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QUALIFICATION OF UNS N07028 FOR FORGED STEAM TURBINE ROTORS

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ABSTRACT

The US Advanced Ultra-Supercritical (A-USC) Consortium conducted an extensive program to evaluate available superalloys for use in rotors for steam turbines operating at a nominal temperature of 760 °C (1400 °F). Alloys such as 282®, Waspaloy, 740H®, 720Li, and 105 were tested in the form of bar supplied from the alloy producers. Ultimately, alloy 282® was down-selected for the turbine rotor based on its combination of creep strength, phase stability, ductility, and fatigue resistance. The next step in development was to produce a full-size rotor forging for testing. A team was established consisting of GE Power (project management and testing), Wyman-Gordon (forging and testing) and Special Metals (melting and billetizing) to pursue the work. A research license to melt the alloy was obtained from Haynes® International.

The first step of the development was to devise a triple melt (VIM-ESR-VAR) practice to produce 610 mm (24 inch) diameter ingot. Two ingots were made, the first to define the VAR remelting parameters and the second to make the test ingot utilizing optimum conditions. Careful attention was paid to ingot structure to ensure that no solidification segregation occurred. A unique homogenization practice for the alloy was developed by the US Department of Energy (DOE) and National Energy Technology Laboratory (NETL). Billetization was performed on an open die press with three upset and draw stages. This procedure produced an average grain size of ASTM 3.

A closed die forging practice was developed based on compressive flow stress data developed by Wyman Gordon Houston for the consortium project. Multiple 18 kg forgings were produced to define the forging parameters that yielded the desired microstructure. The project culminated with a 2.19 metric ton (4830 lb), 1.22 m (48 inch) diameter crack-free pancake forging produced on Wyman Gordon's 50,000 ton press in Grafton, MA. The forging process produced a disk with an average grain size of ASTM 8 or finer.

Forging cut-up, microstructural characterization, and mechanical property testing was performed by GE Power. Fatigue and fracture toughness values of the disk forging exceeded those previously reported for commercially available rolled bar.

Keywords: turbine rotor, A-USC, coal, steam, 282®, triple melt, disk, forging

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BACKGROUND

Development of turbines for advanced ultra-supercritical (A-USC) coal-fired power plants (inlet temperatures up to 760 °C) was a multi-year effort through government/industry collaboration. Funding came from two separate programs for turbines and boilers supported by the U.S. Department of Energy (DOE) and the Ohio Coal Development Office (OCDO). Multiple studies [1-5] in the United States, Japan, and Europe have determined that the goal of operating plants at temperatures as high as 760 °C (1400 °F) and higher stresses can be achieved by the use of nickel based superalloys. A previous study identified alloys 282®, 105, 740H®, Waspaloy, and 263 as potential alloys that met the requirements for the necessary inlet conditions [6]. A key requisite for the success of the program was a need to demonstrate the successful scale up of the down-selected alloy(s) to large components. All property evaluations in the past were performed on commercially available bar/billet.

Components in power plant equipment such as rotors and castings are several orders of magnitude larger than equivalent aerospace components, driving a need to resolve scalability issues. Alloy 105 for example, easily meets the requirements of A-USC conditions, but contains a high volume fraction of γ' (>50%), making it difficult to produce as a large forging. The alloy is best suited for small forgings, valve internals, bolts, and small blades. Alloy 282® contains 20 - 25% volume fraction γ', and meets the down selected criteria for the A-USC conditions. Alloy 282® was therefore selected for large rotating components, though never scaled up for testing and qualification.

DEVELOPMENT OF A TRIPLE MELT PROCESS

Alloy 282® was primarily developed as sheet, bar, and welding consumables for non-rotating components and has been processed via a double melt process [vacuum induction melting (VIM) + electroslag remelting (ESR)] prior to the interest from this program. Alloy 282® is not considered a strongly segregating alloy despite its relatively high molybdenum content [7]. Freckle trajectories in this alloy tend to be upward (similar to Waspaloy) during directional solidification. Nevertheless, the inherently deep pool in ESR combined with melt instability associated with VIM electrode pipe are favorable conditions for freckle formation in very large ingots. Triple melt via VIM + ESR + vacuum arc remelting (VAR) allows the producer to gain refining benefits of ESR and the superior structure control provided by VAR with a sound electrode. Accordingly, in this program it was decided to adopt the triple melt process.

