FORGING OF 718 - THE IMPORTANCE OF T.M.P.

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Abstract

Optimized and consistent levels of a range of mechanical properties in engineered 718 products requires that the interactions of chemical composition, ingot solidification, hot working and final heat treatment are understood.

The criticality of the need for clear definition and subsequent control of metal deformation conditions during forging and the limits imposed on the "Processing Window" are discussed. The underlying factors responsible for the sensitivity of 718 to T.M.P., such as grain size; distribution and morphology of precipitating phases and sub structural conditions are reviewed. The influences of the processing parameters of temperature and deformation on such structural factors are discussed together with their effects on mechanical properties.

The impact of such parametric needs and their recognition in the manufacture of closed die forgings for gas turbine disk application is reviewed with illustrative typical mechanical properties.

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Introduction

Thermo mechanical processing is the practice of exploiting temperature and strain (deformation) interactions to enhance specific mechanical properties in a material. The concept was perhaps first applied to early iron based superalloys back in the 1950's but really began to take hold in the early to mid 1960's with Waspaloy and Astroloy being used or considered for use in disk form in aircraft gas turbines.

Alloy 718 was introduced also in the early 1960's and found its first major disk application mid to late 1960's in the GE TF39 engine for the C5A military transport airplane. TMP as an approach to disk manufacture was utilized from these first 718 components and has been used ever since albeit with some changes in the details of the TMP. Early problems experienced with forged disks in this alloy were with stress rupture ductility and notch sensitivity, the extent of which was modified by forging practice to control the grain size and microstructure that was obtained after subsequent heat treatment. The same problem was also attacked by controlled additions of magnesium in the melting practice and the combination of these practices permitted successful application and ongoing utilization of the alloy as a classic demonstration of T.M.P.

The first "Seven Springs" international symposium on superalloy held in 1968 was devoted to "Structural Stability in Superalloys" and contained an early reference to TMP of 718 in a paper by Cremisio Radavich and Butler[1] in which they studied the interaction of strain on Ni_3Cb precipitation. One of the observations was that the presence of many particles of Ni_3Cb tended to inhibit grain growth in newly recrystallized material. This concept was further explored by P&WA and resulted in the Mini grain process described by Brown Boettner and Ruckle[2] in which they demonstrated doubling of the fatigue strength when the grain size was reduced by TMP from ASTM 3 to ASTM 12. Grain size has always been a key factor in the design of TMP procedures for 718.

Ingot and Billet Forging Stock

A paper on TMP is not the place for in depth discussion of ingot solidification and hetrogeneity problems, but it is important to recognize that in making a successful forging particularly by TMP, that the cornerstone has to be a homogeneous ingot. Segregation will influence microstructural control of the final product. Localized areas of elemental enrichment or denudation may well respond differently to a given TMP resulting in the presence of undesirable grain size distribution, concentrations of laves, delta phase, and γ'', which may then adversely effect notch rupture sensitivity or become fatigue crack initiation sites. Over the years a great deal of effort has been put into melting and solidification control of 718 and to this day it is still one of the most difficult alloys to produce in cast ingot form, at least to the level of homogeneity and cleanliness desired for critical applications.

Mechanical property enhancement through microstructural control is what TMP is all about. It is for this reason that material uniformity is so important and critical. Forging design therefore recognizes the importance of ingot quality and TMP really starts with ingot conversion. In some cases, for critical disk application, double homogenization with double upset and draw back practice is used in conversion of the ingot to forging billet, with a requirement imposed for a specific grain size and/or specified microstructure in the billet prior to the commencement of forming in contoured dies. This practice is not required for all parts, its use is selective, based on final forging practice. In order to achieve the consistency and reproducibility required for todays gas turbine application a holistic approach must be adopted for successful TMP. For optimization of 718, it is no longer possible to operate successfully in a metallurgically compartmentalized fashion i.e., melting, ingot conversion, forging and heat treatment without recognition of their inter-dependence.

Reasons for TMP

Since mechanical property enhancement is the reason for TMP's existence it is perhaps useful to review the major mechanical properties of interest for a disk application in the aircraft gas turbine industry. A typical list would include:

- o Tensile strength and ductility
- o Fatigue strength/life (LCF and HCF)
- o Crack growth rate (short and long cracks)
- o Fracture toughness
- o Creep and stress rupture
- o Notch sensitivity

Individual engine builders will have many variations on the above characteristics, covering a range of environment conditions, and interactions e.g., elevated temperature fatigue testing with a hold time under stress between cycles, thus introducing a creep-fatigue interaction. Stress concentration in the form of notches or holes may also be introduced into the test pieces. Laboratory tests meaningful to engine performance vary between engine builders.

