PROPERTY OPTIMIZATION IN SUPERALLOYS THROUGH

THE USE OF HEAT TREAT PROCESS MODELLING

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Abstract

One important variable in maximizing tensile, creep, stress rupture and toughness properties in superalloys is the cooling rate from the alloy solutioning temperature. Correlations between properties and cooling rates may be conveniently developed using small blanks of material. Implementation of the data in complex geometries such as aircraft engine disks, however, is most effectively done through finite element modelling of the heat treatment process.

The application of heat treat process modelling to predict the property levels at various locations in parts having relatively complex shapes are discussed. An example of the use of models to obtain the required properties while reducing residual stress levels in the part is given together with an example where the properties are maximized against the tendency of the part to crack during quenching.

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Introduction

The designers of aircraft engines are continually seeking improved properties from existing alloys so that components can be operated at higher stress levels and higher temperatures, thereby, giving increased engine performance. One important variable that determines the strength of many superalloys is the cooling rate from its solutioning temperature. Correlations between properties such as tensile, creep and stress rupture strength and cooling rate can be conveniently developed using simple pancakes of a material. The application of this data to superalloy forgings of complex shapes, however, is most effectively done through finite element modelling.

Over the past few years Cameron has developed heat transfer data and modelling techniques to enable the temperatures and stresses in components during heat treatment to be calculated. Coupling the modelling work with data correlating the properties to cooling rate has enabled the properties in relatively complex shapes to be maximized, and has eliminated the costly and time consuming trial and error methods of the past.

The Mathematical Models

The first step in the development of the mathematical models was the determination of the heat extraction rates in various quenching media. Instrumented disks were used to obtain time-temperature data upon quenching. These data were used as input into a finite difference inverse heat conduction program (1) which calculates the surface temperature of the disk together with the corresponding heat transfer coefficient. The heat transfer coefficients obtained are used in finite element models (2,3) to predict the temperatures and stresses in parts during quenching. Validation of the models was carried out with several instrumented parts, both sub-scale and full size. The comparison between the measured and calculated temperatures in a full size turbine disk made of alloy 901 is given in Figure 1 (4). In the example shown the disk was heated to 1175°C, then transferred from the furnace to a forced air cooling system in 0.83 minute, forced air cooled for 2 minutes, transferred to an oil tank in 0.75 minute and finally oil quenched. The correlation between the measured and calculated temperatures may be seen to be good even in a relatively complicated multiple step heat treatment.

Correlation of Properties with Cooling Rate

Correlations between mechanical properties and the cooling rate from the solution temperature are obtained by instrumenting small blanks of material (typically, 10 cm to 12 cm square or round and 4 cm thick). The cooling rate at different locations in the disk are thereby obtained during quenching in different media. Solid blanks of the same size and material are then similarly quenched and cut up for property testing. Testing is carried out with specimens taken from locations where the cooling rate is known. This work allows the tensile, creep and stress rupture properties of an alloy to be obtained as a function of cooling rate. The prediction of the properties that will be obtained in a forging having a complex shape is subsequently made by comparing the cooling rates in the forging, as calculated by the mathematical models, with the established property/cooling rate relationship.

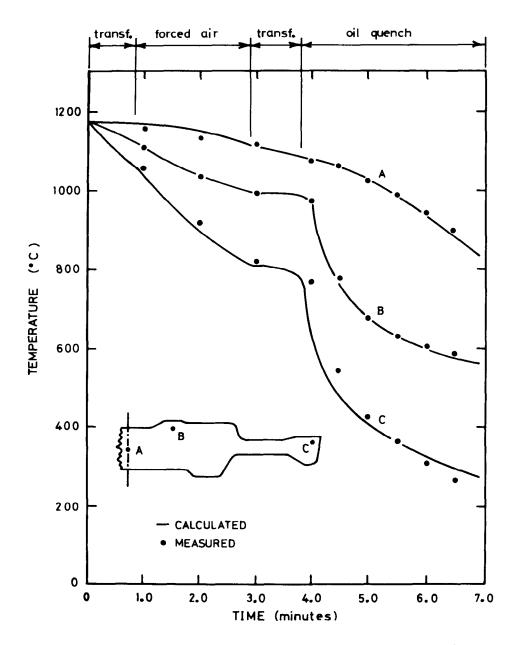


Figure 1 - Comparison between experimental and calculated cooling curves (4).

