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PLASTIC STRAINING OF IRIDIUM ALLOY DOP-26 DURING CUP SIZING OPERATIONS

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PLASTIC STRAINING OF IRIDIUM ALLOY DOP-26 DURING CUP SIZING OPERATIONS

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1. ABSTRACT

DOP-26 iridium alloy cups are used for fuel cladding for radioisotope power systems. The cups are deep drawn and recrystallized prior to final fabrication operations. This study characterizes the plastic deformation of cups during a sizing operation following the recrystallization heat treatment. The purpose of the sizing operation is to achieve the specified roundness, diameter, and radius dimensions of the cup. The operation introduces various levels of plastic strain in the cup. Plastic strain can be a cause of inhomogeneous or abnormal grain growth during subsequent exposure to elevated temperature during the service life of the fuel cladding. This is particularly true in the case of cups which have irregularities in the cup walls from the deep drawing operations. Diameter and roundness measurements were made on two cups both before and after sizing. Plastic strain levels were calculated using the ABAQUS™ finite element software. The calculated plastic strain levels in both cups were below 0.025, a value shown to be below the critical strain for abnormal grain growth during a simulated service exposure. The calculated maximum plastic strain was found to increase with increased applied sizing load and was not sensitive to the input value for the clearance between the cup and the sizing die. The calculated geometry of the sized cups was in good agreement with the measurements on the finished cups.

2. INTRODUCTION

Iridium alloy cups are used for fuel containment in radioisotope power systems. A typical cup is shown in Figure 1. The DOP-26 iridium alloy (Ir-0.3% W- 0.006% Th – 0.005% Al, by weight) provides the desired mechanical properties, oxidation and corrosion resistance, and chemical compatibility with the fuel and carbon insulation materials. The mechanical properties, and in particular the tensile ductility at high strain rates, are effected by the grain size of the alloy. The cups are formed by deep drawing (in two drawing operations) of stress-relieved iridium alloy blanks at 925°C using punches and dies preheated to 250°C. The cups are cleaned and recrystallized at 1375°C followed by cold sizing in a closed steel die. Sizing pressure is applied through a polyurethane punch to obtain the specified cup diameter, radius, and roundness dimensions. Plastic strains are introduced into the cup during the sizing operation, the values of which depend on the details of the initial cup geometry. Under normal conditions the plastic strains are less than 1% and are of no concern. However, on infrequent occasions build-up of dried and hardened lubricant material on the second-forming die can result in local depressions or grooves in the outer contour of the cup wall and concomitant bulges on the inner contour. The subsequent sizing operation can decrease the extent of these impressions with a consequential introduction of a local plastic strain in that region. This strain is a potential source of abnormal grain growth.

Figure 1. Iridium DOP-26 alloy deep drawn cup.

It has been shown for iridium [1] as well as other metals and alloys [2,3] that plastic strains in the range of 2 to 10% can result in abnormal grain growth during subsequent heating at elevated temperature. Abnormal grain growth is non-uniform grain growth in which a few grains grow rapidly while the majority of grains in the structure exhibit little or no growth. The nature of the grain growth and its dependence on prior plastic strain depends on the material composition, initial grain size, texture effects, and the subsequent time-temperature profile. Generally some distribution of second phase particles is present to inhibit normal grain growth. There is an incubation time for abnormal grain growth which decreases with increased temperature and prior plastic strain level. The final grain size is greatest for an intermediate level of plastic strain - about 5% for iron. [2]

In the case of the DOP-26 iridium alloy [1] it was shown that it was possible to induce abnormal grain growth in formed cups containing localized impressions from hardened lubricant on the forming die that were subsequently recrystallized, sized, and then heated for 100 hours at 1500° C. The study also showed that plastic bending strains as low as 1.3% at the specimen surface could initiate abnormal grain growth at 1500 C. The material, in actual service, would not be exposed to temperatures above 1330 C for extended periods of more than one hour. Exposures of 3 months at 1330 C showed minimal evidence of abnormal grain growth for material with 2.5% strain in bending. For sheet material with 5% strain in bending a region of abnormal grain growth extended about one quarter of the material thickness from both the inner and outer surfaces.

The purpose of this study was to evaluate the use of finite element analysis to determine plastic strain distributions in two selected iridium alloy cups following sizing operations. The strain distribution in bend specimens was also modeled to provide a direct comparison to the earlier study of abnormal grain growth.

3. MATERIALS AND PROCEDURES

Nine of 24 cups from a single lot were formed with noticeable depressions in the outer cup wall resulting from lubricant build-up on the second-forming die. The outer contours of all of the cups were characterized using a Formscan 3200 Circular Geometry Gage (Federal Products Co. Providence, RI – currently Mahr Federal Inc.) in the least squares circle (LSC) mode. The measuring stylus had a teardrop shape with both maximum width and diameter of 1.6 mm (0.062 in) and length of 4.1 mm (0.160 in). Measurements were made using the 1.6 mm-wide face - not the sharp tip of the teardrop. Plots of the deviation of the outer contour of the cup from roundness using the least squares circle method, or roundness plots, were evaluated at heights of 8.8, 11.4, and 14.1 mm from the bottom of each cup. Roundness was measured as the difference between the maximum and minimum deviations from the least squares circle. The depression depths were measured as the local minimum negative deviation from the least squares circle. The cups with forming lubricant depressions were found to have maximum out-of-roundnesses and depression depths at the 8.8 mm height. Cups without forming lubricant depressions were found to have maximum out-of-roundnesses and depression depths at the 14.1 mm height.

The two cups analyzed in this study, identified by their serial numbers 4359 and 5363, were selected from the group of nine cups formed with noticeable depressions, as representative of cups with the respective smallest and largest depression depths. Roundness plots of the outer contour for these cups are shown in Figures 1 and 2. The maximum depression depths for cups 4359 and 5363 are 0.05 and 0.07 mm, respectively. Inside and outside diameter measurements were made at the 8.8 mm latitude for these cups using a Cordax 1820 (Sheffield Measurement, a division of Hexagon Metrology, Inc. Fond du Lac, WI) coordinate measuring machine with a Renishaw (Gloucestershire, UK) PH9/Mk2 probe head and TP2 ruby tip (2 mm ball diameter). Surface contour measurements of both the inside and outside of the cups with forming lubricant depressions made at the 8.8 mm heights confirmed that depressions on the outside coincided with protrusions on the inside. Figure 3 is a representative concentricity plot showing this for cup 5363. Although the origins of inner and outer contours are offset, it is clear that the contour deviations are not associated with significant variations in wall thickness. The dimensional characteristics of cups 4359 and 5363 at their 8.8 mm heights are summarized in Table 1. All of these data were the basis for the modeling described below.

After the pre-sizing contour measurements were completed, the cups were cleaned, recrystallized in vacuum at 1375° C for 1 hour, and then sized in a closed steel die of 29.749 mm inside diameter with a roundness of 0.006 mm at the 8.8 mm height from the die bottom. Sizing was performed on a Wabash (Wabash, IN) 30 ton hydraulic press using a polyurethane punch with an applied load on the order of 55 kN (12000 lb). The measurements of roundness of the outer contour and diameter were repeated. The measured outer contours at the 8.8 mm height are shown in Figures 4 and 5. The cup dimensions following sizing are also listed in Table 1.

