UTILIZATION OF COMPUTER MODELING

IN SUPERALLOY FORGING PROCESS DESIGN

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Summary

The forging of a superalloy high pressure turbine disk has been simulated using ALPID, an FEM code for analysis of large plastic deformation problems. The modeling was carried out to determine the cause of coarse grains and relatively high sonic noise at some locations in a disk. The simulation indicated a temperature increase in the forging that occurred as a result of deformation heating. Compression testing was carried out at temperatures between 1010°C and 1149°C (1950°F and 2100°F) to generate microstructures for comparison to microstructures from the forging. The comparisons of the modeling results and the microstructures support a conclusion that the coarse grains and high sonic noise in the forging occurred because the temperature in the forging rose too high in some locations, partly because of deformation heating. The changes made in the forge process as a result of the modeling are described.

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Introduction

Computer simulation of superalloy metal forming is now an integral part of forging design. Process modeling is being used for tasks such as definition of preform and die geometries, prediction of forging defects such as laps or underfill, determination of stress, strain, strain rate and temperature profiles, point tracking and flow line prediction, and determination of the loading on tooling for die stress analysis. The costly cycle of physically trying out the dies, testing, and redesigning is now being replaced by an iterative process utilizing computer modeling prior to manufacturing.

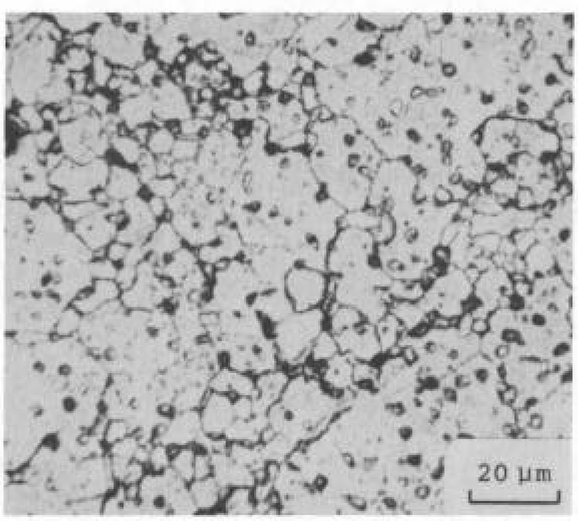
A code being used in the forging industry to simulate metal flow is the finite element method code ALPID[1] (Analysis of Large Plastic Incremental Deformation.) ALPID is a 2-dimensional rigid-viscoplastic code capable of performing non-isothermal analyses of metal flow in arbitrarily shaped dies. In this paper the use of ALPID to assess the effects of forge temperature and strain rate on actual workpiece temperature and resulting microstructures in a disk forging will be described.

Experimental Procedure

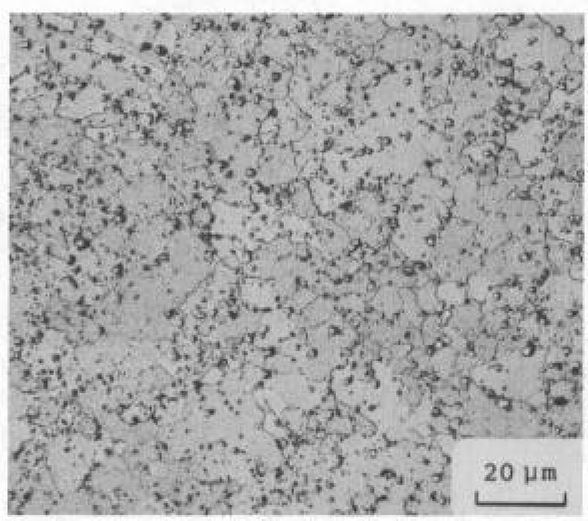
Forged Microstructures

The metal flow simulations were carried out to help determine the cause of coarse grains and high sonic noise in a superalloy high pressure turbine disk forging. The shape of the forging can be seen in Figure 7 which is part of the simulation results. The alloy is a high γ' volume fraction -150 mesh extruded powder superalloy. In a disk forged at 1121°C (2050°F) with a nominal strain rate of 8.3×10^{-3} sec^{-1} (0.5 min^{-1}) the sonic inspectability was found to be nonuniform. In the ultrasonic inspection at a sensitivity of 21dB most of the forging was found to exhibit a background noise level of 10% or less of the screen. Parts of the forging, particularly at the rim, however, exhibited a significantly higher noise level.