Modelling to Meet Property Requirements and Reducing Residual Stress/Distortion Problems

Forgings having relatively thin cross-sections, or large differences in cross section can present distortion problems during heat treatment. For example, a thin disk made of a nickel-base powder alloy was initially produced using oil quenching to meet the property requirements. This relatively rapid quench rate enabled the properties to be met, but resulted in residual stresses being set up in the part which made subsequent machining extremely difficult due to the part "springing" on the machine. This problem led to an investigation into the stress levels being developed in the forging during quenching. Figure 2 shows the stresses being developed at several locations during the oil quenching (solid lines). These stresses arise from the very steep temperature gradients that develop in the part shortly after it is immersed in the oil tank, as shown in

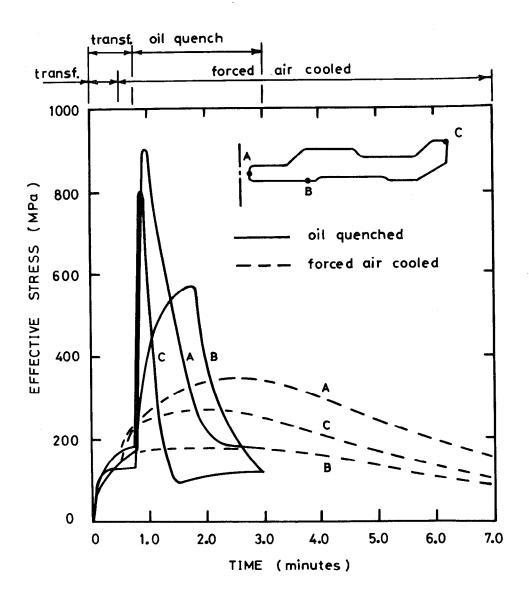


Figure 2 - Calculated stresses generated in disk during cooling.

Figure 3. The stresses developed during the quench exceeded the elastic limit of the material at high temperature, which led to plastic deformation, which, in turn, led to residual stresses being present in the part at the end of the heat treatment.

The solution to the problem, therefore, lay in reducing the cooling rate in the part such that the stresses during heat treatment were reduced. The properties of the material are a function of the cooling rate, hence, the solution automatically reduces the properties in the final part. The effect of cooling rate on the yield strength of the material (at room temperature and at 650° C) is given in Figure 4 for a solution temperature of $1120 \pm 15^{\circ}$ C. Also shown is the actual property data taken from cut up tests on oil quenched forgings (cooling rates $235-300^{\circ}$ C/min.). These strength levels are typically 140 MPa higher than the specified requirements, leaving the possibility to reduce the cooling rate (and hence the properties) and, thereby, the residual stress levels.

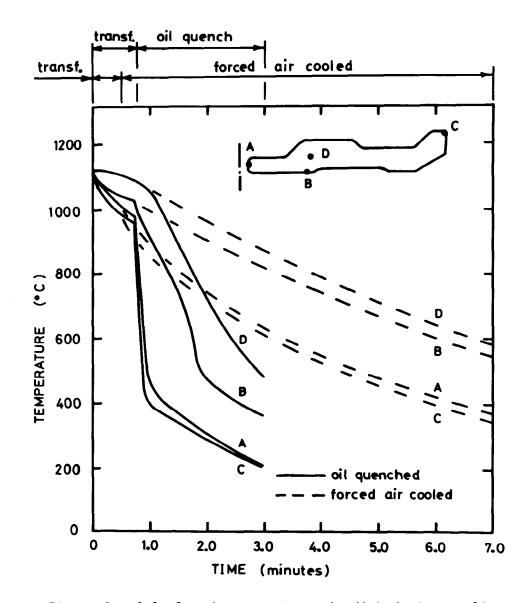


Figure 3 - Calculated temperatures in disk during cooling

Process modelling was carried out to examine alternative heat treatment processes such as static-air cooling or forced-air cooling from the solution temperature. This showed that static air cooling would give cooling rates of about 70°C/minute. This was considered inadequate to meet the property requirements. Forced-air cooling was therefore selected as the alternative to oil quenching. The resultant stresses and temperatures during forced air cooling may be seen in Figures 2 and 3. The stresses were significantly reduced (half those developed during oil quenching). The forced-air cooling also resulted in much lower cooling rates (typically 90-135°C/min.). Referring to Figure 4, the predicted cooling rates obtained with forced air cooling would be expected to give yield values between 1210 and 1300 MPa at room temperature and between 1135 and 1170 MPa at 650°C in locations A, B, C, D and E. Thus, the change from oil quenching to forced-air cooling has reduced the yield strength approximately 70-100 MPa. The properties predicted, however, remained above the specification. Following this investigation several parts were produced utilizing forced-air cooling, and cut up tests revealed properties in the range shown in Figure 4. The data median lay within the laboratory generated property bands demonstrating correlation between the predicted and the observed properties.