Numerical simulations of the dimensional changes in the cylindrical portion of closed-bottom deep drawn iridium cups were performed in a static analysis conducted using a two-dimensional finite element model for mechanical analysis developed within the commercial software ABAQUS™. It was assumed that the polyurethane punch used for sizing was in a state of hydrostatic compression equivalent to the applied load divided by the cross sectional area of the 28.3 mm inner diameter of the cup. Two levels of applied load, 55 kN (12,000 lb) and 90 kN (20,000 lb), nominally equivalent to pressures of 85 MPa and 145 MPa respectively, were modeled for each of the two cups in order to evaluate the effect of this parameter. The lower of these two loads is the approximate load applied to the cups during sizing. The larger load value is estimated to be the highest load that might be applied during cup sizing with the existing equipment. In the case of cup 4359, a mean clearance to the sizing die of 0.05 mm was modeled in addition to the measured value of 0.03 mm to determine the sensitivity of sizing strain to this parameter.

Table 1. Dimensional Characteristics of Cups After Forming and After Sizing

Measurement*, mm	No. 4359	No. 5363
	Formed Cup	
Cup maximum depression depth	00.050	00.070
Cup roundness, inside	00.097	00.120
Cup roundness, outside	00.098	00.133
Cup wall thickness	00.685	00.658
Cup outer diameter	29.686	29.650
Cup radial die clearance	00.032	00.050
	Sized Cup	
Cup maximum depression depth	00.028	00.035
Cup roundness, outside	00.034	00.042
Cup outer diameter	29.754	29.759

*All cup measurements at cup height of 8.8 mm

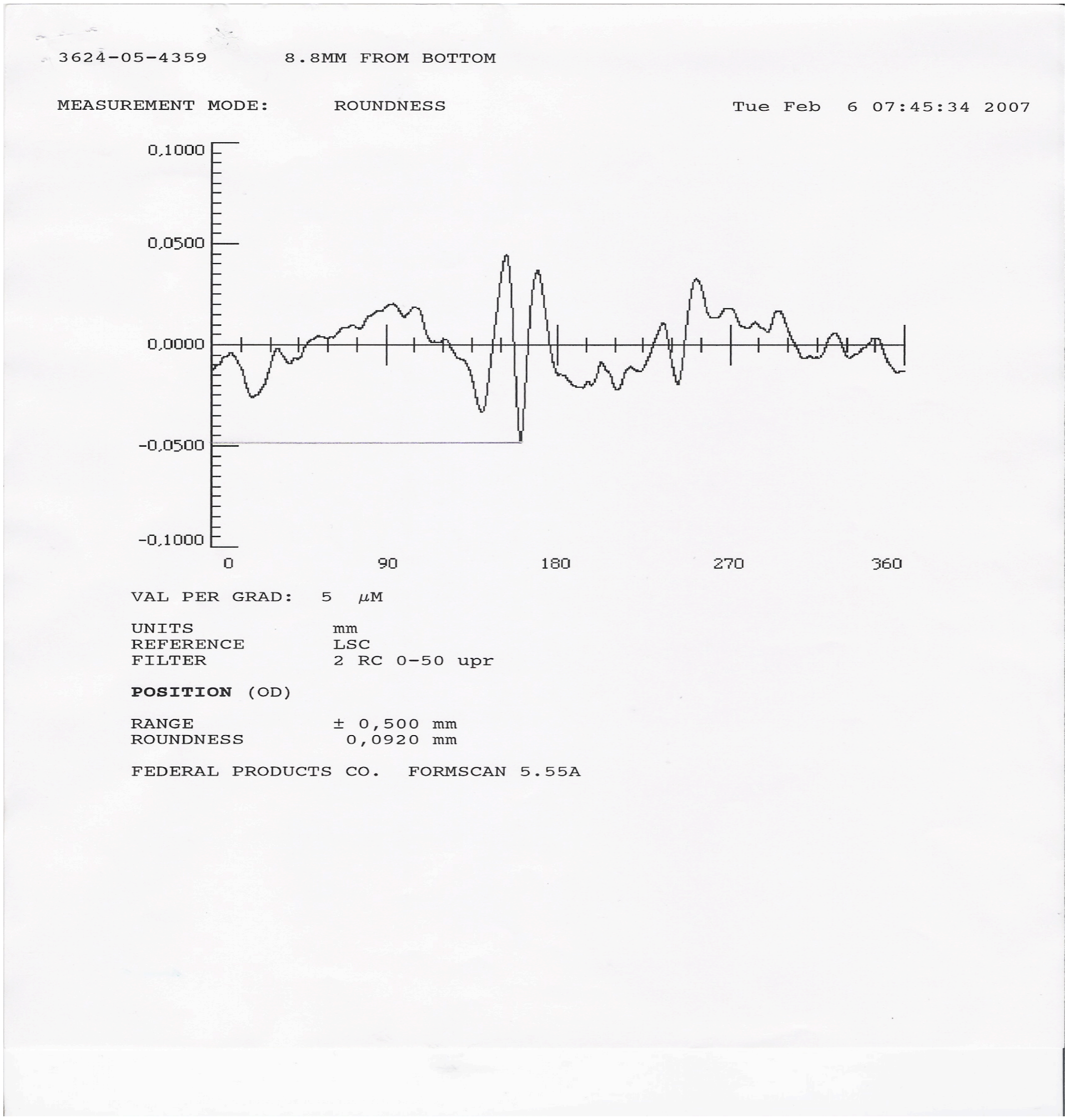
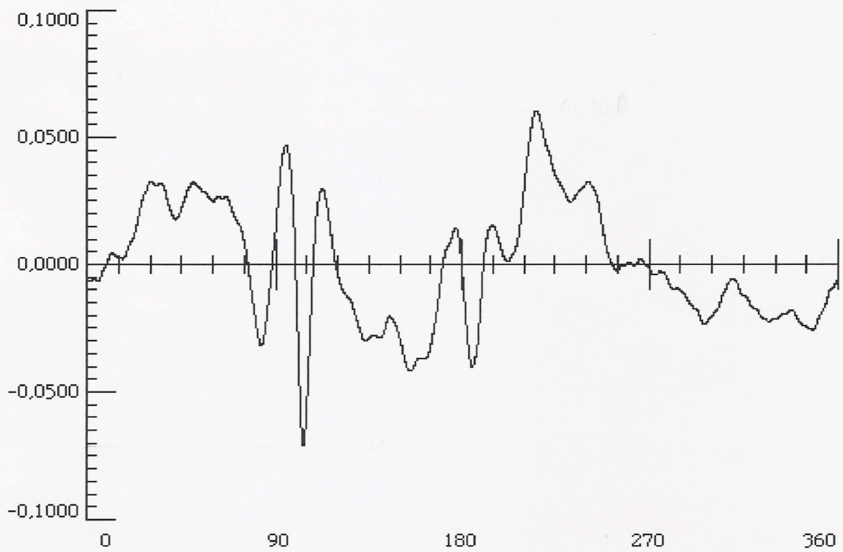


Figure 2. Roundness plot of outer contour of deep drawn cup 4359 has maximum depression depth of 0.05 mm.