Two 457 mm (18 inch) diameter VIM electrodes were cast and remelted into 559 mm (22 inch) diameter ESR ingots (Fig. 1). The nominal composition of alloy 282® was specified with charge adjustments to account for losses in the additional remelt step. The first ingot was used for VAR process development and the second ingot was used as feedstock for a large disk forging to be described later. The ingot chemistries were confirmed to meet the specified chemistry designation of UNS N07028.

A procedure involving stepwise VAR parameter changes in a single ingot has been developed to minimize the number of test ingots. The changes are built into the remelt profile and usually involve step changes in the melt rate set point and a deliberate power interruption. Based on process simulation software developed by the Special Metals Processing Consortium (SMPC) [8], it is possible to simulate the metal pool profile and thereby identify cutting planes for microstructure validation. Normally the ingot is forged to bar to facilitate inspection. If the ingot is free of segregation at high and low melt rates, these parameters can be used as rejection limits for a qualified melt.

Figure 1: Two VIM electrodes (left) were remelted into two ESR ingots (right).

Large superalloy ingots are well known for their tendency to crack from triaxial stresses generated due to contraction during cooling and a coarse, low ductility cast ingot microstructure. Consequently in this program, careful control of the multiple heating and cooling cycles in the melting, homogenization, and forging stages was applied.

The two VIM-ESR ingots were remelted again by VAR to produce a 610 mm (24 inch) diameter triple melt (VIM-ESR-VAR) product. The first ingot was remelted utilizing a variable melt rate profile and an intentional sixty-second power interruption as shown in Fig. 2. The ingot was then homogenized using a heating cycle determined by Dr. Paul Jablonski at the National Energy Technology Laboratory (NETL) utilizing the DICTRA® software [9]. The homogenized ingot was forged into a 203 mm (8 inch) diameter bar (Fig. 3) for the evaluation of microstructure and macro-structure. No internal cracking was experienced. Multiple transverse sections from the billet were etched with Canada's Etch to reveal segregation tendencies for the various remelt conditions as shown in Fig. 4. No indications of freckles or white spots were observed. Microstructural analysis was also performed on the cross-sections to confirm the grain size obtained during the manufacturing of billet. Representative micrographs are shown in Fig. 5 showing an average grain size of ASTM 6-7 with grains as large as ASTM 3 at the center. The second VIM-ESR piece was then remelted into a 610 mm (24 inch) diameter VIM-ESR-VAR ingot under melt rate control based on a set point derived from the successful segregation-free remelt of the first ingot.

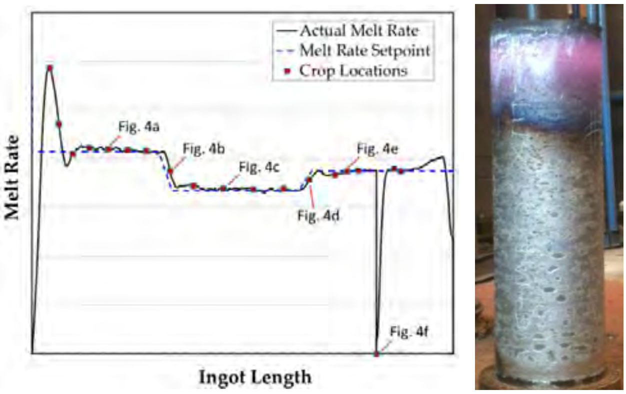
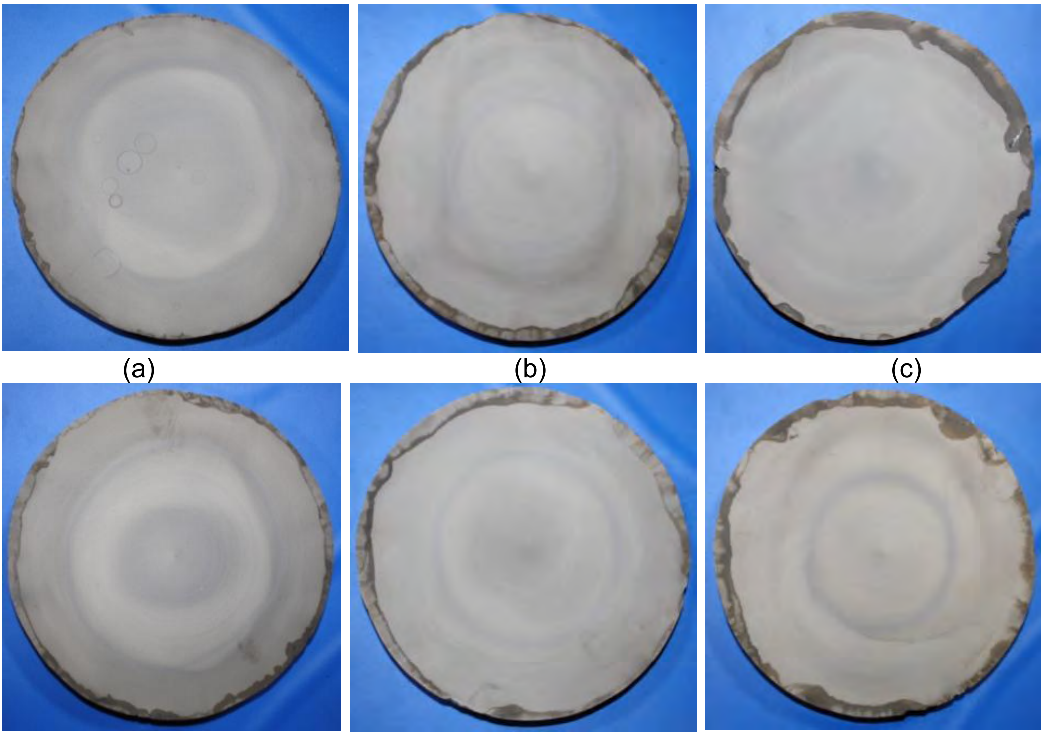


