

# Computer Simulation of Microstructure Evolution during Hot Forging of Waspaloy and Nickel Alloy 718

D. Huang, W.T. Wu, D. Lambert, and S.L. Semiatin \*

Scientific Forming Technologies Corporation,  
Columbus, OH 43220

\*Air Force Research Laboratory,  
Materials and Manufacturing Directorate,  
Wright-Patterson Air Force Base, OH 45433

## Abstract

Computer simulation of microstructure evolution during hot forging of superalloys is of great interest, particularly for the manufacture of critical components for aerospace applications. To this end, recrystallization and grain growth were modeled using a phenomenological approach and implemented in the commercial metal forming code DEFORM™ that establishes the thermomechanical history. Necessary material parameters used in the analysis were collected from available literature. To validate the model with Waspaloy, an industrial disk forging process was simulated. Predictions of recrystallized volume fraction and grain size were in good agreement with the measurements. For nickel alloy 718, simple upsetting and double-cone forging were simulated and compared with experimental data. A three-dimensional cogging simulation was also performed for as-cast 718 ingot material to demonstrate the capability of the model.

## Introduction

Waspaloy and nickel alloy 718 are used in critical components for aerospace applications, such as turbine-engine disks, due to their good creep and fatigue resistance at elevated temperatures. To obtain optimal properties, close and robust control of the grain size is crucial. For instance, a fine grain size is desirable near the hub to resist crack initiation while a larger grain size is preferred near the rim for creep resistance. In order to achieve a desirable microstructure distribution, as-cast materials usually undergo multiple stages of forming, such as billet conversion and closed-die forging, and multiple heat treatment steps such as solution heat treating and aging.

During thermomechanical processing, a dislocation substructure is developed as deformation is imposed. The stored energy can provide the driving force for various restorative processes such as dynamic recovery or recrystallization. The process of recrystallization, be it static or dynamic, involves the nucleation of dislocation-free grains and their subsequent growth. Upon the completion of recrystallization, the energy can be further reduced by grain growth, in which grain boundary area is reduced. The kinetics of recrystallization and grain growth processes are complex. In order to predict the grain-size distribution in finished components, a basic understanding of the evolution of

microstructure evolution during complex manufacturing sequences, including the primary working processes (ingot breakdown, rolling, or extrusion), final forging, and heat treatment, must be obtained. Hence, the development of microstructure evolution models has received considerable attention in recent years. Most early work [1-6] focussed on the hot rolling of steels due to the commercial importance of such materials. Furthermore, rolling processes can be simulated assuming a steady-state approximation. Thus, the simulation procedure is inherently much simpler than that involved in the modeling of forging processes. Recently, microstructure-modeling efforts have been extended to the forging of wrought Waspaloy by Shen, et al. [7], the breakdown of nickel alloy 718 ingots by Zhao, et al. [8], and the forging of 718 turbine disks by Brand, et al. [9]. The success of their work has shown great potential to utilize computer simulation to design manufacturing processes to achieve desired grain sizes and grain-size distributions.

This paper summarizes recent efforts to incorporate phenomenological recrystallization and grain growth models into the commercial finite-element-method (FEM) code DEFORM™. The required material parameters used in the study were collected from the literature. The overall approach was validated for both Waspaloy and 718. For Waspaloy, an industrial disk forging process was simulated. For nickel alloy 718, simple upsetting and double-cone forging were modeled. To further demonstrate the capability of the approach, a three-dimensional (3-D) ingot-to-billet conversion process was simulated for the 718 alloy.

### Recrystallization and Grain Growth Models

Recrystallization behavior can be classified into three broad categories [6, 7, 10, 11]:

- *Static recrystallization (SRX)*: Recrystallization that occurs *after* deformation in which the imposed strain is less than a certain critical strain. Recrystallization begins in a nuclei-free environment.
- *Metadynamic recrystallization (MRX)*: Recrystallization that occurs *after* deformation in which the imposed strain is greater than the critical strain. Because the strain exceeds the critical strain, nuclei are present when recrystallization starts.
- *Dynamic recrystallization (DRX)*: Recrystallization that occurs *during* deformation when the strain exceeds the critical strain.

The description of each recrystallization mode as well as static grain growth is further described below. Microstructure evolution in superalloys is complicated by the precipitation of  $\gamma'$ ,  $\gamma''$ , and  $\delta$  phases [12]. However, the present phenomenological approach neglected the specific effect that such phases have on the mechanisms of microstructure evolution.