3625-05-5363 8.8 MM FROM BOTTOM

MEASUREMENT MODE: ROUNDNESS Tue Feb 6 08:30:32 2007



VAL PER GRAD: 5 µM

UNITS mm
REFERENCE LSC
FILTER 2 RC 0-50 upr

POSITION (OD)

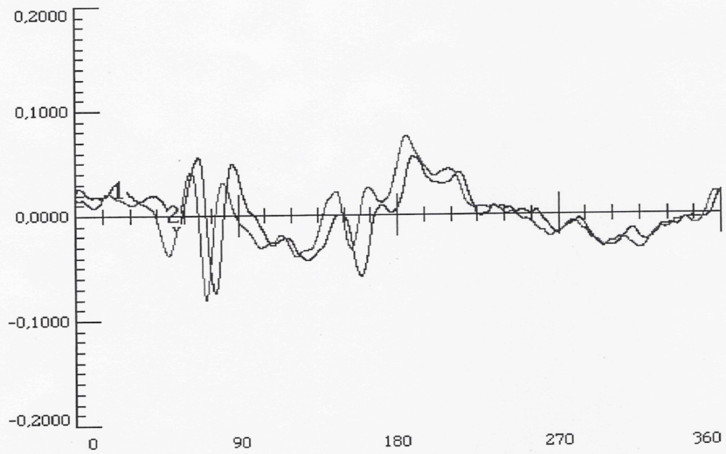
RANGE ± 0,500 mm
ROUNDNESS 0,1312 mm

FEDERAL PRODUCTS CO. FORMSCAN 5.55A

Figure 3. Roundness plot of outer contour of deep drawn cup 5363 shows maximum depression depth of 0.07 mm.

3625-05-5363 concentricity @ 8.8mm

MEASUREMENT MODE: CONC. 2 TO 1 Mon Feb 26 09:10:55 2007



VAL PER GRAD: 10 µM

UNITS	METRIC
REFERENCE	LSC
FILTER	2 RC 0-50 upr

POSITION 1 (ID)

RANGE	± 0,500 mm
HEIGHT	8,80 mm
ROUNDNESS	0,1296 mm

POSITION 2 (OD)

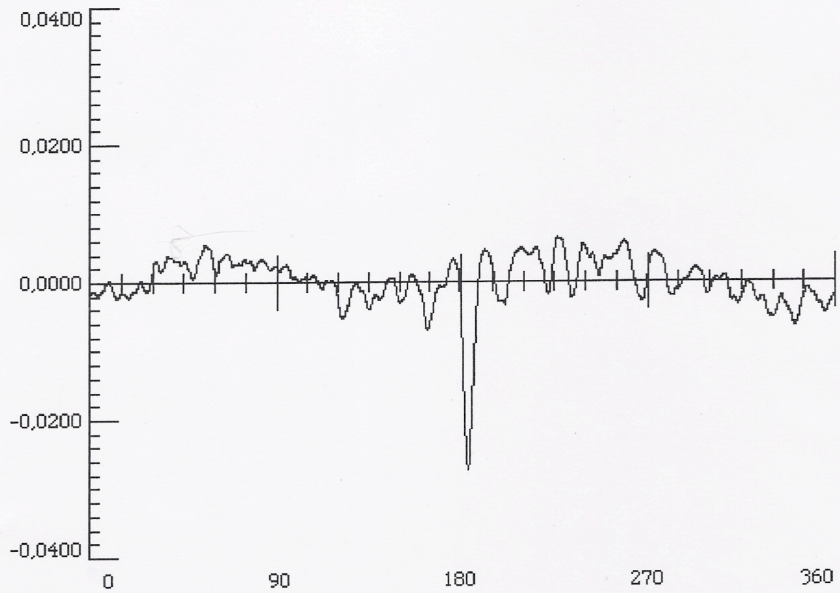
RANGE	± 0,500 mm
HEIGHT	8,80 mm
CONC.	0,0224 mm
VECTOR DIR.	188 °
ROUNDNESS	0,1398 mm
RUNOUT	0,1560 mm
Hi Pt RUNOUT	185 °

FEDERAL PRODUCTS CO. FORMSCAN 5.55A

Figure 4. Second roundness plot of deep drawn cup 5363, with both inner and outer contours, shows no change in wall thickness in the regions of depressions.

3624-05-4359 OD

MEASUREMENT MODE: ROUNDNESS Mon Mar 5 10:43:43 2007



VAL PER GRAD: 2 µM

UNITS mm
REFERENCE LSC
FILTER 2 RC 0-50 upr

POSITION (OD)

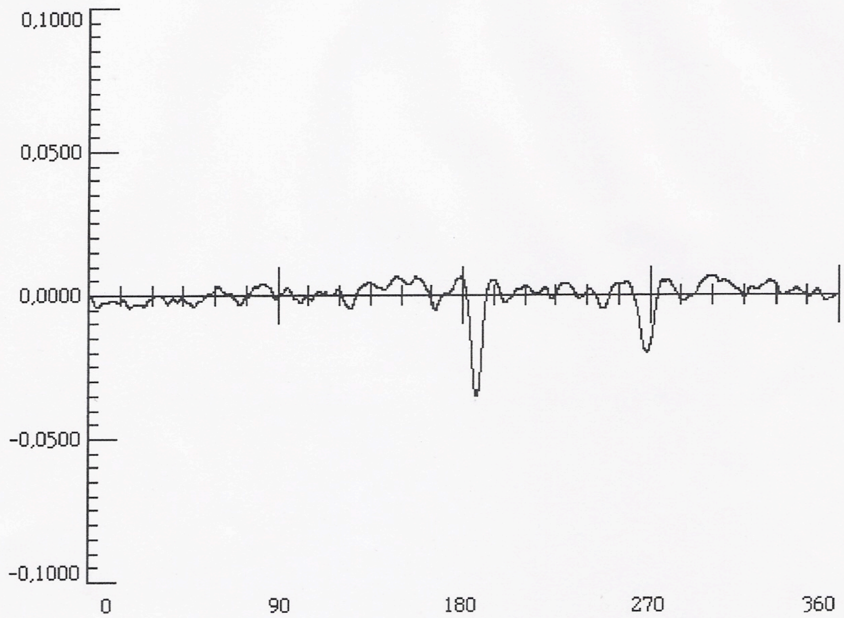
RANGE ± 0,500 mm
ROUNDNESS 0,0336 mm

FEDERAL PRODUCTS CO. FORMSCAN 5.55A

Figure 5. Roundness plot of outer contour of cup 4359 after sizing shows maximum depression depth of 0.028 mm.

3625-05-5363 OD

MEASUREMENT MODE: ROUNDNESS Mon Mar 5 10:01:53 2007



VAL PER GRAD: 5 μM

UNITS mm
REFERENCE LSC
FILTER 2 RC 0-50 upr

POSITION (OD)

RANGE ± 0,500 mm
ROUNDNESS 0,0418 mm

FEDERAL PRODUCTS CO. FORMSCAN 5.55A

Figure 6. Roundness plot of outer contour of cup 5363 after sizing shows maximum depression depth of 0.035 mm.

