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High Temperature Spin Testing of a Superalloy Disk With a Dual Grain Structure

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Introduction

Gas turbine engines for future subsonic aircraft will probably have higher pressure ratios. This will require nickel-base disk alloys with temperature capability in excess of 1300 °F. NASA's Advanced Subsonic Technology Program initiated a task to develop manufacturing technologies for advanced disk alloys toward the later half of the last decade. Under this program, Honeywell and Allison focused their attention on Alloy 10, a high strength nickel-based disk alloy, developed by Honeywell for application in regional gas turbine engines. Since tensile, creep, and fatigue are strongly influenced by grain size, the effect of heat treatment on grain size and the attendant properties were studied in detail (refs. 1 and 2). It was observed that a fine grained material offered the best tensile and fatigue properties while a coarse grained material offered the best creep and crack growth properties. Therefore a disk with a dual microstructure, fine grain bore and coarse grain rim, should have a high potential for optimal performance.

Additional disk work, funded by NASA's Ultrasafe and Ultra Efficient Engine Technology Programs, was initiated to assess the feasibility of producing a disk from Alloy 10 with a dual grain structure. The objectives of these programs were twofold. First, existing Dual Microstructure Heat Treatment (DMHT) technology was refined and subsequently employed to produce a dual grain structure in full scale disks of Alloy 10 (ref. 3). Second, key mechanical properties from specimens extracted from the bore and rim of the DMHT Alloy 10 disk were measured and compared to "traditional" solution heat treatments to assess the benefits of DMHT technology (ref. 4). The results of these tests showed the DMHT disk had a fine grain, high strength bore similar to that found in subsolvus heat treated disks, and a coarse grain, creep resistant rim similar to that found in supersolvus heat treated disks.

While test data on small coupons machined from the DMHT disk was encouraging, the benefit of the dual grain structure on the entire disk needed to be demonstrated. To address this issue spin testing of Alloy 10 disks with a dual grain structure would be required. The objective of this paper was a controlled comparison of high temperature spin tests run on a subsolvus and DMHT disk of Alloy 10. In particular, disk growth was monitored to assess the potential benefit of DMHT technology versus a traditional subsolvus heat treatment. Test data were subsequently analyzed using finite element methods to obtain a better understanding of the deformation characteristics of the DMHT disk.

Materials and Procedures

Material Processing

While a complete description of the processing history of all forgings used in this study can be found elsewhere (refs. 1 and 3), a brief description is presented here for the convenience of the reader. Alloy 10 powder of the composition shown in table I was produced by argon atomization. The powder was screened, canned, HIPed, and extruded to billet. The billet was subsequently cut to mullets and isoforged as "pancake" shapes 14 in. in diameter and 2 in. thick. These forgings were then machined to the shape shown in figure 1 for heat treatment.

An existing DMHT process was applied to two forgings, one for spin testing and one for coupon testing, while a third forging, to be used for spin testing, was given a traditional subsolvus solution heat treatment. The DMHT process was refined for Alloy 10 by Wyman-Gordon based on earlier work described in U.S. Patent 5,527,020. It consists of a thermally insulated box that encloses the bore of the disk but allows the rim to be exposed. The assembly is placed in a furnace at a temperature above the solvus of Alloy 10. Prior to insertion into the furnace an air flow is begun. This air flow is maintained at a rate which keeps that portion of the disk inside the insulated box below the solvus. The temperature differential between the bore and rim produces a dual grain structure in the disk. Removal of the disk is a rather slow process, which necessitated a subsolvus resolution step. The two DMHT and one subsolvus forgings were solution heat treated at 2125 °F for 2 hr, followed by fan cooling and aging at 1400 °F for 16 hr to obtain the high strength required for disk applications. Visual inspection of the disks revealed no evidence of quench cracking or other abnormalities after heat treatment.

Spin Testing

In order to test the entire disk in a spin pit, heat treated forgings, one DMHT and one subsolvus, were machined to the configuration shown in figure 2. The design was developed to produce a uniformly high stress region in the web of the disk while minimizing stress in the bore. This philosophy maximizes the deformation in the web, which encompasses the grain size transition zone of the DMHT disk.

All spin testing was performed at 1500 °F and 20000 rpm, which produced a web stress of about 50 ksi, utilizing facilities of the Balancing Company located in Dayton, Ohio. These test conditions were selected for two reasons. First, creep deformation of coarse grain microstructures is significantly slower than fine grain microstructures under these conditions. Second, disks for advanced military turbine engines are being developed which envision rim temperatures and stresses of this magnitude. Growth of the DMHT and subsolvus disk were measured and compared at selected locations. As in-situ measurements were not viable with available equipment, measurements of dimensional changes were made upon removal of a disk from the spin pit after a predetermined period of time. Dimensional information checked included diameters at the bore hole and the rim, as well as rim thickness. Each of these values was checked at four angular positions, 0, 45, 90, and 135 degrees.