Microstructures were obtained from both high noise and low noise areas

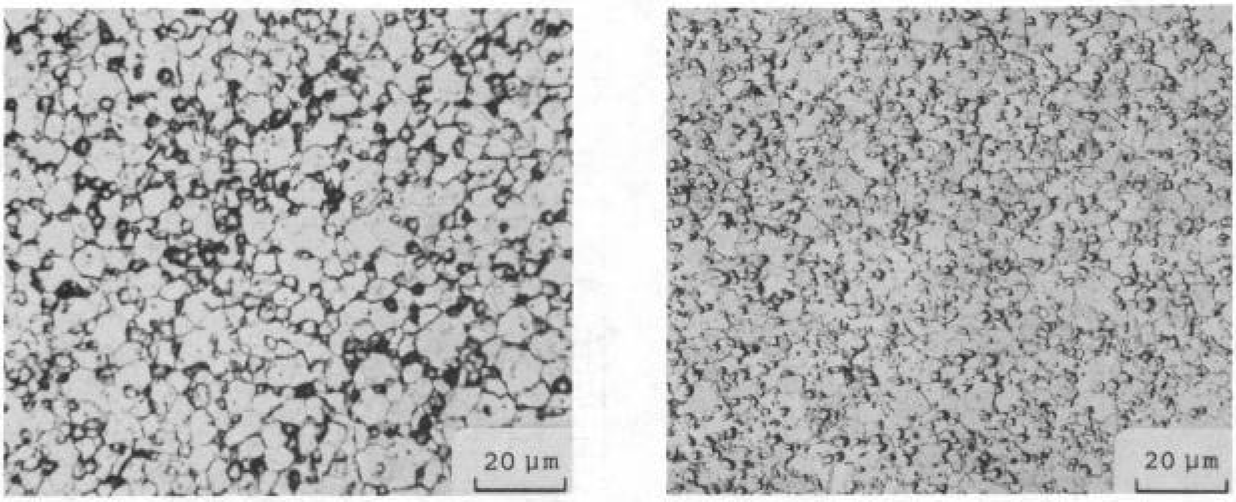


(a)



(b)

Figure 1 - Microstructures from: a) high sonic noise area at the rim of a disk forging; b) compression specimen deformed at 1149°C (2100°F) and 0.0083 sec^{-1} (0.5 min^{-1}.)



(a) (b)

Figure 2 - Microstructures from: a) low sonic noise area of a disk forging; b) compression specimen deformed at 1135°C (2075°F) and 0.0083 sec^{-1} (0.5 min^{-1}.)

of the forging. The high noise optical microstructure, Figure 1a, is characterized by a coarser grain size and a lower volume fraction of the large primary γ' than the low noise microstructure, Figure 2a. Also included for comparison in Figures 1 and 2 are microstructures from compression specimens deformed at 1149°C (2100°F) and 1135°C (2075°F), respectively. The compression testing and the comparisons in Figures 1 and 2 will be discussed in more detail below. The differences between the forged microstructures, Figure 1a and Figure 2a, suggest that the high noise material has, during forging, experienced a higher temperature and been heated closer to the γ' solvus than the low noise material. The γ' solvus for the heat of material from which the forging was made is 1152°C (2105°F.) How this nonuniform heating could happen was investigated by process modeling.

Computer Simulations

The flow data required to carry out metal flow simulations were available from compression testing. The compression specimens had been machined from extruded stock and upset at temperatures between 1010°C and 1149°C (1850°F and 2100°F) and strain rates between 10^{-3} sec^{-1} and 1 sec^{-1}. These ranges encompass the feasible hot working conditions for this alloy. Also needed were thermal property data for both the workpiece and dies: thermal conductivity and specific heat.

The first simulation was carried out for a forge temperature of 1121°C (2050°F) and a strain rate of 8.3 X 10^{-3} sec^{-1} (0.5 min^{-1}.) Both the workpiece and the die were initially at the same temperature and a constant friction factor of 0.2 was used. The initial die velocity was selected to give a strain rate of 8.3 X 10^{-3} sec^{-1} based on the initial height of the billet. The die velocity was continuously reduced throughout the simulation to maintain a constant strain rate. A two step forge operation was simulated. In this case, for lubrication and inspection, the forging was carried out part way to the finish in the first step (the prefinish step) and then forged to the final configuration in the same dies in a second step (the finish operation.)

The initial finite element meshes of the workpiece and die are shown in Figure 3. The workpiece mesh at the end of the prefinish step is shown in Figure 4. The workpiece mesh at the end of the prefinish step is not

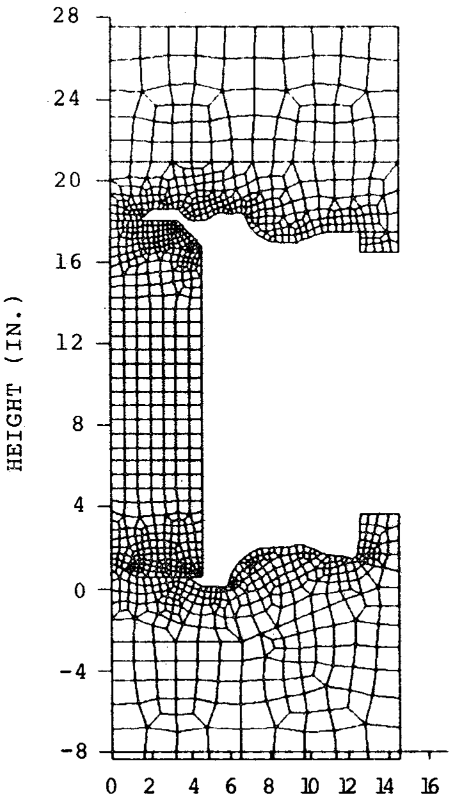


Figure 3 - Initial finite element meshes of the workpiece and dies.