Final optimization of component mechanical properties is usually a compromise between some of the above listed characteristics, biasing toward those properties which may be design limiting. TMP to be employed is then designed, based on those micro structural characteristics known to favor the properties to be improved, but with minimal jeopardy to the other properties. Grain size is of course a classic consideration, with coarser grain favoring creep strength and perhaps crack growth rate (beyond short cracks) and fine grain improving HCF and cycles to crack initiation and tensile yield strength.

In the gas turbine engine, allowable design stresses are usually derived statistically, using a minus two or three standard deviations (sigma) from a mean value. Historically such data has been obtained from a quantity of component cut up tests. A wide scatter range of test data thus produces significantly reduced permissible stressing at say the -2σ level when compared to the potential capability of the alloy. Over the years continuous demand for increased disk design life, improved specific fuel consumption, or engine thrust have demanded increases in the allowable stresses. Alloy 718 has been able to not only retain but to increase its level of application in gas turbine engines by increase in both the mean values of tensile strength and the minus two sigma lower limit, the latter achieved by reduction in the scatter of data. This improvement has been achieved by a better understanding of TMP of 718, identification of key parameters and process control at all stages of manufacture. Table 1 and Figures 1 & 2 illustrate mechanical property data typical of that being currently achieved in 718 production forgings for aircraft gas turbine application. Data represents tests from various locations within forgings taken from 30 separate parts cut up over an approximate four year period, and Figs 1 & 2 show the range of results obtained. Parts tested include disks, hubs and shafts of varying configurations. Figs 1 & 2 represent approximately 450 test data points. Limit lines were drawn around this data and for clarity, only these limit lines are shown. The data has not been treated statistically, but is simply a plot of typical production data. Three conditions of supply are represented - direct age, fine grain/high strength solution and age and conventional solution and age

Table I Typical Mechanical Properties Obtained From Cut-up Aircraft Gas Turbine Forgings in Alloy 718 (Direct Age, High Strength & Standard)

A. Tensile

	UTS(MPa)	0.2% YS(MPa)	% EL(4D)	% R of A
R.T. Tensile	1344-1517	1138-1413	13-25	17-40
399°C "	1255-1413	1069-1207	15-22	25-40
454°C "	1241-1344	1069-1172	15-22	27-36
538°C "	1207-1413	965-1138	15-25	25-35
649°C "	1103-1276	931-1103	18-32	25-65

B. Stress Rupture

		Hrs.	% Elong^{n}"
649°C	758.4 MPa	25-240	15-35
649°C	724.0 MPa	60-300	10-35
649°C	689.5 MPa	100-300	10-35

C. Fracture Toughness

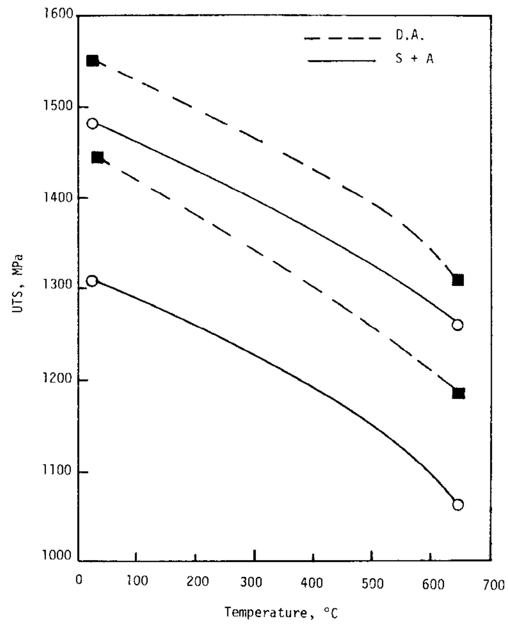
K_Q = 82.4 - 165 MPa$\sqrt{m}$ (75 - 150 ksi $\sqrt{ins}$)

D. LCF (Axial loading, A = 1, frequency 30 cycles/min, Temp 454°C)

Strain	Cycles to Failure
0.60%	30,000 - 1,000,000
0.85%	7,000 - 140,000
0.95%	7,000 - 13,000
1.15%	4,000 - 5,000