Spin pit facilities used for this program employed “off-the-shelf” technology with the exception of the arbor. A photograph of the disk, arbor, and furnace are presented in figure 3. As creep was a concern at these temperatures, the arbor was fabricated from superalloy using the design shown in figure 4. Two clamping mechanisms were employed in this design to hold the disk. The primary clamping mechanism was provided by a 9 in. stretch bolt, while a secondary clamping mechanism was provided by capture flanges. In this design, the clamping force exerted by the capture flanges increases as the disk grows and therefore tends to counteract any decrease in clamping force provided by the stretch bolt over an extended period of time. As with any spin test, the disk and arbor were balanced before testing. A static temperature survey of the disk was also performed before testing. Results of that survey indicated the bulk of the disk was within 5 °F of the target temperature, 1500 °F. However, the arbor caused the bore of the disk to run about 100 °F lower than the web and rim.

Finite Element Analysis

Analysis of the spin pit experiments was performed with Algor’s finite element package using the 2D-axisymmetric finite element model shown in figure 5. Also shown in that figure is the assumed temperature distribution used in the analysis. As the stresses were below the yield strength of Alloy 10 at 20000 rpm, the analysis assumed a viscoelastic material response ($E = 26 \times 10^6$ psi and $\nu = 0.3$) governed by a power law creep expression (ref. 5) of the form shown below:

$$\Delta\epsilon_{\text{creep}}/\Delta t = K\sigma^4$$

where $\Delta\epsilon_{\text{creep}}$, is the effective creep strain increment for a given time increment, Δt , and effective stress level, σ . The value of K depends on grain size and temperature. Measurements of creep rates from coupon tests run on specimens cut from the bore and rim of the second DMHT forging showed the value of K to be 1.8×10^{-22} for fine grain Alloy 10 and 2.6×10^{-24} for coarse grain Alloy 10 at 1500 °F. In the bore of the disk where temperatures approach 1400 °F, the value of K was found to drop by about two orders of magnitude. A reasonable fit to the creep data between 1400 and 1500 °F was obtained by using the tabulated values of K found in table II for fine grain Alloy 10.

Results and Discussion

DMHT Microstructure

As previously stated, a dual grain structure was successfully produced in two of the Alloy 10 disks. The bore of each disk has a fine grain size, about ASTM 12, while the rim has a coarse grain size, about ASTM 6 to 7. Both grain sizes are typical of subsolvus and supersolvus heat treatments respectively. The transition region is located about 4 in. from the center of the disk and is remarkably symmetric. This structural transition is fully documented in figure 6.

Subsolvus Spin Testing

The first spin trial was conducted on the subsolvus disk. The disk was spun at 20000 rpm and 1500 °F for twelve hours with no abnormal events. Afterwards the disk was inspected and measured as previously described. The dimensional changes are summarized in table III. On average the disk diameter grew about 0.063 in. while the growth of the bore hole was minimal, about 0.001 in. The Poisson effect resulted in 0.006 in. reduction of the rim thickness.

Finite element analysis of this spin trial was performed using the parameters outlined in the previous section for fine grain Alloy 10. The initial loading, from 0 to 20000 rpm, produced the stress distribution shown in figure 7. As the disk exhibits a complex multi-axial stress pattern, the Von Mises stress was employed to provide an overview of the stress distribution in a single plot. The response in this plot is essentially elastic. At the end of the twelve hours, the stress distribution is altered as a result of creep deformation as seen in figure 8, and upon unloading, from 20000 to 0 rpm, a residual stress pattern, shown in figure 9, is generated. Also shown in this figure is the outline of the disk before the spin trial. The dimensional changes shown in this fashion have been magnified by a factor of ten for the convenience of the reader and reflect the growth of the disk resulting from creep deformation at 1500 °F. The overall changes of key dimensions in the disk model are summarized in figure 10. The rapid change in dimensions at the beginning and end of the analysis is a direct result of the change in disk rpm, however, the gradual change over the bulk of the test reflects creep deformation at 1500 °F. As seen in this plot, the disk growth was predicted to be 0.078 in., which is somewhat greater than the experimentally measured growth, 0.063 in. The difference between experiment and analysis could result from normal variations in creep data within the disk.

DMHT Spin Testing

For comparative purposes, the first spin trial on the DMHT disk was also run at 20000 rpm and 1500 °F for twelve hours. No abnormal events were noted during this time. Afterwards the disk was inspected and measured. The dimensional changes are summarized in table IV. On average the DMHT disk

diameter grew 0.012 in. compared to the 0.063 in. of growth for the subsolvus disk. Reduction of rim thickness was also smaller for the DMHT disk, about 0.001 in. The growth of the bore hole for the DMHT disk was still minimal, about 0.001 in.