#### Static Recrystallization (SRX)

SRX occurs after deformation in which the imposed strain is less than the critical strain  $\epsilon_c$ . The critical strain is usually a fraction of the strain  $\epsilon_p$  at which the flow stress reaches its maximum (and flow softening due to dynamic recrystallization commences). The value of  $\epsilon_p$  is determined experimentally and is often a function of strain rate, temperature, and initial grain size, viz.,

$$\epsilon_p = a_1 d_o^{n_1} \dot{\epsilon}^{m_1} \exp(Q_1 / RT) + c_1 \quad (1)$$

$$\epsilon_c = a_2 \epsilon_p \quad (2)$$

Because recrystallization is usually controlled by nucleation and growth, isothermal annealing kinetics are typically fit by an Avrami equation to describe the relation between recrystallized volume fraction and time:

$$X_{srx} = 1 - \exp \left[ -\beta_s \left( \frac{t}{t_{0.5}} \right)^{k_s} \right] \quad (3)$$

$$t_{0.5} = a_3 d^{h_3} \dot{\epsilon}^{n_3} \exp(Q_3 / RT), \quad (4)$$

in which  $t_{0.5}$  denotes the time for 50 percent recrystallization.

The recrystallized grain size is given as a function of initial grain size, strain, strain rate, and temperature:

$$d_{srx} = a_6 d_0^{h_6} \varepsilon^{n_6} \dot{\varepsilon}^{m_6} \exp(Q_6 / RT) + c_6 \quad (\text{if } d_{srx} > d_0 \text{ then } d_{srx} = d_0). \quad (5)$$

#### Metadynamic Recrystallization (MRX)

MRX occurs when the retained strain at the conclusion of deformation is greater than the critical strain. MRX is modeled similarly to SRX but with different sets of material constants, i.e.,

$$X_{mrx} = 1 - \exp\left[-\beta_m \left(\frac{t}{t_{0.5}}\right)^{k_m}\right], \quad (6)$$

$$t_{0.5} = a_4 d_0^{h_4} \varepsilon^{n_4} \dot{\varepsilon}^{m_4} \exp(Q_4 / RT), \quad (7)$$

and 
$$d_{mrx} = a_7 d_0^{h_7} \varepsilon^{n_7} \dot{\varepsilon}^{m_7} \exp(Q_7 / RT) + c_7 \quad (\text{if } d_{mrx} > d_0 \text{ then } d_{mrx} = d_0). \quad (8)$$

#### Dynamic Recrystallization (DRX)

DRX is an inherently complex process due to the simultaneous generation of dislocations and their annihilation by recrystallization. Experimental data are usually collected under various strain, strain rate, and temperature conditions. DRX is then modeled phenomenologically as a function of strain at a fixed temperature and strain rate. An Avrami equation is also used to describe the relation between DRX volume fraction and the effective strain:

$$X_{drx} = 1 - \exp\left[-\beta_d \left(\frac{\varepsilon - a_{10} \varepsilon_p}{\varepsilon_{0.5}}\right)^{k_d}\right] \quad (9)$$

$$\varepsilon_{0.5} = a_5 d_0^{n_5} \dot{\varepsilon}^{m_5} \exp(Q_5 / RT) + c_5, \quad (10)$$

in which  $\varepsilon_{0.5}$  denotes the strain for 50 percent recrystallization.

The SRX grain size is expressed as:

$$d_{drx} = a_8 d_0^{h_8} \varepsilon^{n_8} \dot{\varepsilon}^{m_8} \exp(Q_8 / RT) + c_8 \quad (\text{if } d_{drx} > d_0 \text{ then } d_{drx} = d_0). \quad (11)$$

From a modeling standpoint, it is very difficult to estimate DRX behavior *during* a hot forming simulation. Therefore, DRX is actually computed immediately *after* an increment of deformation using the average temperature and strain rate of the deformation period as input.

#### Grain Growth

Grain-growth modeling is performed for the material in the *strain-free state*; i.e., before hot working or after recrystallization is completed. For this purpose, the classical phenomenological grain-growth relation is employed:

$$d_{gg} = \left[ d_0^m + a_9 t \exp\left(-\frac{Q_9}{RT}\right) \right]^{1/m}. \quad (12)$$

### **Applications**

The modeling approach embodied in Equations (1) – (12) was implemented in the FEM code DEFORM<sup>TM</sup> and applied to the subscale hot forging of the iron-nickel-base superalloy 718 and the nickel-base superalloy Waspaloy as well as to the cogging of alloy 718 ingots.