E. Creep

		Hours to 0.2% Strain
593°C	827.4 MPa	50 - 700



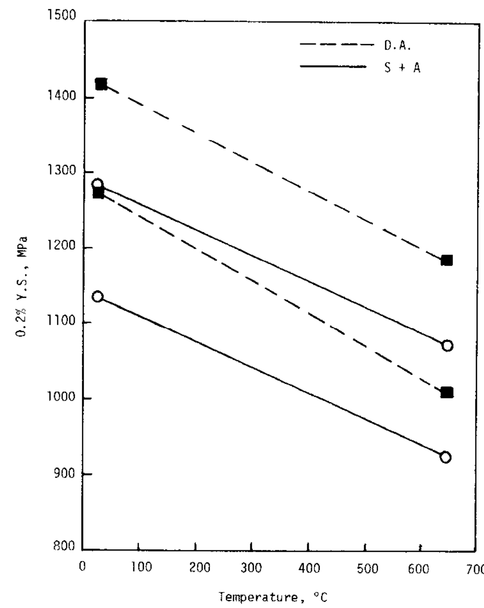


Figure 1 - U.T.S. property range of typical aircraft gas turbine components.

Figure 2 - 0.20% yield strength property range of typical aircraft gas turbine components.

Major Considerations in TMP

TMP of 718 as a disk forging usually involves relatively low forging temperatures at least during the final deforming operation. Historically the alloy has been forged over the range, 980°C - 1095°C (1800°F - 2000°F) but for most applications forging temperatures do not exceed 1040°C (1900°F). Selection of the temperature to which the metal is heated prior to forging is based on consideration of the microstructure of the original starting billet, the solvus temperatures of the γ''(BCT Ni_3,Al,Ti,Cb), γ' (FCC Ni_3,Al,Ti,Cb) and δ(orthorhombicNi_3Cb), and the grain coarsening characteristics of the alloy. Figure 3 illustrates a typical grain coarsening curve for 718. Some variation should be expected dependent on the grain size of the material prior to heating. There is also of course a time dependency which has to be recognized and chemistry variations will influence the solvus temperatures of any precipitated phases thus modifying the location of the curve with respect to the temperature axis.

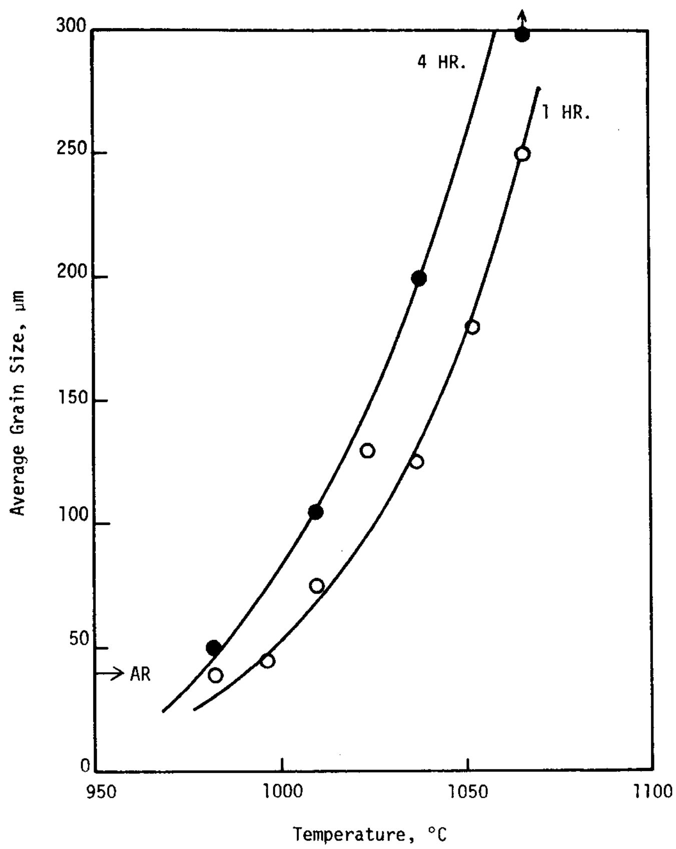


Figure 3 - Grain coarsening behavior of Alloy 718.

TMP revolves around deformation and deformation considerations are primarily strain, strain rate and temperature. The combinations of these deformation parameters coupled with any subsequent thermal treatment will determine the final microstructure and hence mechanical properties in the component. During die forging, interactions of the above three considerations are complex. The temperature of a forging billet within a furnace prior to forging may be determined with some level of accuracy, but once removed from the furnace, then heat loss by radiation to the air will occur. There may also be some conduction through handling equipment and unless the part is isothermally forged, then some heat loss to the dies will also occur, to an extent dependant on the die temperature and contact time, the accumulated effects then generating a temperature gradient from the surface into the interior of the work piece. During deformation, if the strain rate is too high, due either to ram speed of the forging equipment, or localized preferential flow within the forging, then a local temperature increase can occur by adiabatic heating. Such temperature increases can be significant.