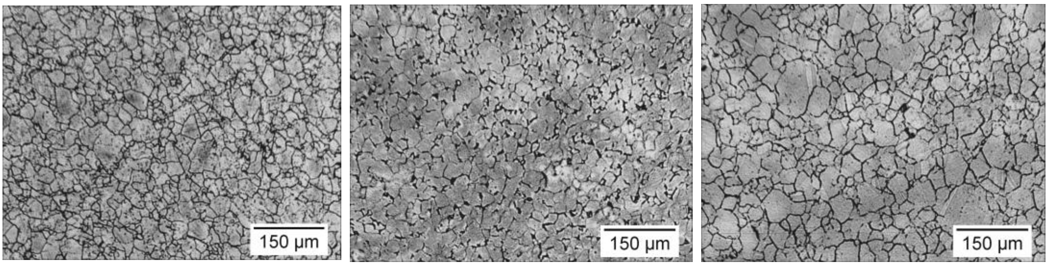
Figure 2: VAR trace (left) from the first triple melted 610 mm diameter alloy 282® ingot showing the varying melt rate profile and intentional power interruption. Indicated crop locations show the areas of sectioning for macro-etch evaluation. Representative macro-etch photos are shown in Fig. 4 from locations indicated on the melt profile.

Figure 3: Triple melted ingots forged to 203 mm diameter for macro-segregation evaluation.


(a) (b) (c)

(d) (e) (f)

Figure 4: Representative macro slices from first VIM-ESR-VAR ingot, shown etched with Canada's Etch to reveal segregation tendencies of the alloy. Macro-etch images correspond to remelt locations indicated in Fig. 2.



(a) (b) (c)

Figure 5: Representative microstructures showing hot worked structure of the homogenized and forged bars at the (a) surface, (b) mid-radius, and (c) center location.

FORGING PROCESS DEVELOPMENT

During the remelting trials, hot deformation experiments on alloy 282® were performed in parallel at Wyman Gordon Houston with commercially available VIM-ESR bar to develop optimum forging conditions. Multiple cylindrical specimens with 12.7 mm (0.5 inch) diameter x 19 mm (0.75 inch) height were heat treated to 1040 °C (1900 °F) for 4 hours and fan cooled prior to hot compression testing. The specimens were then preheated for deformation to ranging temperatures (870-1100 °C or 1600-2012 °F) and compressed to a strain of 0.7 at ranging strain rates (0.001-3.2 s^{-1}). Flow stress data and the resultant microstructures were evaluated and modeled.

