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MODEL FOR GRAIN GROWTH IN DOP-26 IRIDIUM CLAD

R. J. Lipinski and V. Tikare

Sandia National Laboratories, Albuquerque, NM 87185

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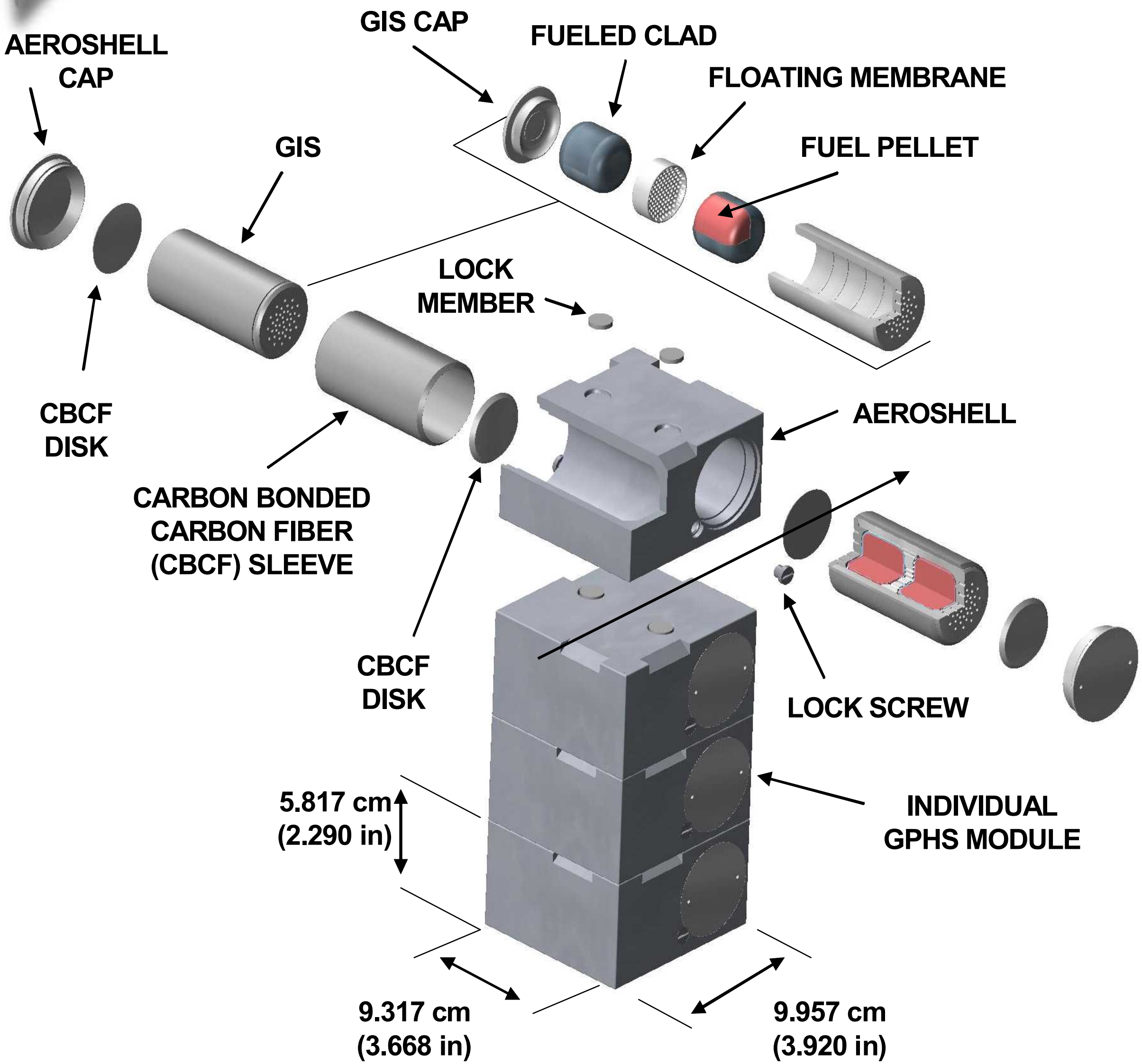
Step-2 GPHS Modules



- DOP-26 iridium clad is one of several containment and protection layers for the fuel
- The clad has around 25 grains through its thickness to enhance ductility
- Grains grow when temperatures are high
- Quantifying this effect helps assure safe operation and good safety analyses

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Grain Growth Data in Vacuum

Pressure O_2 (mPa)	T (C)	t (hr)	diameter (ST) (μm)	t_0 (hr)	d_0 (μm)
0	1300	1	24	1.0	24
0	1300	4	25	1.0	24
0	1300	18	28	1.0	24
0	1300	70	31	1.0	24
0	1300	250	30	1.0	24
0	1300	480	36	1.0	24
0	1300	1000	42	1.0	24
0	1400	1	29	1.0	29
0	1400	2	30	1.0	29
0	1400	4	34	1.0	29
0	1400	16	39	1.0	29
0	1400	100	50	1.0	29
0	1400	250	56	1.0	29
0	1400	520	63	1.0	29
0	1400	1000	72	1.0	29
0	1500	0.2	30	0.2	30
0	1500	0.5	32	0.2	30
0	1500	1	33	0.2	30
0	1500	2	39	0.2	30
0	1500	4	42	0.2	30
0	1500	18	52	0.2	30
0	1500	100	71	0.2	30
0	1600	0.2	37	0.2	37
0	1600	0.5	43	0.2	37
0	1600	1	48	0.2	37
0	1600	4	77	0.2	37
1.3	1230	0	22.5	0.0	22.5

- **McKamey, Gubbi and Cohron present grain growth data for DOP-26 Ir in vacuum and in a slight background of oxygen**