Input data for the model consisted of tensile stress strain data, elastic modulus, and cup and die geometry. Mechanical property data was obtained from room temperature tensile test data for recrystallized DOP-26 alloy at a strain of 10^{-3} s^{-1}[4]. The tensile true stress – true strain data are shown in Fig. 6. The elastic modulus of pure iridium of 528 GPa was used [5]. The output consisted of calculated dimensions, displacements, and strain. The strain was calculated as an equivalent plastic strain, ε^p_{eq}, which is determined by integration over time from the equivalent strain rate, $\dot{\varepsilon}^p_{eq}$, expressed as:

$$\varepsilon^p_{eq} = \int_0^t \dot{\varepsilon}^p_{eq} dt \; ; \qquad (1)$$

in which

$$\dot{\varepsilon}^p_{eq} = \sqrt{\frac{2}{3}\sum_{ij} \dot{\varepsilon}^p_{ij}\dot{\varepsilon}^p_{ij}} \; . \qquad (2)$$

The pressure was increased in several steps to insure good convergence properties in the numerical simulations of the sizing operation. The simulations were conducted in the static mode and the die walls were considered to be rigid. After the loading step was complete, the unloading step was considered, including the relaxation of the elastic strains. The initial cup geometry for the deformation model was simplified to include only those features in the region of the deepest depression in each cup. The cup was considered to be symmetrical with respect to the axis of the depression. In the case of cup 4359 a protrusion on the cup surface in the vicinity of the depression was included in the input geometry for the case of die clearance of 0.05 mm, but was truncated in the input for the case of the 0.03-mm die clearance to avoid a geometric interference. (The geometric measurements indicated that the cup would not fit in the sizing die without some elastic deformation, which was not treated in this analysis.) The two variations in the input geometry for cup 4359 are shown in Figure 7. The overall input geometry for cup 5363 is shown in a polar plot in Figure 8. The details of the measured geometry of the depression used in the model are shown in Figure 9.

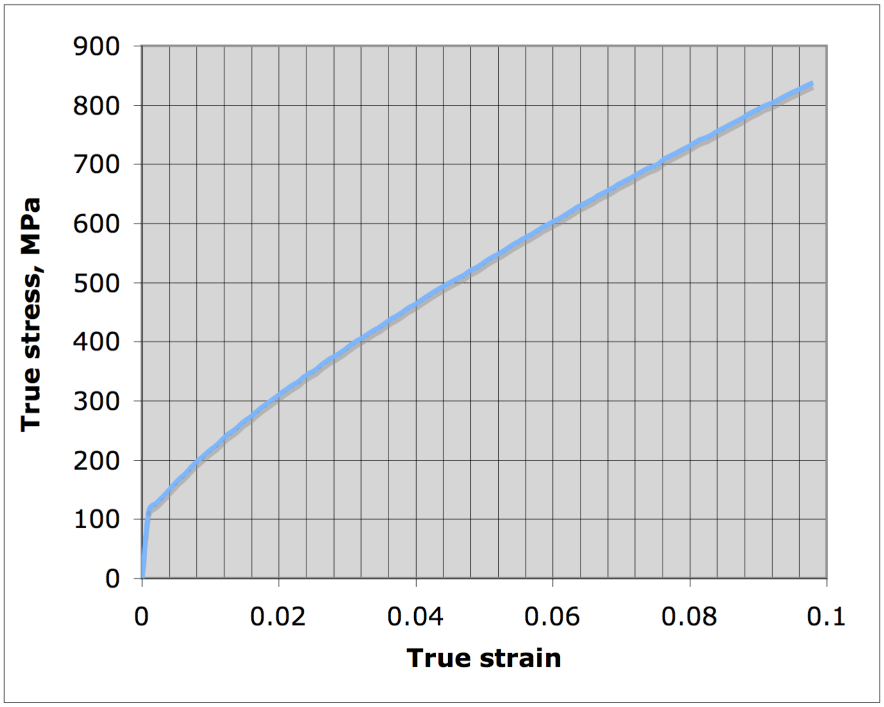


Figure 7. True Stress – True Strain Data for DOP-26 Iridium Alloy at 20° C, from reference 4.

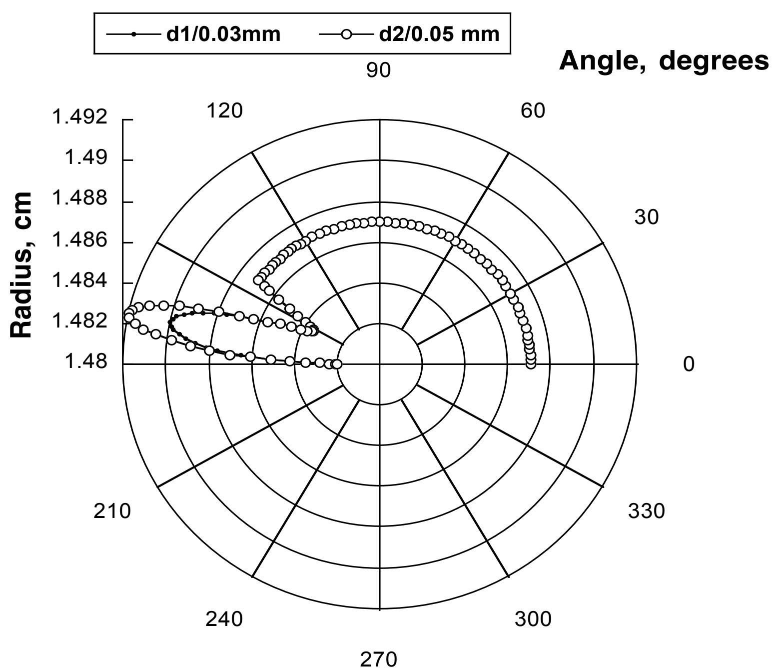


Figure 8. Overall geometric input for modeling of cup 4359 with variations in input labeled as d1 and d2 to accommodate die clearances of 0.03 mm and 0.05 mm. The cup radius was assumed to be symmetrical about the centerline of the depression located at 180°.