During normal upset forging using a constant ram speed, on say a hydraulic press, then the strain rate within a part will be constantly changing as the height reduces and the diameter increases. Fortunately however, with alloy 718 the processing window is not so narrow as to preclude reasonable operating limits for existing equipment and experience. Operating limits are however sufficiently restricted that it is easy to get into trouble if the parameters are not understood and recognized in the forging procedure devised for a specific component.

Recovery and Recrystallization

One major result of the interaction of strain and temperature is material recovery and recrystallization. This may be dynamic or static, sometimes with the latter occurring almost immediately after strain has occurred. If processed at a sufficiently low temperature, then no recrystallization may occur and the material is cold worked, but will recrystallize if subsequently reheated to an appropriate temperature. All of these mechanisms may be utilized in T.M.P., but in 718 disk forging it is usual to select a combination of conditions typically between 980°C-1040°C (1800°F -1900°F) preheat temperature and forge with enough strain to promote recrystallization to the size of grain required. Figure 4 is an example of the relationship between temperature, deformation, recrystallization and grain size. In a dynamic mechanism with sufficient total strain and high enough strain rate, then after initial recrystallization, the new grains are further strained and such new grains will then further recrystallize effecting an overall grain refinement. As a general statement, the recrystallized grain size is finer with deformation at lower temperatures, the use of higher strain rate and greater reduction. The trick then, is to select the combination of these parameters to produce the required grain size and then to prevent subsequent grain growth from occurring. With 718 disk forging, the forging temperature is usually selected so that solution of the Ni_3Cb (δ) phase is incomplete and some of this phase remains available in the matrix to pin the boundaries of the newly recrystallized grains, restraining the grain growth phase.

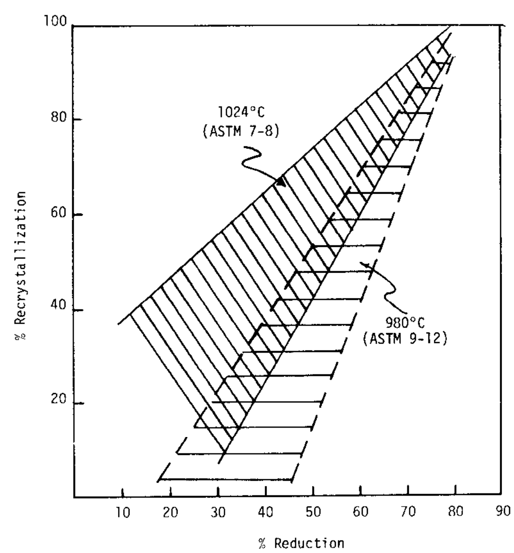
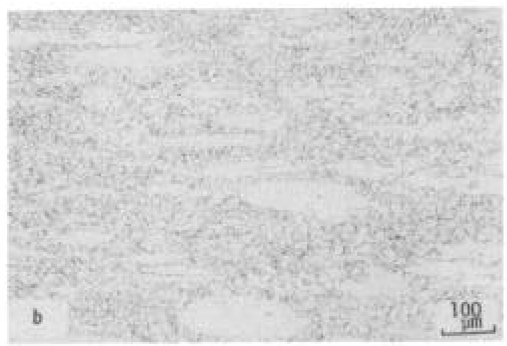


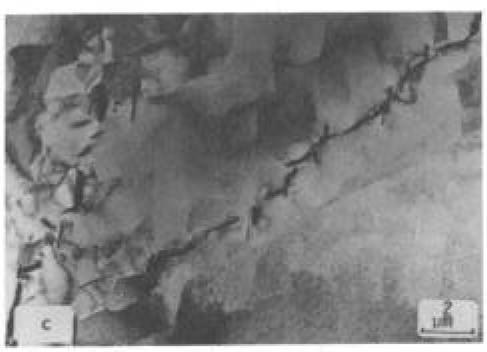
Figure 4 - Deformation\Recrystallization behavior of Alloy 718.

In many 718 forgings used in the direct age or low psuedo solution treated condition, recrystallization may be incomplete, and remnants of larger grains remain which have undergone recovery. The extent of recrystallization achieved will depend on the strain, strain rate and temperature and in marginal cases only limited "necklace" recrystallization will occur (Fig 5A). Using light optics metallography, these unrecrystallized grains may appear to be cold worked based on their deformed shape, or assumed to be, since they have not recrystallized. Under acceptable TMP conditions, these grains will have developed a recovered cellular sub structure identifiable by TEM. The presence of some amount of such unrecrystallized but recovered grain remnants has not been shown to be detrimental, at least in a number of mechanical properties, e.g., tensile, creep, and some fatigue tests, wherein characteristics are virtually indistinguishable from the fully recrystallized structure, provided that the δ morphology and γ'' size and volume are comparable. Figure 5 shows recovered grain structure. Figure 5(a) shows only limited recrystallization and 5(c) is the sub structure within the unrecrystallized grain of this sample. Fig 5(b) illustrates remnants of unrecrystallized grains in a predominantly recrystallized matrix, such remnant grain also exhibit recovery. The extent of unrecrystallized grain that is acceptable should be evaluated for each application in conjunction with other microstructural characteristics rather then just rejected as aesthetically unacceptable.

