APPLICATION OF ULTRA FINE GRAIN ALLOY 718

FORGING BILLET

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Abstract

Alloy 718 has been frequently used for aerospace applications where excellent high temperature strength and resistance to fatigue are required. Thermomechanical processing plays a vital role in controlling the microstructure and properties in this alloy. The effect of a "delta dump" process during billet conversion on the thermomechanical response of an Alloy 718 hot die forging is presented. A billet with an essentially uniform microstructure of ASTM 9 grain size was produced and was ultrasonic inspected to a 0.4mm (1/64in.) FBH. A typical aircraft engine contoured disk was hot die forged from the ultra fine grain billet, sectioned, and the effect of direct age and solution heat treatment at various temperatures from 1750°F-1900°F plus age on mechanical properties was studied. The microstructural changes were characterized using optical microscopy, SEM, and quantitative metallographic techniques. Mechanical properties are presented and compared to changes in both grain size and delta content It is shown that the "delta dump" process can be used to improve billet quality and ultrasonic inspectability and that mechanical properties of forgings made from this billet can be optimized using an appropriate solution heat treatment temperature.

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Introduction

Advances in aircraft engine component design will require that the properties of a material be used to their full extent. For rotating components such as disks, spools, and shafts, this generally requires maximizing the cyclic capability and tensile properties through material selection and control of final forging grain size (1). By controlling both the quality of the input material (billet chemistry and grain size) and the forging process (temperature, strain, strain rate etc.), forgings that consistently exhibit desired properties can be produced. The use of the press forging process, especially with warm or hot dies, has reduced the variability between forgings; however, billet processing, including melting and conversion, remains variable(2).

Alloy 718 has been one of the most frequently used alloys in aircraft engines because of the wide variation in properties that can be developed through thermomechanical processing(3). Numerous reports in the literature describe the microstructural constituents that control Alloy 718 properties. These include grain size, orthorhombic delta phase, and the coherent precipitates γ'' and γ'(1). Low temperature/fine grain processing has been applied to billet/bar with ultrasonic inspectability equivalent to a 2/64 FBH(4,5). This inspection level has been attributed to controlled billet grain size. Additional improvement in billet inspectability, to an equivalent 1/64 FBH, and elimination of the effects of forging die chill could be achieved if forgings were made from billet that exhibited final forging grain size, i.e. "ultra fine grain" billet. This paper describes the processing of ultra fine grain Alloy 718 billet and the resulting properties of a hot die forging as a function of various heat treatments.

Materials and Testing

The Alloy 718 billet material was produced from a 500 mm (20") diameter double melt ingot (VIM-VAR). The chemical composition met typical rotating grade specifications and had a combined tantalum plus columbium content of 5.35 wt. %. The ingot was thermomechanically processed by press cogging to 280mm (11") diameter in accordance with now standard fine grain processing which included a double homogenization and double upset and draw. The billet product at this diameter had a grain size of ASTM 6-8 at the surface and ASTM 4-6 at the center.

The billet conversion deviated from standard fine grain processing at 280mm (11") diameter. The billet was heated to 1675°F for 28 hours to produce a large volume fraction of delta phase, in order to pin grain boundaries and promote recrystallization during subsequent cogging. An example of this "delta dump" microstructure is shown in Figure 1. The delta phase has precipitated both intergranularly and transgranularly as continuous or semi-continuous precipitates.

After the precipation heat treatment, billet conversion was continued, reducing the billet diameter from 280mm (11") to 200mm (8"). The cogging was performed at a lower than normal temperature so as to maintain the high delta concentration. After conversion, the billet was air cooled and bar peeled for sonic inspection prior to forging.

The resultant grain structure was generally uniform across the diameter. The grain size was ASTM 9-10 with less than 20% highly worked (unrecrystallized) grains as large as ASTM 7. This is a finer microstructure than observed in standard fine grain billet. The resultant structure in the center of the billet is shown in Figure 1. The delta phase laths have been fractured by the deformation into smaller size particles, which act as grain boundary pinning points.

