PREDICTION OF GRAIN SIZE DURING MULTIPLE PASS

RADIAL FORGING OF ALLOY 718

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Abstract

Multiple pass radial forging was simulated by generating compression data for Alloy 718 with a Gleeble testing machine. Specimens were taken from a press forged billet preform 343mm in diameter. Variables evaluated were strain per pass, number of passes, temperature, and time per pass. Recrystallized grain size was found to be independent of the number of passes after the first couple passes for deformation above the delta solvus. Strain per pass and temperature were found to be the dominant factor affecting microstructure. A predictive relation was found that relates recrystallized grain size to the strain per pass and the starting grain size for constant temperature. Grain sizes predicted by multiple pass simulation agreed well with actual grain sizes for radial forging on a GFM machine when cooling from temperature after deformation was duplicated.

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Introduction

Radial forging is an open die process used in the conversion of ingots to billets with round, square, or rectangular shapes; also, hollow shafts can be forged. The workpiece is deformed by four hammer dies arranged radially around the workpiece. For the SXP-55 GFM radial forging machine at Teledyne Allvac, the stroke rate of the hammer is 200 strokes per minute. After each forging blow, the workpiece is fed axially toward the entrance of the dies. The workpiece is held at each end by chuckheads, which are track bound manipulators. When producing round products, the chuckheads rotate the workpiece between blows to obtain a uniform forged surface.

The consistency of radial forging and the generation of heat by the rapid stroke rates provide the opportunity to meet stringent grain size requirements needed by forgers and end users such as aircraft engine builders. However, establishing a practice for radial forging a given product entails selecting parameters for a number of parameters such as furnace temperature, axial feed rate, reduction per pass, reheat size, time per pass, and billet lengths. Selection of these parameters by trial and error is expensive and time consuming. Therefore, some excellent finite element models have been developed for predicting temperatures, strains, and strain rates during radial forging. To be effective, these models must be coupled with a method to relate temperatures, strains, and strain rates to grain structure [1-3]. Most of the methods reported in the literature have focused on microstructured predictions during rolling and finish forging [4-8]. Little information is available regarding microstructural evaluation during radial forging. Therefore, a joint program was initiated between the Ohio State University and Teledyne Allvac to simulate multiple pass forging and to help develop a method for predicting as-forged microstructures in Alloy 718 billets during radial forging.

Experimental Procedure

Multiple pass forging sequences for radial forging were simulated by compression testing on a Gleeble 1500 thermomechanical testing machine from DSI International. Test specimens had a diameter of 10mm and were 10mm in height. All testing was performed at a constant strain rate of 1.0 per second. Chromel-alumel thermocouples were percussion welded at mid-span of each specimen to provide a closed loop for temperature control. Each specimen was heated to temperature over a three minute period and then held at temperature for seven minutes to equilibrate the microstructure prior to the simulation. Prior to each pass sequence, a 60 second hold time at temperature was performed to simulate the transfer time from the furnace to the radial forging machine. Following the deformation corresponding to a pass, specimens were held at temperature for a time equal to the pass time during radial forging plus an additional 10 seconds to simulate the time between passes. Deformation corresponding to the next pass was then imparted and the above sequence was repeated. The parameters evaluated are shown below in Table I.

Table I. Test Matrix for Gleeble Compression Testing Simulating Multiple Pass Radial Forging of Alloy 718.

Temperature:	**954, 1010, and 1066 degrees C**
Strain Per Pass:	**0.0, 0.1, and 0.2**
Number of Passes:	**1, 2, 3, and 4**
Time Per Pass:	**30, 60, and 90 seconds**

Two additional strains per pass (0.15 and 0.30) were evaluated at 1066°C for a 60 second pass time to help confirm a quantitative relation observed between grain size and strain per pass.

In order to analyze the influence of the above parameters on grain structure and to determine if any multi-factor interactions were important, an Analysis of Variance was performed.

Grain structures from a radially forged billet were compared to those predicted by the multiple pass compression testing. Radial forging of this billet used pass throughs between each pass so that forging was always in the same direction; this means that pass time was the same for each location along the billet. However, results are generally applicable even when pass time varies along the length of the billet as a result of forgings in both directions. Metallographic examination of billets converted by radial forging have shown that, with the exception of billet ends, the variation in grain size is minimal for billets under about 9 meters in length [8].