Finite element analysis of the DMHT spin trial was performed using the same methodology as that for the subsolvus disk, except two material groups were employed as shown in figure 11. Up to the 4 in. radial location, all elements were assigned properties for fine grain Alloy 10. Beyond that point, all remaining elements were assigned properties for coarse grain Alloy 10. For the viscoelastic analysis employed in this study, the difference in material behavior for coarse and fine grain Alloy 10 manifested itself as different values for K in the power law creep expression. Elastic properties for either grain size were taken to be identical. As a result, the stress distribution in the DMHT disk was virtually identical to the subsolvus disk upon loading. However, after twelve hours, the difference in creep rates of the fine grain bore and coarse grain rim resulted in a dramatically different stress distribution as seen in figure 12. Notice the high stress region in the web associated with the coarse grain material in the DMHT disk. This behavior is not observed in the subsolvus disk, figure 8. Predicted changes in dimensions of the DMHT disk after twelve hours are shown in figure 13. Once again, the rapid change in dimensions at the beginning and end of the analysis is a direct result of the change in disk rpm. The predicted growth of the disk diameter, 0.014 in., is very close to the measured value, 0.012 in.

A second spin trial of the DMHT disk was run for an additional twelve hours at 20000 rpm and 1500 °F. Upon completion of this trial, measurements of the disk dimensions revealed the diameter had grown an additional 0.014 in. for a total growth of 0.026 in., which was still less than half that of the subsolvus disk after twelve hours. As before, this spin trial was analyzed and the predicted growth of the DMHT disk, in total, was 0.026 in.

These experimental and analytical spin data for the DMHT and subsolvus disks are summarized in the bar chart presented in figure 14. One can clearly see the DMHT technology minimizes disk growth at high temperatures compared to a traditional subsolvus solution heat treatment. For the geometry and conditions employed in this study, the DMHT technology reduced disk growth by about a factor of five over a traditional subsolvus heat treatment.

Summary and Conclusions

Comparative spin tests were run on superalloy disks at an elevated temperature to determine the benefits of a DMHT disk, with a fine grain bore and coarse grain rim, versus a traditional subsolvus disk with a fine grain structure in the bore and rim. The results of these tests showed that the DMHT disk exhibited significantly lower growth at 1500 °F. Further, the results of these tests could be accurately predicted using a 2D viscoelastic finite element analysis.

These results indicate DMHT technology can be used to extend disk operating temperatures when compared to traditional subsolvus heat treatment options for superalloy disks. However, additional research is required to ensure the safe operation of a DMHT disk under more realistic engine operating conditions. This includes testing to determine the burst margin and cyclic capability of DMHT disks in a spin pit, at a minimum, and ultimately running an engine test with a DMHT disk.

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1. S.K. Jain, "High OPR Core Materials, AOI 4.2.4, Regional Engine Disk Development," Final Report NAS3-27720, November 1999.
2. J. Gayda, P. Kantzos and J. Telesman, "The Effect of Heat Treatment on the Fatigue Behavior of Alloy 10," NASA AST Report 32, February 2000.
3. A.S. Watwe and H.F. Merrick, "Dual Microstructure Heat Treat Technology," Honeywell Report 21-11619A, May 2001.

4. J. Gayda, "Dual Microstructure Heat Treatment of a Nickel-Base Disk Alloy," NASA/TM—2001-211168, November 2001.
5. G.E. Dieter, "Mechanical Metallurgy," McGraw-Hill Book Company, p. 367, 1961.

TABLE I.—COMPOSITION OF ALLOY 10 IN WEIGHT PERCENT

Cr	Co	Mo	W	Al	Ti	Nb	Ta	C	B	Zr	Ni
10.2	15	2.8	6.2	3.7	3.8	1.9	0.9	0.03	0.03	0.1	BAL

TABLE II.—VISCOELASTIC DATA FOR FINE GRAIN ALLOY 10

Temperature, °F	Modulus, psi	K	n
1400	25,000,000	1.8×10^{-24}	4
1450	25,000,000	1.8×10^{-23}	4
1500	25,000,000	1.8×10^{-22}	4

TABLE III.—GROWTH DATA FOR SUBSOLVUS DISK

Location	Initial Value	Final Value	Change
Rim OD at 0°	12.878	12.940	0.062
Rim OD at 45°	12.876	12.940	0.064
Rim OD at 90°	12.875	12.939	0.064
Rim OD at 135°	12.876	12.939	0.063
Rim Thickness	1.408	1.402	-0.006
Bore ID at 0°	1.497	1.498	0.001
Bore ID at 45°	1.505	1.507	0.002
Bore ID at 90°	1.520	1.520	0.000
Bore ID at 135°	1.500	1.500	0.000

TABLE IV.—GROWTH DATA FOR DMHT DISK

Location	Initial Value	Final Value	Change
Rim OD at 0°	12.871	12.884	0.013
Rim OD at 45°	12.871	12.883	0.012
Rim OD at 90°	12.872	12.884	0.012
Rim OD at 135°	12.872	12.884	0.012
Rim Thickness	1.411	1.410	-0.001
Bore ID at 0°	1.500	1.501	0.001
Bore ID at 45°	1.500	1.501	0.001
Bore ID at 90°	1.500	1.501	0.001
Bore ID at 135°	1.500	1.501	0.001