Data from: C. G. McKamey, A. N. Gubbi, Y. Lin, J. W. Cohron, E. H. Lee and E. P. George, *Grain Growth Behavior and High-Temperature High-Strain-Rate Tensile Ductility of Iridium Alloy DOP-26*, ORNL-6935, Oak Ridge National Laboratory, Oak Ridge, TN 1998

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Grain Growth Data with mPa of Oxygen

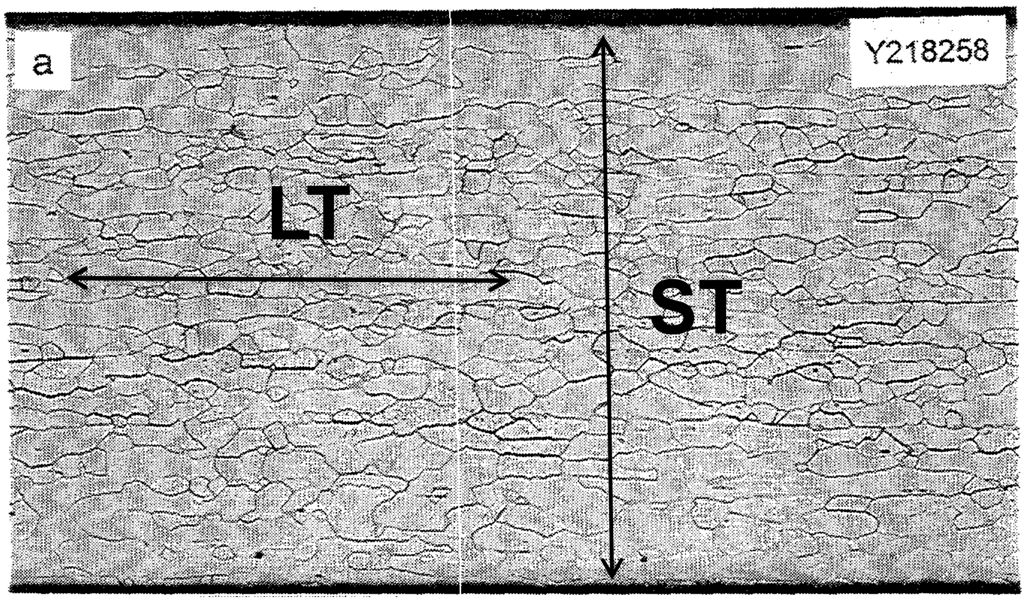
Pressure O_2 (mPa)	T (C)	t (hr)	diameter (ST) (μm)	t_0 (hr)	d_0 (μm)
1.3	1230	0	22.5	0.0	22.5
1.3	1230	768	27.1	0.0	22.5
1.3	1230	1512	29	0.0	22.5
1.3	1230	2252	27.8	0.0	22.5
1.3	1230	3000	31.4	0.0	22.5
1.3	1280	0	22.7	0.0	22.7
1.3	1280	144	26.5	0.0	22.7
1.3	1280	380	32.5	0.0	22.7
1.3	1280	764	35.3	0.0	22.7
1.3	1280	1508	35.5	0.0	22.7
1.3	1280	2250	35.4	0.0	22.7
1.3	1280	3000	40.2	0.0	22.7
1.3	1330	0	19.1	0.0	19.1
1.3	1330	166	26.5	0.0	19.1
1.3	1330	340	29.3	0.0	19.1
1.3	1330	760	38.2	0.0	19.1
1.3	1330	1524	37.8	0.0	19.1
1.3	1330	2265	54.6	0.0	19.1
1.3	1330	3000	50.4	0.0	19.1
13.3	1330	0	24.1	0.0	24.1
13.3	1330	170	35.3	0.0	24.1
13.3	1330	720	40.1	0.0	24.1
13.3	1330	3000	46.7	0.0	24.1

Data from: C. G. McKamey, A. N. Gubbi, Y. Lin, J. W. Cohron, E. H. Lee and E. P. George, *Grain Growth Behavior and High-Temperature High-Strain-Rate Tensile Ductility of Iridium Alloy DOP-26*, ORNL-6935, Oak Ridge National Laboratory, Oak Ridge, TN 1998

Grain Dimensions vs. Roll Direction

ST is "short traverse", is 90^o to roll direction
LT is "long traverse", is 0^o to roll direction
Traversing through the clad thickness is "ST"

Slice through Iridium Sheet



From: C. G. McKamey, A. N. Gubbi, Y. Lin, J. W. Cohron, E. H. Lee and E. P. George, *Grain Growth Behavior and High-Temperature High-Strain-Rate Tensile Ductility of Iridium Alloy DOP-26*, ORNL-6935, Oak Ridge National Laboratory, Oak Ridge, TN 1998