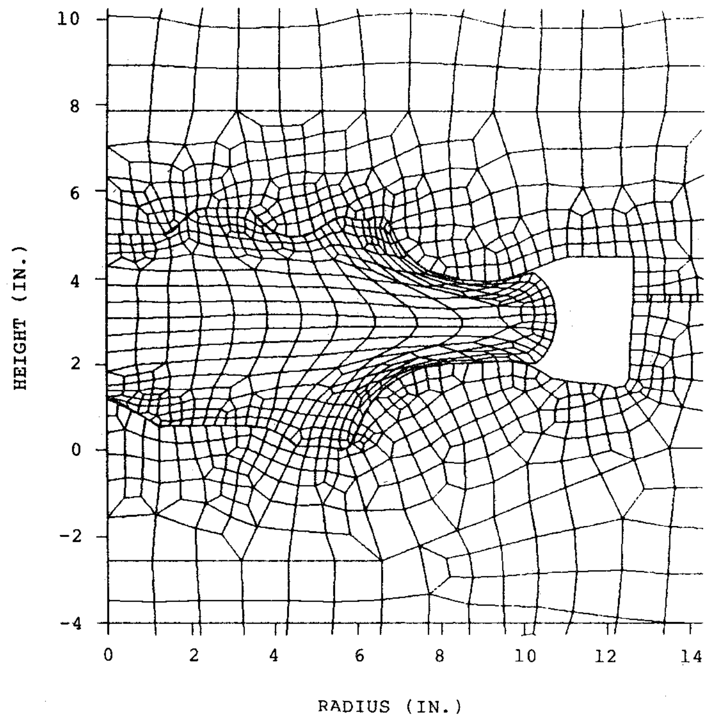


Figure 4 - Deformed workpiece mesh and die meshes at the end of the 1121°C (2050°F) prefinish forge operation.

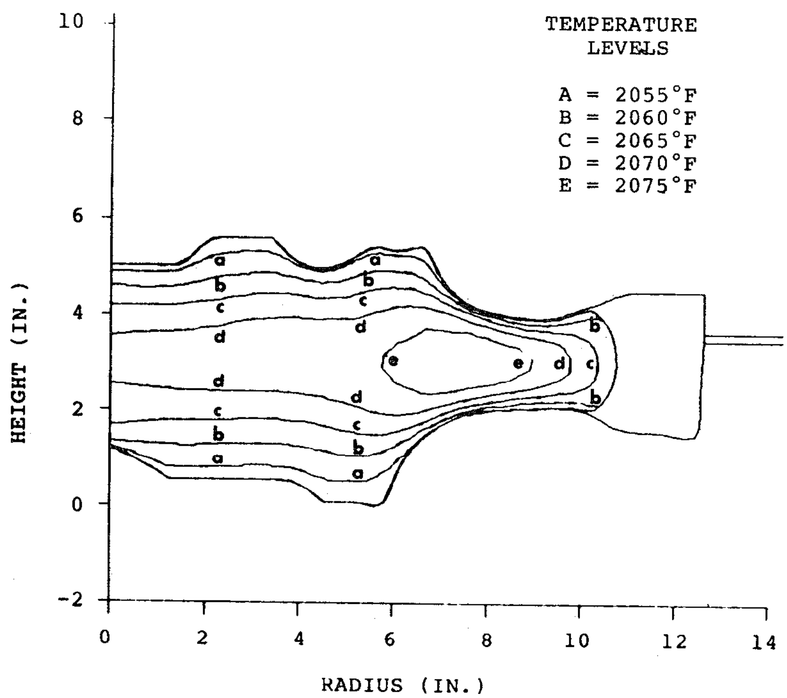


Figure 5 - Temperature contours in the workpiece at the end of the 1121°C (2050°F) prefinish forge operation.

