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Mechanical Properties of a Superalloy Disk With a Dual Grain Structure

John Gayda and Timothy Gabb
Glenn Research Center, Cleveland, Ohio

Peter Kantzos
Ohio Aerospace Institute, Brook Park, Ohio

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John Gayda and Timothy Gabb
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Peter Kantzos
Ohio Aerospace Institute
Brook Park, Ohio 44142

Introduction

Advanced nickel-base disk superalloys, such as ME3, have been developed recently which have the potential to improve performance of future gas turbine engines by allowing higher operating temperatures compared with today's gas turbine engines (ref. 1). This is achieved by using alloy compositions with high levels of gamma prime and refractory elements. However, there is a longer term need for disks with even higher rim temperature capability of 1400 °F (760 °C) or more. The increased temperature capability of the rim could be achieved, in part, by utilizing disks with a coarse grain microstructure in the rim, which yields optimal creep resistance, coupled with a fine grain microstructure in the bore, which yields optimal fatigue resistance in the bore where temperatures are lower (ref. 2).

To date, most nickel-base superalloy disks are heat treated at a uniform solution temperature either below the gamma prime solvus resulting in a fine grain microstructure (subsolvus heat treatment) or above the gamma prime solvus resulting in a coarse grain microstructure (supersolvus heat treatment). Several recent developments in heat treatment technology have sought to produce disks with a dual grain structure (refs. 3 to 5), specifically a fine grain bore and coarse grain rim. One of these technologies, termed Dual Microstructure Heat Treatment (DMHT), has been developed by NASA (ref. 5) and can be performed in a conventional gas fired furnace at relatively low cost compared to competing approaches which require specialized heating and/or cooling fixtures.

The primary objective of this paper is to measure the mechanical properties of a nickel-base superalloy disk with a dual grain structure produced using the DMHT process. In addition, a detailed microstructural characterization of the DMHT disk, from rim to bore, will be presented.

Materials and Procedures

A fine grain forging of an advanced nickel-base, powder metallurgy superalloy, ME3, was processed using NASA's DMHT technology to obtain a disk with a dual grain structure, consisting of a fine grain bore and a coarse grain rim. The DMHT conversion was performed at the Ladish Company in Cudahy, Wisconsin. A complete description of the DMHT process can be found in reference 5, however, for the reader's convenience the main points of that report are summarized as follows.

The basic concept behind the DMHT technology utilizes the natural thermal gradient between the bore and rim of a disk during the initial phase of a conventional heat treatment. By enhancing these thermal gradients with heat sinks, it is possible to design a solution heat treatment which can produce a disk with the desired dual grain structure. The heat sinks are solid metal cylinders, termed thermal blocks, which have large thermal mass that chill the central portion of the disk. Two thermal blocks were utilized, one on the top face and one on the bottom face of the disk. To enhance the effectiveness of the thermal blocks an insulating jacket was employed to slow the temperature rise of the thermal blocks. To perform the heat treatment, the disk and heat sinks were placed in a standard, gas fired furnace maintained at a temperature above the gamma prime solvus of ME3, and removed when the rim of the disk exceeded the solvus but before the bore had reached the solvus temperature of ME3. A thermocouple embedded in the top heat sink next to the bore of the disk was used to determine the point at which the disk and heat sinks were removed from the furnace. A schematic representation of the disk, heat sinks, and thermocouple are presented in figure 1. The DMHT conversion process used in this study employed a furnace temperature of 2175 °F (1191 °C). The disk and heat sinks were removed from the furnace when the embedded thermocouple reached 2100 °F (1149 °C). After removal from the furnace, the disk and heat sinks were quickly separated, and the disk was quenched in oil with a total transfer time from furnace to quench tank, including removal of the heat sinks, of less than one minute. The disk was then aged at 1500 °F (815 °C) for 8 hr and air cooled.

The heat treated disk was sectioned as shown in figure 2 so that key mechanical properties could be measured in air over a range of temperatures. Tensile specimens, employing a cylindrical gage section with a 0.25-in. (6.4-mm) diameter, were cut from the bore, transition, and rim of the disk and tested according to ASTM E8 and E21 using axial extensometry. Creep and crack growth specimens were cut from the bore and rim while fatigue specimens were cut from the bore of the disk. Creep tests were run according to ASTM E139 up to 0.2 percent axial creep strain using test specimens employing a cylindrical gage section with a 0.25-in. (6.4-mm) diameter. K_b bar crack growth tests were employed in this study using the test procedures outlined in reference 6. The K_b bar is a surface flaw crack growth specimen employing a rectangular cross section which allows a high net section stress, approximately 100 ksi (690 MPa), similar to that found in disks. Fatigue tests were run using specimens employing a cylindrical gage section, with a 0.25-in. (6.4-mm) diameter, according to ASTM E606. An axial strain controlled, 0.3 Hz sinusoidal waveform with an R-ratio of 0.0 was employed in these tests. Test temperatures were chosen to reflect specimen location, i.e., rim specimens were generally tested at higher temperatures than bore specimens although a certain degree of overlap was maintained for comparative purposes. In addition to the mechanical properties, the grain size and gamma prime distribution from bore to rim was characterized using metallographic mounts cut from a central slice through the cross section of the disk.

Results and Discussion

As previously stated, a dual grain structure was produced in an ME3 forging using NASA’s DMHT process. The boundary between the fine grain and coarse grain microstructure is illustrated by the macroetch section shown in figure 3. The transition region is located about 2 in. (5 cm) from the outer diameter of the disk and is remarkably symmetric. Starting at the bore hole, high magnification metallographic sections reveal a very fine grain structure, about ASTM 14 (3 µm), containing a significant amount of primary gamma prime about 1µm in size. As one moves radially outward the grain size increases gradually to about ASTM 12 (6 µm) in the web. At the same time the amount of primary gamma prime decreases while the amount of cooling gamma prime increases. Near the transition zone, a duplex grain structure exists with less and less primary gamma prime and more cooling gamma prime. Finally, a uniformly coarse grain structure develops near the outer diameter of the disk, about ASTM 6 to 7 (45 to 32 µm). The gamma prime is present as cooling gamma prime, about 0.1 to 0.3 µm in size, with little if any primary gamma prime present. The transition in grain size and gamma prime distribution is documented in figures 4 to 6 as a function of radial position in the disk.