Effect of oxygen is mostly on surface

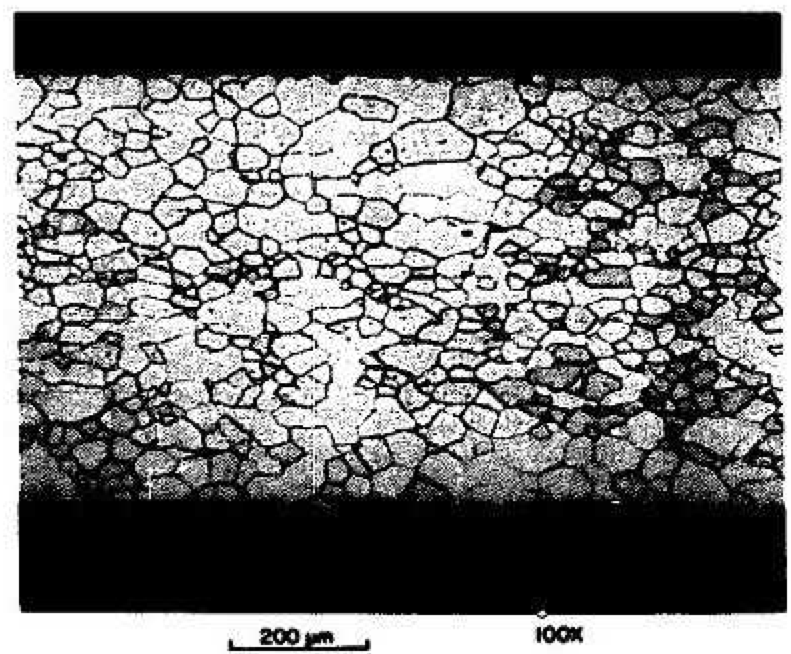


Fig. 5. Optical photomicrograph of the DOP-26 alloy after 3000 h of exposure to 1.3 mPa oxygen at 1230 °C.

McKamey, Gubbi, George, *J. Alloys & Compounds, 244, pp 175-183 (1996)*

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McKamey, et al 1996 Grain Growth Equation

$$d = \left(d_0^2 + k_0 t \exp\left(-Q / RT\right)\right)^{1/2}$$

d	is the average grain size after time t (mm)
d_0	is the initial grain size across the thickness (mm)
t	is time at the annealing temperature (hr)
k_0	is a constant = 2.78e18 mm^2/hr
Q	is the activation energy = 563 kJ/mol
R	is the gas constant = 8.314 J/mol/K
T	is the anneal temperature (K)

- Classic grain growth equation for metals without impurities

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McKamey, et al 2002 Grain Growth Equation

$$d = d_0 + k_0 \exp\left(-Q / RT\right) t^{0.2}$$

At about 1280 K:

k = k_0 exp(-Q/RT) = 3.1 mm/hr$^{0.2}$ = 3100 μm/hr$^{0.2}$

Authors note that the Ir_5Th particles slow the growth, resulting in the value of 0.2 for the power of t

It is noted that the power of "t" might vary with temperature

This Work Grain Growth Equation

$$d = \left(d_0^p + k_0 t \exp\left(-Q / RT\right)\right)^{1/p}$$

d	is the average grain size after time t (mm)
d_0	is the initial grain size across the thickness (mm)
t	is time at the annealing temperature (hr)
k_0	is a constant = 6.13e30 $\mu m^6/hr$
Q	is the activation energy = 734 kJ/mol
R	is the gas constant = 8.314 J/mol/K
T	is the anneal temperature (K)
p	is the grain growth exponent (dimensionless)

- Pinning of the Ir grains by Ir_5Th particles slows the growth
- The data were analyzed using different powers
- p=6 seemed to give the best fit for vacuum and oxygen data
- The oxygen data fit in well with the vacuum data