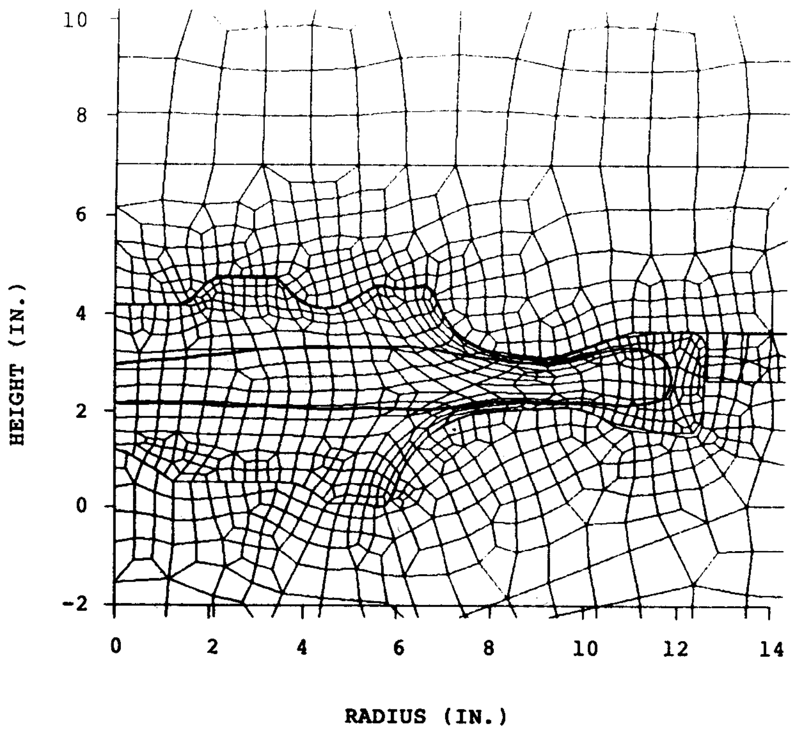


Figure 6 - Workpiece and die meshes at the end of the 1121°C (2050°F) finish forge operation. Superimposed on the workpiece mesh is the final position of material that was heated 11-14°C (20-25°F) over the nominal forge temperature during the prefinish forge operation (see Figure 5.)

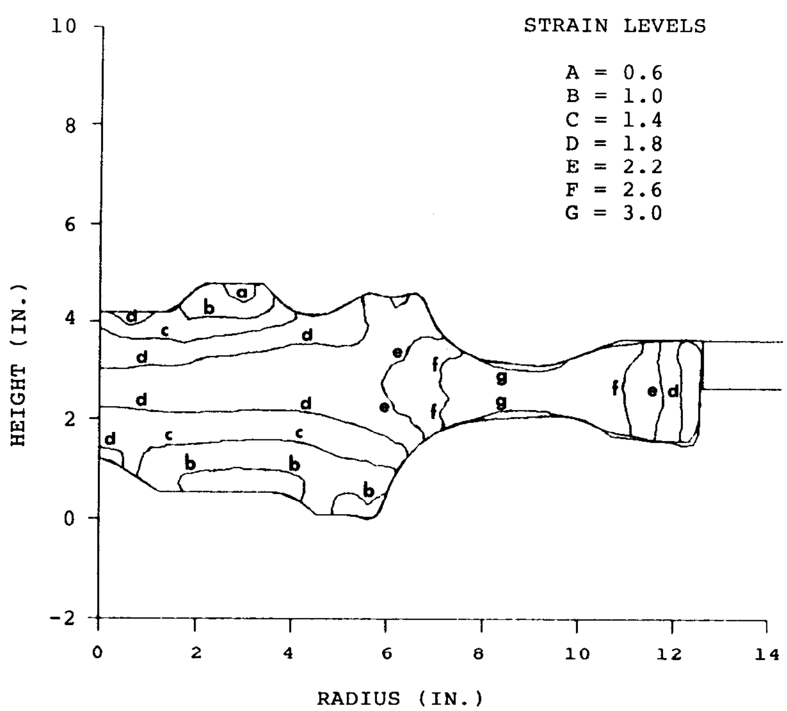


Figure 7 - Final effective strain contours in the workpiece at the end of the finish forge operation.

the original mesh. A remeshing of the workpiece was required because of distortion of the original mesh. Typically several remeshings are required to complete an analysis. The temperature distribution in the workpiece and the dies at the end of the prefinish step is shown in Figure 5. At this intermediate stage the modeling predicts a temperature rise in the workpiece of up to about 14°C (25°F) due to deformation heating, particularly in the narrow region of the forging where the material is being extruded out toward the rim.

To carry out modeling of the finish forge step, the workpiece was remeshed. In the remesh the strain field was carried over from the old mesh to the new mesh but the temperature field was reset to 1121°C (2050°F) to simulate a reheating for the finish forge operation. The mesh at the end of the finish forge operation, and the final effective strain distribution are shown in Figures 6 and 7, respectively. The strain field at the finish indicates effective strain levels in the forging as high as 3.0 and as low as about 0.6 in one local area where material is trapped in a die impression.

The maximum temperature rise due to deformation heating in the finish forge operation is predicted to be about 11°C (20°F), again in the narrow region of the forging where the material is being extruded out toward the rim. Of more interest is the position in the finish forged shape of material which was heated 11-14°C (20-25°F) over the forge temperature in the prefinish step. The final location of this material is superimposed on the workpiece mesh in Figure 6.