The mechanical properties of the DMHT disk, tensile, creep, fatigue, and crack growth, will be compared with data from subsolvus and supersolvus ME2 alloy generated in NASA's Advanced Subsonics Transport (AST) Disk Program (ref. 7) and, where available, ME3 alloy generated in NASA's Ultra Efficient Engine Technology (UEET) Disk Program (ref. 1). Differences in alloy chemistry, disk size, and heat treatment exist, and therefore limit the validity of the comparison. However, the AST, UEET, and the current DMHT data sets are representative of next generation disk alloys.

A compilation of the tensile and creep data for the DMHT disk can be found in table I. The tensile ductility of the DMHT disk is seen to be acceptable, elongation values of 9 percent or greater, for all locations and temperatures evaluated. The strength levels of the DMHT disk are compared with the AST and UEET data sets in figure 7. In general bore strength levels from the DMHT disk are comparable to the AST and UEET subsolvus data sets, however, the rim strength levels from the DMHT disk generally exceed that of the AST and UEET supersolvus data sets. In fact, the bore and rim strength levels are virtually identical for the DMHT disk. This was somewhat surprising, but may be explained as follows. While the fine grain size of the bore specimens would boost strength compared to rim specimens, the slower cooling rate and diminished cooling gamma prime content in the bore may have offset the grain size advantage. This scenario was tested by taking bore and rim blanks from the DMHT disk and resolutioning them at a subsolvus solution temperature, 2070 °F (1132 °C), followed by an air cool and age. After this heat treatment, the cooling rate difference is eliminated while the grain size differential between the bore and rim remains, although the bore grain size did coarsen somewhat from ASTM 14 (3 µm) to ASTM 12 (6 µm). As shown in figure 8 the bore strength now exceeds that of the rim. Before proceeding to a discussion of creep results, it should be noted that the tensile strength through the transition region was similar to that of the bore and rim, as seen in figure 7, and therefore does not represent a "weak link" in the DMHT disk.

Creep rates, i.e., time to 0.2 percent creep, were measured at 1300 and 1500 °F (704 and 815 °C) for bore and rim specimens from the DMHT disk. The data, shown in table I, indicated a significant advantage, slower creep rates, for the coarse grain rim specimens at both temperatures compared to the fine grain bore specimens. Using a Larson-Miller plot, the creep rates of the DMHT data were compared with the AST and UEET data in figure 9. While the data for the DMHT rim specimens were equivalent or superior to that for the AST and UEET supersolvus data, the DMHT bore specimens were inferior to the AST subsolvus data set. Once again, bore and rim blanks from the DMHT disk were resolutioned and then tested at 1300 °F/100 ksi (704 °C/690 MPa), to determine if the creep performance of the fine grain bore specimens could be improved. As seen in figure 10, the creep rate of the bore specimen showed a dramatic improvement, while the creep rate of the rim specimen showed a small adverse impact from the resolution heat treatment.

Minimum fatigue life of a disk is often observed at intermediate temperatures, between 700 and 1000 °F (371 and 538 °C), and high stresses produced in the bore. For this reason, low cycle fatigue tests were run on DMHT bore specimens at 750 °F (399 °C). The results of these tests are presented in figure 11 along with data from the AST Program. As seen in this plot the fine grain microstructures, DMHT bore and AST subsolvus, have superior fatigue lives compared to the coarse grain AST supersolvus data set. This trend is especially pronounced at 0.6 percent, an important design point for disk alloys.

The last property to be evaluated in this paper was crack growth. As previously stated, K_b bar crack growth tests were employed in this study. Cyclic crack growth tests were run at 1000 °F (538 °C) and 0.3 Hz on DMHT bore specimens, while 90 sec dwell crack growth tests were run at 1300 °F (704 °C) on DMHT rim specimens. This choice reflects design limiting crack growth criteria for modern disk applications. The cyclic crack growth results for the DMHT bore are plotted in figure 12 along with data from the AST and UEET programs. The AST and UEET data includes subsolvus and supersolvus data from 750 °F (399 °C), lower bound, to 1300 °F (704 °C), upper bound. The 1000 °F (538 °C) DMHT data clearly falls within this range indicating the cyclic crack growth properties of the DMHT disk were acceptable. The 1300 °F (704 °C) dwell crack growth results for the DMHT rim are plotted in figure 13 with the AST and UEET data sets. The AST data set clearly shows coarse grain microstructures improve dwell crack growth resistance. While the coarse grain rim specimen from the DMHT disk shows better dwell crack growth resistance than the subsolvus AST material, it was clearly inferior when compared to the supersolvus AST material. This shortfall may be attributed to differences in heat treatment, specifically cooling rates and aging sequence, between the supersolvus AST disk and the DMHT disk. Previous work (refs. 1 and 7) has shown that these factors can affect dwell crack growth resistance. The effect of resolutioning on dwell crack growth rates of rim material from the DMHT disk was checked. Using the same heat treatment employed on tensile and creep specimens, 2070 °F (1132 °C) subsolvus solution followed by an air cool and age, no significant impact was found on rim dwell crack growth rates as seen in figure 14. This result was somewhat surprising and requires further investigation, although it does suggest that one could resolution a DMHT disk and not adversely impact dwell crack growth resistance in the rim.