Limited Recrystallization



Remnant Unrecrystallized Grains



Sub Structure of Unrecrystallized Grains

Figure 5 - Recovered Grain Structure (As Forged)

Importance of Ni_3Cb

As mentioned earlier, the presence of some δ phase during forging is important. The amount present however, is fairly critical, since too much out of solution will rob the matrix of Cb resulting in inadequate volume fraction of γ" to effect full hardening during subsequent heat treatment, particularly when using a direct age process. It is also pertinent when a low "pseudo" solution temperature is used which is well below the δ solvus temperature. Creep strength is usually affected by such a condition of too much δ and insufficient γ". If insufficient δ is present during forging, then grain boundary pinning may be inadequate resulting in coarser grains than desired. Additional to the amount, the morphology of the delta phase is important to the mechanical properties. During forging any delta present tends toward spheroidization, which appears to be a preferred morphology. If strain is occurring in a temperature range where δ is precipitating, then growth of this phase tends to be discontinues and occurs in short lath type particles within and eminating from the grain boundaries, growing into the grains along crystrallographic planes. If material is heated into a temperature range for delta precipitation and no deformation is carried out, or deformation is inadequate, then δ precipitation tends to occur in a more continuous fashion along the grain boundaries and in long needles across the grain width. This is more deleterious in coarser grained structures due to the longer δ laths. This morphology has been shown to have an adverse effect on stress rupture ductility and fracture toughness. Smaller particles tending toward a more spheroidal form are generally preferred. Coarse δ precipitates have been reported by Mills and Blackburn[3] to initiate secondary dimples during crack growth, that pre-empt continued growth of primary carbide nucleated dimpling. Figures 6 & 7 show respectively the typical 718 morphology in a disk forging and also the less desirable δ state.

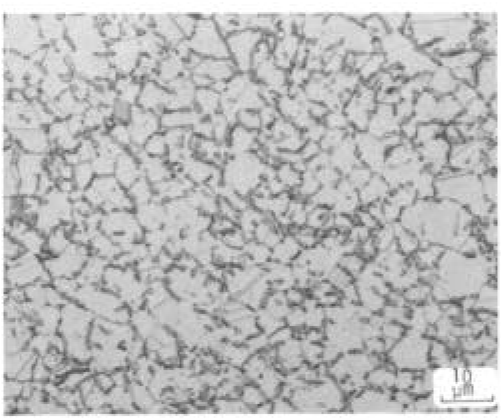


Figure 6 - Preferred type δ

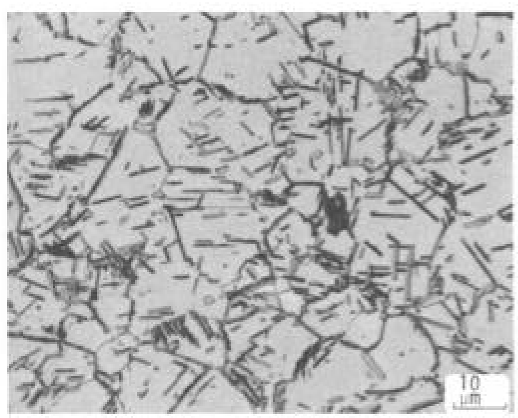


Figure 7 - Undesirable needle like δ

Die Temperature

Die temperature is important and has an effect in TMP. It was noted earlier that if the die surface temperature is less than the billet temperature, then unless insulation practices are employed, temperature loss will occur on the billet surface during contact, i.e., die chill. Typical conventional forging dies are manufactured from alloy steels and are heated to around 315°C prior to use. Under these conditions die chill can be significant, dependent on contact time, which in turn will vary with the type of forging equipment that is being utilized. Figure 8 illustrates one effect, that of forging tonnage requirement as a function of die temperature. Die chill will lead to zones of non representative microstructure, since within these zones, due to lower temperature, the flow stress is higher and thus less strain is achieved, the load applied being transferred to a more deformable area. Less strain occurring at a lower temperature will produce a quite different microstructure to the main body of the forging and this point needs to be recognized in the design of the forging route if uniformity of structure in the component is important. One way to minimize die chill is the use of hot dies. Such dies are usually Ni base material and heated to between 540°C and 830°C dependent on material used. Other special purpose tooling may permit die temperatures to be elevated to the forging temperature, permitting isothermal forging (not necessarily superplastic). The benefit of using dies at greater than 650°C is in the control which is exercisable over the temperature uniformity and strain achieved and hence the resultant microstructure that can be produced. This is particularly important when producing D.A. 718 i.e., direct age with no solution treatment, wherein the final microstructure is totally dependent on the forging operation. Die cost and complexity have to be balanced against need.