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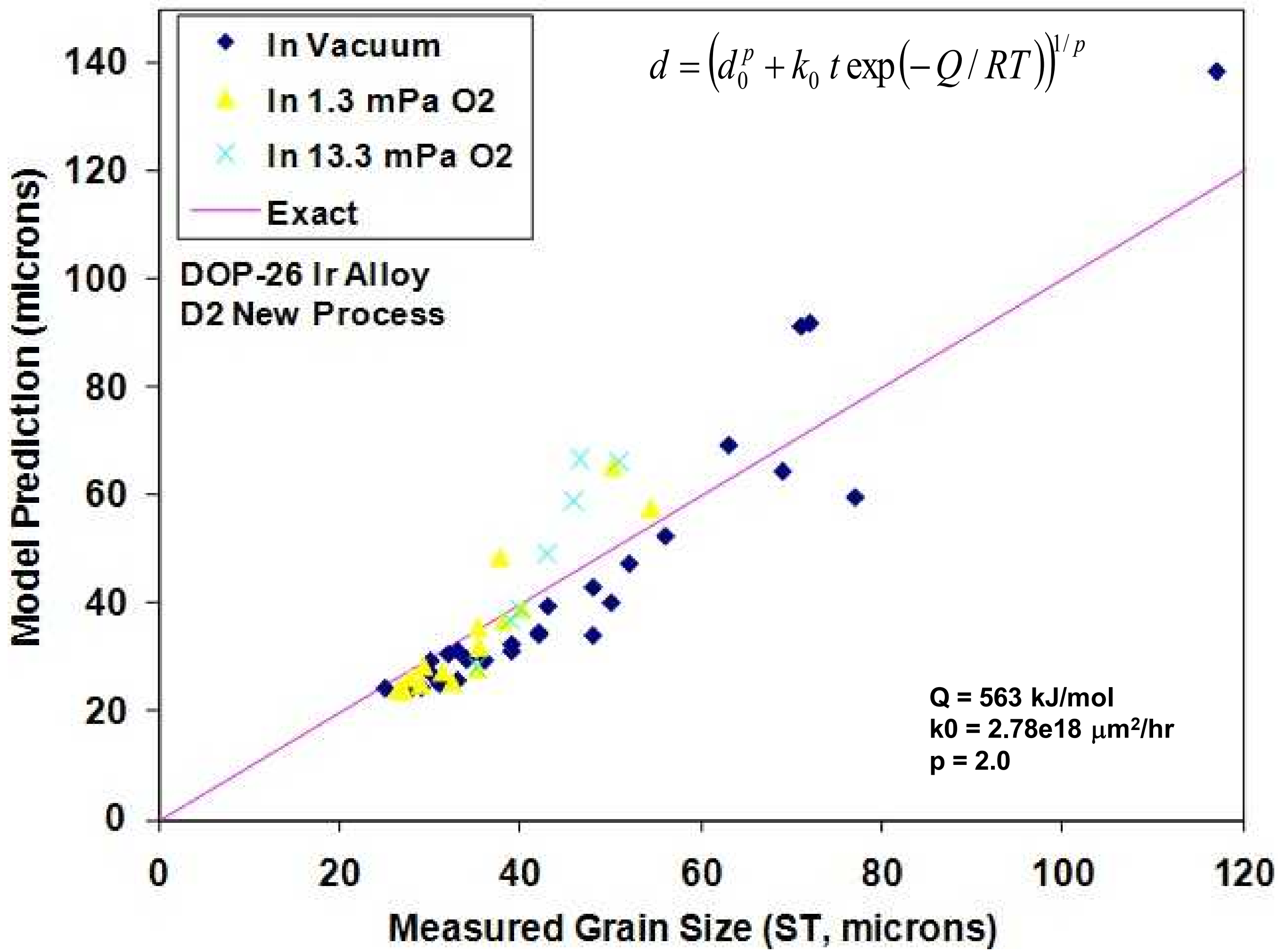
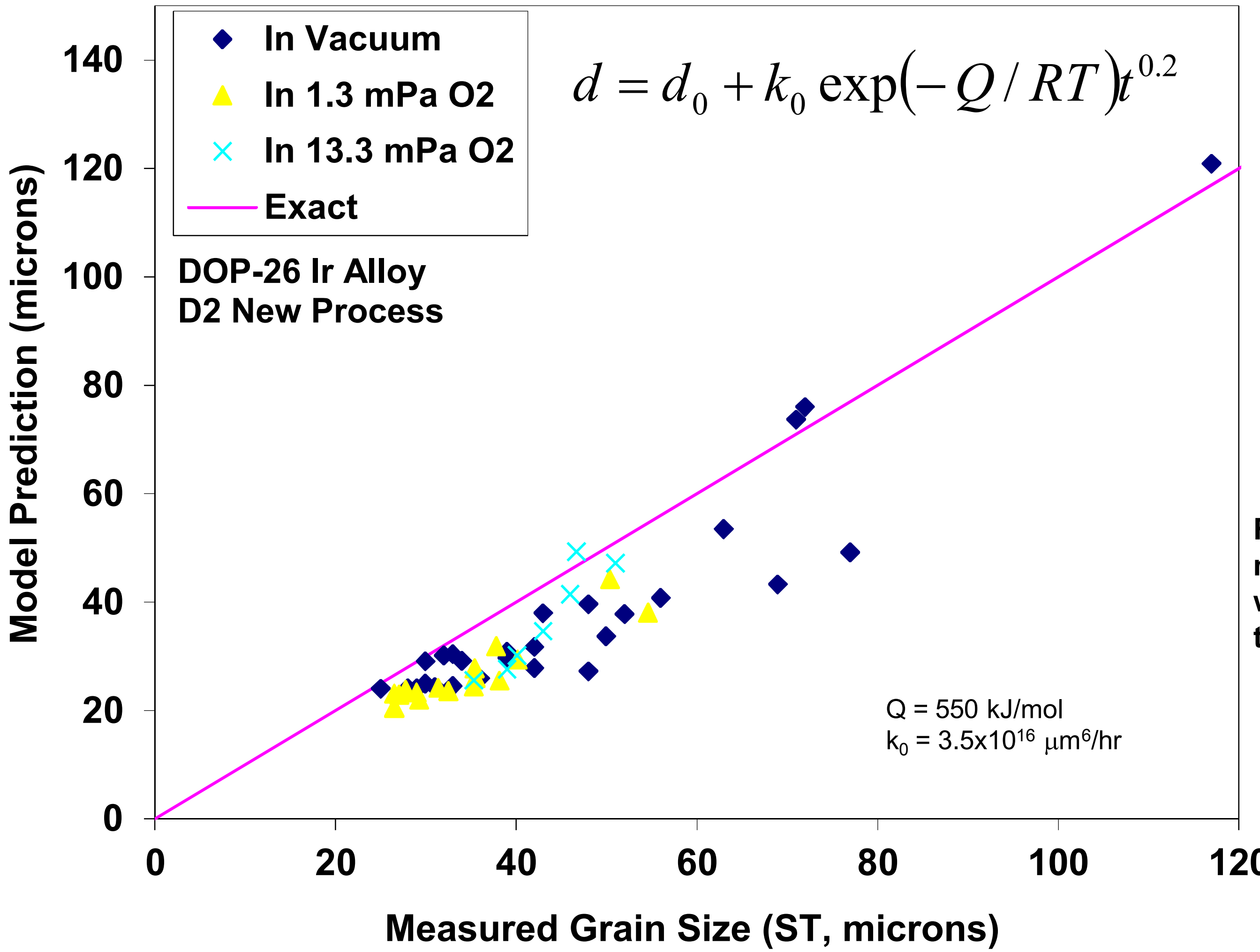
Predicted vs. Measured (McKamey 1996, p=2)



First grain size measurement was taken as time zero

Data from: C. G. McKamey, A. N. Gubbi, Y. Lin, J. W. Cohron, E. H. Lee and E. P. George, *Grain Growth Behavior and High-Temperature High-Strain-Rate Tensile Ductility of Iridium Alloy DOP-26*, ORNL-6935, Oak Ridge National Laboratory, Oak Ridge, TN 1998

Predicted vs. Measured (McKamey 2002 form)



Unable to find good fit in this form.