Based on the mechanical property data and microstructural information presented in this report, a more complete study of the DMHT processing sequence would appear to be warranted. In particular, the effect of a subsolvus solution cycle before or after the DMHT conversion step may prove beneficial for several reasons. First and foremost, bore properties of blanks from the DMHT disk which were given a resolution heat treatment showed significant improvement. Further, rim properties of blanks from the DMHT disk given the same resolution heat treatment showed little if any detriment. Second, from a production standpoint, a post DMHT resolution cycle would enhance the economics of the DMHT process by alleviating the need for a rapid quench directly following the DMHT conversion. This becomes extremely important if one intends to run several DMHT disk assemblies in a single furnace run. Resolutioning also allows one to set the optimal bore microstructure more precisely.

Summary and Conclusions

Mechanical properties from an advanced, nickel-base superalloy disk, with a dual grain structure consisting of a fine grain bore and coarse grain rim, were evaluated. The dual grain structure was produced using NASA’s low cost DMHT process.

The results showed the DMHT disk to have a high strength, fatigue resistant bore comparable to a subsolvus (fine grain) heat treated disk, and a creep resistant rim comparable to a supersolvus (coarse grain) heat treated disk. Additional work on subsolvus solutioning before or after the DMHT conversion appears to be a viable avenue for further improvement in disk properties.

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TABLE I.—TENSILE AND CREEP DATA FOR DMHT DISK.

Tensile Data				
Location	Temperature, °F (°C)	Yield, ksi (MPa)	UTS, ksi (MPa)	ELONG, percent
Bore	75 (24)	173 (1193)	237 (1634)	22
Bore	1000 (538)	167 (1151)	222 (1531)	19
Bore	1300 (704)	156 (1076)	174 (1200)	14
Transition	1300 (704)	159 (1096)	181 (1248)	9
Rim	75 (24)	174 (1200)	240 (1655)	20
Rim	1300 (704)	158 (1089)	194 (1338)	18
Rim	1500 (815)	124 (855)	140 (965)	9
Creep Data				
Location	Temperature, °F (°C)	Stress, ksi (MPa)	0.1 Percent Creep, Hr	0.2 Percent Creep, Hr
Bore	1300 (704)	100 (690)	4	11
Bore	1300 (704)	100 (690)	6	16
Bore	1500 (815)	50 (345)	----	0.2
Rim	1300 (704)	100 (690)	170	294
Rim	1300 (704)	100 (690)	81	360
Rim	1500 (815)	50 (345)	54	123
Rim	1500 (815)	50 (345)	25	80

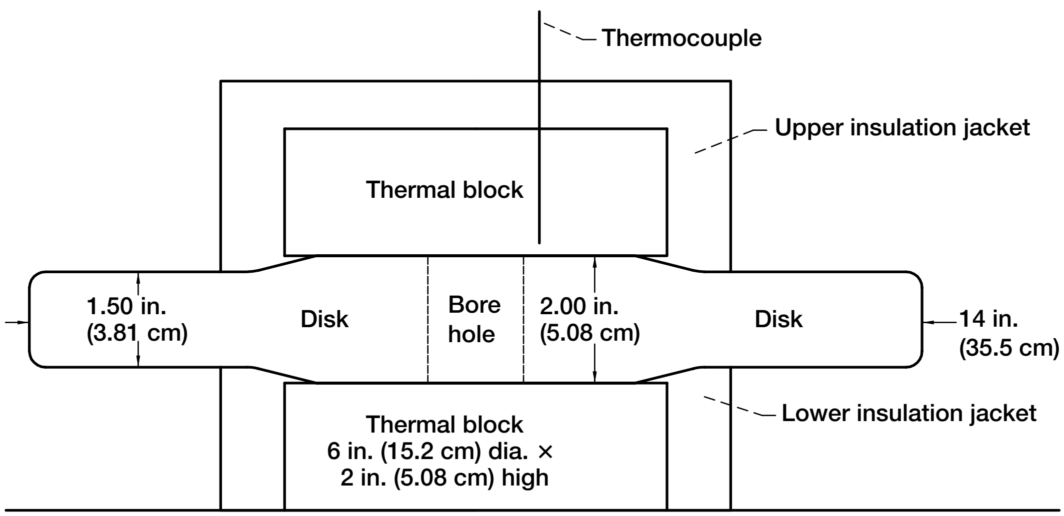

Figure 1.—Schematic illustration of DMHT assembly.