#### Hot Forging of 718

*Input Data.* The recrystallization behavior of 718 has been studied extensively, but few comprehensive or quantitative models are available in the literature. Nevertheless, experimental data were collected from various publications to determine the required material constants for the model

equations. Although the alloy compositions varied slightly in the previous investigations, the data do indicate the basic characteristics of the material.

Typical industrial processing of nickel alloy 718 is performed at temperatures between 980 and 1040°C and strain rates between 0.1 and 5 s<sup>-1</sup>. Under these conditions, DRX occurs rather slowly [13]. Hence, primary attention was focussed on MRX and SRX.

From the work of Brand, et al. [9], the strain at the peak stress for 718 is given by the following expression:

$$\varepsilon_p = 0.4659 \times 10^{-2} \dot{\varepsilon}^{0.1238} \exp\left(\frac{49520}{RT}\right). \quad (13)$$

The MRX kinetics were determined mainly from Zhou's experimental data [13]. Work by Weis, Mosser, and their coworkers [14, 15] was also used to determine the effect of strain on MRX kinetics. The experimental data on MRX grain size were collected primarily from Medeiros [16]. The dependence on strain was modified based on Zhang's work [17]. The influence of initial grain size was ignored. The relationships developed to describe MRX are as follows:

$$X_{mrx} = 1 - \exp\left[-0.693\left(\frac{t}{t_{0.5}}\right)\right] \quad (14)$$

$$t_{0.5} = 5.043 \times 10^{-9} \varepsilon^{-1.42} \dot{\varepsilon}^{-0.408} \exp\left(\frac{196000}{RT}\right) \quad (15)$$

$$d_{mrx} = 4.85 \times 10^{10} \varepsilon^{-0.41} \dot{\varepsilon}^{-0.028} \exp\left(\frac{-240000}{RT}\right) \quad (16)$$

The SRX model was based on the results in Reference 18 for cast 718. In this work, it was found that the SRX volume fraction is weakly dependent on strain rate, and the recrystallized grain size is not a strong function of strain rate or strain. Thus, the following *approximate* relations were obtained:

$$X_{srx} = \exp\left[-0.693\left(\frac{t}{t_{0.5}}\right)\right] \quad (17)$$

$$t_{0.5} = 3.16 \varepsilon^{-0.75} \exp\left(\frac{74826}{RT}\right) \quad (18)$$

$$d_{srx} = 6.78 \times 10^2 \exp\left(\frac{-31710}{RT}\right) \quad (19)$$

Prior experimental data [18, 19] were also employed to derive a relation for static grain growth for times less than 30 minutes:

$$d_{gg} = \left[ d_0^2 + 9.44 \times 10^{19} t \exp\left(-\frac{467114.7}{RT}\right) \right]^{1/2} \quad (20)$$

The flow stress, thermal conductivity, and heat capacity of 718 as well as interface-heat transfer-transfer and friction coefficients were obtained from References 20 and 21.

*Simulation Results.* To verify the microstructure evolution model for 718, simulations of upsetting and the forging of double-cone samples were conducted. Initial attention was focussed on Zhou's results for simple upsetting of cylindrical samples to a height strain of 0.7 [13]. Experimental and simulation results at the center of the workpiece are listed in Table 1. The agreement of predicted and measured recrystallized volume fractions was very good. The good agreement is not a surprising inasmuch as the material coefficients in the MRX volume fraction equations were determined primarily from Zhou's experiments. With respect to recrystallized grain size, there were some discrepancies

between the experiments and simulations. Nevertheless, the magnitudes of the predicted grain size were correct, and the expected grain-size dependence on temperature was replicated.

The upset tests of Medeiros, et al. [16] were also simulated. In these experiments,  $\epsilon = 0.6$ ,  $\dot{\epsilon} = 0.1 \text{ s}^{-1}$ , and a helium gas cool was used. The simulation results agreed well with the measurements (Table 2). The observation of a fully-recrystallized microstructure was also predicted by the simulations.