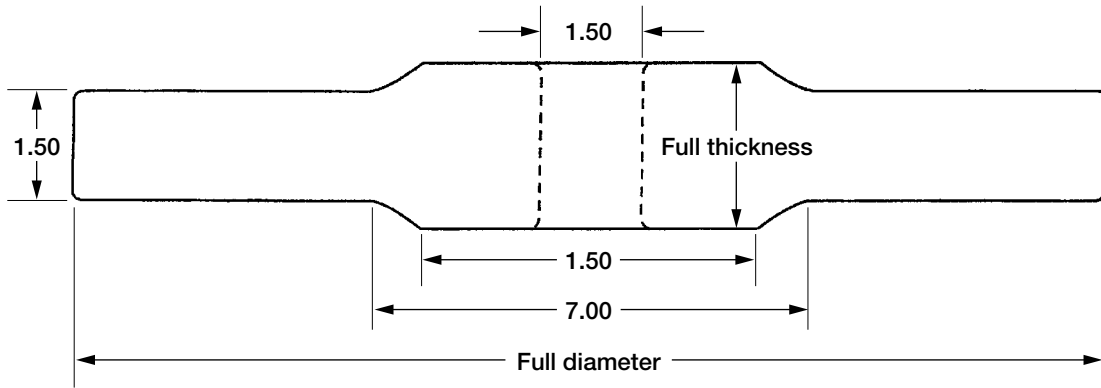


Figure 1.—Machining plan for heat treat shape of Alloy 10 forgings.
All dimensions in inches.

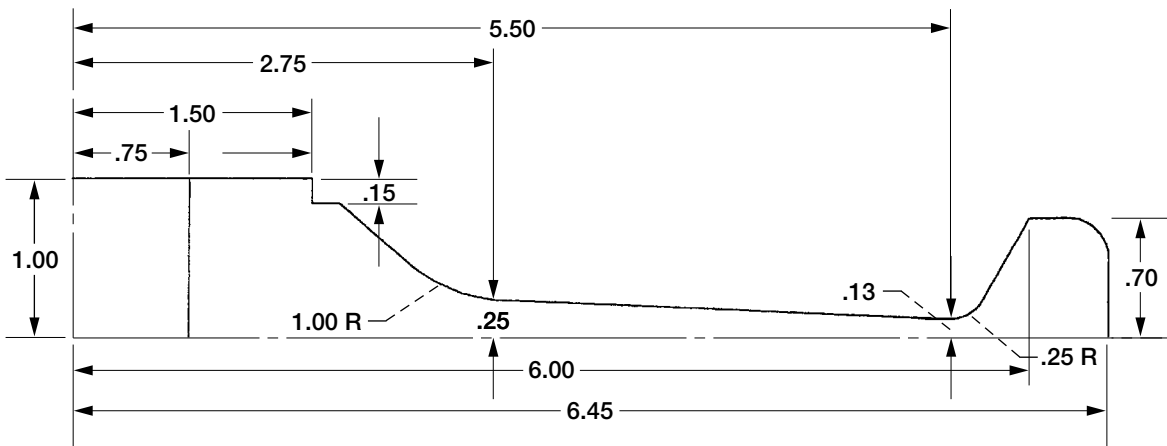


Figure 2.—Machining plan for finished disk used in spin testing.
All dimensions in inches.

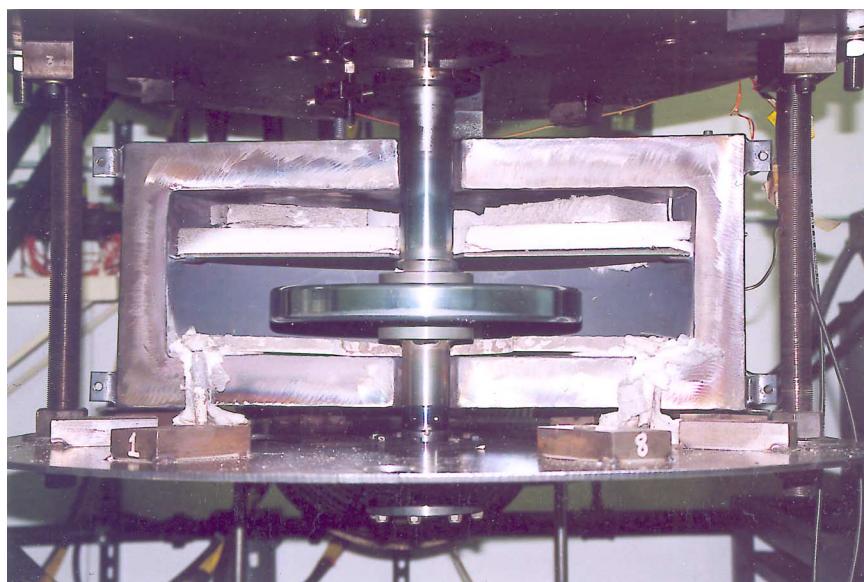


Figure 3.—Photograph of the disk, arbor, and furnace used for spin testing.