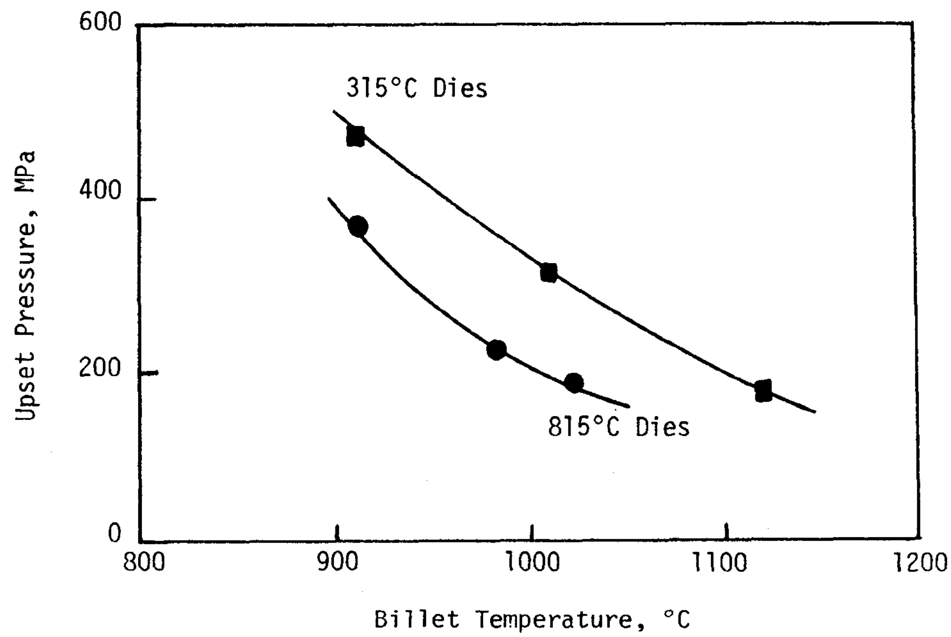


Figure 8 - Effects of die temperature on required forging tonnage for alloy 718.

TMP-Microstructure and Mechanical Properties

A comparison of some of the mechanical properties of the various forms of 718 has been given by E.A. Loria[4]. This paper shows the tensile strength improvement of D.A. 718 to be about 10% over solution treated fine grain high strength 718 and about 20%-25% improvement over conventional coarser grained structures. Data from production cut up forgings evaluated for this review showed D.A. improvement to be more in the 5% - 8% over H.S. (high strength) and 10% - 20% above conventional over the useable temperature range of the alloy. (Figs 1 & 2)

Loria also indicated about a 30% improvement of DA over conventional 718 in fatigue at $N_f = 10^4$, but that there is some debit in creep rupture between 593°C (1100°F) and 649°C (1200°F). Unpublished work at Cameron Forge company has shown that improvement in the creep strength of DA 718 certainly up to 593°C with a load of 827 MPa (120 ksi) can be made by control of volume fraction Ni_3Cb (δ) during forging. The selection of forging conditions can control the availability of hardening constituents for subsequent precipitation during direct aging, primarily influencing the volume fraction and size of the γ". Creep strength appears to be influenced by these parameters, at least up to 593°C but this improvement does not appear to hold at 650°C. The major influence is seen in the primary creep rate as illustrated in fig 9.