Table 1. Comparison of Measurements and Predictions for the Simple Upsetting of 718

Temperature (°C)	Strain Rate (s <sup>-1</sup> )	Recrystallized Volume Fraction (Pct.)/Recrystallized Grain size (µm)	
		Experiments [13]	Simulations
950	0.1	76 / --	76 / 6
	0.05	63 / --	66 / 5
1000	0.1	94 / 9	94 / 12
	0.05	88 / 10	89 / 13
1050	0.1	100 / 17	100 / 27
	0.05	100 / 18	100 / 26

Table 2. Comparison of Measured and Predicted Grain Sizes (µm) in 718 Upset Tests of Medeiros, et al. [16]

Temperature (°C)	Measured Grain Size	Simulation Results
950	5	4
1000	7	10
1050	25	23

As a second example, the forging of alloy 718 double-cone samples, reported by Jain et al. [20], was simulated. The workpiece was 152 mm in diameter and 64 mm high (Figure 1). It had been heated to 982°C before forging and upset on dies heated to 665°C at a ram speed of 8 mm/s. The cooling conditions after forging were not clearly described in Reference 20, but helium-gas cooling was assumed. Subsequently, the microstructure was determined at four locations (Figure 2, showing one quarter of the workpiece) using optical metallographic techniques. The measured recrystallized volume fractions and average grain sizes were estimated (Table 3). The order of recrystallized fraction was  $2 > 3 \geq 4 > 1$ , and the order of average grain size was  $1 > 4 \geq 3 > 2$ .

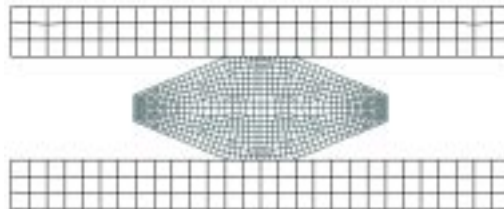


Figure 1. Mesh geometry for the simulation of double-cone forging.

Table 3. Microstructures Observed in a 718 Double-Cone Forging [20]

Point	Recrystallized Fraction	Grain Size
1	Low	Coarse
2	High	Fine
3	Medium-High	Duplex-Fine
4	Medium	Duplex

The simulation results did not match the observations exactly. Instead, the majority of the workpiece was predicted to be fully recrystallized. Nevertheless, a predicted microstructural pattern similar to the experimental results was evident at one instant during the cooling process; at this time, the recrystallized volume fraction pattern was  $2 > 3 > 4 > 1$  (Figure 2). Point tracking was performed to reveal the history at the four sampling points (Figure 3). These plots revealed that the order of grain size was indeed  $1 \geq 4 \geq 3 > 2$  (as had been observed) before recrystallization was completed (at  $t \sim 3.6$  s).

The discrepancies between the simulations and the experimental observations could have been a result of the fact that the material input data were extrapolated outside the range of measurement. Specifically, the strain was much larger than in Zhou's experiments, the initial grain size ( $20 \sim 30 \mu\text{m}$ ) was significantly smaller, and the temperature was lower for the double-cone forging. Moreover, the unspecified cooling condition could have caused discrepancies. In fact, a better correlation was obtained when a larger environmental heat transfer coefficient was used.

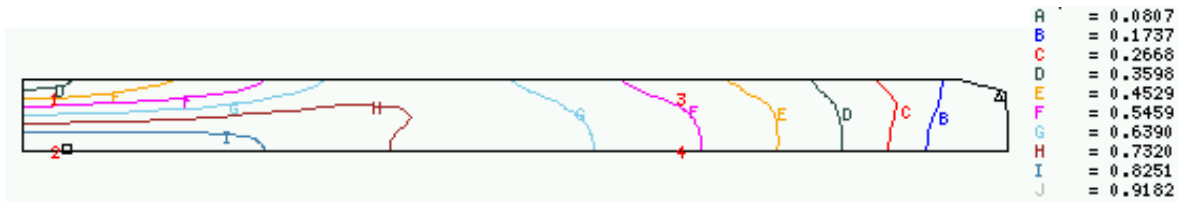


Figure 2. FEM predicted recrystallized volume fraction at  $t = 3.6$  s for forging of a 718 double-cone sample.