Compression Testing

Compression testing to obtain microstructures was performed on an MTS servohydraulic system in a controlled atmosphere (the platens were TZM.) The material was as-extruded stock with a microstructure shown in Figure 8. The γ' solvus temperature of the material was determined by DTA to be 1159°C (2119°F.) Testing was performed in the temperature range of 1010°C - 1149°C (1950°F - 2100°F) at a strain rate of 8.33×10^{-1} sec^{-1} (0.5 min^{-1}.) Test specimens, 0.5" Ø X 0.75" tall, were cut so that the axis of each cylinder was parallel to the extrusion axis. Tests were conducted under constant true strain rate control. The specimens were heated in vacuum to the test temperature for 15 minutes prior to testing. A graphite lubricant was used. All specimens were upset to a final true axial strain of 0.69 (50% upset.) At the conclusion of each test the test chamber was filled with helium gas to quench the specimens.

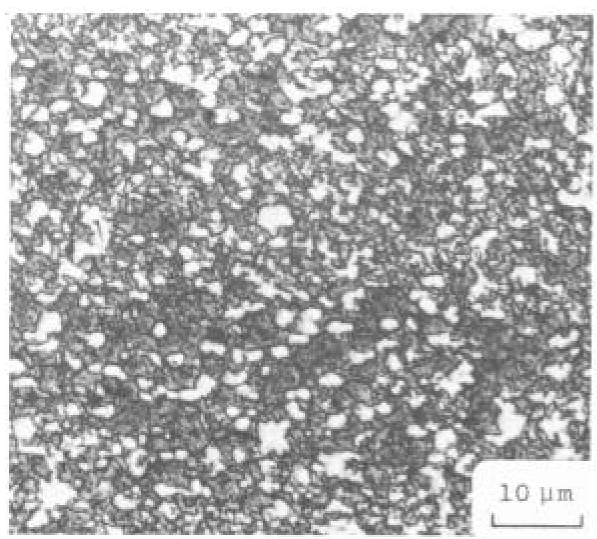
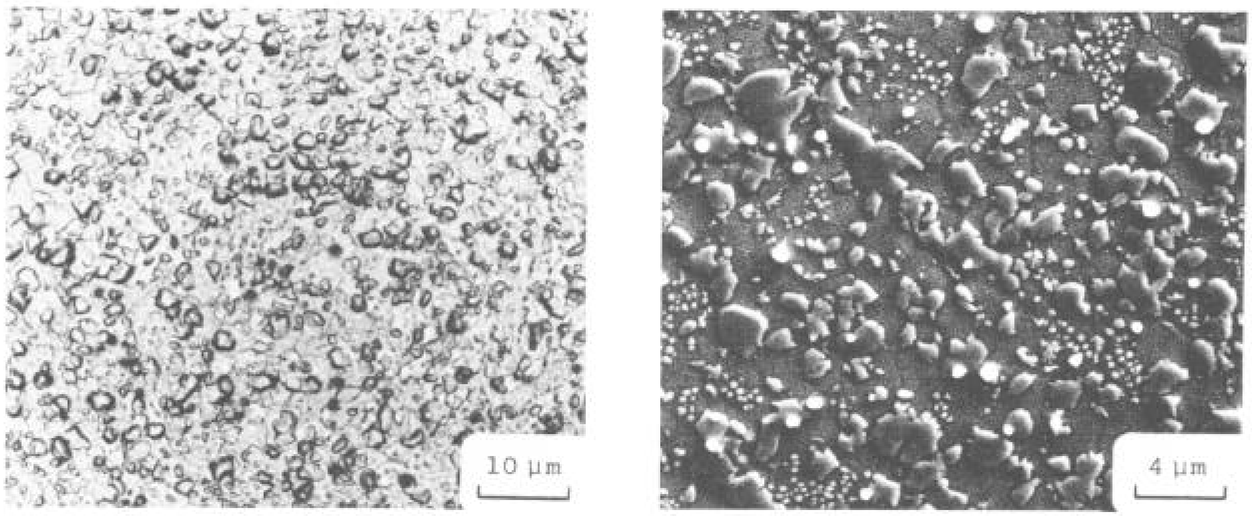
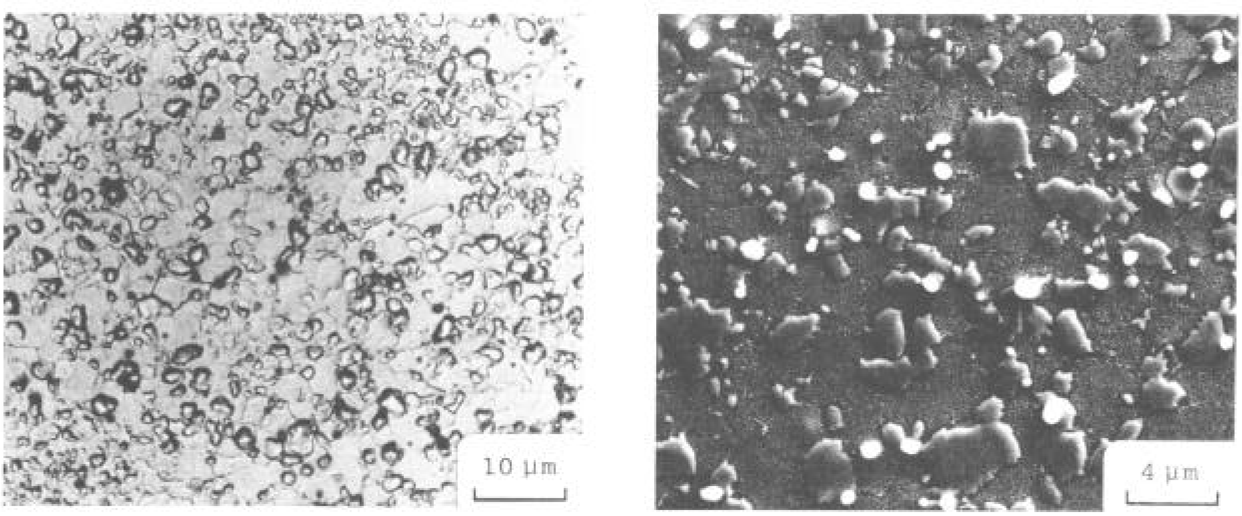