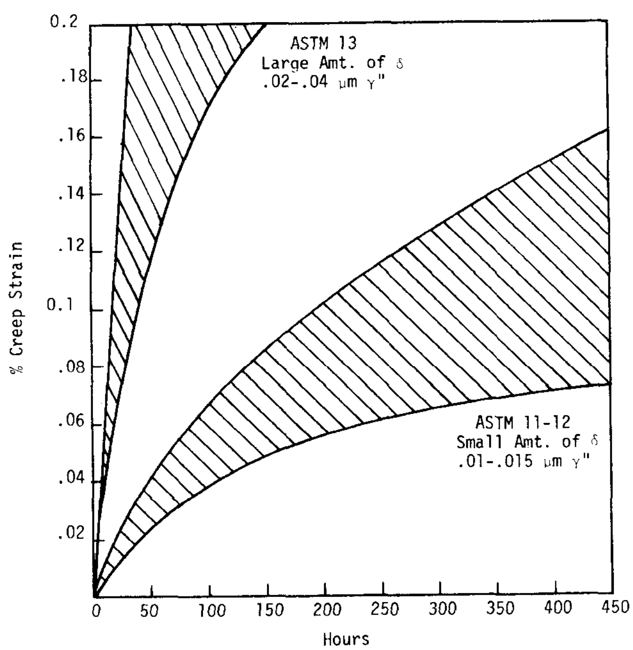


Figure 9 - Variation in primary creep characteristics of D.A. 718. Influence of forging conditions.

Mention has already been made of the effect of grain size on certain mechanical properties. Krueger Antolovich and Van Stone[5] found a reduction in fatigue crack growth rate of 718 with coarse grain material of 250μm versus fine grained material of 20μm. It was noted that the fine grained material contained areas of coarser grains up to 100μm i.e., remnants of unrecrystallized grains. It is likely that such grain being in a recrystallized structure, would be in a recovered state, but this was not established in their paper.

The above work showed the effect of hold time under load during fatigue cycling over a stress ratio of 0.05 to 0.75 and explained the improvement (reduction) in fatigue crack growth rate to dislocation reversability and slip band length. Long planer slip bands accommodating dislocation reversal for a larger number of loading cycles that short planer slip bands due to the longer distance between dislocation pile-up obstacles.

Other work on fatigue crack propagation behavior in 718 by K.M. Chang[6] at GE indicated interesting phenomena resulting from various TMP routes. The work indicated difference between deformed (cold worked?) 40-50μm grain size structures and equiaxed grain structures of both 5-10μm and 35μm grain sizes. The work suggested a possible favorable environment (air) related improvement in the low frequency, time dependent, elevated temp LCF behavior of 40μm - 50μm deformed grain. It was suggested that the improvement may be due to transgranular propagation and secondary crack formation, whereas both of the equiaxed grain structures exhibit crack growth rates which were similar to one another and were higher than that of the deformed grain. The variation was not apparent for high frequency cycling, but it would appear to be an area worthy of further study in the search for reduced crack growth rate which is the current hot topic under fracture mechanics design criteria.

Returning to hot work deformation and its control, forging with conventional (warm) dies can promote very non-uniform deformation. This is illustrated in Figure 10 which shows a macro etched cross section of a simple pancake which has been upset 60% at 1038°C (1900°F). A "dog bone" pattern of deformation due to die lock promoted by significant die chill top and bottom, and also perhaps influenced by die lubrication practice, is readily observable. The top and bottom die chilled areas have undergone varying degrees of recrystallization from zero at the surface, increasing toward the middle. The outside diameter is influenced by radiation cooling and again may have varying degrees of recrystallization. The thermal gradients developed cause local change in material flow strength which in turn gives rise to preferential flow in the hotter and lower flow stress areas resulting in significant change in strain, strain rate and temperature. The effect of temperature on the flow stress of 718 is shown in Figure 11. As can be seen, the flow stress at 960°C (1760°F) is approximately double that at 1066°C (1950°F). The pattern shown in fig 10 is classical for pancake forging, albeit in this case, a rather severe example. Such effects can be minimized by attention to insulation, die lubrication, and die and forging temperatures, but it illustrates the significant potential effect of die chill on promoting non uniform temperature distribution within a forging.

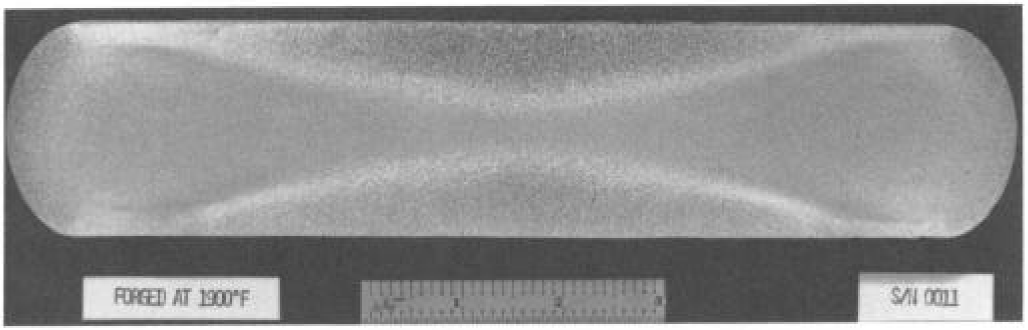


Figure 10 - Upset pancake of alloy 718 showing effect of die chill.