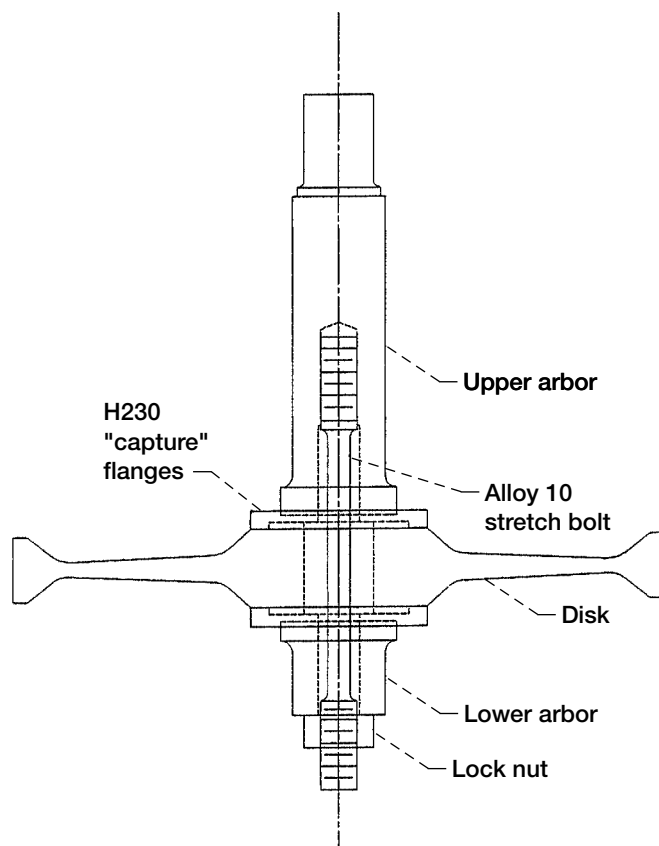


Figure 4.—Design of the arbor used for spin testing.

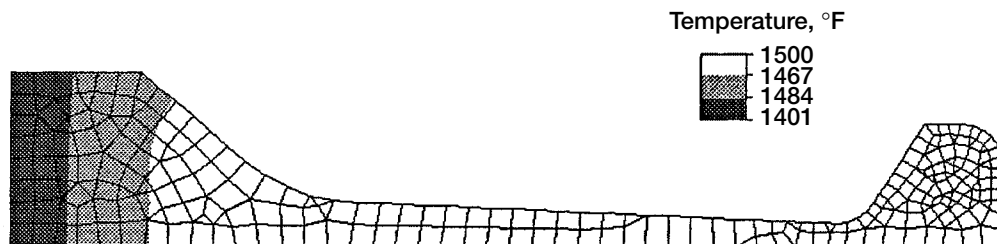


Figure 5.—2D finite element model of disk showing assumed temperature distribution.