The most commonly used equation to model the effect of strain rate and temperature on the steady state flow stress is shown in Equation 1 [10]:

$$\dot{\varepsilon} = Z \exp\left(\frac{-Q}{RT}\right) \qquad \text{(Eq. 1)}$$

where $\dot{\varepsilon}$ is strain rate, Q is the activation energy for deformation, R is the ideal gas constant, T is temperature, and Z is the Zener-Holloman parameter, defined in Equation 2 as [10]:

$$Z = A_1\left[\sinh(\alpha_1\sigma)\right]^n \qquad \text{(Eq. 2)}$$

where A_1 and α are empirical material constants, n is a stress exponent (defined as the inverse of strain rate sensitivity), and σ is steady state flow stress.

Using the flow stress data from hot compression tests and non-linear regression to determine the activation energy, strain rate sensitivity, and material constants, the model shown in Equation 3 was developed to predict steady state flow stress in alloy 282®:

$$\sigma = 470\sinh^{-1}\left\lfloor \left(4.77\times10^{-7}\right)\dot{\varepsilon}^{0.26}\exp\left(\frac{19{,}165}{T}\right)\right\rfloor \qquad \text{(Eq. 3)}$$

The hot compression flow stress computational model was used to design the ingot breakdown/billetizing procedure at Special Metals for the second triple melted ingot. Finite element modeling was used to simulate stress, strain, and temperature. This simulation showed that a forge practice with three upset and draw operations was needed on an open die press to ensure a minimum 4:1 reduction ratio. The simulation also allowed the upset percentage, starting and reheat temperatures, and draw pass schedule to be designed.

The ingot was successfully converted to a 508 mm (20 inch) diameter “bingot” (defined as billetized ingot) at Special Metals with minor surface cracking and shape control issues. Following forging, the bingot was homogenized utilizing the NETL-developed process described earlier. The homogenized ingot was spiral ground, cropped, and shipped to Wyman Gordon Grafton for disk forging.

In order to determine the optimum forge sequence and heating temperature for producing a disk forging, a slice was taken from the end of the bingot for sub-scale forging trials. Two 127 mm (5 inch) diameter X 171 mm (6.75 inch) length slugs were machined from the slice, heated to 1040 °C (1900 °F), and upset forged into pancakes at Wyman Gordon Houston. The first slug was forged using two 2:1 reduction ratio upset operations with an intermediate air cool and reheat for a total 4:1 reduction ratio. The second slug was forged to a 4:1 reduction ratio in one upset operation. A one-inch slice was removed from each sub-scale forging and a center-to-edge specimen was prepared and etched for metallography. A representative grain size map is shown in Fig. 6 from the first sub-scale forging. The grain size matched expectations from the hot compression test evaluations described earlier.

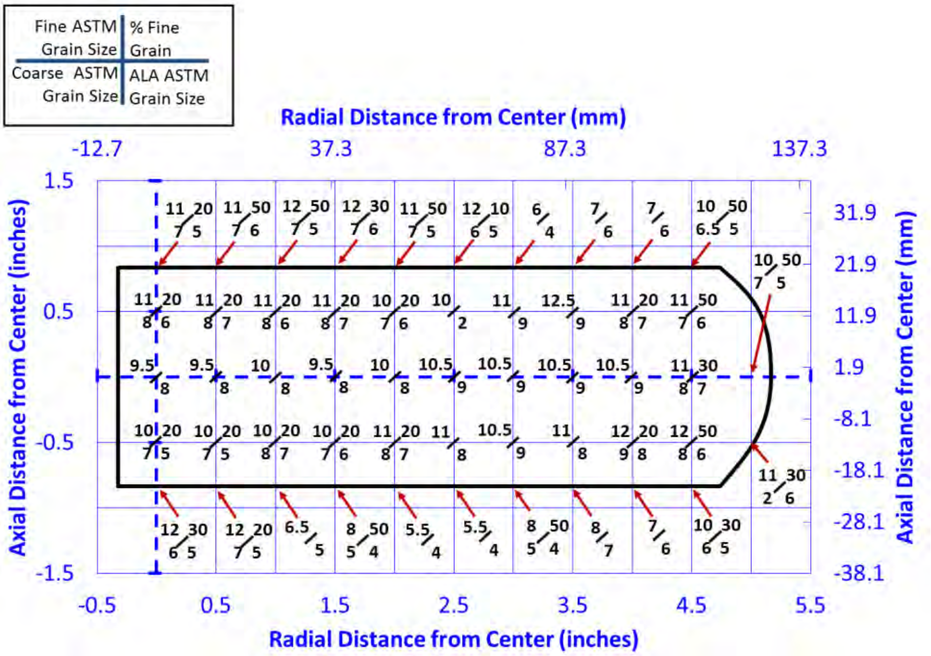


Figure 6: Microstructural map of a sub-scale forging manufactured with two 2:1 reduction ratio upset operations at Wyman Gordon Houston.

