MICROSTRUCTURE MODELING OF FORGED WASPALOY DISCS

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Abstract

An effort has been undertaken to develop, validate and refine a modeling tool for the prediction of forged Waspaloy microstructures. Previous work on steel materials [1] has shown that microstructural modeling is possible and can be readily accomplished through use of metallurgically-based mathematical equations. Experimentation is required to develop and tailor the equations for the kinetics of the material of interest.

This paper outlines the steps required to determine the kinetics for microstructural evolution for Waspaloy, and their application to the metallurgically-based equations. Examples of the predictions and actual measured results show that this methodology is effective to develop practical tools to aid forging engineers develop and optimize processes for specific final component requirements.

Nomenclature

A	*constant for grain growth in preheating*
d	final grain size, μm
d_0	as-preheated grain size, μm
d_1	starting grain size for post-deformation grain growth, μm
d_i	initial grain size (before preheating), μm
d_{dyn}	dynamically recrystallized grain, μm
$d_{m\text{-}dyn}$	meta-dynamically recrystallized grain, μm
m	exponent for grain growth in preheating
n	exponent for Avrami equation
Q	activation energy, J/mol
Q_{g1}	activation energy for grain growth in preheating, J/mol
R	gas constant, 8.314J/(mol*K)
T	temperature, K
t	time, s
$t_{0.5}$	time for 50% meta-dynamic recrystallization
X_{dyn}	fraction of dynamic recrystallization
$X_{m\text{-}dyn}$	fraction of meta-dynamic recrystallization
Z	Zener-Hollomon parameter, 1/s
e	effective strain
$e_{0.5}$	effective strain for 50% dynamic recrystallization
e_c	critical strain for dynamic recrystallization
e_p	peak strain for dynamic recrystallization
$\dot{e}$	effective strain rate

Introduction

Forging methods and approaches for complex, high-technology components for aerospace and general industrial applications has evolved to greater levels of sophistication in recent years under economic and market pressures. Metal flow simulations which were once impossible, except for plastic and clay physical models, are now common-place using the latest, high-speed computers and latest generation of computer processing codes [2, 3]. The understanding and prediction of microstructures which develop during deformation processing has long been the "art" of forging metallurgists. Many tools, such as wedge tests were used in the past to understand the impact of temperature, strain and strain rate and to guide metallurgists in the processing direction of success [4]. These methods were good, but quantitative extraction of vital processing data and microstructural results, and the deconvolution of the separate effects of the various processing parameters on the measured results were not effectively accomplished.

Modern forging design and development relies heavily on computer process modeling. Process modeling provides a scientific tool for rapid evaluation of process changes for process optimization. Bulk metal flow modeling has been highly successful in elimination of shop tryouts for nearly all forging methods. Microstructure modeling is now the major emphasis in advanced forging design and development. The development and utilization of physical metallurgy based microstructural models has allowed for grain size and property prediction in steel [1], and in titanium [5].

An alloy of considerable importance to modern turbine engine applications is Waspaloy. It is used for numerous rotating and non-rotating turbine engine components, and is processed by numerous thermomechanical processing routes [6]. Many of the methods used for the processing of Waspaloy were developed by iterative shop trials. This method to define specific manufacturing processes for new components is not acceptable due to excessive development time and cost for trial component manufacture.

A model has been developed and implemented for the prediction of microstructures of forged Waspaloy discs [7, 8, 9]. This model considers grain growth in preheating prior to forging, dynamic recrystallization during forging, and meta-dynamic recrystallization and grain growth during post-forging cool down. The model has been integrated into finite element software to predict microstructures developed for different forging processes. The actual implementation of this model has been highly successful in the prediction of microstructures of numerous actual production components processed under widely varied processing conditions.

Superalloys 1996
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A. D. Cetel, M. V. Nathal, T. M. Pollock, and D. A. Woodford
The Minerals, Metals & Materials Society, 1996

Experimental Procedure

Three sets of experiments were used in the model development.