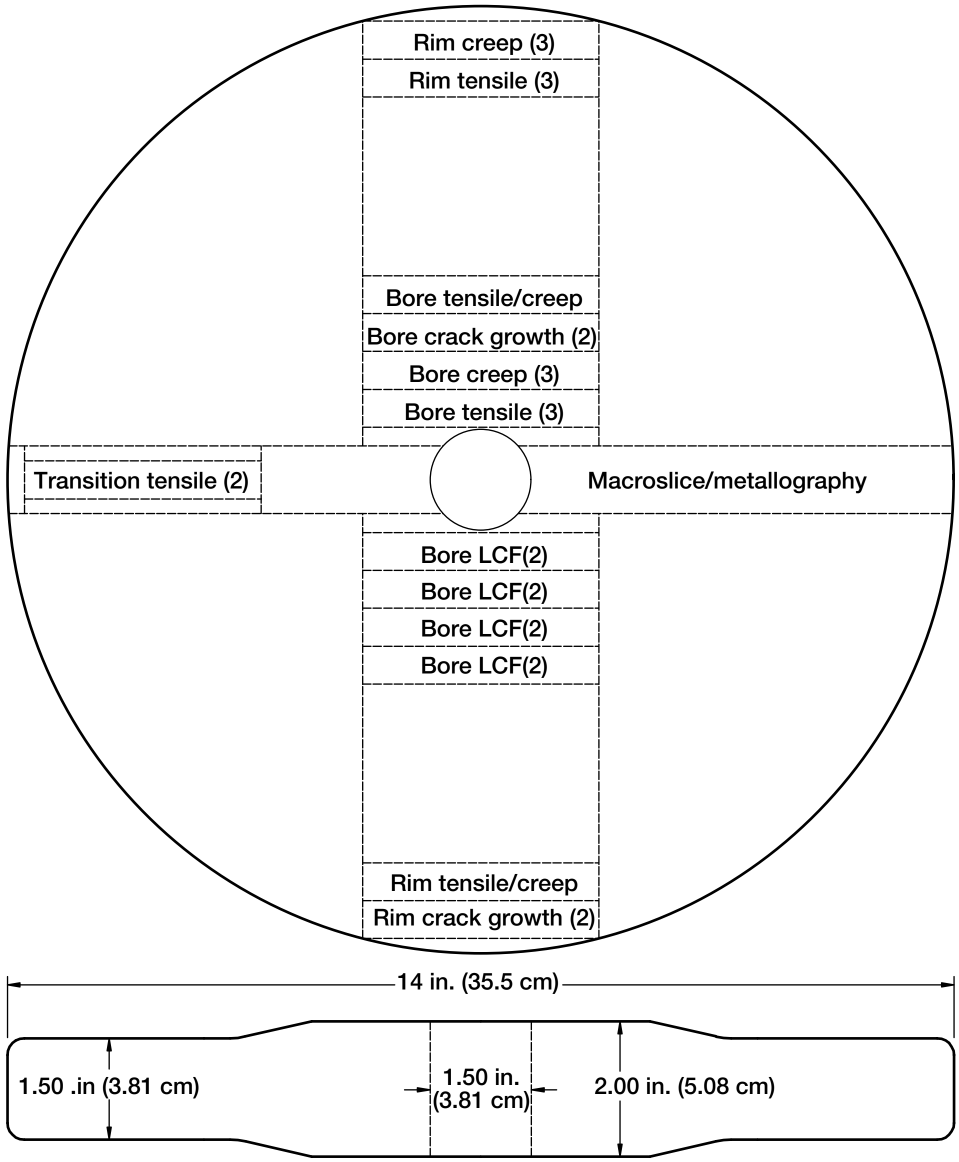

Figure 2.—Cut-up plan for DMHT disk.

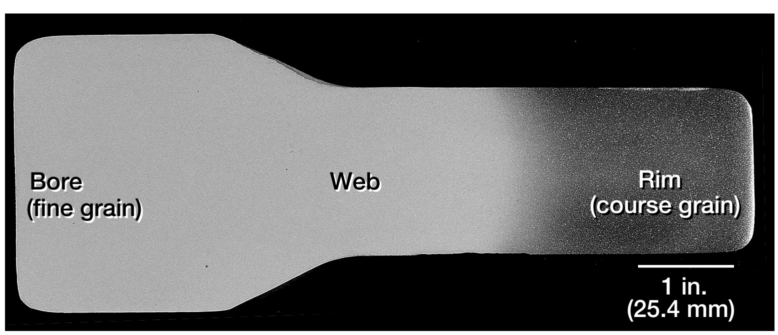

Figure 3.—Macroetch of DMHT disk showing location of grain size transition.