Based on the data obtained from hot compression lab studies and the sub-scale forgings, a triple upset process was developed to forge a large diameter disk at Wyman Gordon Grafton using the triple melted bingot supplied by Special Metals. The 508 mm (20 inch) bingot was heated at 1038 °C (1900 °F) and successfully forged to a 1.25 m (49 inch) bulge diameter/1.12 m (44 inch) minimum diameter x 241 mm (9.5 inch) height disk using three upset operations at Wyman Gordon. The progression of forging and resulting disk is shown in Fig. 7 with very little observed tearing.

PROPERTY EVALUATION

The disk forging was divided into multiple zones for property evaluation, as shown in Fig. 8. Each zone was tested and evaluated for microstructure, grain size, grain orientation, tensile properties, fatigue, fracture toughness, and stress rupture. Test specimens were obtained from each section in the radial, tangential, and axial orientations.

Figure 9 shows a grain misorientation map from the disk forging obtained by Philip Maziasz at Oak Ridge National Laboratories (ORNL) utilizing Electron Backscatter Diffraction (EBSD). Typical grain size was ASTM 8-9, consistent with the sub-scale pancake forging described previously and shown in Fig. 6. As indicated by the color distribution, the grains were randomly oriented with no apparent texture.

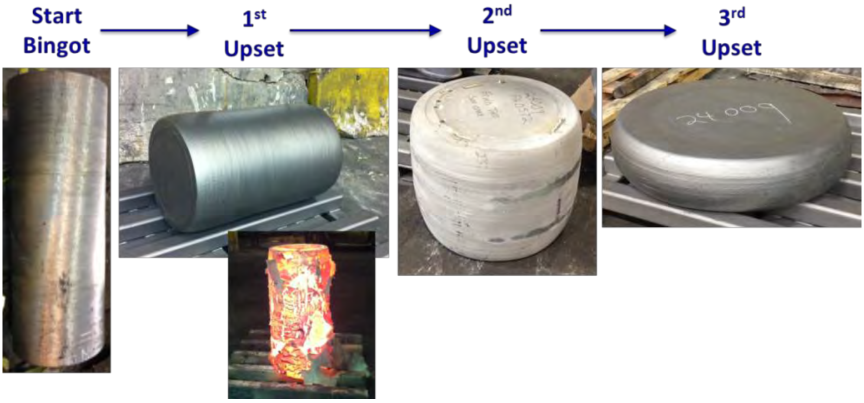


Figure 7: Disk forging progression of triple melted ingot. The final disk forging dimensions were 1118 mm diameter at the top, 1257 mm diameter at the bulge, and 241 mm thickness.

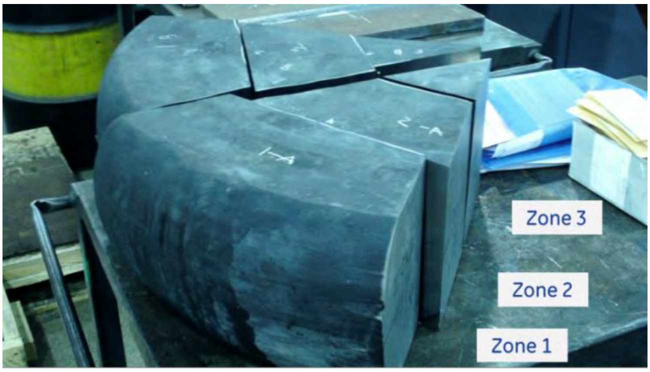


Figure 8: Final forged disk, shown cut into various zones for property evaluation.