(1) Preheating Tests: Heat treatment studies were conducted with different temperatures and hold times to model the as-preheated grain size for a forging operation. From these tests, the grain growth model for preheating of a particular billet pedigree was developed. This model was then used to establish the grain size just prior to subsequent forging operations.

(2) Compression Tests: Laboratory upset tests were conducted with different temperatures, strains, strain rates, starting grain sizes, and post-deformation hold times to characterize dynamic recrystallization during forging, and meta-dynamic recrystallization and static grain growth during post-forging cool down. An MTS compression stand was used for the simulation of isothermal forging conditions and a Gleeble test unit for non-isothermal forging conditions. From these compression tests with rapid post-deformation cooling, information related to dynamic recrystallization kinetics were obtained. The kinetics information included: peak strain for dynamic recrystallization, which is related to the critical strain for dynamic recrystallization; strain which corresponds to 50% dynamic recrystallization, fraction of dynamic recrystallization and the size of dynamically recrystallized grains. Information regarding meta-dynamic recrystallization and post forging grain growth were also obtained from compression tests with controlled post-forge hold times and cooling rates. This information included: time for 50% meta- dynamic recrystallization, fraction of meta-dynamic recrystallization, meta-dynamically recrystallized grain size, and grain growth at a given temperature and time after the completion of meta-dynamic recrystallization.

(3) Pancake and Generic Forgings: In addition to laboratory tests, large pancakes and generic component configurations were produced on production equipment under various forging conditions and methods to verify and refine the microstructure model.

Finite element analysis for each experiment provided detailed information for each test. This quantified specific data was used to develop the models for the microstructure evolution of Waspaloy during the forging process.

Results

PREHEATING MODEL

It is the as-preheated grains which go through deformation processes and have changes take place to their structure. Therefore, a model of the as-preheated grain size is the necessary first step in microstructure modeling. For Waspaloy, there is no grain size changes in sub-solvus preheating. However, grain growth occurs rapidly under super-solvus preheating conditions. An equation was developed for the prediction of the grain size in production preheating conditions of the following form:

$$d_0^m - d_i^m = A\ t\ \exp(-Q_{g1}/[RT]) \qquad [1]$$

HOT WORKING MODEL

The processes that control grain structure evolution during hot working of Waspaloy were found to be dynamic recrystallization, meta-dynamic recrystallization, and static grain growth. The equations developed for the quantitative prediction of these phenomenon are summarized in Table 1.

TABLE 1. Mathematical Model for Microstructure Development in Waspaloy Forging.