The die stack for Gleeble testing consisted of a set of 19mm diameter tungsten carbide platens mounted in 304 Stainless Steel jaws. To minimize barreling induced by friction, graphite foil was used as a lubricant. The effective value of the friction factor, m found through FEM simulation, was found to be 0.25 which is typical for a graphite based lubricant.

Material

Gleeble compression samples were from the mid-radius of Alloy 718 billet 343mm in diameter. It had been press forged from a 508mm diameter ingot and represented a preform for radial forging. The nominal composition of the billet is shown in Table II. The microstructure was duplex with about 50% ASTM 6.0 and about 50% ASTM 8.5 unrecrystallized grains at the mid-radius location as shown in Figure 1.

Table II. Nominal Composition of the Alloy 718 Preform Slice (in wt. %).

C	Cr	Mo	B	Al	Ti	Cb	Fe	Ni
0.035	17.8	2.90	0.004	0.70	1.00	5.40	18.30	Bal.

Cylindrical test specimens were EDM machined from a billet slice such that the compression axis of the specimen was parallel to the longitudinal axis of the preform. To minimize scatter in the starting grain size, all samples were taken from a 50mm band located at mid-radius of the billet slice. However, some variation in the relative amounts of coarser and finer grains did prevail.

Experimental Results

Table III shows grain size data from Gleeble compression testing simulating multiple pass radial forging with a 30 second pass time. Similar data was obtained for pass times of 60 and 90 seconds. The major reasons for a series of samples with no reduction was to establish structures at temperature before deformation and to examine structure versus times for the various temperatures. With strains of 0.10 and 0.20, grain size did not change with increasing passes at the lower temperature of 954°C. This is related to 954°C being below the delta solvus temperature and to the lack of sufficient thermal energy for recrystallization. Grains did become elongated with deformation as shown in Figure 2, which represents the fourth pass at 954°C with 0.10 strains per pass for a pass time of 60 seconds. An example of the recrystallized grain structures at higher temperatures is shown in Figure 3 for 1066°C after three passes at 0.20 strain per pass.

Table III. Grain Sizes of Gleeble Compression Samples for a Pass Time of 60 Seconds.

	NO REDUCTION			
	PASS 1	PASS 2	PASS 3	PASS 4
956°C	6, 50% 8.5	6, 50% 8.5	5, 50% 8.5	6, 50% 8.5
1010°C	6, 3% 8	6	6	6
1066°C	4	4	4	4

	0.10 STRAIN PER PASS			
	PASS 1	PASS 2	PASS 3	PASS 4
954°C	6, 50% 8.5	6, 50% 8.5	6, 50% 8.5	6, 50% 8.5
1010°C	5, 50% 8.5	8.5, 45% 6	8.5, 1% 6	8.5 ALA 6
1066°C	6.5, 1% 5	6.5 ALA 5	6.5	6.5

	0.20 STRAIN PER PASS			
	PASS 1	PASS 2	PASS 3	PASS 4
954°C	6, 50% 8.5	6, 50% 8.5	6, 50% 8.5-10	6, 30% 8.5
1010°C	8, 30% 6	9.5, 3% 6	9.5, ALA 6	8.5
1066°C	4, 30% 7	7	7	7

Figure 4 provides recrystallized grain sizes versus number of passes for 30, 60, and 90 seconds, respectively, for temperatures of 1010 and 1066°C. The trend of the data is for the grain size achieved by the second pass to remain constant with increasing number of passes. This final grain size increases with decreasing temperature and increasing strain per pass.

Analysis for Deformation Above the Delta Solvus

As an initial step in building a predictive model for super-solvus forging, the data was analyzed using Analysis of Variance (ANOVA) to identify significant factors and interactions. The results of the F-test in Table IV indicate the temperature and strain per pass are the most significant factors by almost two orders of magnitude at a 99% confidence level in affecting the recrystallized grain size. The time per pass and the number of passes were also found to be significant at a 99% confidence level but had much lower F-values. Two interaction terms are also significant. It is indicated that the as-forged grain size will be affected by both temperature and the number of passes with the effect of each factor being conditioned by the level of the other. This is also true for the interaction between time and temperature.