Need to vary exponent and k with temperature

First grain size measurement was taken as time zero

Data from: C. G. McKamey, A. N. Gubbi, Y. Lin, J. W. Cohron, E. H. Lee and E. P. George, *Grain Growth Behavior and High-Temperature High-Strain-Rate Tensile Ductility of Iridium Alloy DOP-26*, ORNL-6935, Oak Ridge National Laboratory, Oak Ridge, TN 1998

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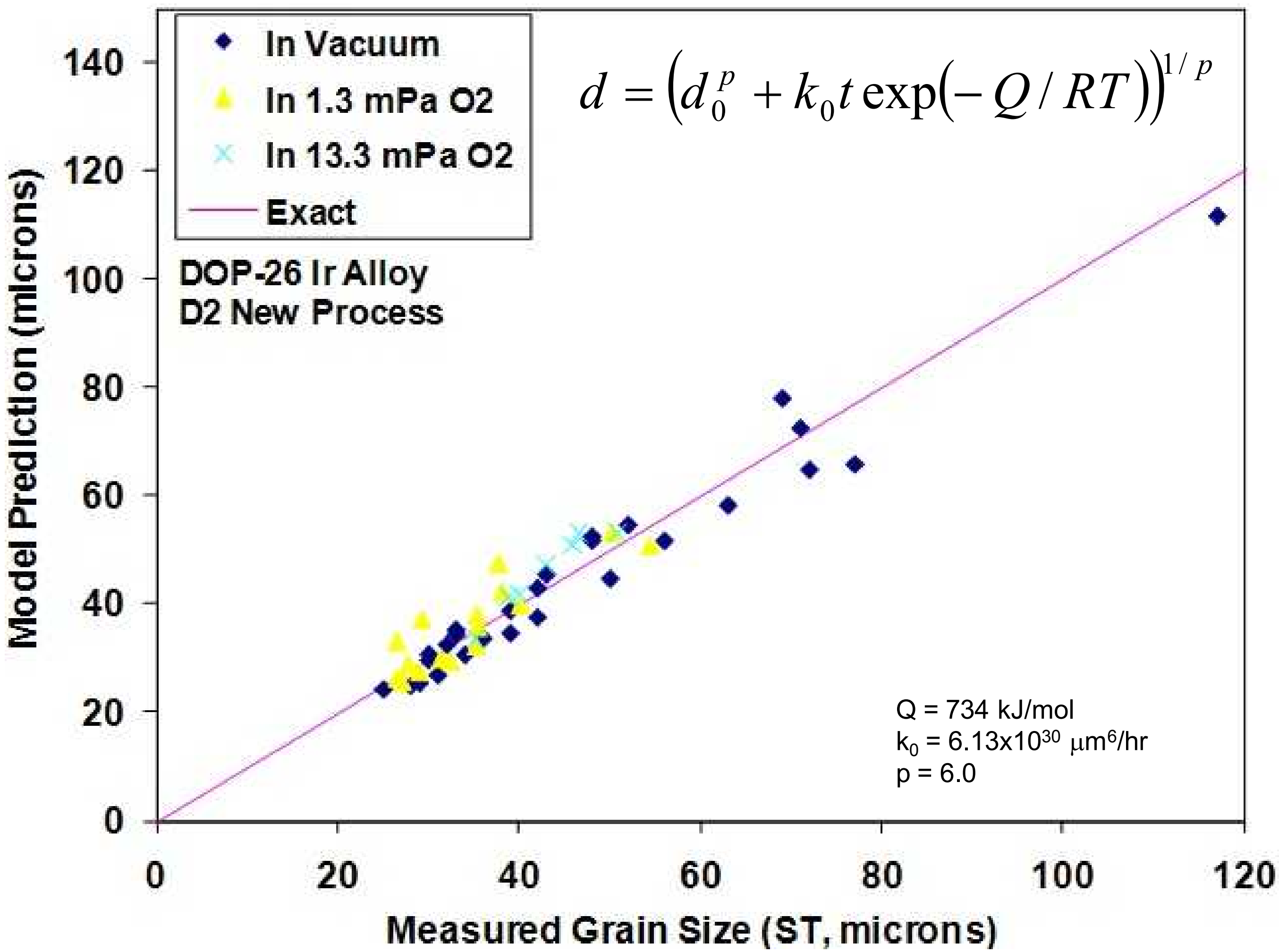
Predicted vs. Measured (this work, p=6)



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Data from: C. G. McKamey, A. N. Gubbi, Y. Lin, J. W. Cohron, E. H. Lee and E. P. George, *Grain Growth Behavior and High-Temperature High-Strain-Rate Tensile Ductility of Iridium Alloy DOP-26*, ORNL-6935, Oak Ridge National Laboratory, Oak Ridge, TN 1998