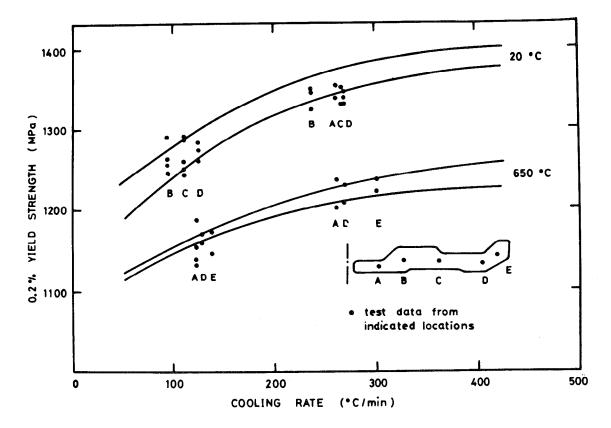


Figure 4 - Yield Strength as a function of cooling rate together with cut up test data for two cooling techniques.

The other concern of reduced cooling rate was the associated degradation of creep properties. This aspect was also investigated through the model predicted cooling rates as shown in Figure 5. Oil quench properties which lay in region A were predicted to be reduced to the values given by region B for forced-air cooling. However, the creep strength associated with region B was still above the specification. Actual cut up data were found to be consistent with the model predictions as shown by the solid scatter bars in Figure 5.

Following this investigation a series of disks were heat treated using forced-air cooling. These parts were found to meet property requirements, and did not exhibit residual stress related problems during machining.

Maximizing Properties Against Quench Cracking

In the design of components for new engines, improved properties are being called for from existing alloys. The improved properties are being obtained, in part, by the rapid quenching of forgings from their solution temperature. There is, however, a limit to how fast a particular alloy can be quenched before it will crack. This limit has been reached for several superalloys, and part geometry along with alloy structure and required cooling rates has become an important factor in the development of heat treatment practices and, hence, the property levels that can be achieved in a part.

As an example, consider the heat treatment of another powder alloy forging which required a yield strength level of 1076 MPa. Investigations were carried out to determine the effect of grain size and cooling rate on

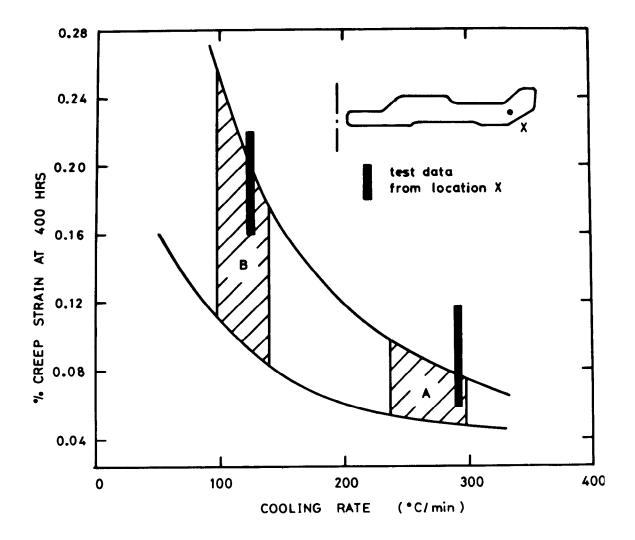


Figure 5 - Creep deformation as a function of cooling rate together with expected and actual data for two cooling techniques.

properties. Figure 6 shows the laboratory generated 500°C yield strength for two grain sizes as a function of cooling rate. To meet the strength requirement with the finer grain structure (3 μm), a cooling rate of 80°C/minute would be required at point D (the slowest cooling point in the forging). However, with a coarser grain size (5 μm) a much higher cooling rate (133°C/minute) would be required. Modelling was carried out to determine the appropriate cooling technique from the solution temperature to meet properties.

Three cases were considered: forced-air cooling and oil quenches with a 120 second and a 60 second delay from the furnace to the oil tank. The property range for the three cases are shown in Figure 6 by vertical lines at the appropriate cooling rate. It may be seen that forced-air cooling is inadequate at either grain size. The 120 second delay oil quench meets property specification with an average grain size of 3 μm , but would be inadequate for a grain size of 5 μm . A 60 second delay time appears most attractive since it meets the specification at either grain size. It should be noted that once the yield strength levels are met, it is desirable to lean toward the coarser grain size from the creep and stress rupture viewpoint. Hence, it was decided to aim at a grain size of 5 μm and a 60 second or lower delay time in oil quenching from its solution temperature.