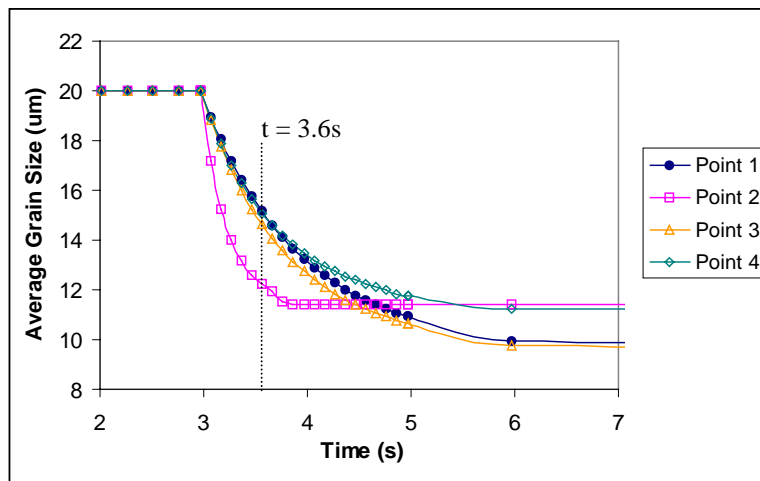


Figure 3. FEM point-tracking predictions for the evolution of the average grain size during the forging of a 718 double-cone sample.

### Waspaloy Disk Forging

To validate the modeling approach for Waspaloy, a disk was forged at Wyman Gordon using a preform with an initial grain size of  $100 \mu\text{m}$  (ASTM grain size of 3.3). A forging simulation was carried out using the die geometry and process conditions used by Wyman Gordon. The microstructure evolution model for the simulation was taken from the work of Shen, et al. [21]. In this earlier study, dynamic and metadynamic recrystallization were found to be significant (Equations (6)-(11)). The FEM simulation covered the entire hot-forming process and final cooling to ambient temperature. Wyman Gordon also provided experimental measurements of the microstructure at 29 points on the cross-section (shown in a schematic fashion in Figure 4).

FEM predictions of the recrystallized volume fraction (Figure 5a) showed very good agreement with the experimental observations. Some discrepancies were found in the rib area where material was partially recrystallized (Points 1, 2, 3, 12, 13, 14, 27, 28, and 29). Average grain size predictions were

based on the recrystallized and original grain sizes and the volume fraction of each. The predicted average recrystallized grain sizes showed fair agreement with the measurements (Figure 5b). The largest discrepancy between the model predictions and observations occurred at points 14 and 29. These errors most likely were a result of the errors in recrystallized volume fraction. Other sources of the discrepancies include the inaccuracy of the predicted temperature distribution due to errors in the interface heat transfer coefficient, the inaccuracy of the predicted strains and strain rates due to inappropriate specification of friction condition or flow stress, and differences in the behavior of the forged material and that used to develop the material database.

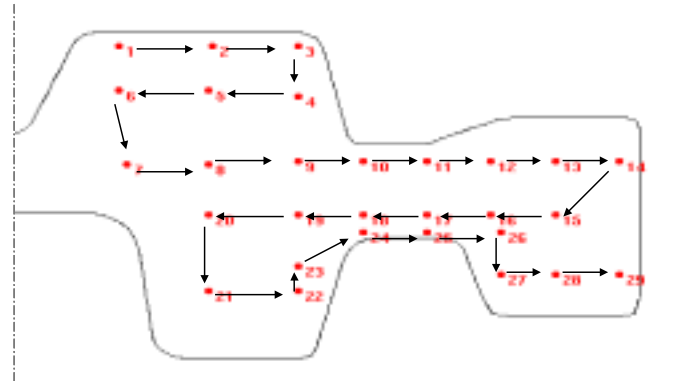


Figure 4. Sampling points on Waspaloy disk.