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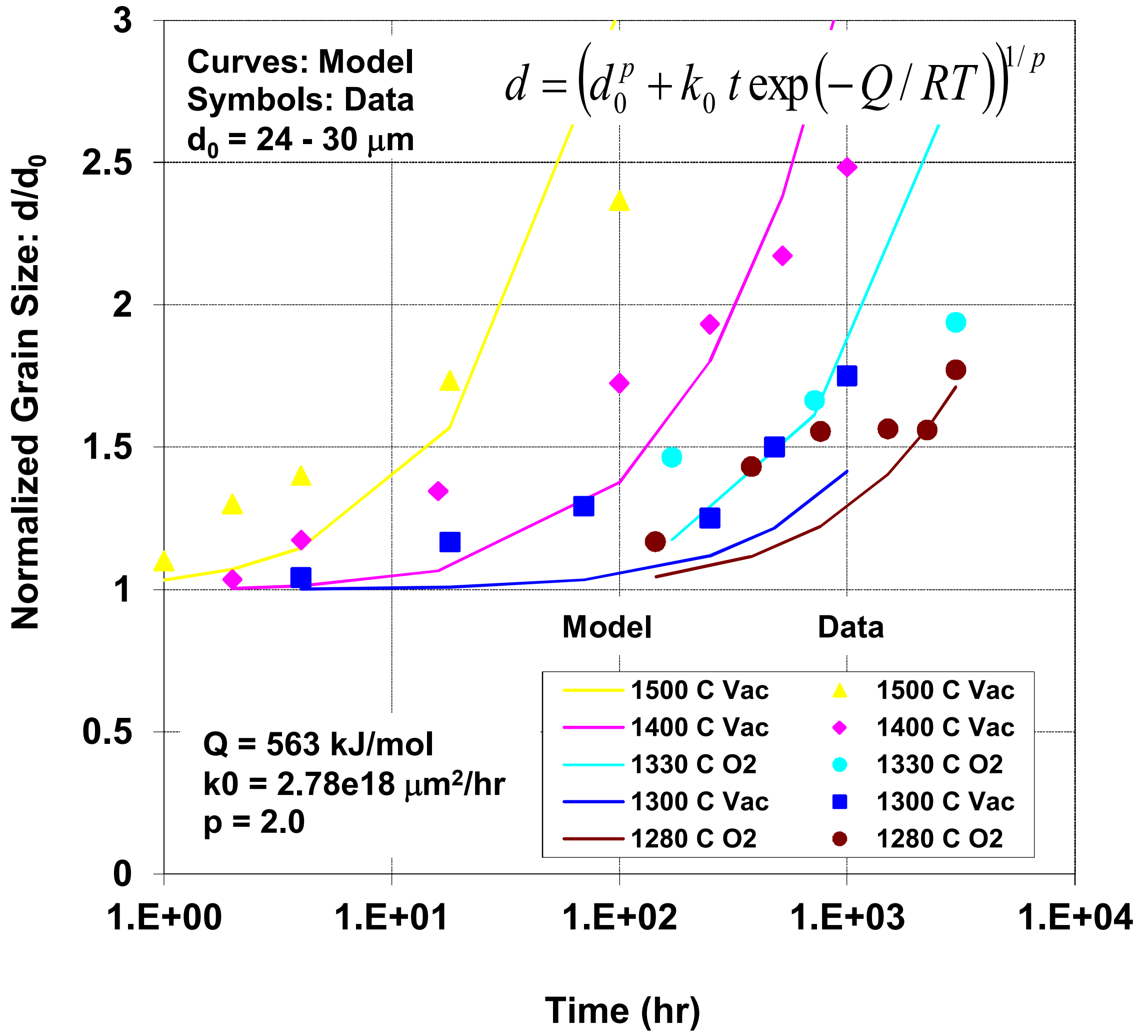
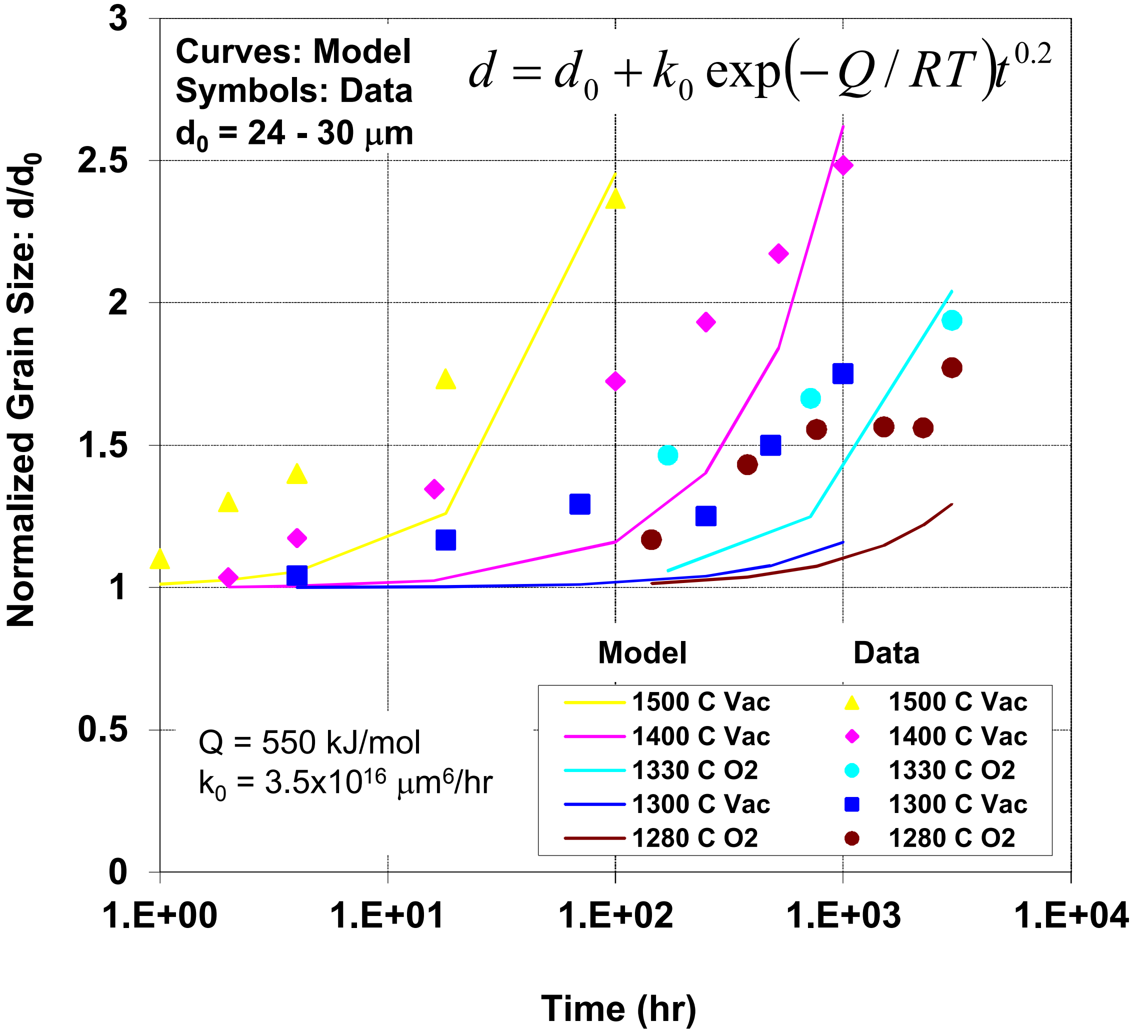
Size vs. Time (McKamey 1996, p=2)