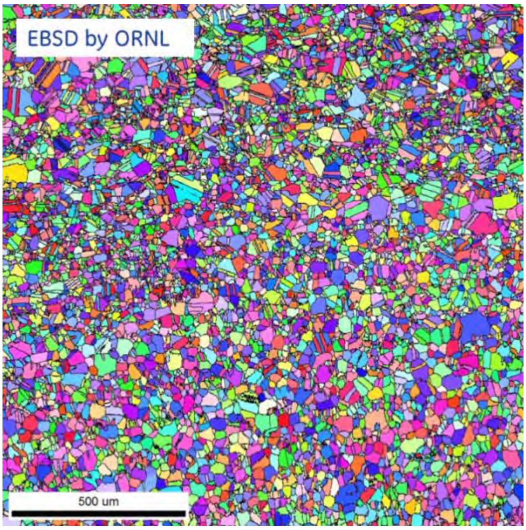


Figure 9: EBSD grain misorientation map showing the grain size distribution obtained in the disk forging (Courtesy of ORNL). Typical grain size was ASTM 8-9, ALA ASTM 4. See electronic version for color.

Tensile properties from the forged disk are shown in Figs. 10 and 11. The disk exhibited uniform and isotropic tensile behavior, as expected. Low cycle fatigue tests at 760 °C (1400 °F) were performed in all orientations at 20 cpm and a triangular waveform. Hold time fatigue tests were performed at the same temperature with a trapezoid waveform with a 6 hour and 1 hour hold at peak strain. Figure 12 compares the debit due to the presence of hold time. The debits in the hold time fatigue life of the fine uniform ASTM 8-9 disk forging were less pronounced when compared to similar studies performed on ASTM 3-4 bar product [11].

Figures 13-15 compare the fatigue, fracture toughness, and stress rupture behavior of the fine grain (ASTM 8-9) triple melted disk to larger grain double melted bar (ASTM 3-4). The forged disk demonstrated superior fatigue and fracture toughness properties when compared to rolled bar due to the finer grains and microstructure cleanliness from triple melting. However, the disk forging had slightly lower rupture strength, likely due to the finer grain size.

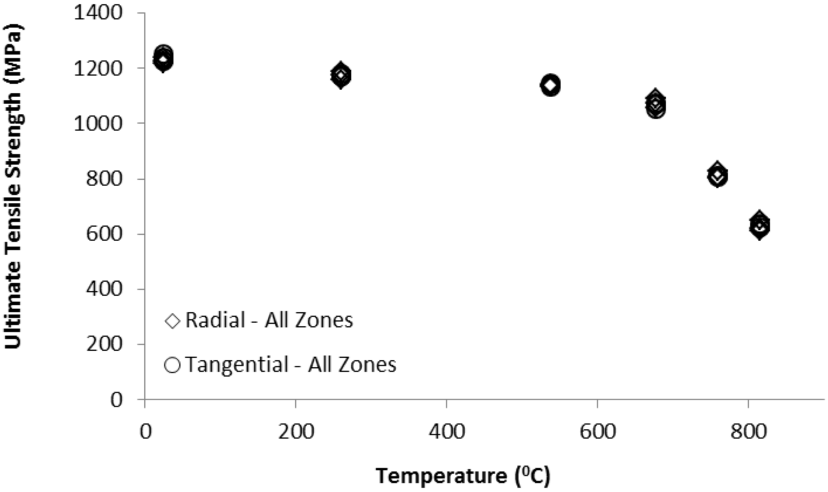


Figure 10: Ultimate Tensile Strength of the disk forging, showing isotropic and uniform behavior in all zones.

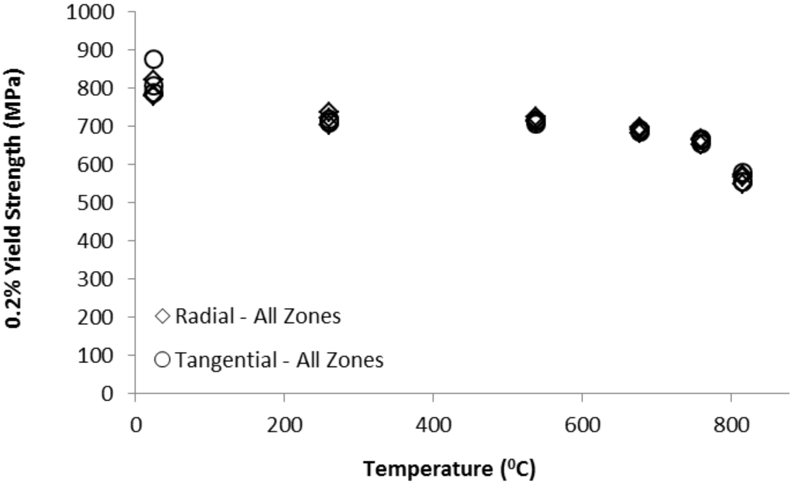


Figure 11: Yield Strength of the disk forging, showing isotropic and uniform behavior in all zones.