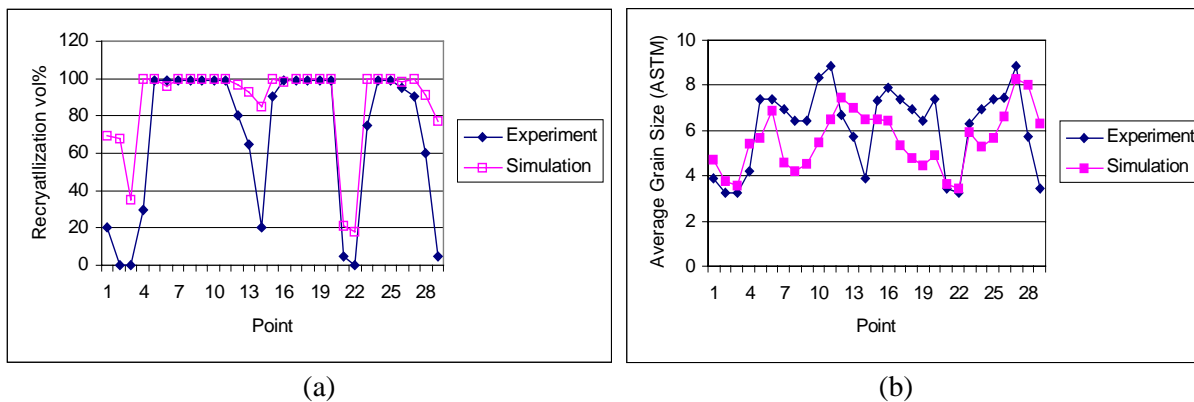


Figure 5. Comparison of measured and predicted microstructural features in a forged Waspaloy disk: (a) recrystallized volume fraction and (b) grain size.

### 3-D Ingot Conversion Simulation

Cogging is one of the most common processes used to breakdown the coarse, cast microstructure of superalloy ingots. The primary objective of the conversion process is to produce a fine grain structure for subsequent secondary forging operations. In essence, the process consists of multiple open die forging (and reheating) operations in which the ingot diameter is reduced and its length is increased. Excessive furnace heating may promote undesired grain growth. On the other hand, insufficient heating or excessive forging time may result in cracking. Control of the forging temperature, the amount of deformation, the forging time, and the precipitation of second phases is especially important for producing a desired grain structure. Modeling the microstructure evolution of the ingot during the cogging process has been of great interest in recent years. Several publications can be found on the prediction of recrystallization and grain growth in cogged superalloy billets [8,22,23].

To demonstrate the capability of the present system, a portion of a cogging process was simulated. The billet alloy was assumed to be alloy 718 with an initial grain size of 250 $\mu$ m (ASTM 1). The workpiece was taken to be octagonal in cross section (with a breadth of 380mm across the flat faces) and 2m in length. Figure 6 illustrates the mesh used for the billet, dies, and manipulators at the beginning of the simulation. The simulations made use of the same microstructural data described

above. Typical industrial processing conditions were applied. One deformation sequence comprising four passes without reheating was simulated.

Figure 7a shows FEM predictions of the average grain size at the end of the fourth pass. Other results for the microstructure *within* the workpiece are shown in Figure 7b, c, d, e for a location at approximately one-quarter of the length. After four passes, the simulation revealed that recrystallization is predicted to be rather inhomogeneous, and a number of “dead zones” are developed near the surface. These trends are consistent with industrial observations.

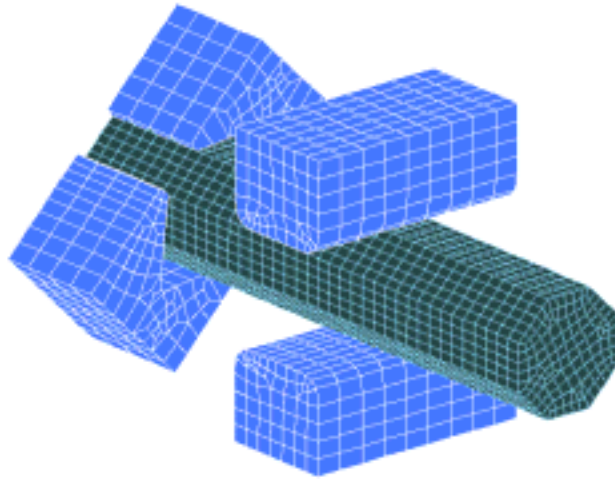


Figure 6. Meshes used for FEM simulation of the cogging process.