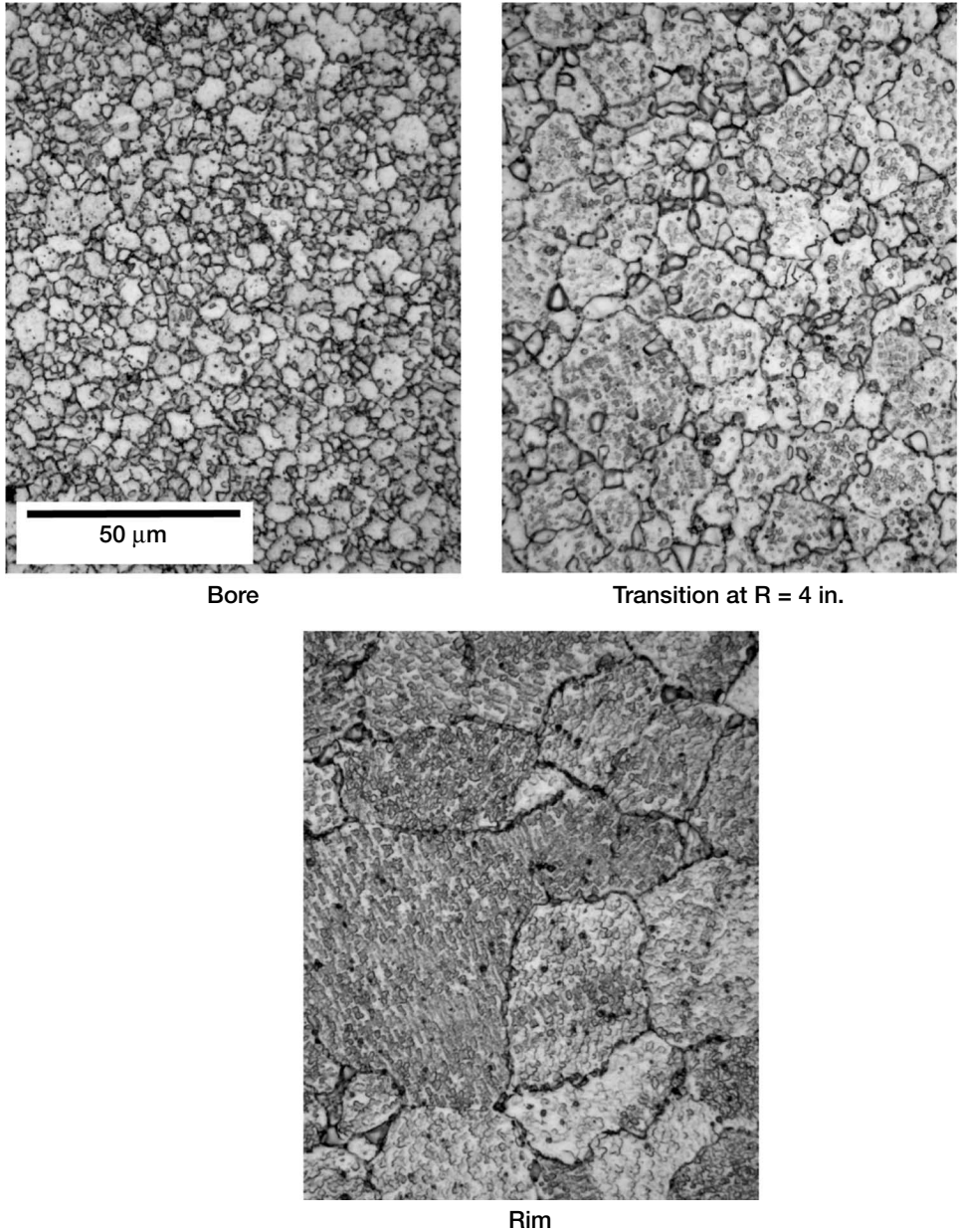


Figure 6.—Actual grain size in DMHT disk.

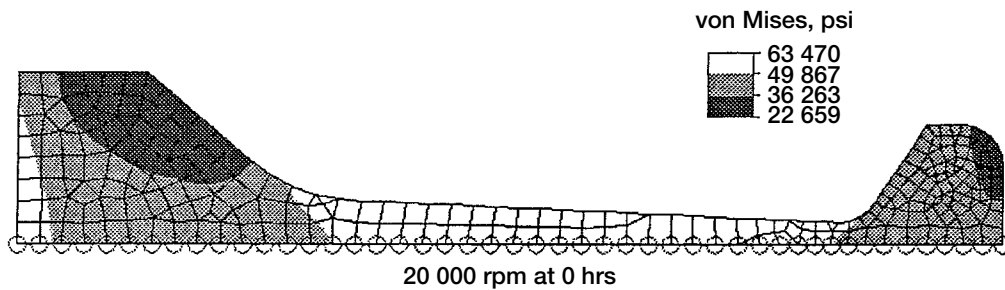


Figure 7.—Stress distribution at the start of the subsolvus spin test.

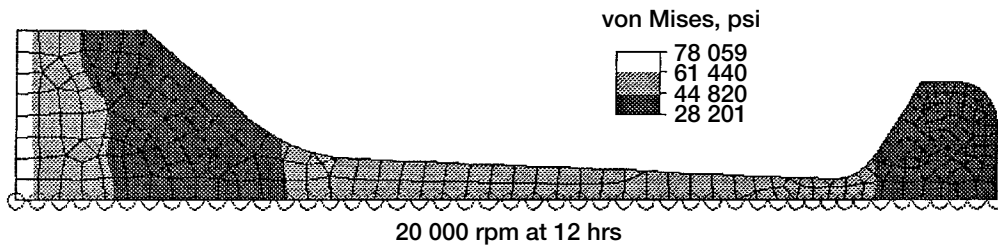


Figure 8.—Stress distribution after 12 hours of spin testing the subsolvus disk.

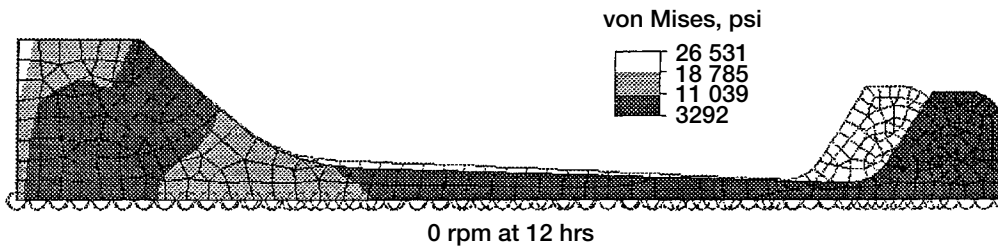


Figure 9.—Residual stress distribution in subsolvus disk after spin testing.