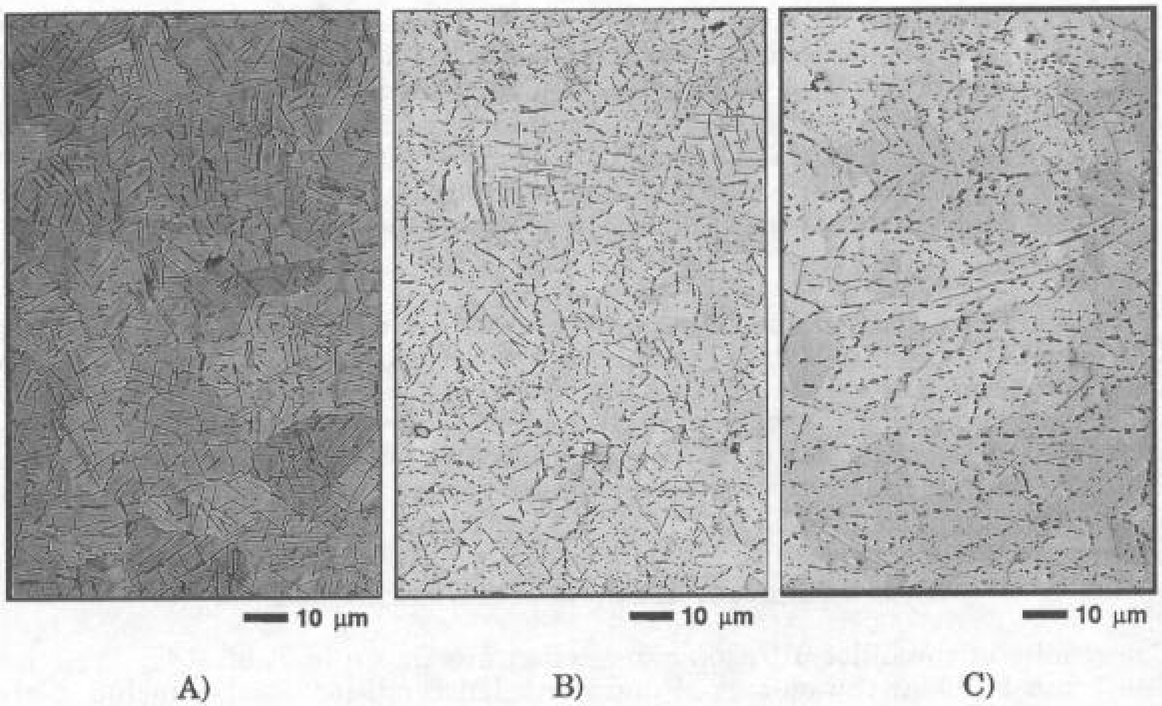


Figure 1. Scanning electron micrographs showing the typical structure of A) "delta dumped" billet, B) ultra fine grain billet, and C) As forged conditions.

The ultra fine grain product was ultrasonic inspected in the as-cogged and after a 1800°F/2 Hour/AC conditions. This anneal heat treatment solutioned some of the delta phase and resulted in a fully recrystallized structure of ASTM 9. The ultra fine grain billet (with and without an anneal), production fine grain billet, and standard production billet were ultrasonic inspected using high sensitivity ultrasonic inspection techniques.

The 200mm (8 ") diameter ultra fine grain billet was forged into a 460mm (18") diameter disk shape in a single forge operation at 1800°F. The die temperature was 1200°F, and the forging was quenched into water directly off the press.

To study the effect of partial solution heat treatment, the forging was sectioned into eight pie shaped pieces. One section was left in the unsolutioned condition (direct age) and one section was solution heat treated for 1 hour at a selected temperature in the range of 1750°F-1900°F, in 25°F increments. After solution, all eight sections were given the widely used Alloy 718 age(1325°F/8hr, 1150°F/8hr).

Mechanical property and metallographic specimens were cut from each of the eight sections as follows: four tensile specimens with a gage diameter of 45mm (0.1785") and a gage length of 25mm (1.0"), four creep specimens with a gage diameter of 6.4mm (.250") and with a 31.75mm (1.250") gage length, and three LCF specimens with a 6.4mm (0.250") diameter and 25mm (1.00") gage. A 12.3mm (0.500") extensometer was used to monitor LCF strain. Tensile tests were run at R.T.(1 test), 750°F (2 tests), and 1200°F(1 test); creep tests were performed at 1100°F/825 MPa (120ksi) and 1200°F/620 MPa (90ksi); and low cycle fatigue tests were carried out in strain control at, A=1, 0. 66% strain range at 750°F.