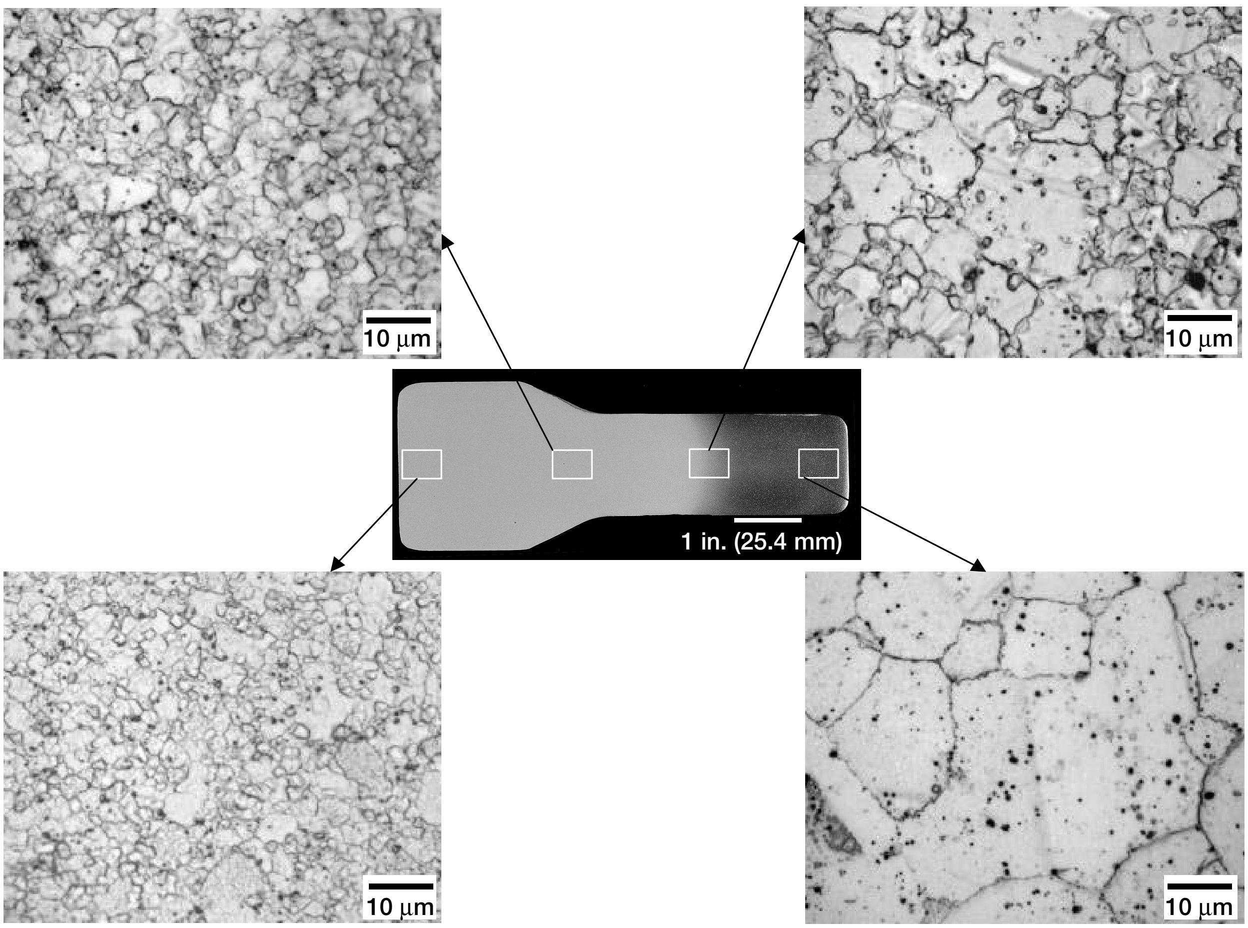

Figure 4.—Grain size at various disk locations.

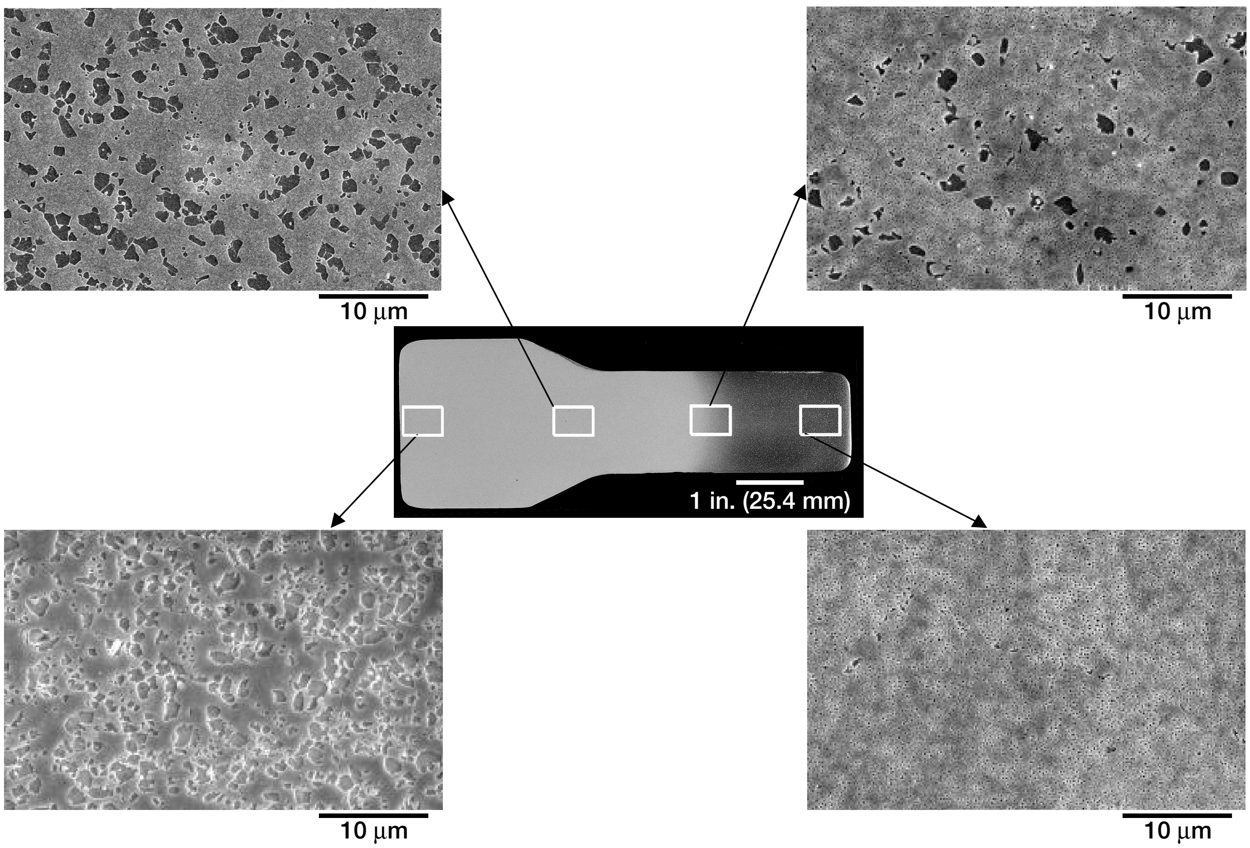

Figure 5.—Primary gamma prime at various disk locations.