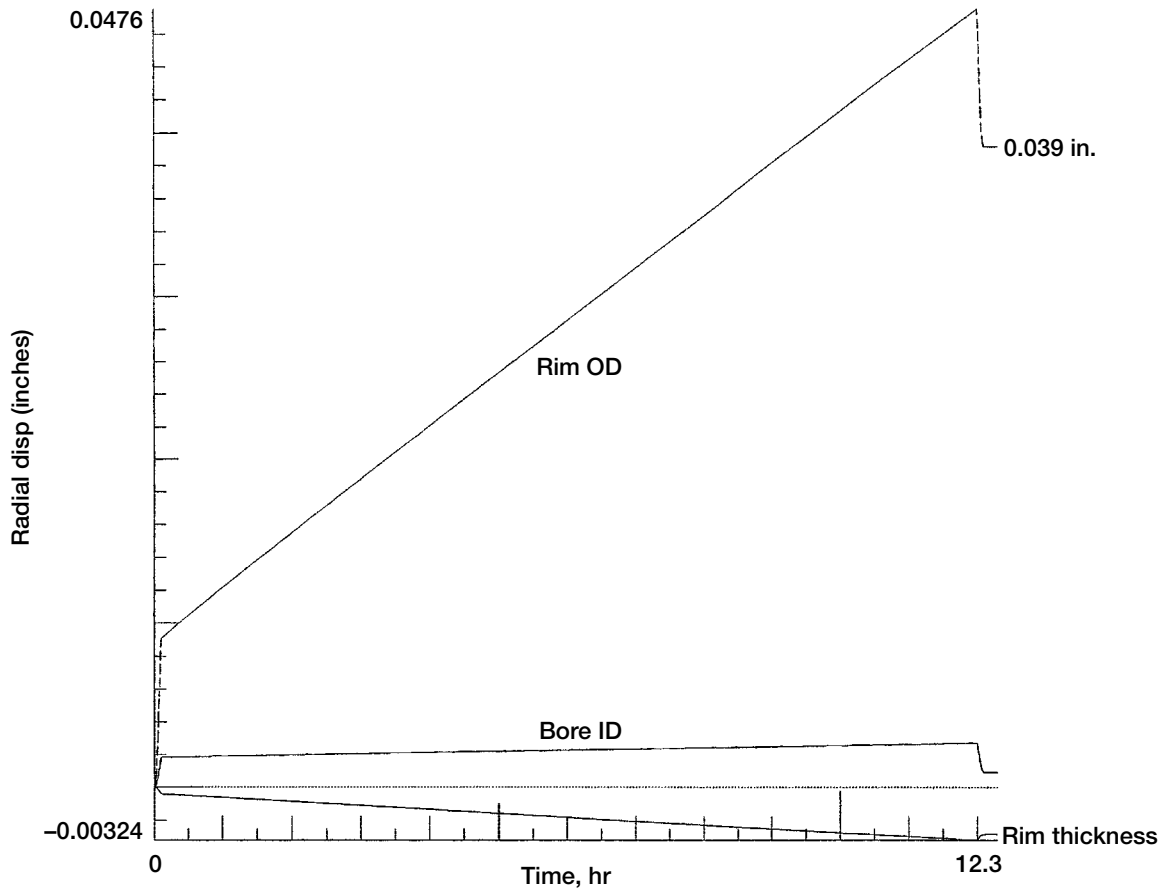


Figure 10.—Predicted growth of subsolvus disk at 20 000 rpm and 1500 °F.

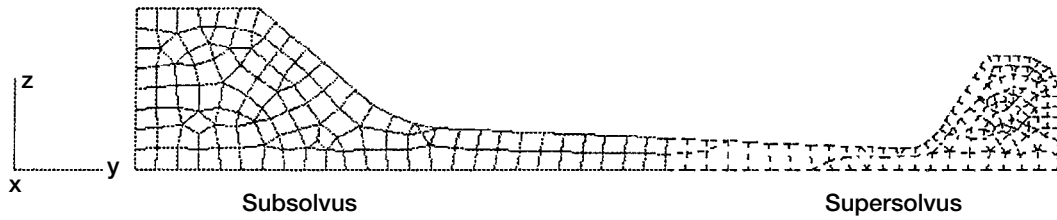


Figure 11.—Assumed distribution of grain size used for modeling the DMHT disk.

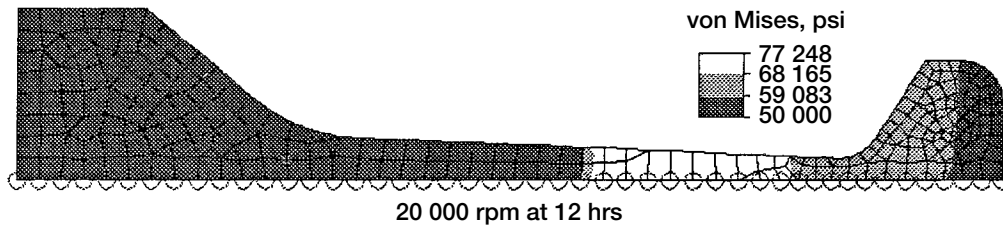


Figure 12.—Stress distribution after 12 hours of spin testing the DMHT disk.