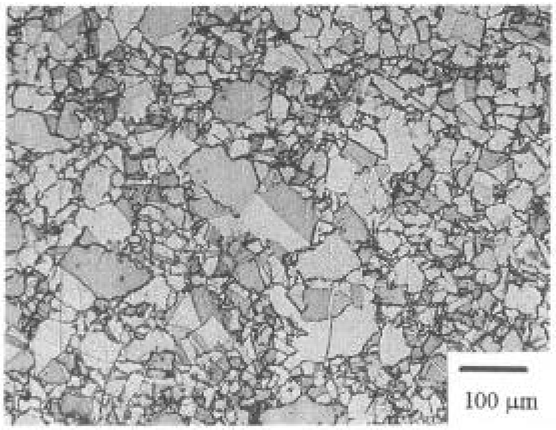


Figure 1. Microstructure of Alloy 718 Preform Billet 343mm in Diameter at Center Location.

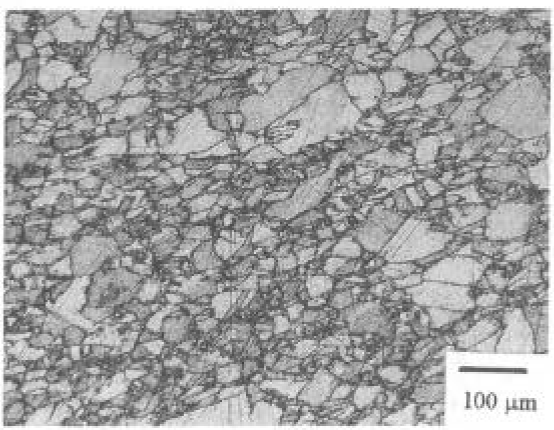


Figure 2. Microstructure of Alloy 718 Gleeble Specimen After Four Passes of 0.10 Strain at 954°C.

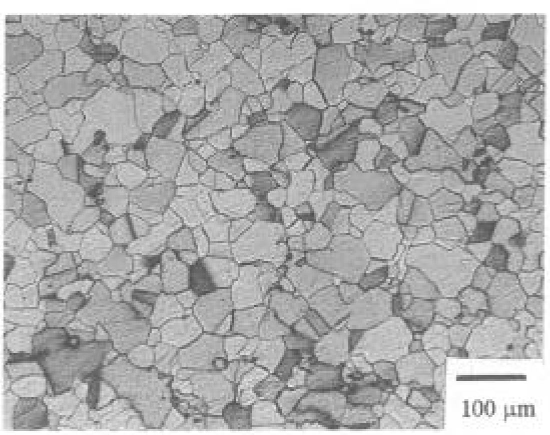


Figure 3. Microstructure of Alloy 718 Gleeble Specimen After Three Passes of 0.20 Strain at 1066°F.