Dynamic Recrystallization

$Z = \grave{e} * \exp(468000/RT)$

$e_c = 0.8 e_p$

sub-solvus forging

$e_p = 5.375*10^{-4}\ d_0^{0.54} Z^{0.106}$

$e_{0.5} = 0.1449 d_0^{0.32} Z^{0.03}$

$X_{dyn} = 1 - \exp\{-\ln 2[e/e_{0.5}]^{3.0}\}$

$d_{dyn} = 8103 Z^{-0.16}$

in-solvus forging

$e_p = 5.375*10^{-4}\ d_0^{0.54} Z^{0.106}$

$e_{0.5} = 0.056 d_0^{0.32} Z^{0.03}$

$X_{dyn} = 1 - \exp\{-\ln 2[e/e_{0.5}]^{2.0}\}$

$d_{dyn} = 8103 Z^{-0.16}$

super-solvus forging

$e_p = 1.685*10^{-4}\ d_0^{0.54} Z^{0.106}$

$e_{0.5} = 0.035 d_0^{0.29} Z^{0.04}$

$X_{dyn} = 1 - \exp\{-\ln 2[e/e_{0.5}]^{1.8}\}$

$d_{dyn} = 108.85 Z^{-0.0456}$

Meta-dynamic Recrystallization

$t_{0.5} = 4.54*10^{-5} d_0^{0.51} e^{-1.28} \grave{e}^{-0.073} * \exp(9705/T)$

$X_{m\text{-}dyn} = 1 - \exp\{-\ln 2[t/t_{0.5}]^{1.0}\}$

$d_{m\text{-}dyn} = 14.56 d_0^{0.33} e^{-0.44} Z^{-0.026}$

Grain Growth

$d^3 - d_I^3 = 2*10^{26}\ t\ \exp(-595000/[RT])$

Dynamic Recrystallization

Dynamic recrystallization happens instantaneously during high temperature deformation. The fraction of dynamic recrystallization can be obtained by examining micrographs obtained from samples quenched after their deformation. Under production conditions pure dynamic recrystallization is difficult to achieve. However, a study of dynamic recrystallization is helpful for understanding the microstructural development in the forging. The amount of dynamic recrystallization is related to the as-preheated grain size, strain, temperature and strain rate in a hot deformation process. There are four important issues related to dynamic recrystallization: the peak strain, the strain for 50% dynamic recrystallization, the fraction of dynamic recrystallization, and the size of dynamically recrystallized grains.

Peak Strain - The strain corresponding to the peak stress (e_p) in the flow stress curve is an important measure for the onset of dynamic recrystallization. The occurrence of dynamic recrystallization modifies the appearance of these curves. At the strain rates typical for forging of Waspaloy, single peak stress-strain curves are most common. As a result of dynamic recrystallization, the stress diminishes to a value intermediate between the yield stress and the peak stress once past the peak strain. The reason for this curve following a single peak is that under the condition of high Z, the dislocation density can be built up very fast. Before recrystallization is complete, the dislocation densities at the center of recrystallized grains have increased sufficiently that another cycle of nucleation occurs and new grain begin to grow again. Thus, average flow stress intermediate between the yield stress and the peak stress is maintained. The equations developed for the peak strain are:

$e_p=5.375*10^{-4}\, d_0^{0.54}Z^{0.106}$ (sub- and in-solvus) [2]

$e_p=1.685*10^{-4}\, d_0^{0.54}Z^{0.106}$ (super-solvus) [3]

Strain for 50% Dynamic Recrystallization -Micrographs taken from quenched compression samples show that dynamic recrystallization progresses in a sigmoidal manner with respect to strain. The Avrami equation can be used to describe a sigmoidal curve for the fraction of dynamic recrystallization versus strain:

$X_{dyn}=1\text{-}\exp\{-\ln2[e/e_{0.5}]^n\}$ [4]

When the constants $e_{0.5}$ and n are determined, the relation for the fraction of dynamic recrystallization is determined. The strain for 50% recrystallization, $e_{0.5}$, can be obtained from compression tests with different magnitudes of strain for a given condition of temperature, strain rate, and as-preheated grain size, as shown in Figure 1. The exponent can be obtained by taking the logarithm of Equation 4. $e_{0.5}$ is related to as-preheated grain size, d_0 and Z by:

$e_{0.5}=0.1449d_0^{0.32}Z^{0.03}$ (sub-solvus) [5]

$e_{0.5}=0.056d_0^{0.32}Z^{0.03}$ (in-solvus) [6]

$e_{0.5}=0.035d_0^{0.29}Z^{0.04}$ (super-solvus) [7]

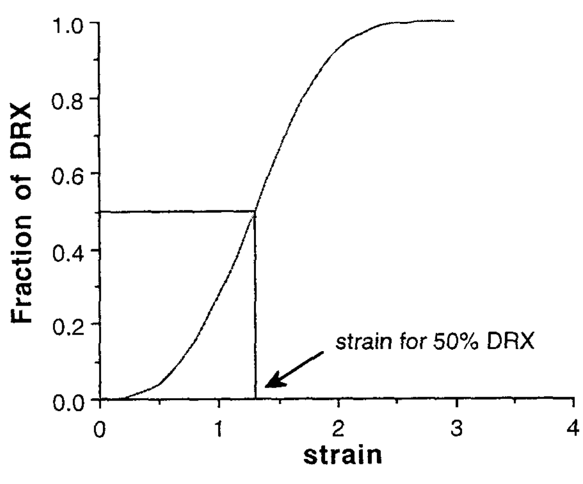


Figure 1. Schematic of strain corresponding to 50% dynamic recrystallization.