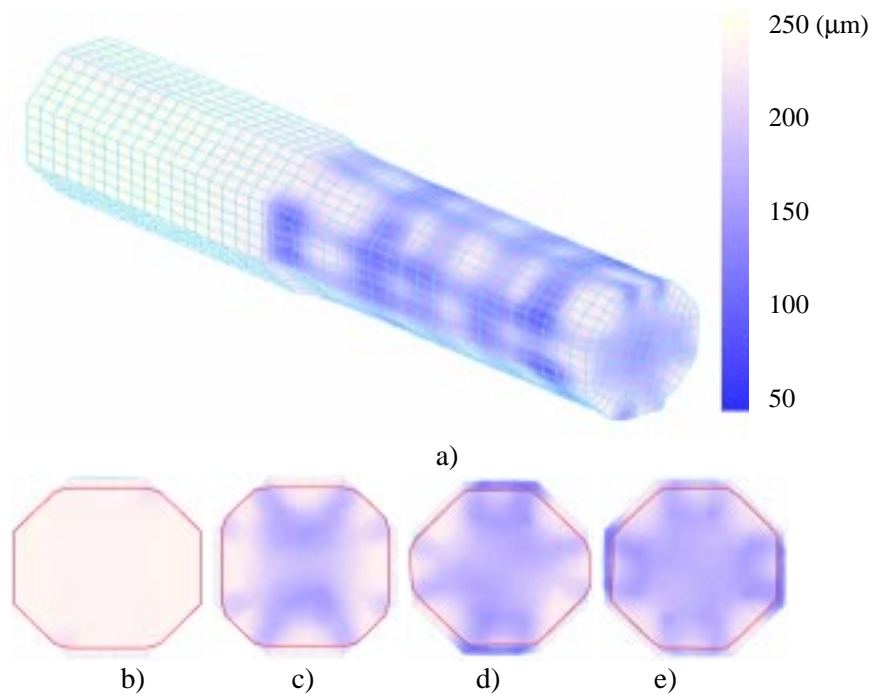


Figure 7. FEM predicted average grain size: (a) On the free surface after the final pass or within the workpiece after pass number (b) 1, (c) 2, (d) 3, or (e) 4.

### Conclusions

A general computer model for the prediction of grain-size evolution during hot working was developed and utilized to simulate the processing of Waspaloy and nickel alloy 718. Simulations were performed using material data from the literature. Reasonable prediction results were obtained in both 2D and 3D simulations, thus suggesting a strong potential for future utilization of this tool for process design and control.

## Acknowledgements

Special thanks are due to Dr. Ron Wallis and Dr. Padu Ramasundaram (Wyman Gordon Co.) for the validation work on Waspaloy disk forging and to Dr. Daqing Jin (Timken) and Dr. Gangshu Shen (Ladish Co.) for valuable discussions during the development of the microstructure evolution models. Three of the authors (DH, WTW, and DL) were supported under the auspices of an SBIR program (Contract No. F33615-95-5238) from the Air Force Research Laboratory and the Naval Air Warfare Center. The support of the Air Force Office of Scientific Research (Dr. Craig Hartley, program manager) is also gratefully acknowledged by SLS.

## Nomenclature

$T$	Absolute temperature
$R$	Gas constant
$t$	Time
$d_0$	Initial grain size before recrystallization or growth
$X_{SRX}$ , $X_{MRX}$ , $X_{DRX}$	Recrystallized volume fraction for SRX, MRX, and DRX.
$d_{SRX}$ , $d_{MRX}$ , $d_{DRX}$	Recrystallized grain size for SRX, MRX, and DRX
$d_{gg}$	Grain size after growth
$\epsilon$	Effective strain
$\epsilon_c$	Critical strain
$\epsilon_p$	Strain at stress maximum
$\epsilon_{0.5}$	Strain for 50 percent recrystallization
$\dot{\epsilon}$	Effective strain rate
$t_{0.5}$	Time for 50 percent recrystallization
$a_{1-10}$	Material coefficient
$b_{1-8}$	Material coefficient
$c_{1-8}$	Material coefficient
$n_{1-8}$	Material coefficient
$m_{1-8}$	Material coefficient
$Q_{1-9}$	Material coefficient
$\beta_{db}$ , $\beta_m$ , $\beta_s$	Material coefficient
$k_{db}$ , $k_m$ , $k_s$	Material coefficient

## References:

1. C. M. Sellars and J. A. Whiteman, "Recrystallization and Grain Growth in Hot Rolling", Metal Science, 13 (1979), 187-194.
2. C. M. Sellars and G. J. Davis, eds., Hot Working and Forming Processes, (London, UK: Metals Society, 1979), 3-15.
3. J. J. Jonas and C. M. Sellars, "Physical and Computer Modeling of the Thermomechanical Processing of Steels", Iron and Steelmaker, Oct. 1992, 67-71.
4. J. J. Jonas, "Recovery, Recrystallization, and Precipitation under Hot Working Conditions", Proceeding of the Fourth International Conference on Strength of Metals and Alloys, (Nancy, France, 1976), 976-1002
5. C. Devadas, I. V. Samarasekera, and E. B. Hawbolt, "The Thermal and Metallurgical State of Steel Strip during Hot Rolling. Part III. Microstructural Evolution", Metallurgical and Materials Transactions A, 22A (1991), 335-349.
6. I. V. Samarasekera, D. Q. Jin, and J. K. Brimacombe, "The Application of Microstructural Engineering to The Hot Rolling of Steel", 38<sup>th</sup> MWSP Conf. Proc., ISS, Vol. XXXIV (1997), 313-326.
7. G. Shen, S.L. Semiatin, and R. Shivpuri, "Modeling Microstructure Development during the Forging of Waspaloy", Metallurgical and Materials Transactions A, 26A (1995), 1795-1803.
8. D. Zhao, et al., "Three Dimensional Simulation of Alloy 718 Ingot Breakdown by Cogging", Superalloys 718, 625, 706 and Various Derivatives, ed. E. A. Loria, (Warrendale, PA: TMS, 1997), 163-172.