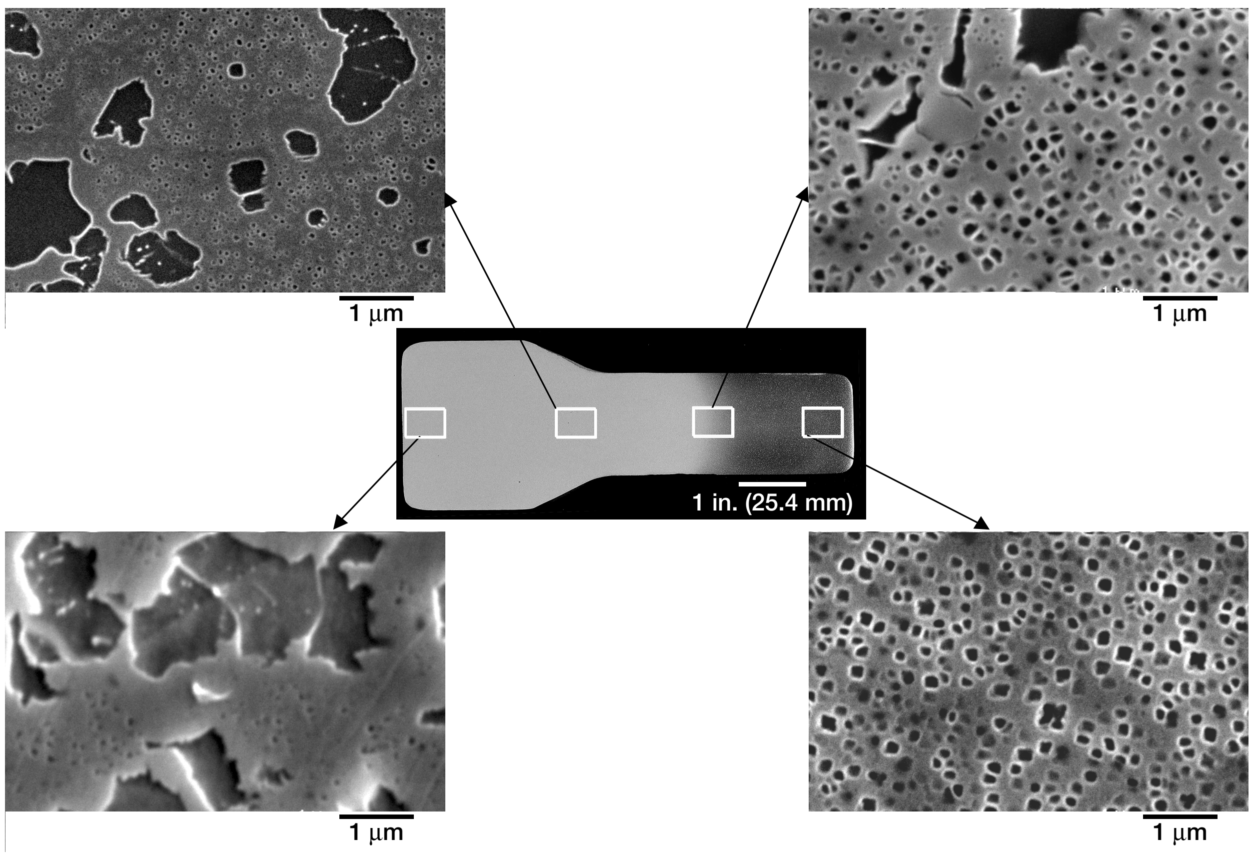

Figure 6.—Cooling gamma prime at various disk locations.

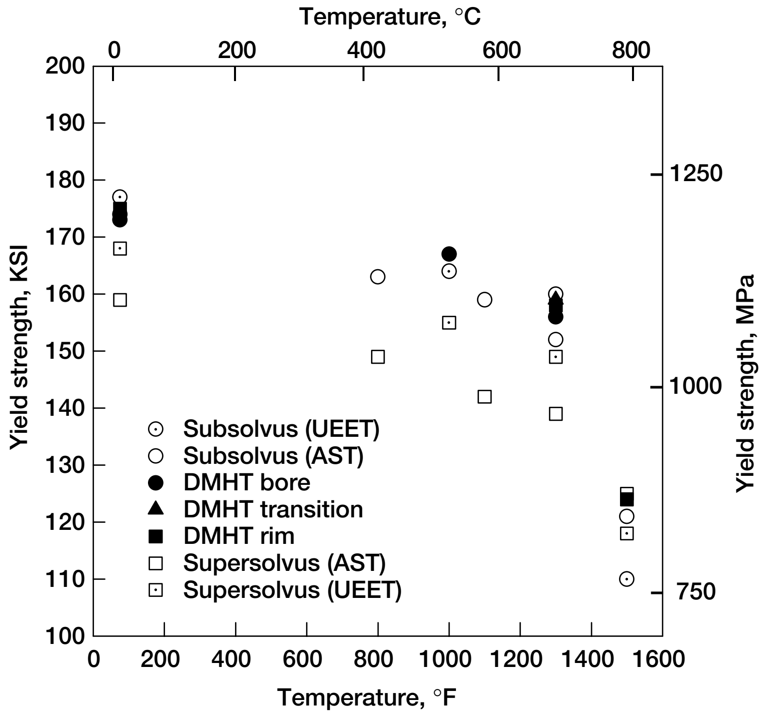

Figure 7.—Comparison of yield strength data for DMHT, AST, and UEET disks.

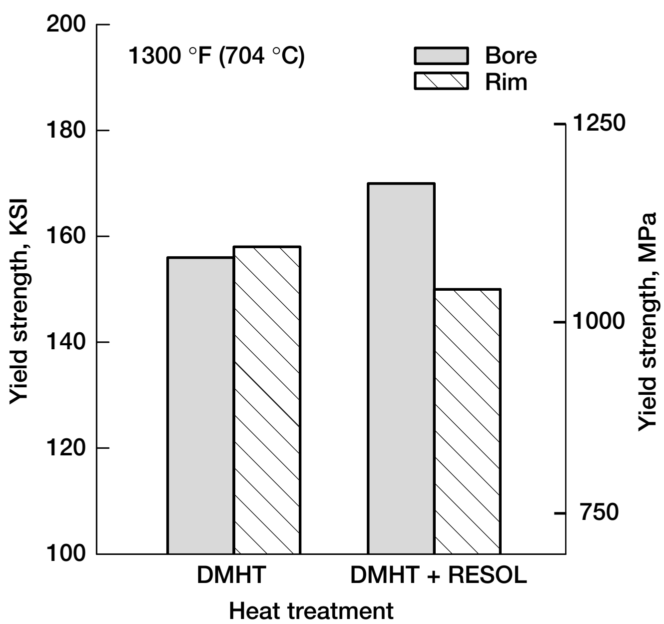

Figure 8.—Effect of resolution treatment on yield strength.

