clad Vent Set (CVS) Formability Study*, MLM-3395, Monsanto Research Corporation, Mound Facility, Miamisburg, OH (November 1986).
6. W. R. Kanne, *Weldability of General Purpose Heat Source New Process Iridium*, DP-1748, E. I. DuPont de Nemours & Company, Savannah River Laboratory, Aiken, SC (May 1987).
7. T. G. George, *High Strain-Rate High-Temperature Biaxial Testing of DOP-26 Iridium*, LA-11065, Los Alamos National Laboratory, Los Alamos, NM (May 1988).



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