Fraction of Dynamic Recrystallization - After the strain for 50% dynamic recrystallization and the exponent for Equation 4 are determined, equations for the fraction of dynamically recrystallized grains can be formulated:

$X_{dyn}=1\text{-}\exp\{-\ln2[e/e_{0.5}]^{3.0}\}$ (sub-solvus) [8]

$X_{dyn}=1\text{-}\exp\{-\ln2[e/e_{0.5}]^{2.0}\}$ (in-solvus) [9]

$X_{dyn}=1\text{-}\exp\{-\ln2[e/e_{0.5}]^{1.8}\}$ (super-solvus) [10]

Figures 2(a) and 2(b) summarize the experimental data and the fitted model for dynamic recrystallization at 1010°C and 1066°C respectively.

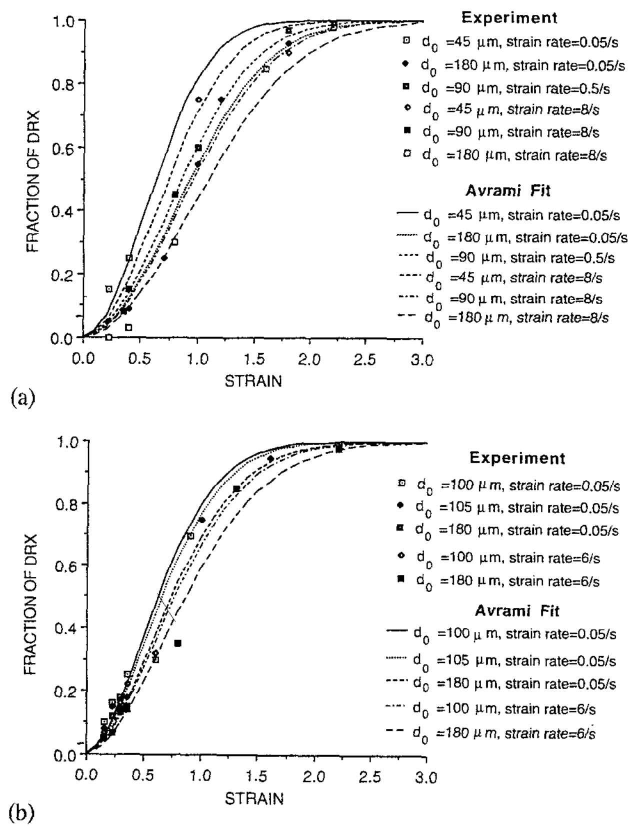


Figure 2. Measured (data points) dynamic recrystallization (DRX) kinetics for hot deformation of Wasplaoy at (a) 1010°C and (b) 1066°C and fitted curves.

The critical strain for the start of dynamic recrystallization usually follows the relationship [1]:

$e_c=0.8e_p$ [11]

The Size of Dynamically Recrystallized Grain - The dynamically recrystallized grain size is the function of Zener-Hollomon parameter, Z, only. This is because Z defines the density of the subgrains and the nuclei. Though the dynamically recrystallized grain size is not related to strain, the strain has to reach the value of steady state strain to result in full dynamic recrystallization. The relationship between dynamically recrystallized grain, d_{dyn}, and Z, is shown in the following equations.

$d_{dyn}=8103Z^{-0.16}$ (sub- & in-solvus) [12]

$d_{dyn}=108.85Z^{-0.0456}$ (super-solvus) [13]

Figure 3 shows how Equations 12 and 13 relate to experimental data. It is seen that there is a difference between subsolvus forging and supersolvus forging in terms of dynamically recrystallized grain size. The subsolvus forging results in finer grain sizes, while supersolvus forging results in coarse grain sizes. However, subsolvus forging needs large strains to finish dynamic recrystallization as shown in Equations 5 and 8.