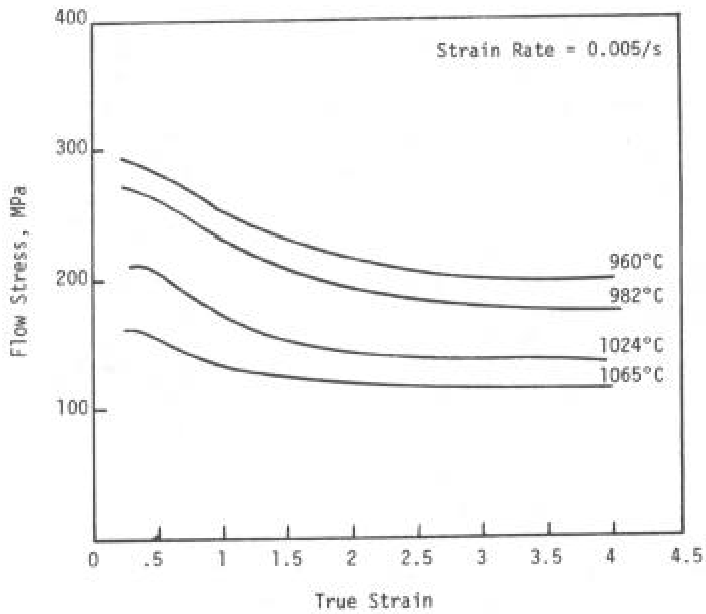


Figure 11 - Effect of temperature on flow stress of Alloy 718.

A configured cavity die forging may exhibit similar effects although in a more localized distribution, dependant on the die cavity shape and the shape/volume distribution of the material to be forged. If inadequate thought is given to the relationship of the preform shape to the final configuration to be forged, then structure control is non existent and results achieved are a matter of luck. It is of course extremely difficult if not impossible to impart absolute uniform deformation to all parts of a shaped die forging. It is for this reason that it is important to develop processing "windows" in TMP to establish upper and lower acceptability limits of process parameters. Such process windows are necessary in order to design the forging shape and deformation sequence to ensure that all portions of the die forging fall within the limits of acceptability. Emperical approximate windows have been developed, but specific limits determined by detailed study of the interactions have not been well defined. Over the past few years however, significant strides have been made with the use of computer modelling techniques. Such developments hold promise for the future. The emergence of ALPID (Analysis of Large Plastic Incremental Deformation) and other similar finite element models (FEM) have provided reasonably accurate predictive "bare bones" deformation models.

The big advantage of modelling is the ability that it provides to visualize the deformation process and its dependent factors e.g. interface conditions of friction and heat transfer, temperature gradient, strain velocities, identification of potential die lock, development of shear planes, etc. The ability to visualize such potentials, then permits a further iterative approach on the computer, permitting design changes to be developed to eliminate undesirable characteristics and thus enhance a "get it right the first time" approach to manufacture on the shop floor.

A lot of work has still to be done in order to permit microstructure and hence mechanical properties prediction in a routine manner on all parts. Each alloy system currently requires a data base of material\metallurgical information in the form of constitutive equations in order to accurately predict interaction results and to be able to handle thermal, stress and strain gradients. Alloy 718 is no exception to this lack of specific date but a start has been made on empirically developing the required coefficients and material data within various laboratories to provide input to the model. The ability to predict deformation conditions and the resultant microstructures in specific alloys in various critical areas with temperature gradients within a forging is developing, but the work is quite laborious. However, with isothermal processing, encouraging results have been obtained and limited success with hot die also. There is no doubt that this technique will be a powerful tool in the gas turbine disk industry, replacing current trial and error methods of TMP. The application of predictive computer modelling will probably be restricted initially in 718 components to those in which the alloy is TMP'd to its upper limit of property capability limits but no doubt will find wider application with time. The future may move more toward more theoretically based internal state models, computing cumulative effects in individual grains, but this approach would seem to be in the longer term rather than near term future.

Finally, the pertinent information on TMP requirements is of not much use unless the forging equipment and peripherals are capable of accurately sensing the selected critical parameters and are fitted with controls, capable of consistently reproducing such parameters within acceptable limits. This being done, then permits the introduction of true S.P.C. (Statistical Process Control) and closes the loop to permit minimum scatter of optimized mechanical properties. Such is the state of TMP art (science) under review and implementation to varying degrees in 718 today.

Acknowledgment

Much of the commentary presented in this paper was drawn from work done by colleagues over the years at Cameron Forge Company, in particular the work of Dr. K. H. Chien, Dr. P. R. Bhowal and Dr. P. Tibbetts.

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