Figure 8 - Microstructure of as-extruded material used for compression testing.

Optical and scanning electron (SEM) microstructures are shown in Figure 9 to illustrate the microstructural changes that occur as the test temperature varies from 1093°C (2000°F) to 1149°C (2100°F.) The grain size after deformation is controlled primarily by the size and spacing of the large γ' present in the microstructure during deformation. As the deformation temperature increases, the volume fraction of γ' in the matrix at the test temperature decreases, and the resulting grain size increases. The difference in microstructures resulting from deformation at 1135°C (2075°F) and deformation at 1149°C (2100°F) is most striking. 1149°C is close to the γ' solvus temperature. The equilibrium concentration of γ' in the matrix changes rapidly with temperature near the solvus. Small changes in temperature result in big changes in the amount of γ' present and in the grain size, and the rapid increase in grain size as the deformation temperature approaches the γ' solvus is evident. A number of other observations can be made about microstructural features such as γ' morphology but that is beyond the scope of this paper. The particles that appear white in the SEM micrographs in Figure 9 are MC carbides.

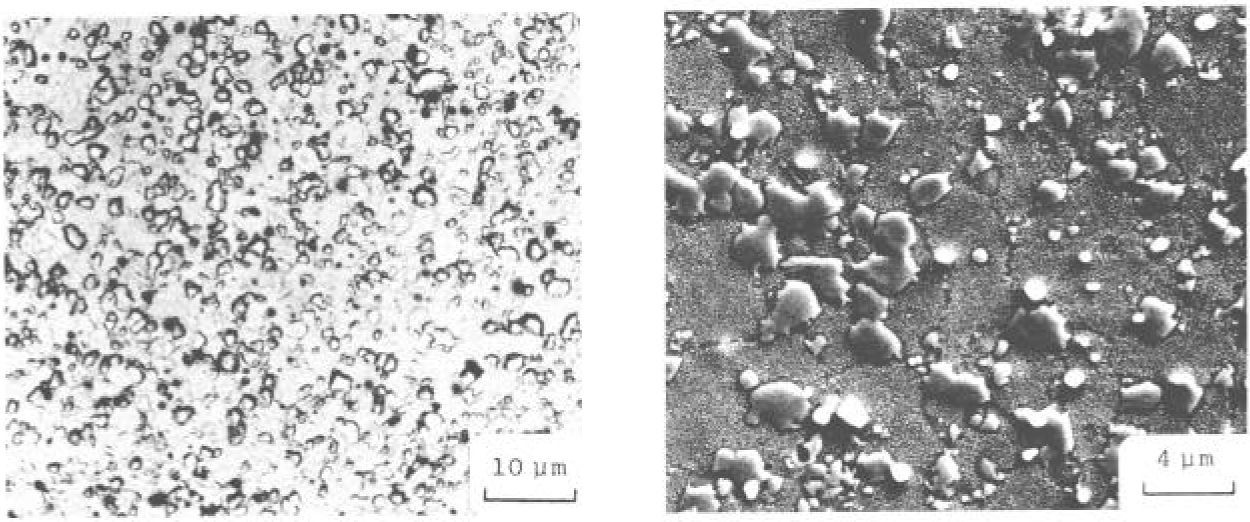


Optical a) 1093°C (2000°F) SEM

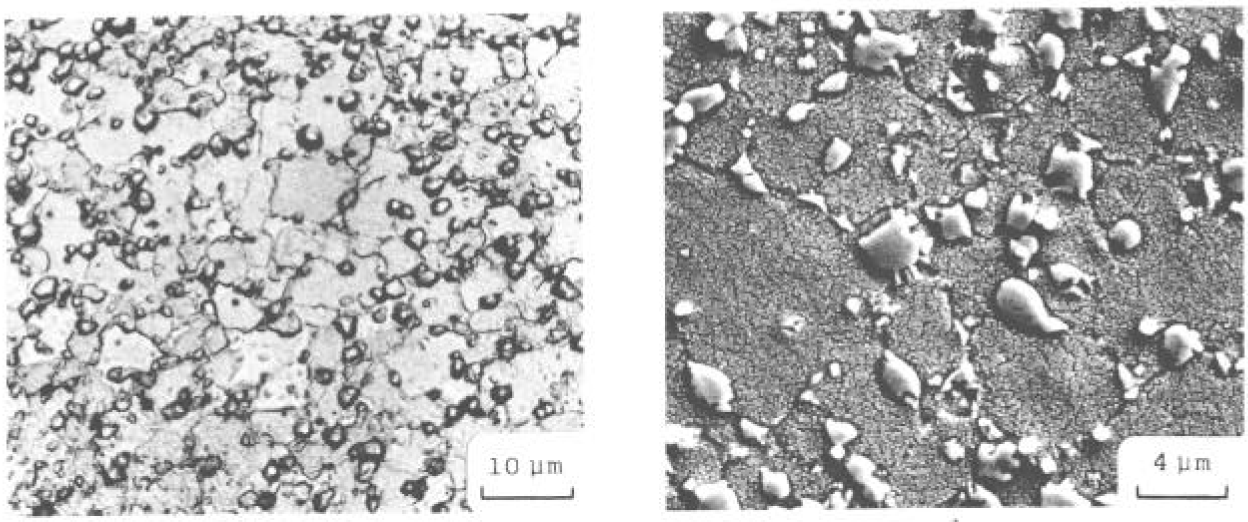


Optical b) 1107°C (2025°F) SEM

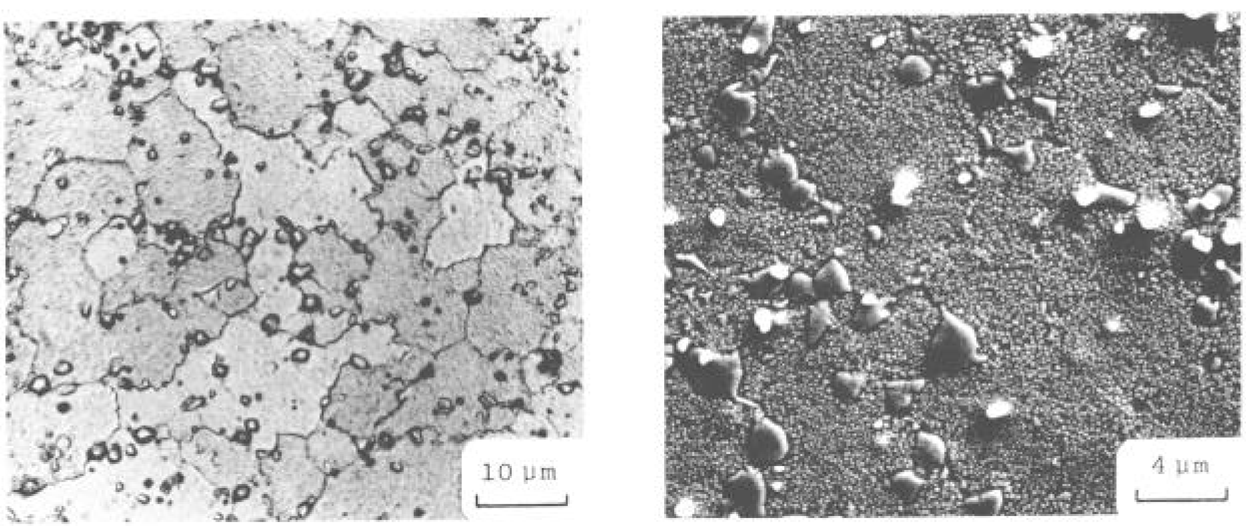
Figure 9 - Optical and SEM micrographs of compression specimens deformed at 0.0083 sec^{-1} (0.5 min^{-1}) and: a) 1093°C (2000°F), b) 1107°C (2025°F), c) 1121°C (2050°F), d) 1135°C (2075°F), and e) 1149°C (2100°F.)