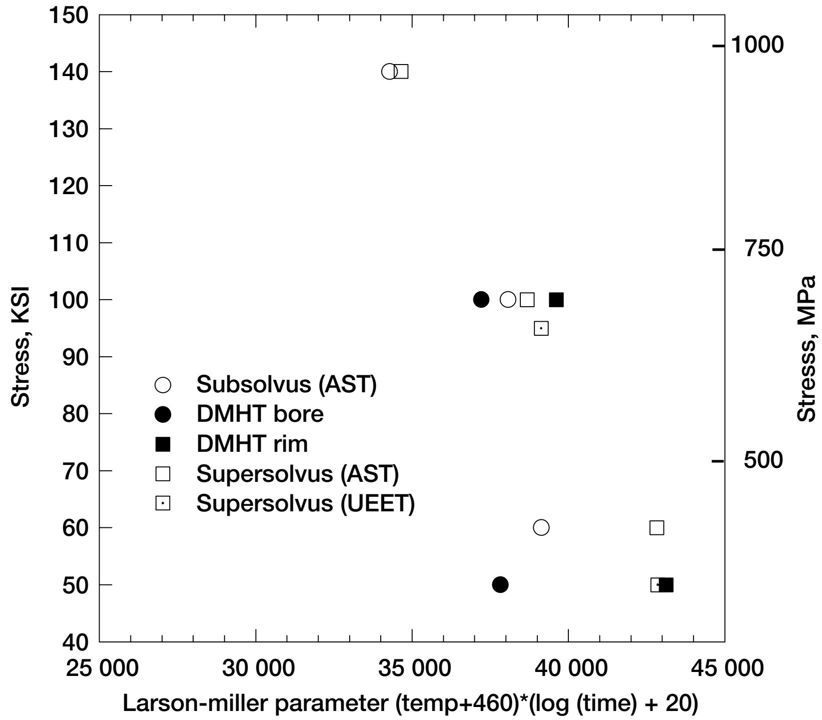

Figure 9.—Comparison of creep rates for DMHT, AST, and UEET disks.

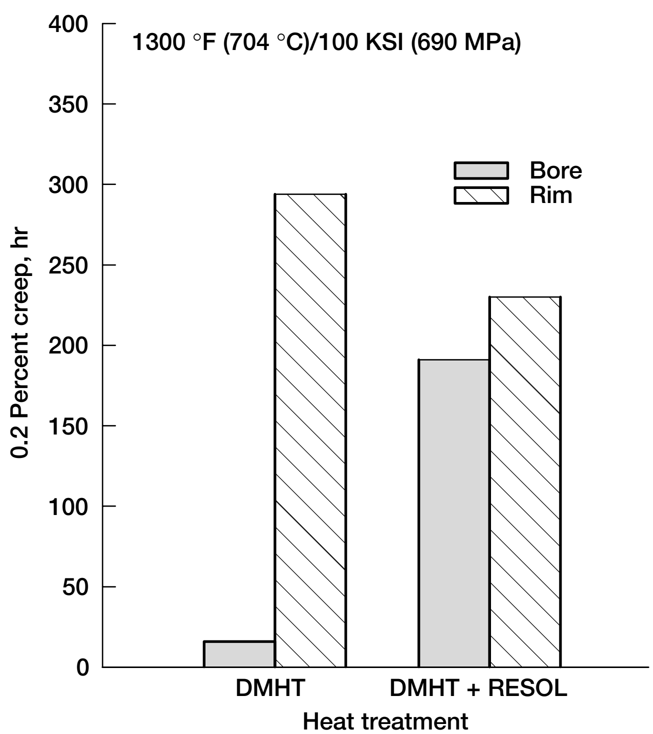

Figure 10.—Effect of resolution treatment on creep rates.

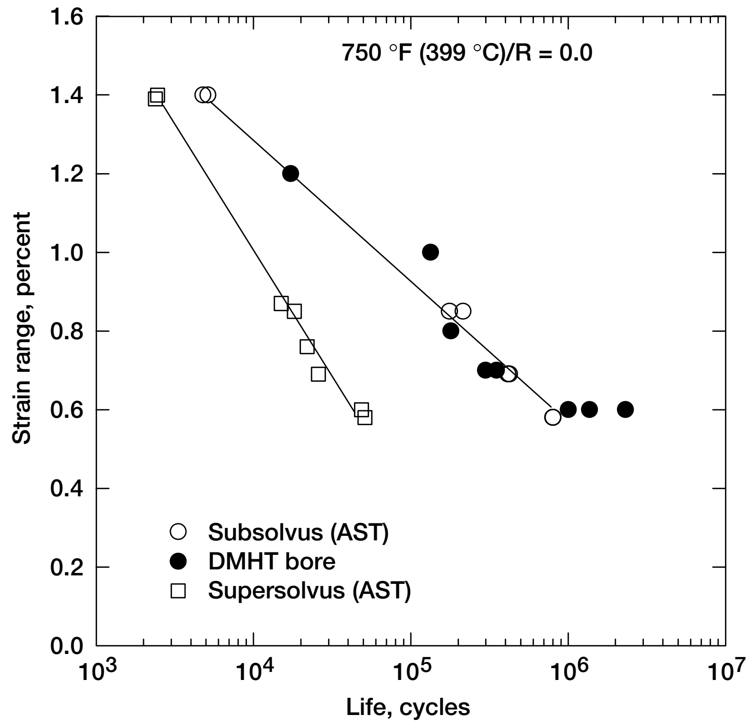

Figure 11.—Comparison of LCF data for DMHT and AST disks.