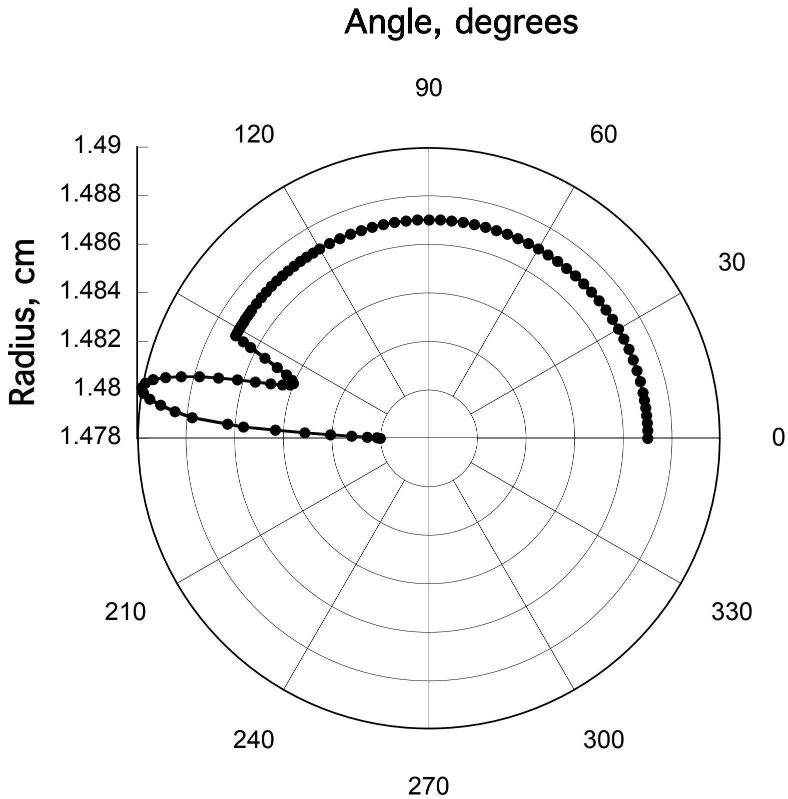


Figure 9. Overall geometric input for modeling of cup 5363. The cup radius was assumed to be symmetrical about the centerline of the depression located at 180°.

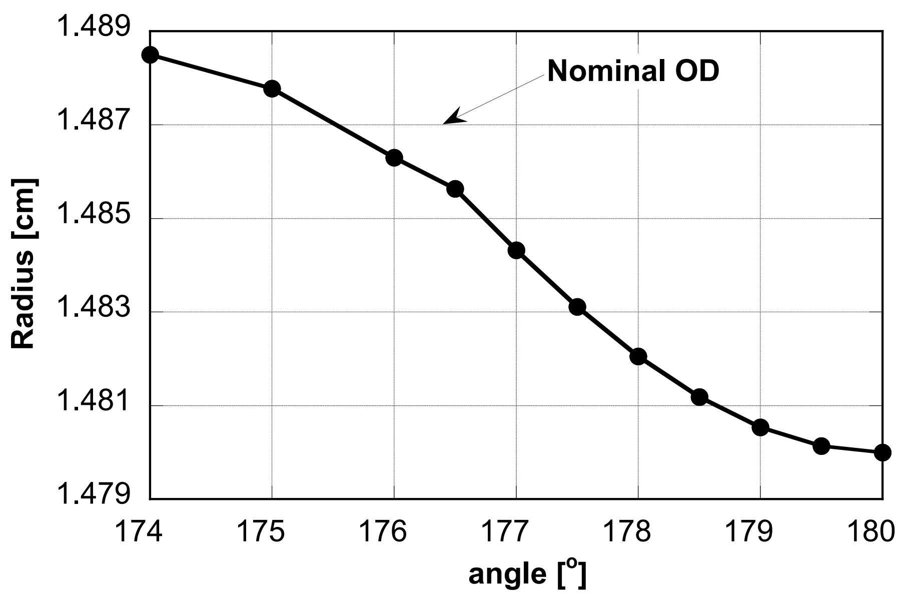


Figure 10. Geometric input detail for modeling of cup 5363 showing one half of a symmetrical groove in the cup.

Numerical simulations of bending of iridium alloy sheet material of 0.67-mm thickness were also performed with the commercial software ABAQUS™ for the purpose of verifying plastic strain calculations in earlier reports. In a previous study [1] bend samples were given long-term exposure at elevated temperature to determine grain growth behavior of strained material. Bends of 90 degrees were made over steel mandrels of various sizes. Plastic strains were estimated using the standard formula for calculation of maximum fiber strain:

$$\varepsilon^{p}_{eng} = t/2r \tag{3}$$

$$\varepsilon^{p}_{true} = \ln(\varepsilon^{p}_{eng}) \tag{4}$$

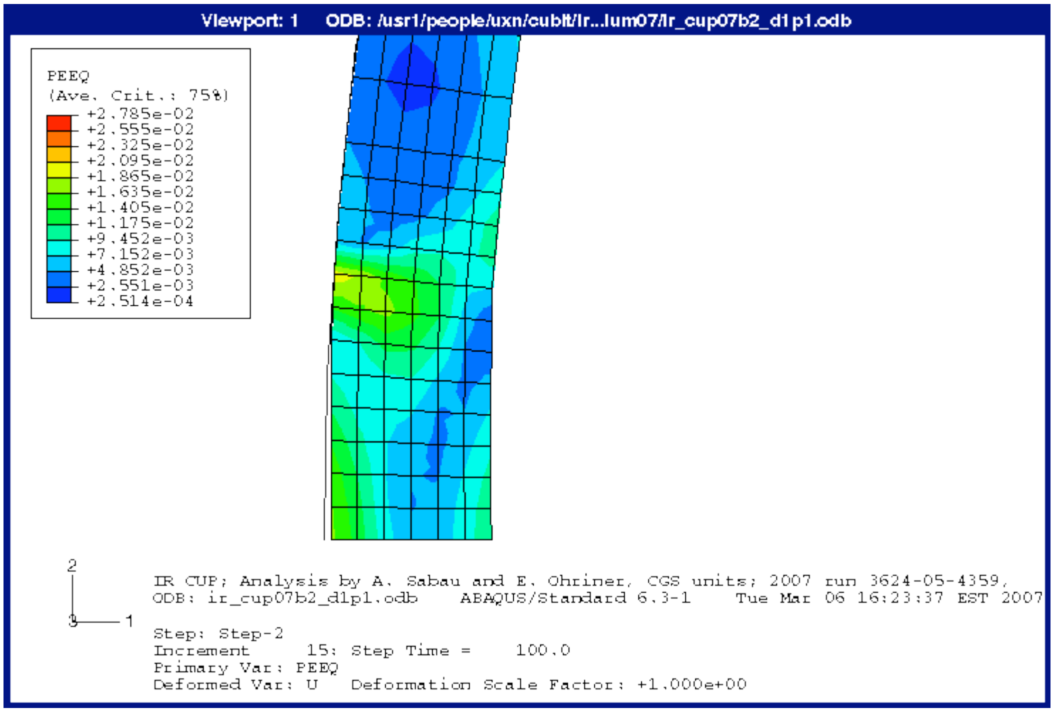
in which

t is the sheet thickness
r is the radius of the bend
ε^{p}_{eng} is the maximum value of the fiber strain measured as engineering plastic strain and
ε^{p}_{true} is the maximum value of the fiber strain measured as true plastic strain.