Optical c) 1121°C (2050°F) SEM



Optical d) 1135°C (2075°F) SEM



Optical e) 1149°C (2100°F) SEM

Figure 9 (Continued)

Discussion

Relatively high background noise in sonic inspection of the rim of a forged superalloy disk was correlated with a grain structure which is coarser than in other areas of the forging where the sonic noise is not as high. The question is whether the grain coarsening occurred as a result of the deformation heating the material experienced in the forge process. Modeling of the metal flow predicts that the workpiece temperature has been raised up to 14°C (25°F) by the heat generated by the deformation, even in this case where the nominal strain rate is only 8.3×10^{-3} sec^{-1} (0.5 min^{-1}.) However, judging from Figures 1, 2 and 9, this change in temperature caused by the deformation heating is not enough to have caused the grain coarsening evident in Figure 1a.

Another factor to consider is the variability in furnace and die temperatures. Because of equipment limitations and productivity issues, established forge practices allow furnace and die temperatures to vary within fixed, controllable limits, typically ±8-14°C (±15-25°F.) In this case the acceptable variation for the furnace and die temperatures was ±14°C (±25°F.) It is possible, then, that the allowable temperature variation added to the increment in temperature resulting from deformation induced heating could have resulted, in this forging, in temperatures about 28°C (50°F) higher than the nominal forge temperature of 1121°C (2050°F.)

In Figure 1 the 500X optical microstructure from the high noise area of the forging is compared to a 500X microstructure from a compression specimen deformed at 1149°C (2100°F.) In Figure 2 a 500X microstructure from the low noise area of the forging is compared to a 500X microstructure from a compression specimen deformed at 1135°C (2075°F.) The comparisons support the premise that the sonic noise and the forged microstructure in Figure 1a have resulted from a process in which the temperature has risen too high, up to 1149°C (2100°F), in localized areas of the forging. The forged microstructure in Figure 1a represents a position in the rim of the forging on the boundary of the region highlighted in Figure 6 of material that was heated in the prefinish forge step 11-14°C (20-25°F) above the nominal forge temperature of 1121°C (2050°F.)

Without the process modeling the deformation heating that is a part of the problem would not have been considered significant. Instead, overheating or nonuniform heating of the workpiece by the die heating system would have been suspected. However, furnace surveys and calibration and monitoring of temperature sensors insure that process temperatures do in fact remain within prescribed limits. The process modeling indicates that in this case the workpiece temperature can locally rise too high because of a combination of factors even though the process parameters are controlled properly.

One additional observation is that the effective strains in the forging predicted by the modeling, Figure 6, are certainly higher than the effective strains in the compression specimens upset 50%. Is it appropriate to compare the forged microstructures to the compression specimen microstructures? Flow curves have been published for this superalloy in the extruded condition for deformation at 1107°C (2025°F.)[2] These curves show that the flow stresses reach a constant value at low strains (about 0.2) in the range of strain rates of interest. This suggests that at the temperatures and strain rates discussed, microstructures evolve rapidly to a steady state and the microstructural comparisons made are valid.

It is worth noting the process change made as a result of the modeling. Additional modeling carried out for a forge temperature of 1093°C (2000°F), a strain rate of 8.3 X 10^{-3} sec^{-1} (0.5 min^{-1}), and a friction factor of 0.2, showed again that in the prefinish step a temperature rise of up to about 14°C (25°F) would occur for this forging due to deformation heating. Under these conditions, taking into account the allowable process temperature variability, the maximum temperature that any part of the workpiece could experience is 1121°C (2050°F.) Another process that was modeled was forging start to finish in one step at 1093°C (2000°F) and 8.3 X 10^{-3} sec^{-1} (0.5 min^{-1}.) That simulation predicted a maximum temperature rise at the end of the forge stroke of about 22°C (40°F.) The process conditions adopted as a result of all the modeling are a forge temperature of 1093°C (2000°F) at a strain rate of 8.3 X 10^{-3} sec^{-1} (0.5 min^{-1}), in a two step operation. Areas of coarser grains and higher sonic noise have not been encountered.

Concluding Remarks

Metal flow simulation, and process modeling in general, are being utilized in forge process design and are moving from the research environment into the production environment. Several factors are responsible for this progress. The first, obviously, is that the software is available. Another is the extraordinary advances in computer technology. Computer speeds are increasing rapidly while computer costs are decreasing, and the computer-intensive finite element analyses of various processes can be done with a computer that sits on a desk. A third is that the database of material properties needed to carry out the modeling has been generated for many of the alloys of interest. Perhaps most important is that a level of confidence in the software has been reached that permits application of the modeling in production. With respect to metal flow this confidence stems from, for example, correct prediction of unfilled areas in die cavities, correct prediction of the formation of forging defects such as laps, and successful manipulation of preform and die shapes to modify strains and microstructures to enhance mechanical properties.

In this paper the application of nonisothermal metal flow simulation with ALPID to analyze suspected overheating in a forging has been described. The modeling has helped redefine the forge process parameters and overcome the problem. Other successful nonisothermal simulations have been carried out to assess the effects of die chilling (when the dies are cooler than the workpiece) on the flow behavior and strains in forgings, and to analyze titanium alloy beta forging. Process modeling is enhancing the ability of the industry to design and manufacture forgings.

References

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