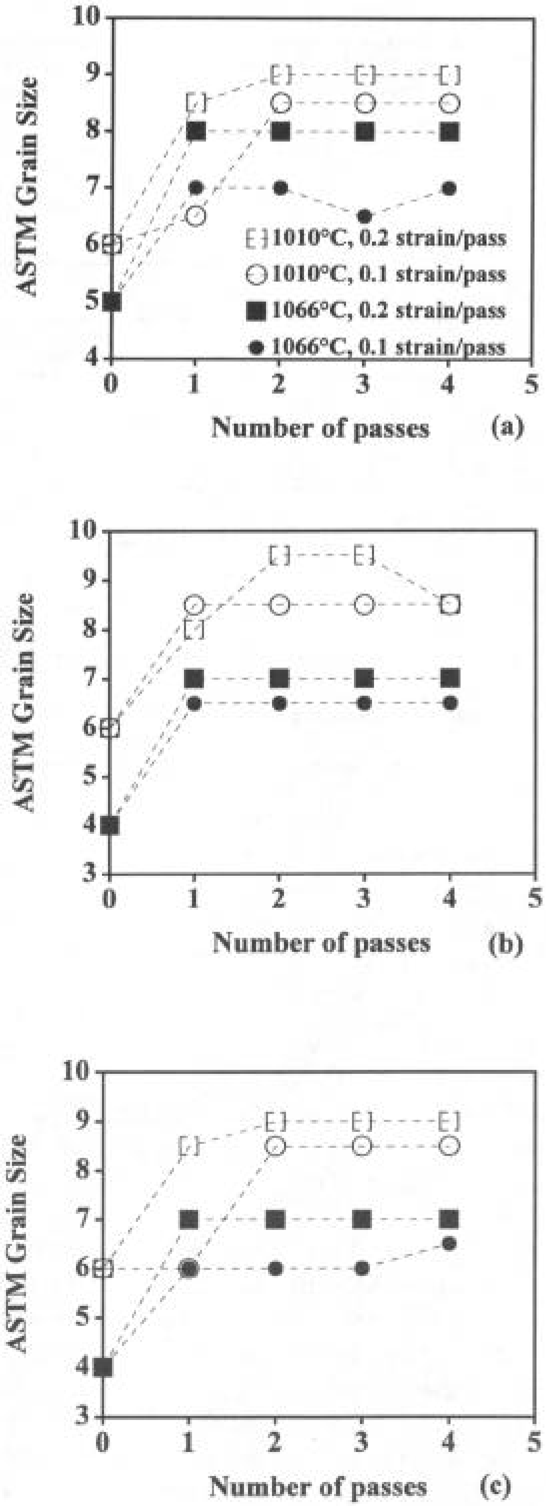


Figure 4. Recrystallized Grain Size Versus Number of Passes for Pass Time of (a) 30 seconds (b) 60 seconds and (c) 90 seconds.

Table IV. ANOVA Table for Recrystallized Grain Size Data from the Gleeble Simulations Conducted at Super-Solvus Temperatures. Significant F-Values are Denoted by an Asterisk.

Source	DOF	Sum Squares	Mean Square	F-Value
Time Per Pass	2	2.42	1.21	9.28*
Temperature	1	49.17	49.17	376.62*
Strain Per Pass	2	107.09	53.55	410.13*
No. of Passes	3	1.79	0.6	4.57*
Temp/Strain	2	0.05	0.02	0.19
Temp/Passes	3	3.21	1.07	8.18*
Strain/Passes	6	2.24	0.37	2.86
Time/Temp	2	4.92	2.46	18.86*
Time/Strain	4	1.31	0.33	2.5
Time/Passes	6	0.74	0.12	0.95
Error	40	5.22	0.13	
TOTAL	71			