In addition to the 1 hour solution heat treatment given the pie sections, coupons were given additional solution heat treatments of either 2 or 4 hours resulting in total exposure times of 1, 3, and 5 hours. Evaluation of the effects of the additional time at temperature were limited to microstructural changes only because of limited material availability. Microstructural analysis consisted of standard metallographic examination and scanning electron microscopy. Grain size determination was by the Heyn intercept method per ASTM E112.

The amount of orthorhombic delta phase present after each heat treatment was determined by quantitative metallographic techniques using a Buehler Omnimet computer system. Scanning electron photomicrographs of polished and etched samples were taken at three magnifications. The percentage of delta phase was determined for each magnification and averaged. This method was chosen to minimize the error associated with inadvertently including a carbide or carbonitride particle as delta phase.

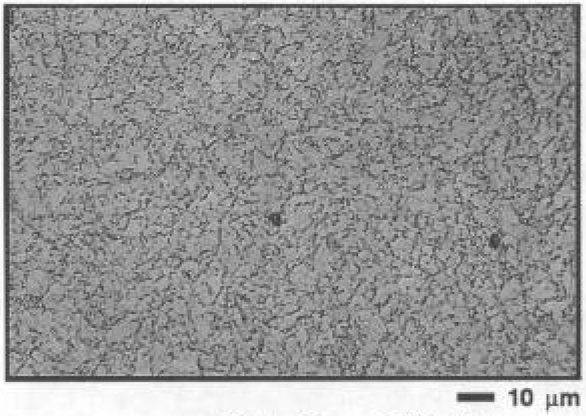
Material Structure and Inspection Results

The results of the billet ultrasonic inspection are shown in Table I for the ultra fine grain billet in the as-cogged and annealed conditions. Also included are comparative data for production fine grain and standard grade billet. The results indicate that there is a significant improvement in the ultrasonic penetrability for the ultra fine grain billet compared to standard fine grain and uncontrolled grain size material. There was no reported difference between the as-cogged and cogged-plus-annealed material.

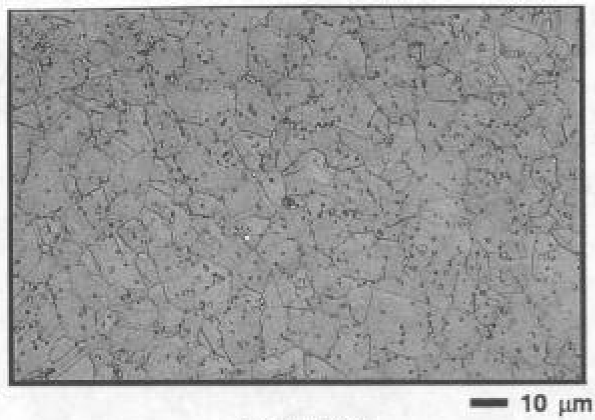
Table 1 Billet Ultrasonic Results

Billet	ASTM Grain Size	Far Zone Noise
Ultra fine grain, As cogged	10	16%
Ultra fine grain, Annealed	9	16%
Production fine grain	Rx 9-6,UnRx 4	40%
Production, Standard grade	NA	50%

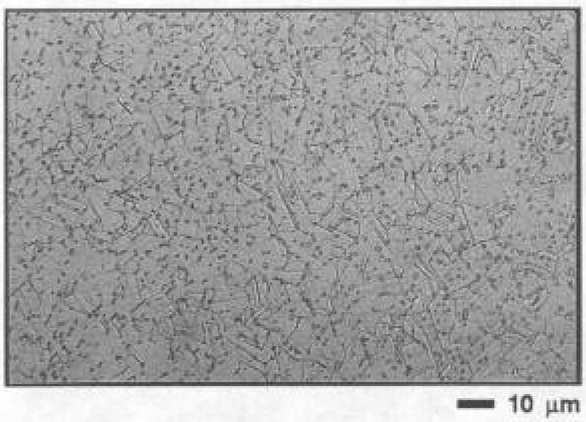
Forging produced further refinement of the billet structure. The forging macrostructure was uniform throughout and the resultant grain size was a uniform ASTM 13. The use of ultra fine grain billet has eliminated any regions of coarse grain that may have been produced because of die lock or die chill. Photomicrographs showing typical structures of the as-forged, and three of the solution heat treatments are shown in Figure 2. A summary of the average grain size vs solution temperature and time at temperature is shown in Figure 3. The accuracy of these measurements was estimated to be ±1.0 ASTM grain size number. As a result of this variability, the grain sizes reported for heat treatments from 1775°-1850°F have been assumed equal.