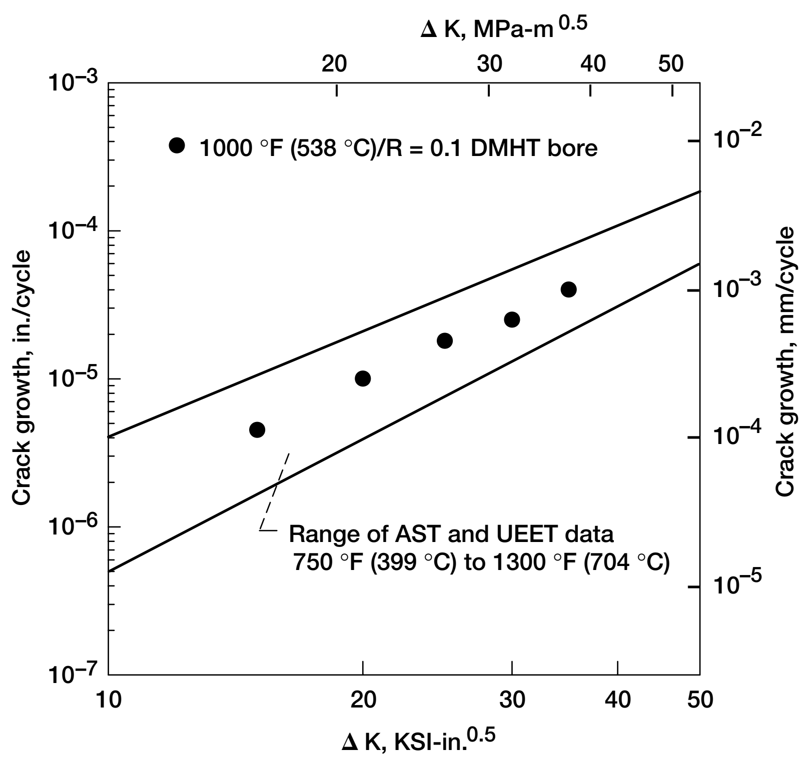

Figure 12.—Comparison of cyclic crack growth data for DMHT, AST, and UEET disks.

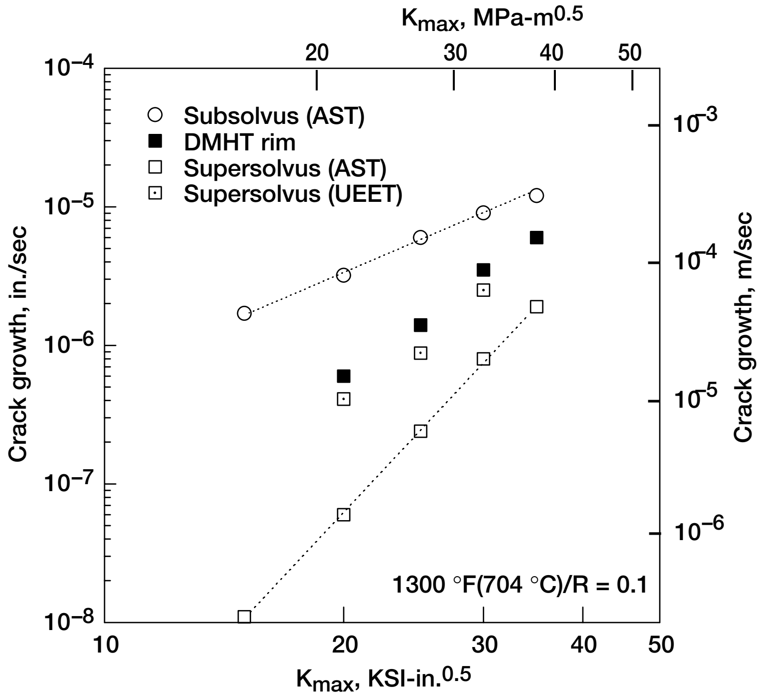

Figure 13.—Comparison of dwell crack growth data for DMHT, AST, and UEET disks.

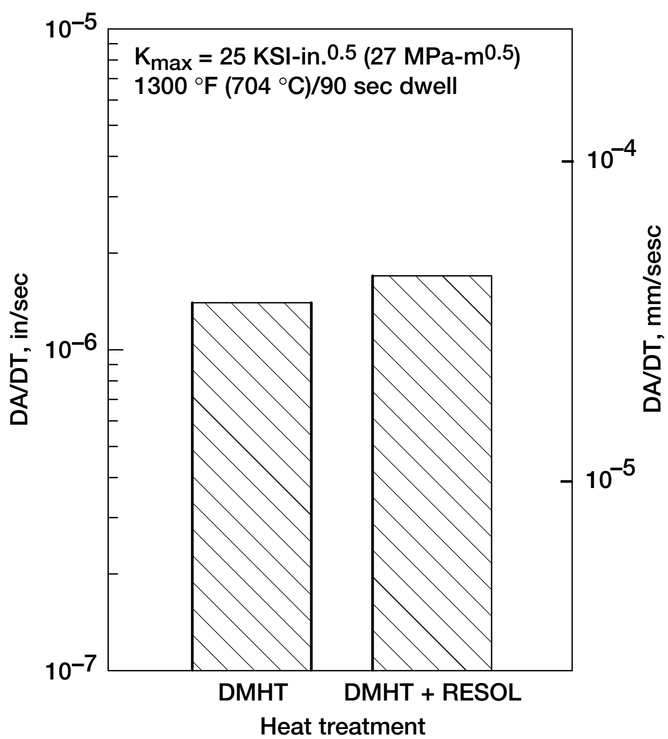

Figure 14.—Effect of resolution treatment on dwell crack growth rate.

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13. ABSTRACT *(Maximum 200 words)*

Mechanical properties from an advanced, nickel-base superalloy disk, with a dual grain structure consisting of a fine grain bore and coarse grain rim, were evaluated. The dual grain structure was produced using NASA's low cost Dual Microstructure Heat Treatment (DMHT) process. The results showed the DMHT disk to have a high strength, fatigue resistant bore comparable to a subsolvus (fine grain) heat treated disk, and a creep resistant rim comparable to a supersolvus (coarse grain) heat treated disk. Additional work on subsolvus solutioning before or after the DMHT conversion appears to be a viable avenue for further improvement in disk properties.

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