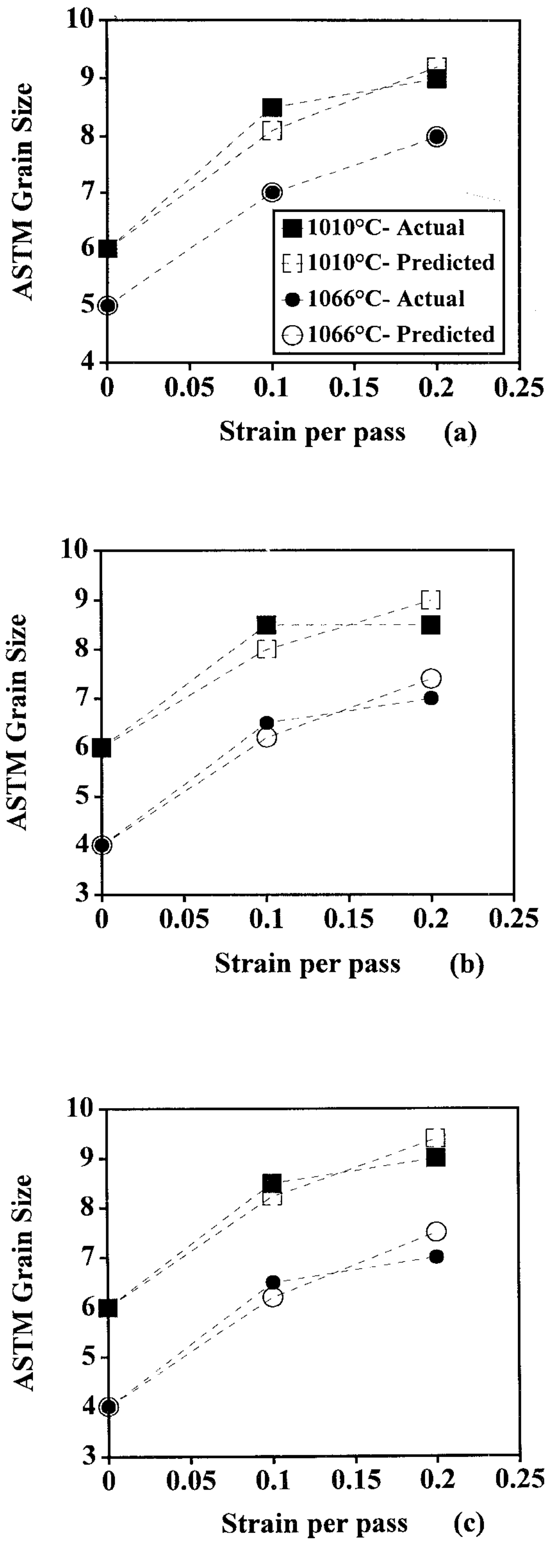
Effect of Strain Per Pass

Grain size became finer with increasing strain per pass. The relation given below in Equation (1) was found to represent the ASTM grain size (d) at the end of each simulated pass sequence for super-solvus deformation.

$$\log d_{gs} = a\sqrt{\epsilon} + \log s \qquad (1)$$

The term s is the starting ASTM grain size of the specimen and a is a constant which is a function of temperature and time per pass. Typical values of a for Alloy 718 were found to be between 0.3 and 0.6.

A comparison of the experimental and predicted results are shown in Figure 5 for pass times of 30, 60, and 90 seconds, respectively, after four passes. Equation (1) provides a good fit with the experimental data; it shows that the recrystallized grain size is primarily sensitive to the strain per pass at a given temperature. Although it gives good results for billet material which achieves a steady-state recrystallized grain size, a comparison based on the experimental data of Mataya and Matlock [9] for as-cast Alloy 718 showed that Equation (1) does not yield good results where large, as-cast grains are continually being refined during each pass as is typical during initial ingot conversion. For example, Alloy 718 billet with a starting grain size of ASTM 1.0 showed continuous refinement with each pass for a four pass sequence of 0.25 strain per pass at 1050°F.



The coarser the starting grain size, the greater the amount of strain needed to achieve the same recrystallized grain size.

In order to further evaluate Equation (1), Gleeble specimens were deformed at strains per pass of 0.15 and 0.30. The resulting recrystallized grain sizes are presented in Figure 6 where agreement with the predicted curve representing Equation (1) is very good.

It is interesting to note that the steady-state recrystallized grain size is a function of the strain per pass and not of the total strain. This indicates that a smaller number of passes at heavier reductions are preferable to a larger number of passes at lighter reductions for achieving a finer recrystallized grain structure.

Effect of Forging Temperature

Decreasing temperatures resulted in a finer recrystallized grain size. The average difference in recrystallized grain size was about 2.5 ASTM grain size numbers between 1066 and 1010°C. The dependence of grain size on forging temperature is shown in Figure 7 for pass times of 30, 60, and 90 seconds.

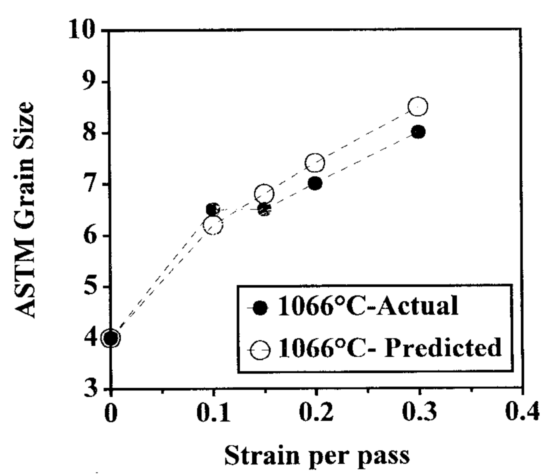


Figure 5. Measured Recrystallized Grain Sizes Compared to Predictions by Equation (1) After Four Passes for Pass Time of (a) 30 (b) 50, and (c) 90 Seconds.

Figure 6. Measured Recrystallized Grain Sizes Compared to Predictions from Equation (1) After Four Passes for a Pass Time of 60 Seconds.

The amount of recrystallization was also dependent on temperature. As illustrated in Table V, the number of passes required for 100% recrystallization decreased with increasing temperature for pass times of 30 and 60 seconds.

Table V. Number of Passes for Complete Recrystallization.