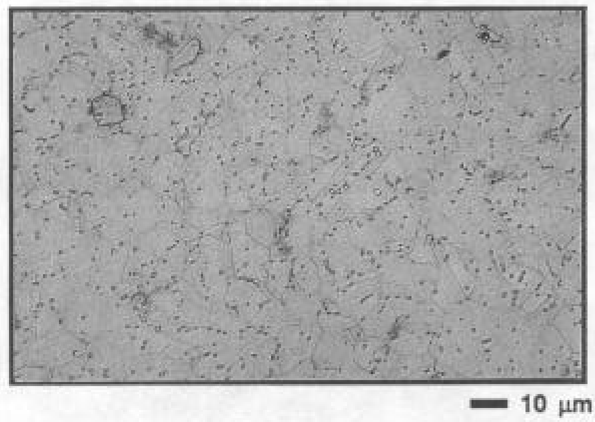
A) As Forged (DA)



B) 1775°F

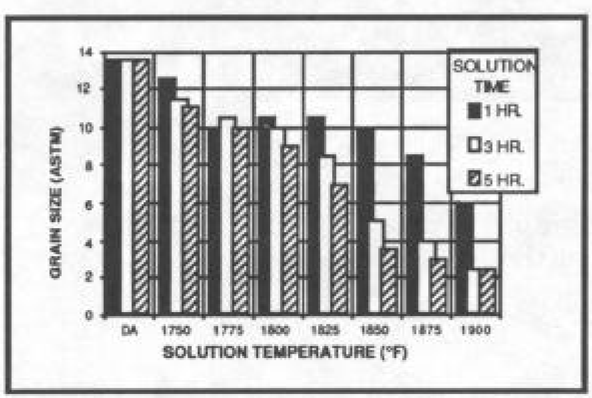


C) 1825°F



D) 1875°F

Figure 2. Photomicrographs of typical structures after one hour solution heat treatment at temperature.



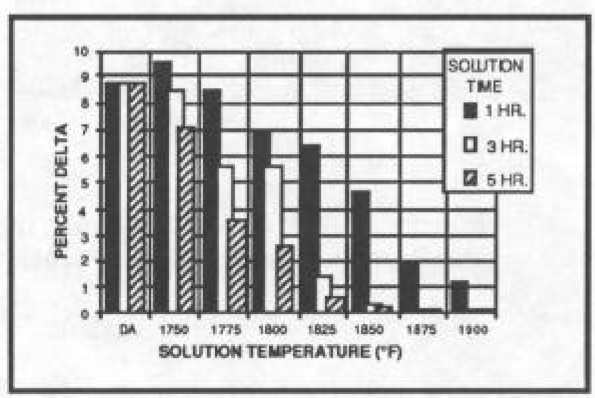
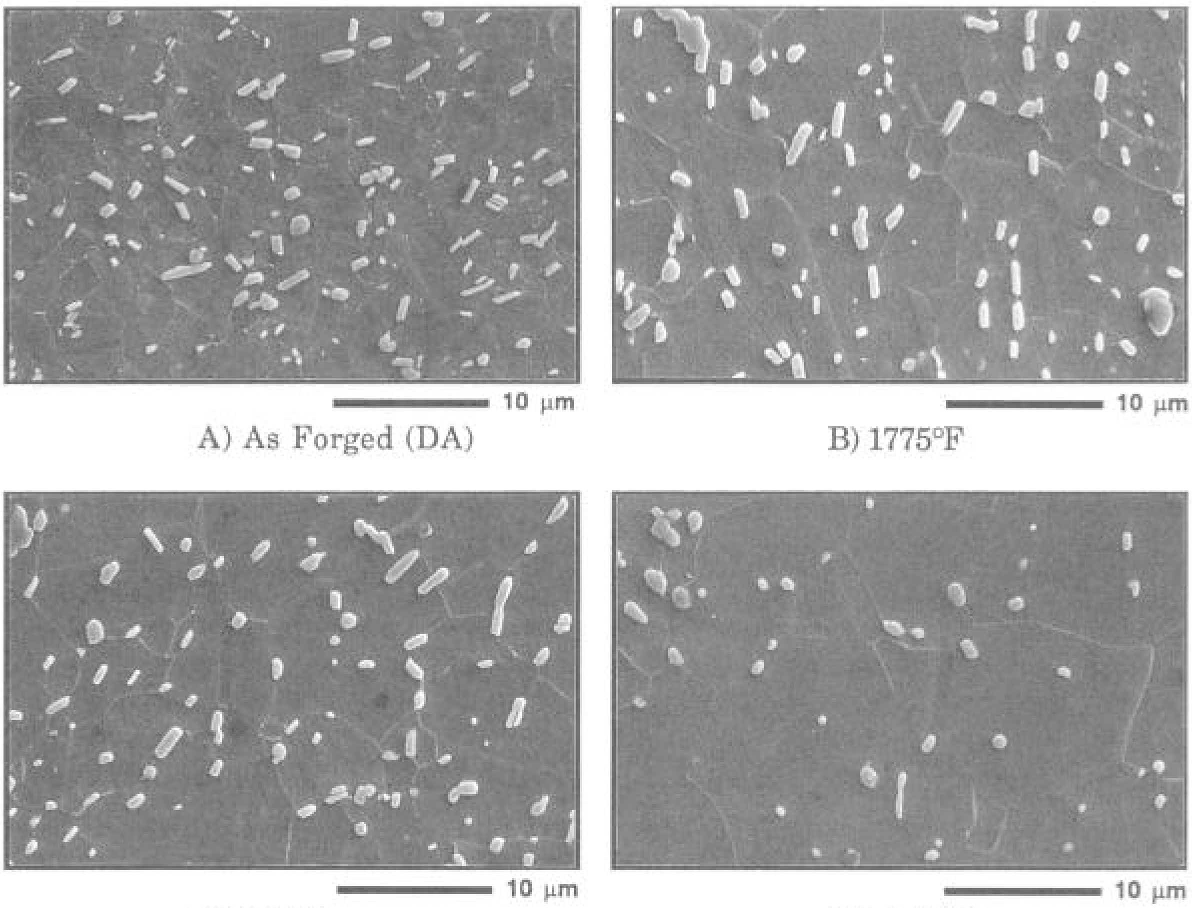