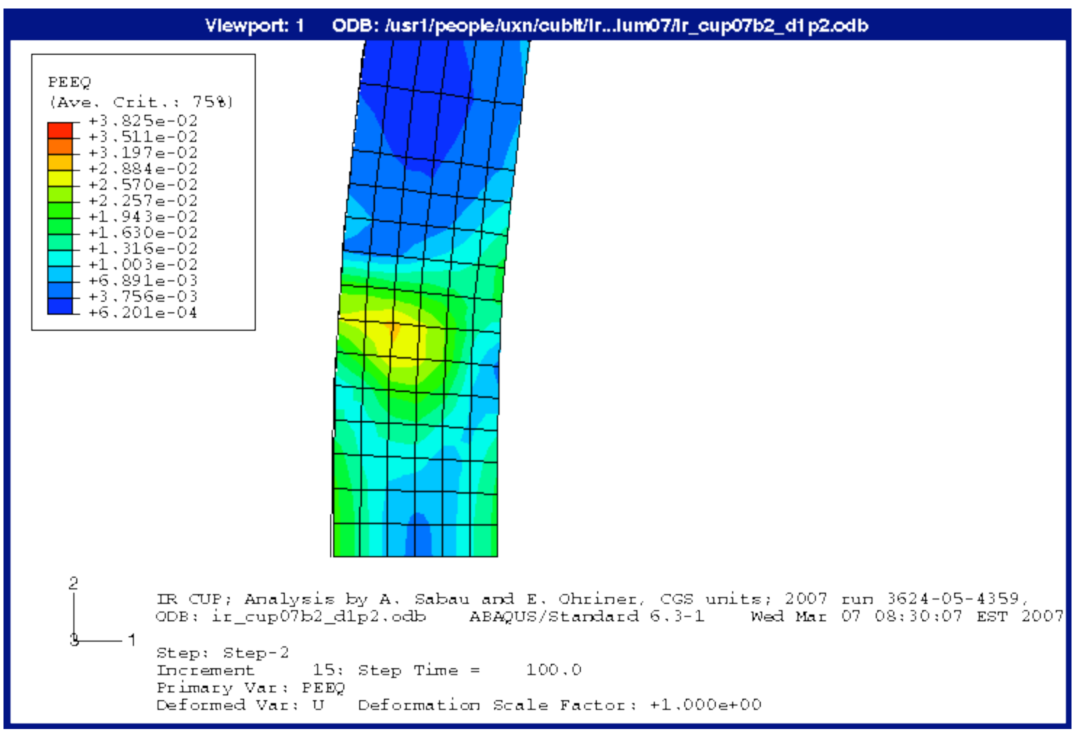
In the current model of three point bending the supports were considered rigid and the bend samples of 25 mm length were considered to deform under an increasing load until a bend of about 90 degrees was obtained.

4. RESULTS

The equivalent plastic strains calculated for cup 4359 are shown in Figure 10 for two conditions of applied load and two conditions of die clearance during sizing. In all four cases the maximum equivalent plastic strain is located about 6 degrees from the centerline of the depression, near the start of the depression. The maximum strain is typically located either at the outer surface of the cup or just beneath it. The maximum value of the equivalent plastic strain for each of the four conditions is summarized in Table 2. The maximum strain is affected by the applied load. It is about 2% for a sizing load of 55 kN and about 3% for a sizing load of 90 kN. The maximum strain is insensitive to normal variations in die clearance. The equivalent plastic strains calculated for cup 5363 are shown in Figure 11 for the same two conditions of applied load –55 kN and 90 kN. The maximum strain locations and values are similar to those for cup 4359 as shown in Table 2.

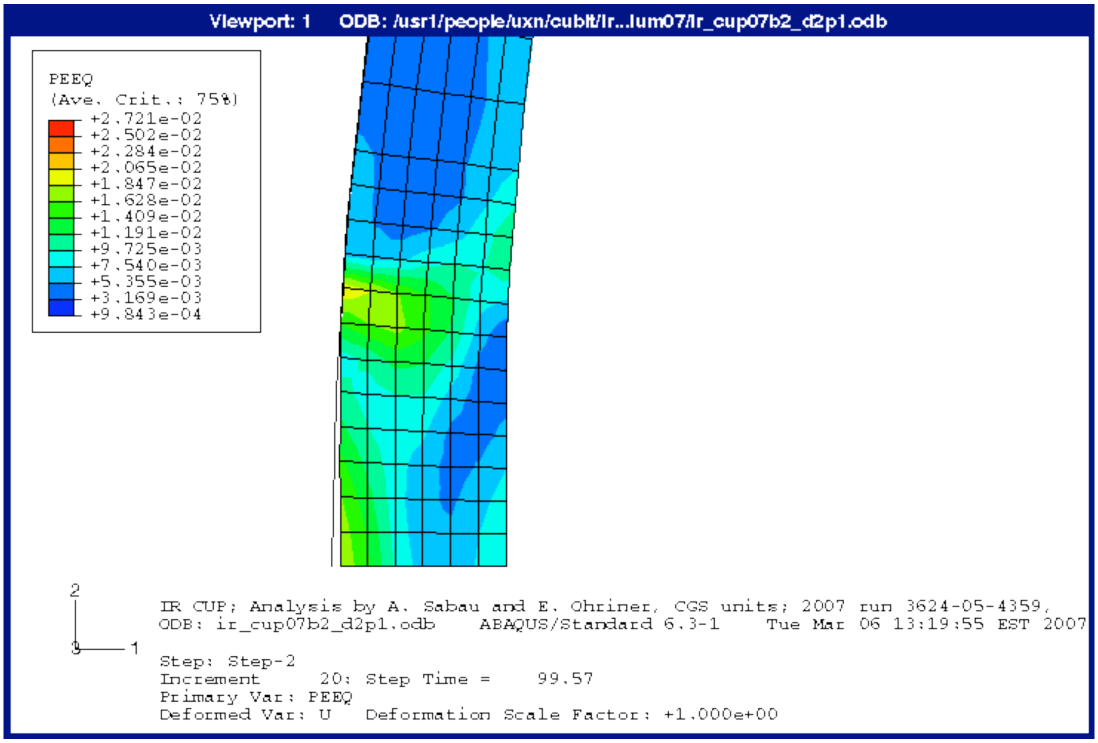


(a)

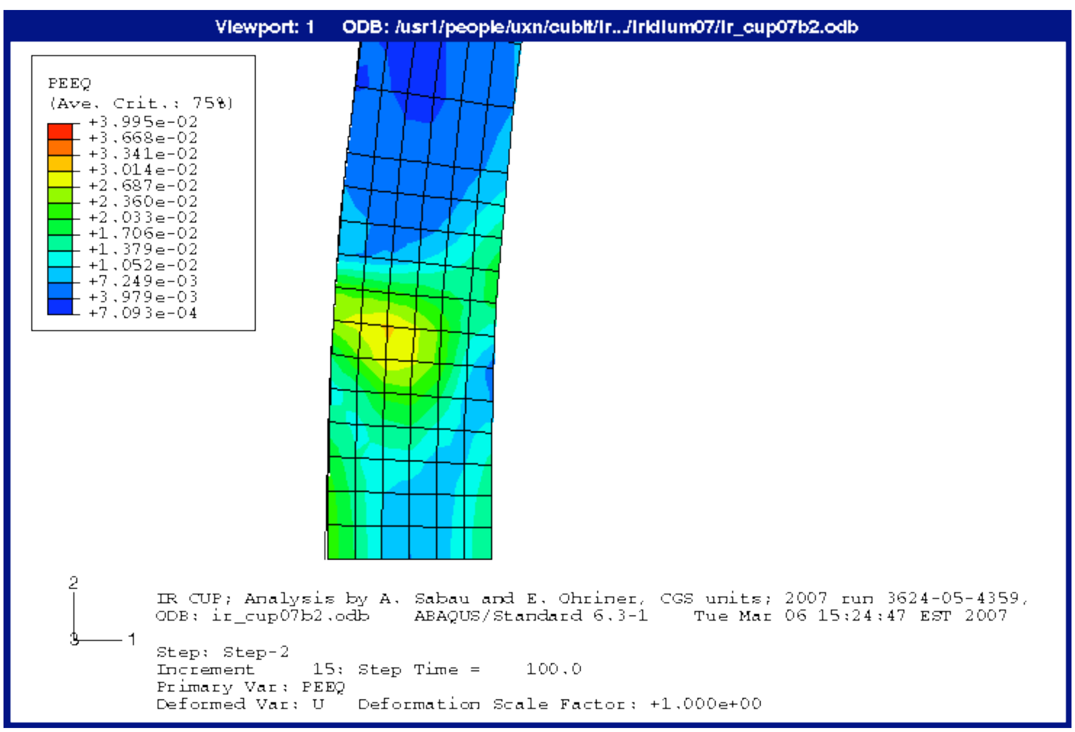


(b)