Pass Time (sec)	Strain Per Pass	Pass for 100% Recrystallization	
		1010°C	1066°C
30	0.1	4	2
	0.2	4	2
60	0.1	4	2
	0.2	3	2
90	0.1	3	3
	0.2	2	2

Effect of Time Per Pass

At 1010°C, time per pass did not influence the recrystallized grain size. However, as shown in Figure 8, grain size did decrease with increasing time per pass at 1066°C. This is attributed to the additional time available for grain growth.

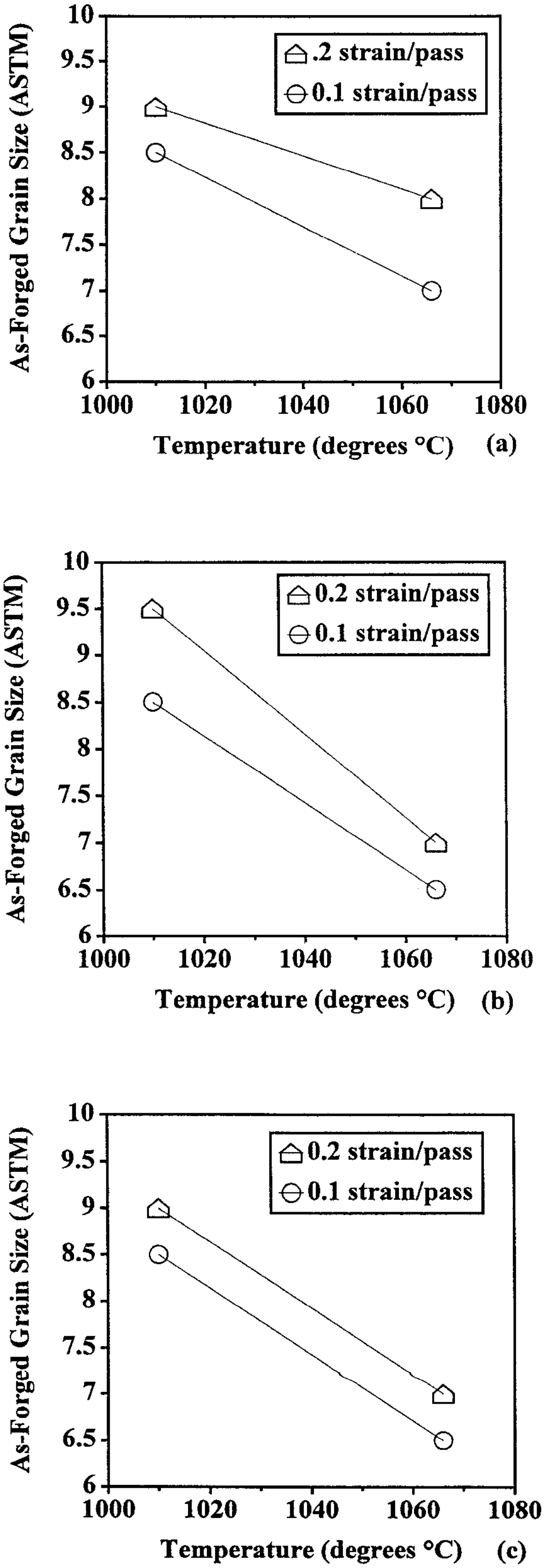


Figure 7. Recrystallized Grain Size as a Function of Temperature for Pass Times of (a) 30 (b) 60, and (c) 90 Seconds.

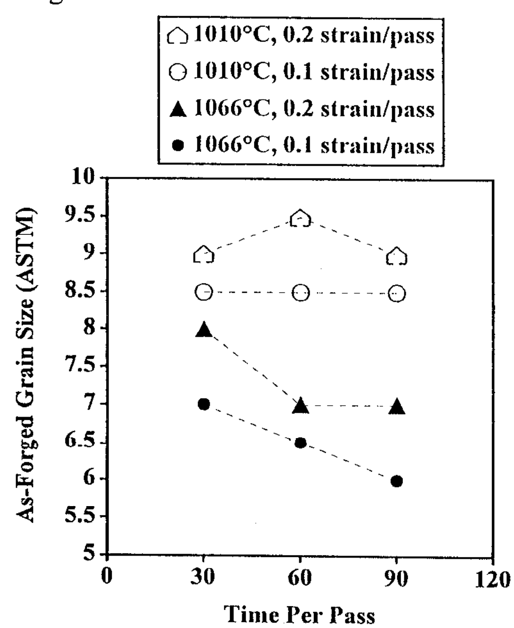


Figure 8. Recrystallized Grain Size Versus Time Per Pass After Four Passes.