First grain size measurement was taken as time zero

Data from: C. G. McKamey, A. N. Gubbi, Y. Lin, J. W. Cohron, E. H. Lee and E. P. George, *Grain Growth Behavior and High-Temperature High-Strain-Rate Tensile Ductility of Iridium Alloy DOP-26*, ORNL-6935, Oak Ridge National Laboratory, Oak Ridge, TN 1998

Size vs. Time (McKamey 2002 form)



Unable to find good fit in this form.

Need to vary exponent and k with temperature

First grain size measurement was taken as time zero

Data from: C. G. McKamey, A. N. Gubbi, Y. Lin, J. W. Cohron, E. H. Lee and E. P. George, *Grain Growth Behavior and High-Temperature High-Strain-Rate Tensile Ductility of Iridium Alloy DOP-26*, ORNL-6935, Oak Ridge National Laboratory, Oak Ridge, TN 1998

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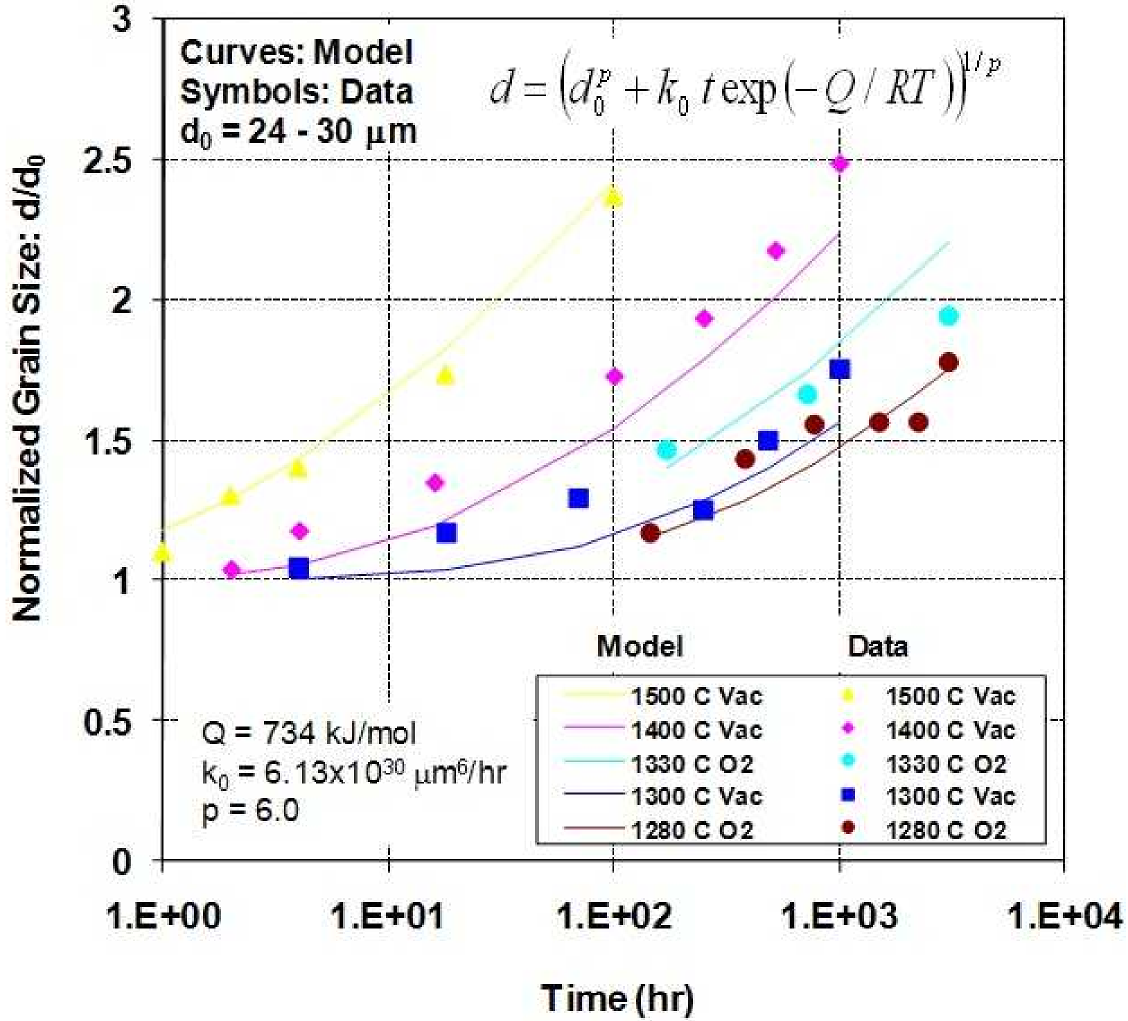
Size vs. Time (this work, p=6)