Figure 11. Calculated equivalent plastic strain for cup 4359 for case a) 0.03 mm radial die clearance at 55 kN load and b) 0.03 mm radial die clearance at 90 kN load. The figure shows the region corresponding to half of the cup cross-section with the centerline of the original depression at the lower left of the section.

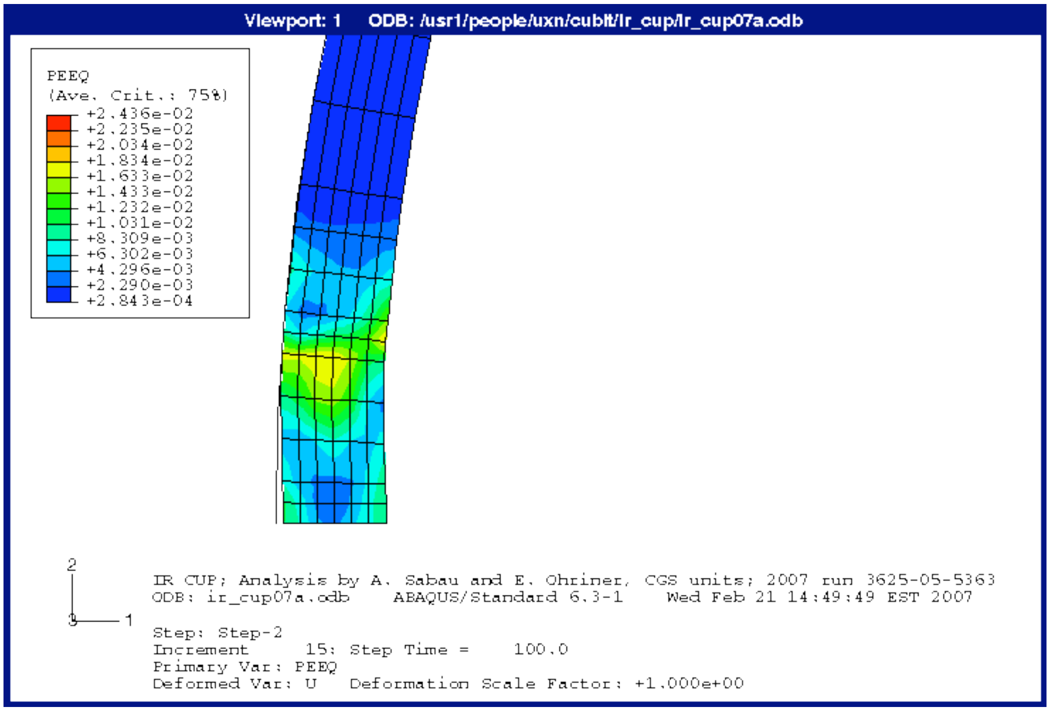


(c)

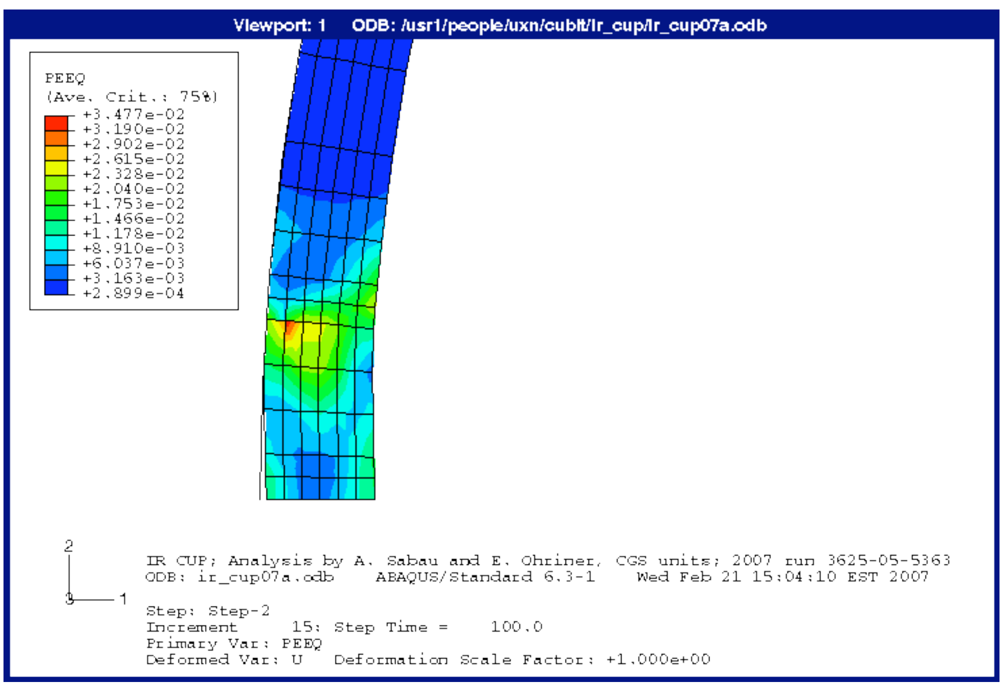


(d)

Figure 11 (continued). Calculated equivalent plastic strain for cup 4359 for case c) 0.05 mm radial die clearance at 55 kN load and d) 0.05 mm radial die clearance at 90 kN load.



(a)



(b)

Figure 12. Calculated equivalent plastic strain for cup 5363 with 0.05 mm radial die clearance for case a) 55 kN load and b) 90 kN load.

Table 2. Calculated Maximum Equivalent Plastic Strain and Depression Depth for Sized Cups

Sized Cup Identity	Applied Load, kN	Initial Die Clearance mm	Maximum Equivalent Plastic Strain %	Change in Depression Depth mm	Final Depression Depth mm
4359	55	0.03	2.0	0.023	0.027
	90	0.03	3.0	0.038	0.012
	55	0.05	2.0	0.022	0.028
	90	0.05	3.1	0.038	0.012
5363	55	0.05	2.3	0.031	0.039
	90	0.05	3.1	0.048	0.022

The depth of the depression following sizing was calculated using displacement values obtained as output from each sizing simulation. The value of the displacement at a location on the cup at 90 degrees from the depression was used as the net change in overall nominal cup radius. This value was subtracted from the displacement at the centerline of the depression to obtain the movement of material with respect to the cup wall. This difference was then subtracted from the original depression depth to calculate the final depth. The calculated final depression depths are listed in Table 2.