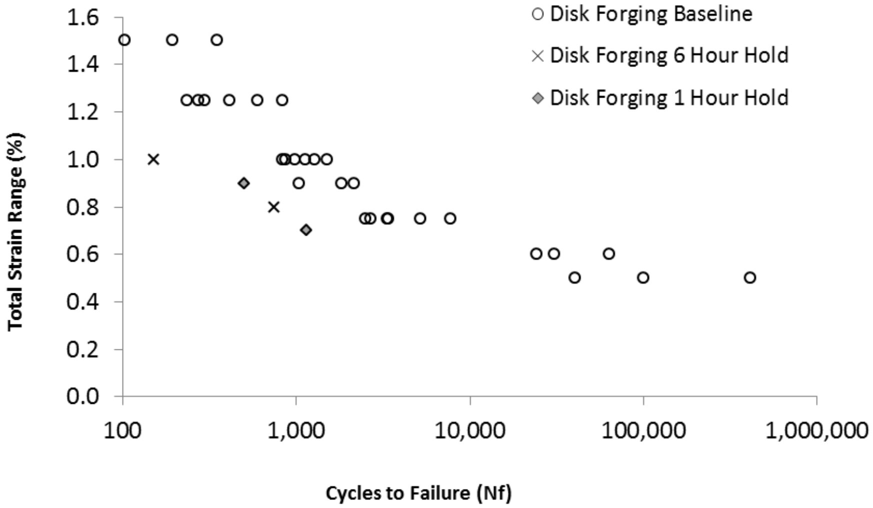


Figure 12: Low cycle fatigue life using a trapezoid waveform (Hold at peak stain for 1 & 6 Hours) of the disk forging at 760 °C.

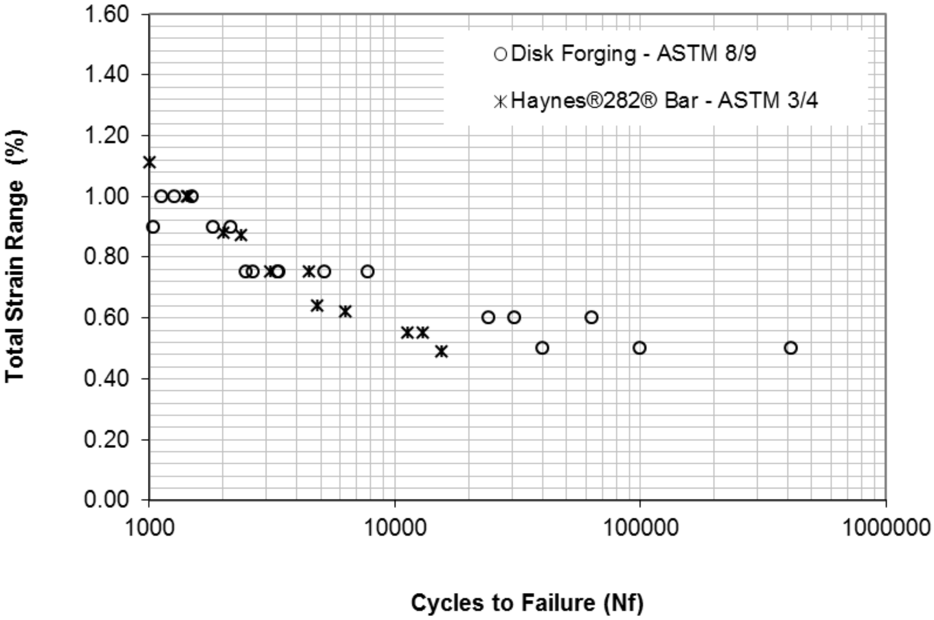


Figure 13: Low cycle fatigue behavior at 760 °C, comparing the fine grain triple melted disk forging to VIM-ESR rolled bar (A_{strain} =1, 20 cpm).