Figure 3. Grain size and Delta phase content as a function of solution temperature and time at temperature.

Scanning electron micrographs showing typical delta phase size and distribution after partial solution heat treatment are shown in Figure 4. A summary of the percent delta phase measurements as a function of solution temperature and time at temperature is included in Figure 3.

As anticipated there is a significant effect of both time and temperature on delta dissolution. The delta content decreased with time even at 1750°F due to the large amount of delta that had precipitated during billet conversion. The rate of dissolution increased dramatically at 1825°F, where the delta content went from 6.5% to 1.5% between 1 and 3 hours. At 1850°F and above there was less than 0.25% delta present in the structure after 3 hours at temperature.

The grain size followed a similar trend with time and temperature as shown in Figure 3. There was some grain coarsening at all solution temperatures, but the most rapid coarsening occurred at 1850°F and above.



A) As Forged (DA) B) 1775°F

B) 1825°F C) 1875°F

Figure 4. Scanning electron micrographs showing typical delta phase distribution after one hour solution at the noted temperature.

Testing Results

The tensile results are presented in Figure 5 which shows the 0.2% yield and ultimate tensile strengths as a function of solution temperature. The yield strength at room temperature and 750°F had a minimum at a solution temperature of 1775°F, increased with solution temperature to 1850°F and then decreased at higher solution temperatures. The 1200°F yield strength followed a similar trend although it exhibited a somewhat steeper slope and there was no minimum at 1775°F. The same trends were observed with the ultimate tensile strength as a function of solution heat treat temperature, although the magnitude of the effects was less.

The low cycle fatigue properties, as a function of the grain size that resulted from the one hour solution heat treatment, are shown in Figure 6. The range of cyclic life (three tests at each condition) is also shown. For comparison the expected average life for Alloy 718 with a grain size of ASTM 6, 8, and 10 are included. The general trend of increasing cyclic life with decreasing grain size is readily apparent. The data grouped around a grain size of ASTM 10 are the result of solutioning at 1775-1850°F.

Figure 7 shows the average creep behavior for each heat treatment at 1100°F/825 MPa and 1200°F/ 620 MPa, respectively. The time to reach 0.2% creep increased with increasing solution temperature. Recall that Figure 4 showed that solution heat treatments 1775°F-1850°F resulted in similar grain size, and that the amount of delta phase decreased with increasing temperature over this temperature range. The creep results indicate that delta content should be minimized to improve creep life.