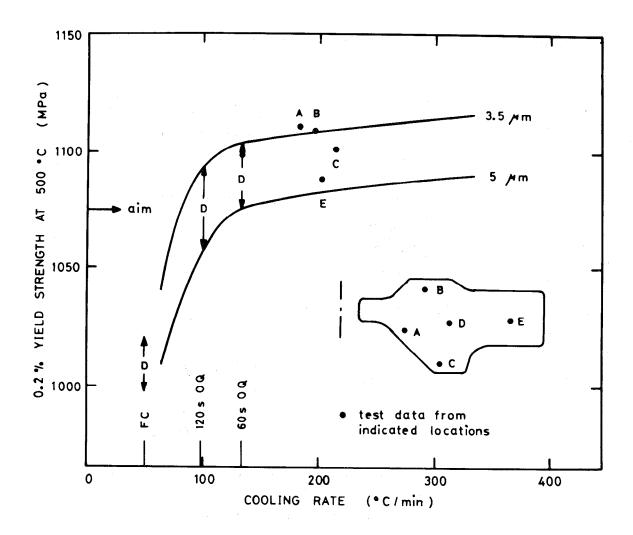


Figure 6 - Yield strength as a function of cooling rate for two different grain sizes showing correlation between expected and measured properties.

Since the cooling rate thus achieved was relatively fast, it was necessary to examine the stress levels imposed at critical locations on the disk during heat treatment. In the first series of computer simulations, a 45 second delay oil quench was used to determine the effect of disk orientation on the stresses developed. Figure 7 shows the stresses developed. The graph shows the stresses at the critical location on the disk as a function of the temperature at that location during quenching. Also given on the graph is the approximate yield strength of the material as a function of temperature. With a 45 second delay, it was found that position 2 (upside down relative to position 1) results in stress levels above the yield point. Hence, depending on the ductility of the material at the temperature, the part could crack during quenching. Also, excessive plastic yielding could cause distortion and residual stress problems. Position 1 was thus considered to be the preferred orientation. At high temperatures (980°C), even in position 1 the stresses are very close to the yield point. A further simulation was carried out with a 60 second delay oil quench which was found to reduce the stresses to safer levels.

The parts were heat treated with a 60 second delay oil quench. The properties at several locations in the disk at their calculated cooling rates are shown in Figure 6. In practice, the structure was bounded by the

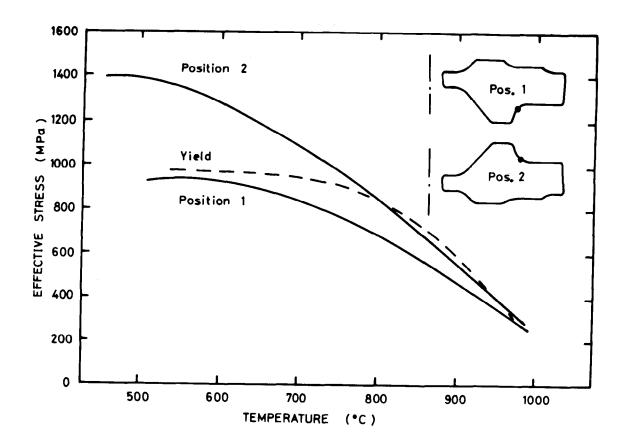


Figure 7 - Stress-temperature curves during cooling showing the effect of part orientation with respect to yielding.

grain size 5 - 3 μ m. It may be seen that the properties obtained in the forging are consistent with predicted values.

The above analysis was carried out prior to the parts being made. The first part manufactured met the property specification without quench cracking and illustrated how these techniques could eliminate costly and time consuming trial and error methods.

Conclusions

Correlations between the mechanical properties of superalloys and the cooling rate from the solution temperature can be obtained using small blanks having a simple geometry. Process models are now available which allow the temperature and stress distribution within a part during quenching to be accurately predicted. Coupling the results from the models with the property/cooling rate data enable the properties in relatively complex superalloy forgings to be determined.

The techniques have proved to be very accurate, and will enable the industry to get the most out of existing superalloys. They are also capable of eliminating costly and time consuming trials, thereby, reducing the lead time from engine design to the production of usable hardware.

References

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