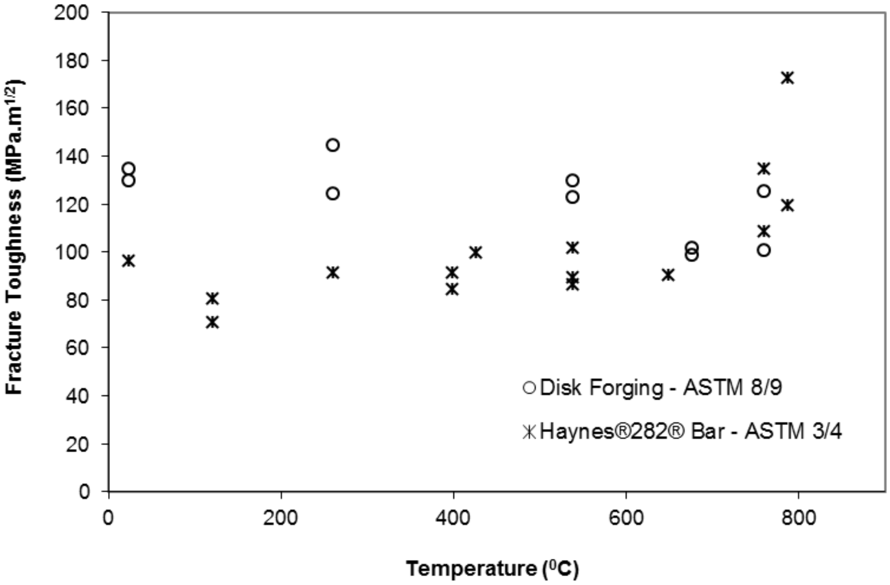


Figure 14: Fracture toughness, showing the difference between coarse grain double melted bar and the fine grain triple melted disk forging.

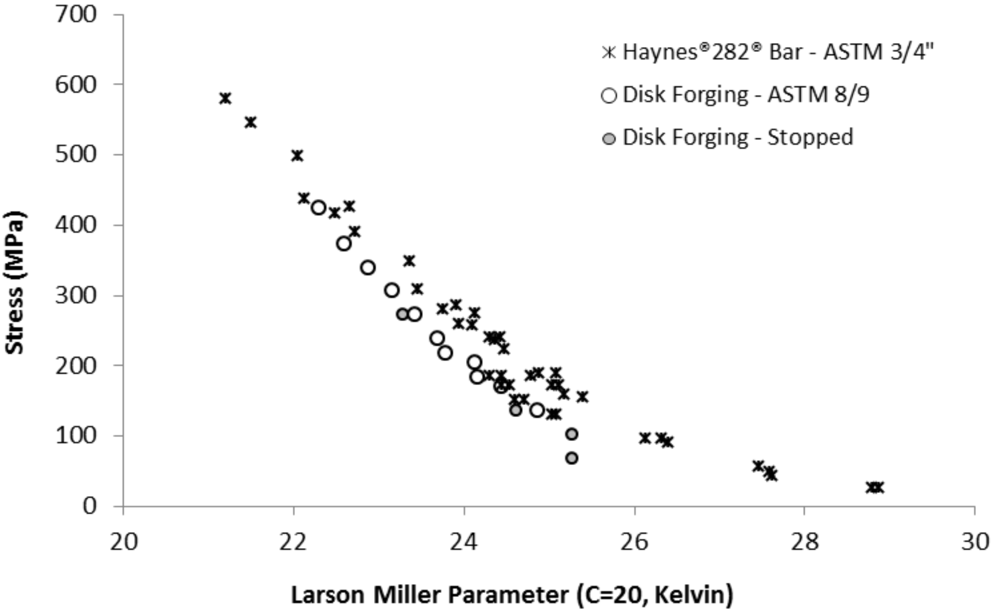


Figure 15: Rupture properties, comparing coarse grain bar and the fine grain disk forging.

CONCLUSIONS

The paper demonstrated the successful scale up of alloy 282® to a large disk forging via a triple melt process. The fine grained alloy 282® disk forging exhibited superior fatigue properties when compared to rolled bar. The debit in rupture properties due to the fine grain structure should be considered as a trade-off between fatigue and creep during the design of the final A-USC turbine component.

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