9. A. J. Brand, K. Karhausen, and R. Kopp, "Microstructural Simulation of Nickel Base Alloy Inconel 718 in Production of Turbine Discs", Materials Science and Technology, 12 (1996), 963-969.
10. F. J. Humphreys and M. Hatherly, Recrystallization and Related Annealing Phenomena, (Oxford, England: Pergamon Press, Elsevier Ltd., 1996), 363-392.
11. J. G. Byrne, Recovery, Recrystallization, and Grain Growth, (New York: Macmillan, 1965), 93-109.
12. J. W. Brooks and P. J. Bridges, "Metallurgical Stability of Inconel Alloy 718", Superalloys 1988, ed. S. Reichmann, et al. (Warrendale, PA: TMS, 1988), 33-42.
13. L. X. Zhou and T. N. Baker, "Effects of Dynamic and Metadynamic Recrystallization on Microstructure of Wrought IN718 due to Hot Deformation", Materials Science and Engineering, A196 (1995), 89-95.
14. M. J. Weis, M. C. Mataya, S. W. Thompson, and D. K. Matlock, "The Hot Deformation Behavior of an As-Cast Alloy 718 Ingot", Superalloy 718 – Metallurgy and Applications, ed. E. A. Loria, (Warrendale, PA: TMS, 1989), 135-154.
15. P. E. Mosser, G. Leconte, J. Leray, A. Lasalmonie, and Y. Honnora, "Metallurgical Aspects of Forge Modeling in Alloy 718", Superalloy 718 – Metallurgy and Applications, ed. E. A. Loria, (Warrendale, PA: TMS, 1989), 179-188.
16. S. C. Medeiros, Y. V. R. K. Prasad, W. G. Frazier, and R. Srinivasan, "Microstructural Modeling of Metadynamic Recrystallization in Hot Working of IN718 Superalloy", Materials Science and Engineering, A293 (2000), 198-207.
17. J. M. Zhang, Z. Y. Gao, J. Y. Zhuang, and Z. Y. Zhong, "Mathematical Modeling of the Hot-Deformation Behavior of Superalloy 718", Metallurgical and Materials Transactions A, 30A (1999), 2701-2712.
18. D. Zhao, S. Guillard, and A. T. Male, "High Temperature Deformation Behavior of Cast Alloy 718", Superalloys 718, 625, 706 and Various Derivatives, ed. E. A. Loria, (Warrendale, PA: TMS, 1997), 193-204.
19. J. M. Zhang, Z. Y. Gao, J. Y. Zhuang, and Z. Y. Zhong, "Grain Growth Model of IN718 During Holding Period after Hot Deformation", Journal of Materials Processing Technology, 101 (2000), 25-30.
20. V. K. Jain, R. Srinivasan, I. Weiss, and S. K. Srivatsa, "High-Temperature Materials Forging Data Base", EMTEC/CT-13/TR-91-13, 1991.
21. G. Shen, "Modeling Microstructural Development during the Forging of Waspaloy", (Ph. D. Thesis, The Ohio State University, Columbus, Ohio, 1994).
22. B. F. Antolovich and M. D. Evans, "Predicting Grain Size Evolution of UDIMET<sup>®</sup> Alloy 718 During the 'Cogging' Process Through the Use of Numerical Analysis", Superalloys 2000, (Warrendale, PA: TMS, 2000), 45-55.
23. C. A. Dandre, S. M. Roberts, R. W. Evans, and R. C. Reed, "Microstructural Evolution of Inconel 718 during Ingot Breakdown: Process Modeling and Validation", Materials Science and Technology, 16 (2000), 14-25.