It can also be seen in Table V that the number of passes for 100% recrystallization decreased with increasing pass time at 1010°C. The increased time allows more static recrystallization to take place.

Application to Radial Forging

A comparison was made between the grain size predicted by the multiple pass simulation and the actual grain achieved in radial forging Alloy 718 on a GFM machine. Parameters for the radial forging were as follows:

Starting Diameter:	13.5" (343mm)
Finish Diameter:	8.0" (203mm)
Furnace Temperature:	1900°F (1038°C)
Time Between Passes:	About 60 Seconds
Reduction Sequence:	Five Passes (15, 15, 20 20, 20%)

The predicted grain size was about 7, while the actual grain size was 6.5 at the mid-radius and 6 at the center location. This deviation from prediction was attributed to grain growth on cooling after radial forging. In order to confirm this assumption, a Gleeble specimen was tested with four passes at 0.20 strain and cooled after deformation at the same cooling profile as the center of the 8" (203mm) diameter billet after radial forging. The cooling profile for the center of the 8" (203mm) billet was obtained from M.S. Ramesh of Teledyne Allvac using a GFM model developed by Erik Thompson of Colorado State University and Teledyne Allvac with the help of Shesh Srivatsa from General Electric. Figure 9 shows temperature during GFM forging and on cooling. It can be seen that the temperature at the center and mid-radius locations increases from 1900°F (1038°C) to about 1950°F (1066°C). The Gleeble specimen with a cooling profile duplicating that at the center of the 8" (203mm) diameter billet exhibited the same grain size as the billet as shown in Figure 10.

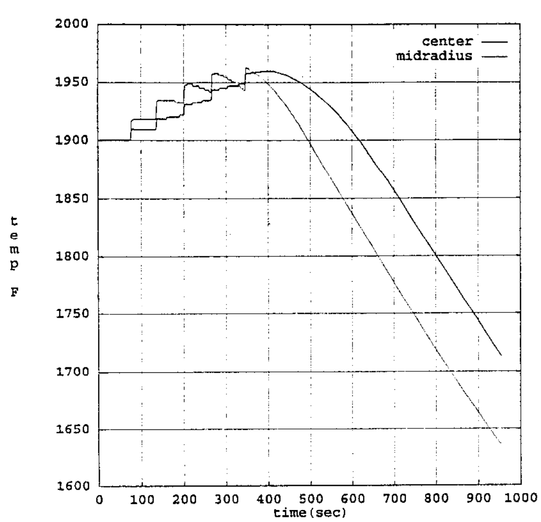


Figure 9. Temperature Versus Time for Radial Forging of Alloy 718 from 13.5" (343mm) to 8" (203mm) in Five Passes from a Furnace Temperature 1900°F (1038°C). Provided by TA Model.

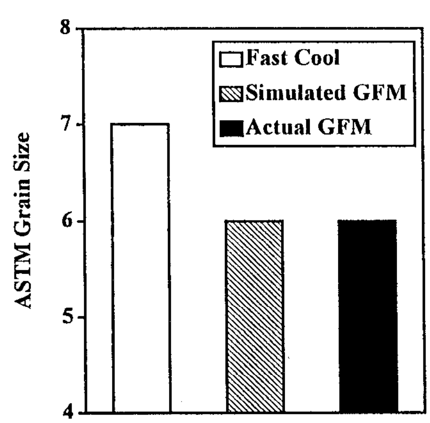


Figure 10. Recrystallized Grain Size from Actual Radial Forging Trial Compared with those from Gleeble Compression Tests with a Fast Cool and a Cooling Profile Simulating that of Radial Forging.

Conclusions

Compression testing with a Gleeble machine was successfully used to predict microstructures for radial forging of Alloy 718. However, account must be taken for the specific cooling profile after radial forging. The following trends were found for super solvus deformation:

- After a couple passes, recrystallized grain size was independent of the number of passes.
- Increased strain per pass and decreased temperature were the dominant factors for producing a finer grain structure.
- Recrystallized grain size became coarser with increasing time per pass at 1066°C but not at 1010°C.
- The number of passes for complete recrystallization decreased with increasing time per pass.

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