The measured final depression depth for cup 4359 of 0.028 mm (Table 1) is close to the calculated values of 0.027 mm or 0.028 mm for an applied sizing load of 55 kN. The measured final depression depth for cup 5363 of 0.035 mm (Table 1) also is close to the calculated value of 0.039 mm for an applied sizing load of 55 kN.

The results of the three-point bend simulation are summarized in Table 3. The strain values obtained from a simple bend formula are in good agreement with the calculated values of the maximum equivalent plastic strain for each of the three bend radii. The equivalent plastic strain for the bend sample with a radius of 12.7 mm and a nominal maximum strain of 2.5% is shown in Figure 12.

Table 3. Maximum Strain Values Calculated for 90 Degree Bend Samples

Mandrel radius mm	Formula engineering fiber strain	Formula true fiber strain	ABAQUS equivalent plastic strain
25.4	0.013	0.013	0.014
12.7	0.026	0.025	0.027
6.4	0.05	0.049	0.053

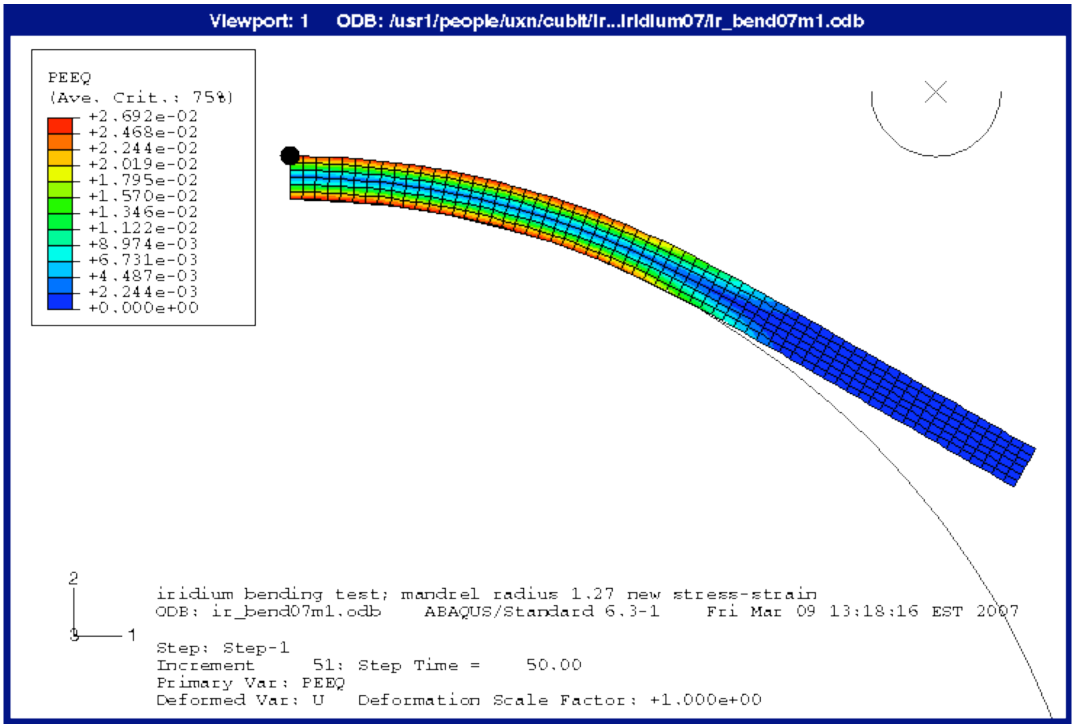


Figure 13. Calculated equivalent plastic strain for simulation of 0.67-mm thick sheet bent 90 degrees over a rigid cylindrical bar of 12.7 mm radius.

5. DISCUSSION

The iridium alloy cup sizing operation has the potential to introduce low levels of plastic strain into the cups. The formed cups are sized after recrystallization and impressions in the formed cups may be subjected to plastic deformation during the sizing operation. A previous investigation [1] evaluated grain growth in bend samples subjected to a "worst-case" thermal exposure. This thermal cycle consisted of the standard fabrication exposures followed by one month at 950 C, plus three months at 1330 C, plus 3 minutes at 1580 C. Under these conditions there was minimal evidence of abnormal grain growth for material with 2.5% strain in bending. In the case of 5.0% strain in bending, a region of abnormal grain growth extended about one quarter of the material thickness from both the inner and outer surfaces. No strain levels between 2.5% and 5.0% were studied.

The potential for abnormal grain growth during a "worst-case" thermal exposure can be evaluated for individual formed cups by using a finite element simulation to determine the maximum equivalent plastic strain introduced during the sizing operation. A value of 2.5% plastic strain or less indicates that cup should exhibit normal grain growth in a "worst-case" scenario. There is good evidence that neither of the two cups evaluated in this study have a local plastic strain value in excess of 2.5%. The calculated maximum plastic strains for cups 4359 and 5363 are 2.0% and 2.3%, respectively, at the nominal sizing load of 55 kN. The change in the depression depth and the final depression depth are in good agreement for the 55 kN sizing load. It is expected, therefore, that these two cups would exhibit normal grain growth and perform normally under all potential conditions of use.

The study also included simulations to evaluate the sensitivity of plastic strain from the sizing operation to process variables of sizing load and sizing die clearance. The plastic strain is sensitive to the sizing load. Although the simulations were limited to two values of load, the results suggest that the maximum plastic strain is roughly proportional to sizing load. The sizing load should be well controlled in order to minimize uncertainties in the plastic strain for cups that have some depressions or wrinkles in the wall surface. The load must be sufficient to obtain cups of acceptable roundness, but not so high as to unnecessarily introduce excess plastic strain in these cups. The maximum plastic strain is not sensitive to the sizing die clearance within the normal range of clearance values.

In general the maximum plastic strain can be expected to be sensitive to local geometry and local changes in geometry during sizing. While normal changes in die clearance can have significant effects on local displacement of the cup, the strains involved are small since the strain is distributed over the entire cup. In contrast, the effect of sizing on a depression is to cause displacements in which strains are concentrated locally. The magnitude of the strain can be expected to increase with the initial depression depth, but it is also affected by the width of the depression.

6. CONCLUSIONS

The conclusions of this study of plastic strain resulting from the sizing of DOP-26 iridium-alloy cups are as follows:

1. The ABAQUS™ finite element software is capable of modeling the deformation and resulting plastic strains caused by sizing operations on cups which have impressions in the cup walls due to irregularities from the deep drawing operations.

2. The calculated maximum plastic strain levels for the two sized cups in this study were below 2.5%, a value shown to be below the critical strain for abnormal grain growth during a simulated service exposure.

3. After sizing, the region of maximum plastic strain is located about 6° away from the centerline of the original depression, near the edge of the depressed region.

4. The calculated maximum plastic strain was found to increase with increased applied sizing load.

5. The calculated maximum plastic strain was found to be insensitive to the clearance between cup and sizing die.

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