Discussion

The "delta dump" heat treatment resulted in delta phase precipitation on (111) planes of the face centered cubic austenitic nickel matrix and as a continuous or semicontinuous grain boundary phase (6,7). Subsequent thermomechanical working during billet conversion from 280mm (11") to 200mm (8") diameter breaks up the intragranular and the grain boundary delta into smaller discrete particles. Although the amount of deformation is sufficient to randomly disperse the matrix delta, the grain boundary delta remains in the "ghost" structure observed in Figure 1. Subsequent deformation during forging was sufficient to further disperse the delta phase resulting in an essentially uniform distribution.

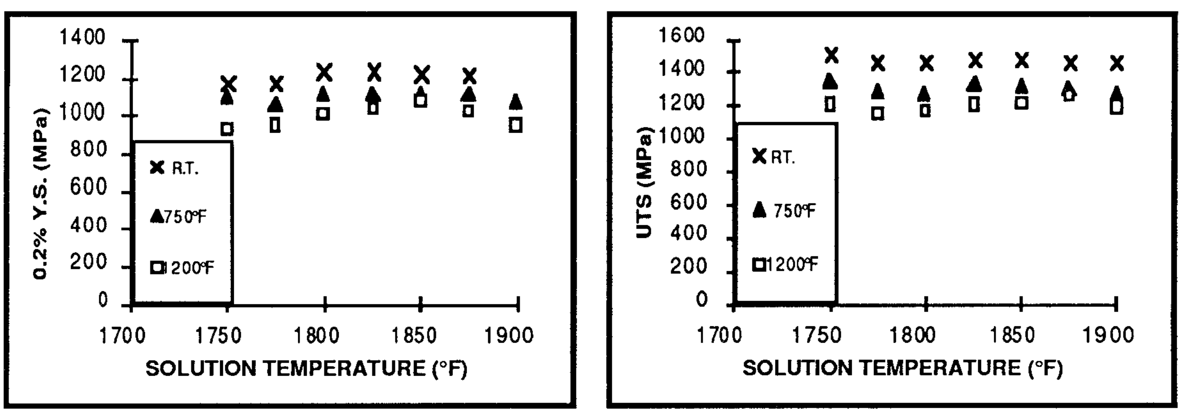


Figure 5. Tensile properties versus solution temperature

Solution heat treatments at 1750°F and above resulted in varying degrees of delta phase solutioning. The amount of delta phase present after any solution heat treatment will be dependent upon the equilibrium delta solvus, which is chemistry controlled, and the system kinetics, which are diffusion controlled (time and temperature). As the volume fraction of delta phase is reduced and the mean free path between delta phase particles increases, grain coarsening can occur.

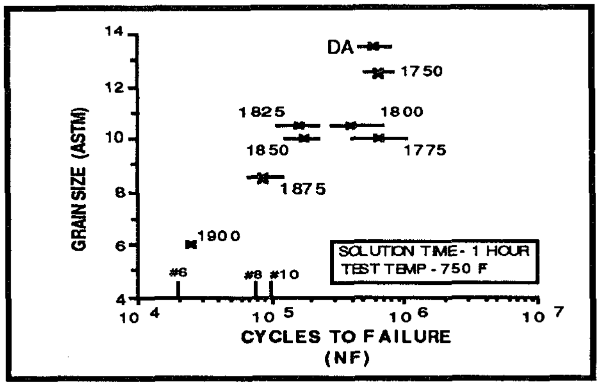


Figure 6. Low cycle fatigue test results as a function of grain size.