First grain size measurement was taken as time zero

Data from: C. G. McKamey, A. N. Gubbi, Y. Lin, J. W. Cohron, E. H. Lee and E. P. George, *Grain Growth Behavior and High-Temperature High-Strain-Rate Tensile Ductility of Iridium Alloy DOP-26*, ORNL-6935, Oak Ridge National Laboratory, Oak Ridge, TN 1998

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Size vs. Time, Two Heating Events

$$d = \left(d_0^p + k_0 t_1 \exp\left(\frac{-Q}{RT_1} \right) + k_0 t_2 \exp\left(\frac{-Q}{RT_2} \right) \right)^{1/p}$$

T_1 **is the temperature of the first heating event (K)**
T_2 **is the temperature of the second heating event (K)**
t_1 **is the duration at temperature T_1 (hr)**
t_2 **is the duration at temperature T_2 (hr)**

Summary

- Dop-26 iridium is used to clad the fuel on radioisotope power systems
- Iridium grains can grow at high temperature and reduce the ductility
- A model was developed to better predict the behavior for grain growth with time and temperature
- Average grain size in the transverse direction for data with a sparse oxygen background appears to fit in with the vacuum data

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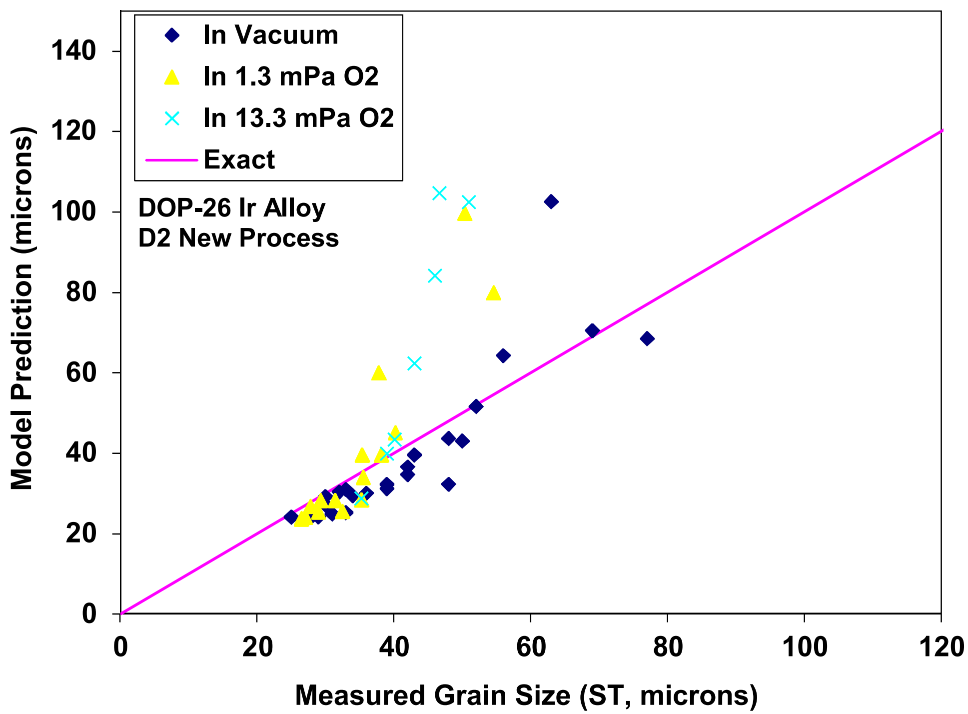
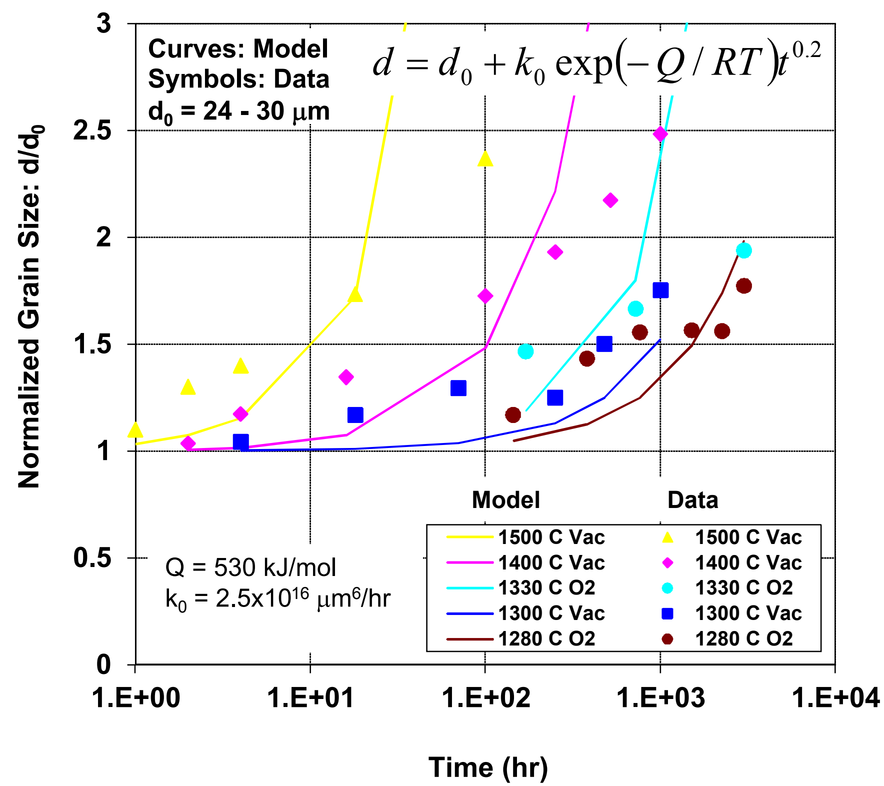
McKamey 2002 form, different values





Unable to get good agreement across the data set