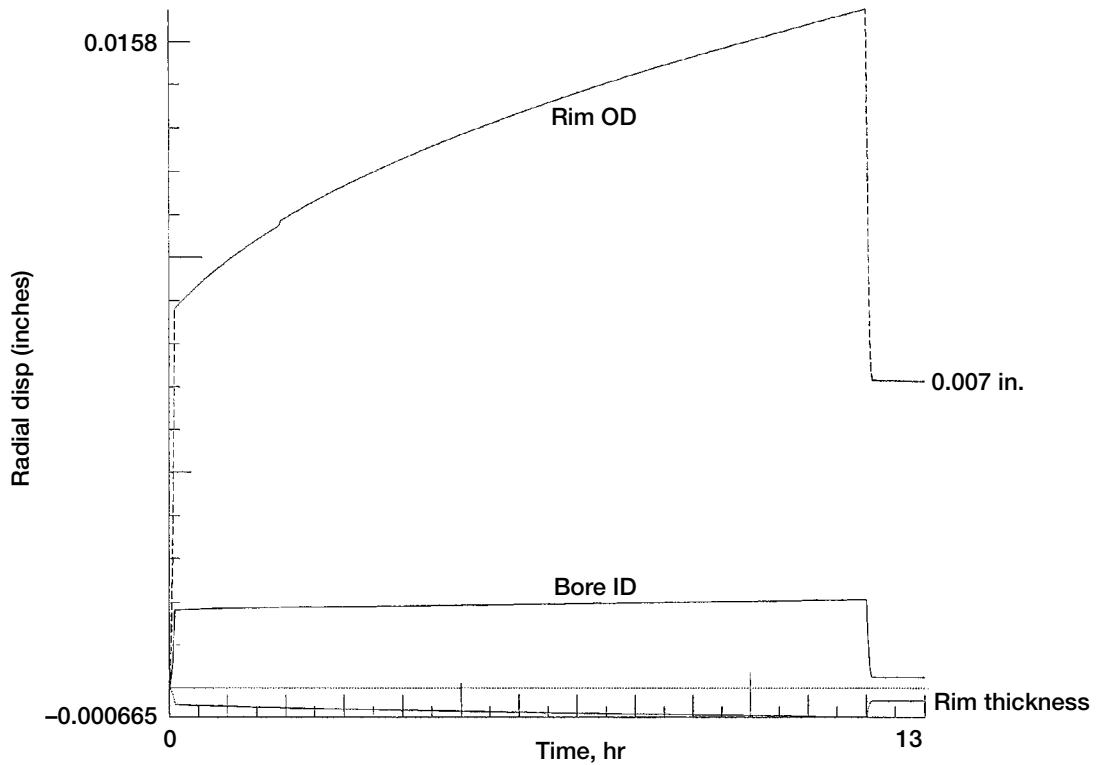


Figure 13.—Predicted growth of DMHT disk at 20 000 rpm and 1500 °F.

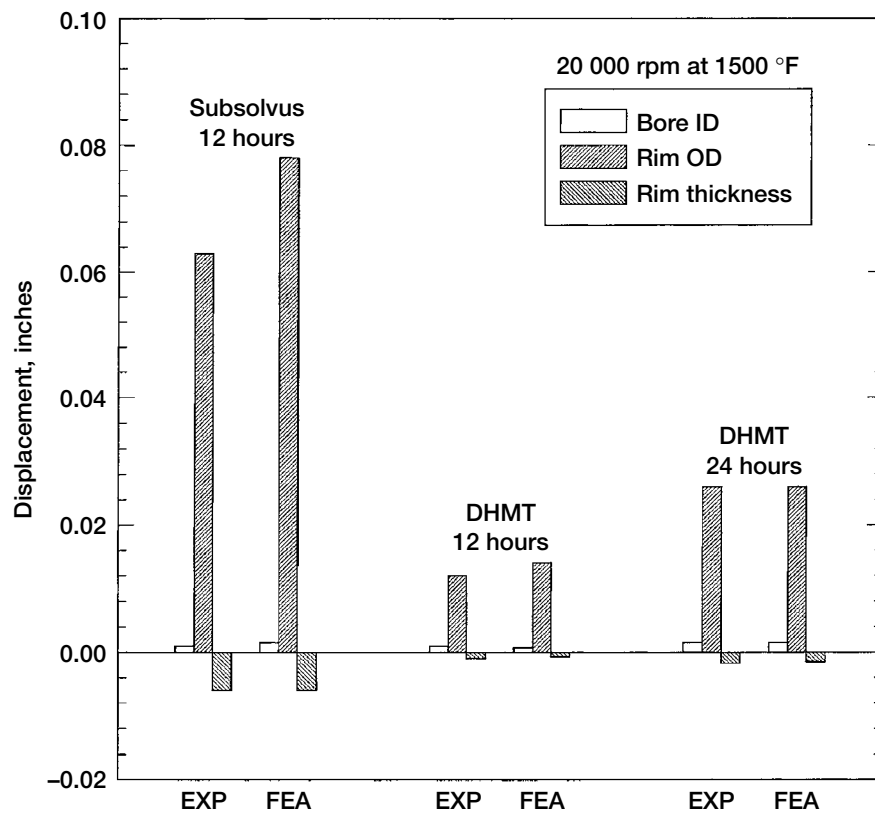


Figure 14.—Creep growth results for spin testing of Alloy 10 disks.

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