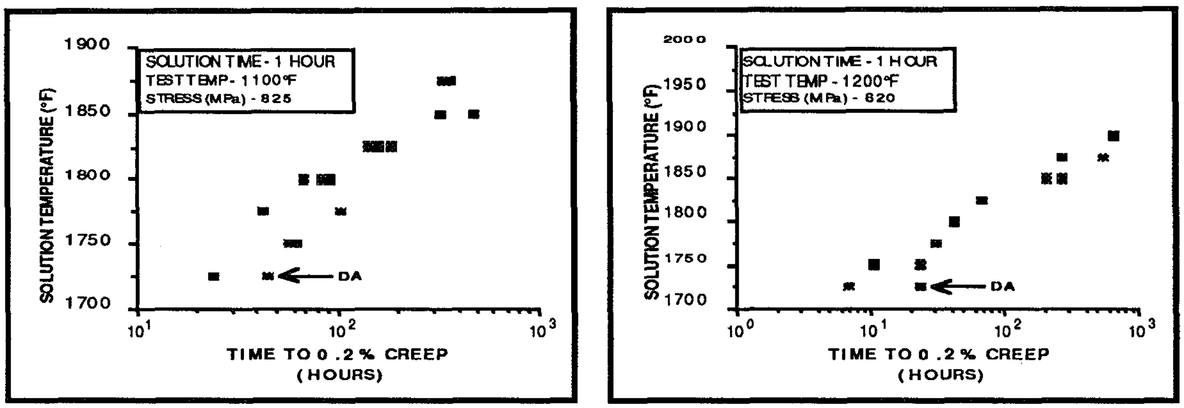


Figure 7. Time to reach 0.2% Creep vs. solution temperature.

The volume percent of delta phase that is present after solution heat treatment as a function of grain size is plotted in Figure 8. The data show that although there is grain coarsening from the direct aged grain size of ASTM 13 for all temperatures studied, the grain size is pinned at a diameter equivalent to ASTM 10 (10 microns) as long as there is approximately 3% delta phase present.

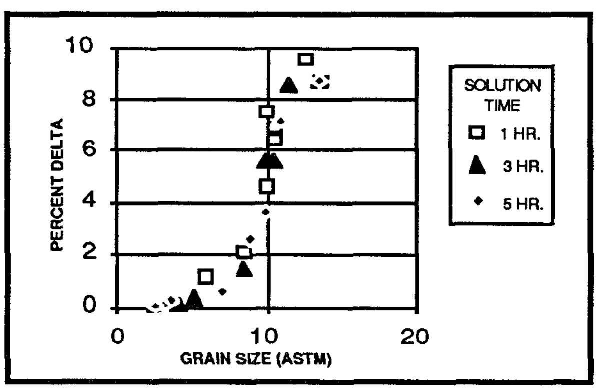


Figure 8. Cross plot of the data shown in Figure 4 showing grain size as a function of delta phase content.

A solution at 1800°F for 5 hours (2.6% delta) resulted in a grain size of ASTM 9, while a 1 hour solution at 1850°F(4.6% delta) resulted in an ASTM 10 grain size. This grain size/ % delta phase relationship, when combined with the time and temperature information in Figure 4, defines the window of opportunity for use of ultra fine grain billet for production forging applications. This window is also dependent upon ingot chemistry and homogeniety, although it is expected that the "delta dump" process may decrease heat to heat variance and banding effects.

The tensile property variation can be attributed to a balance between grain size and γ'/γ'' strengthening. The decrease in yield strength at room temperature and 750°F between the 1750°F and 1775°F solution treatments can be attributed to grain growth from ASTM 12.5 (approx. 4 micron) to ASTM 10 (approx, 10 micron). The increase in yield and tensile from 1775°F-1850°F can be attributed to increases in the hardening phases γ'' and γ' provided by the increased matrix content of Nb and Ti from the dissolution of delta, since the grain size remained essentially constant. Solution temperatures exceeding 1850°F resulted in grain coarsening with a corresponding loss in yield strength as expected.

The low cycle fatigue life was found to increase with decreasing grain size as expected. Comparison with average values at the same grain size (also shown in Figure 6) reveal that the LCF capability for the forging made from ultra fine grain billet exceeded the typical expected life for each grain size. Fractographic examination of the failed test bars revealed that the majority of failures initiated at carbide/carbonitride particles that were equal to or larger that the forging matrix grain size.

Although both the tensile and cyclic capability of the forging made from ultra fine grain billet were equal to or better than standard fine grain forgings, the creep properties were degraded by the large amounts of precipitated delta phase as expected. Creep properties increased with increasing solution temperature as shown in Figure 9. Recall that solution temperatures from 1775°F-1850°F had essentially the same grain size (ASTM 10). Thus the creep property differences observed between solution temperatures in this temperature range can be attributed to the delta phase content.

Summary

This paper has shown the benefit of using a "delta dump" process to produce an ultra fine grain structure in forging billet. The finer grain size resulted in improved billet ultrasonic inspectability, a more uniform forging microstructure, and minimization of final forging die chill/die lock effects. It has been shown that a solution heat treatment can be used to balance the properties controlled by grain size and/or strengthening precipitates. A production process, however, will depend upon billet uniformity and chemistry.

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