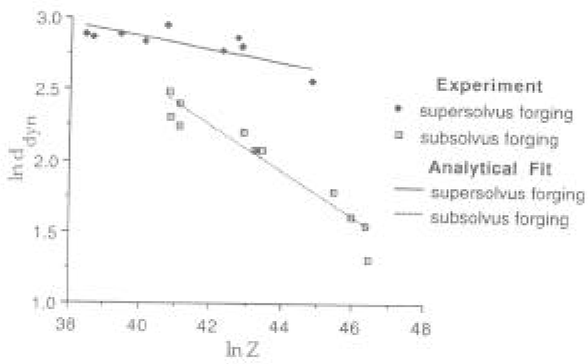


Figure 3. Logarithm of dynamically recrystallized grain size (in μm) versus ln Z obtained from compression tests.

Meta-Dynamic Recrystallization

Meta-dynamic recrystallization is important in the determination of the grain size obtained under practical forging conditions. Meta-dynamic recrystallization occurs when a deformation stops at a strain which passes the peak strain but does not reach the steady state strain for dynamic recrystallization [10], which is the case for most regions in a forged part. Under meta-dynamic recrystallization conditions, the partially recrystallized grain structure which is observed right after deformation [Figure 4(a)] changes to a fully recrystallized grain structure [Figure 4(b)] by continuous growth of the dynamically recrystallized nuclei at a high temperature. The meta-dynamically recrystallized grains are coarser than the fully dynamically recrystallized grains. However, understanding this phenomenon is the key issue in the control of the size and the uniformity of the grains produced under a production condition. The amount of meta-dynamic recrystallization is related to the as-preheated grain size, the strain, the temperature, the strain rate and the holding time in a hot deformation process. Important factors related to meta-dynamic recrystallization are: the time for 50% meta-dynamic recrystallization, the fraction of meta-dynamic recrystallization, and the size of meta-dynamically recrystallized grain.

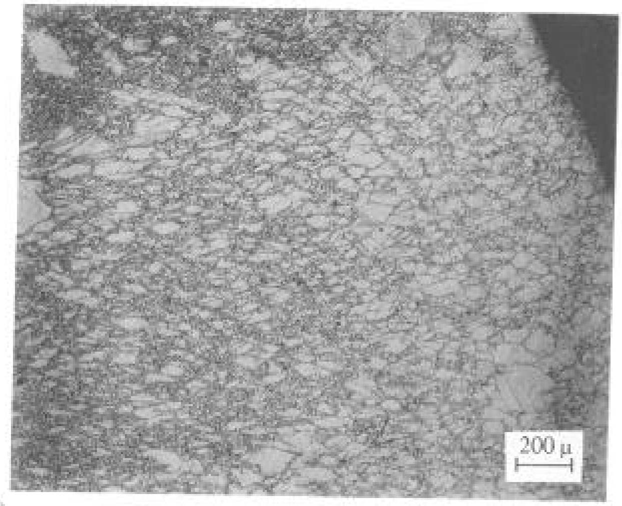
Time for 50% Meta-dynamic Recrystallization -Meta-dynamic recrystallization is time dependent. For a given strain, strain rate, and as-preheated grain size, meta-dynamic recrystallization progresses in the following manner with respect to time:

$$X_{m\text{-}dyn} = 1-\exp\{-\ln 2[t/t_{0.5}]^{n}\} \qquad [14]$$

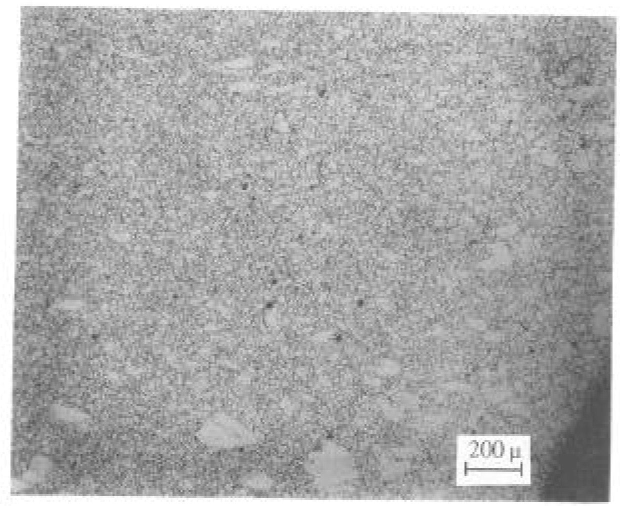
The $t_{0.5}$ can be obtained from compression tests with different holding times for a given temperature, strain, strain rate, and as heated grain size. The empirical $t_{0.5}$ for meta-dynamic recrystallization follows the following relationship:

$$t_{0.5} = 4.54*10^{-5} d_0^{0.51} \varepsilon^{-1.28} \dot{\varepsilon}^{-0.073} * \exp(9705/T) \qquad [15]$$

The experimentally obtained $t_{0.5}$ is shown in Figure 5. It is seen that when the strain is larger than 0.5, the $t_{0.5}$ is below 2 seconds for the processing conditions in this study.



(a)



(b)

Figure 4. Micrographs obtained from Waspaloy samples with different cooling histories after forging: (a) rapidly cooled immediately after deformation, and (b) rapidly cooled after a 3 second hold at deformation temperature (1066°C).

The exponent, n, for meta-dynamic recrystallization is found to be 1 as shown in Figure 6. This number is typical for meta-dynamic recrystallization [11, 12].

Fraction of Metadynamic Recrystallization -The fraction of meta-dynamic recrystallization progresses according to the following equation:

$$X_{m\text{-}dyn} = 1-\exp\{-\ln 2[t/t_{0.5}]^{1.0}\} \qquad [16]$$

Figures 7(a) and (b) shows the fraction of meta-dynamic recrystallization versus time obtained from the experiments and the predictions at 1066°C with different as-preheated grain size, strain, and strain rate conditions. The meta-dynamic recrystallization finishes sooner for cases of larger strain, finer as-preheated grain size, higher strain rate and higher temperature.

Meta-dynamic Recrystallized Grain Size - The grain size obtained at the end of meta-dynamic recrystallization is found to have the following relationship with the strain, the as-preheated grain size, and Zener-Hollomon parameter:

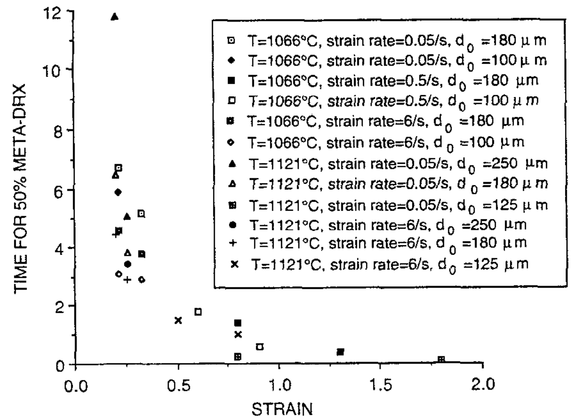


Figure 5. Experimentally obtained time corresponding to 50% meta-dynamic recrystallization.

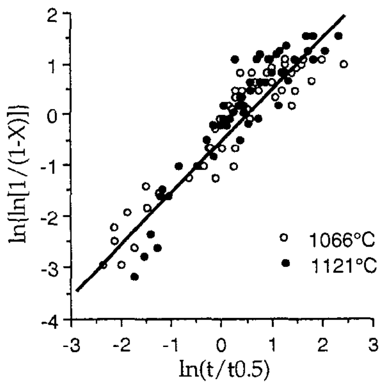


Figure 6. Determination of the Avrami exponent n for meta-dynamic recrystallization. "n" is the slope of the fitted line.

$$d_{m\text{-}dyn}=14.56d_0^{0.33}e^{-0.44}Z^{-0.026} \qquad [17]$$

A finer meta-dynamically recrystallized grain size is associated with cases with larger strain, finer as-preheated grain size, and higher values of the Zener-Hollomon parameter.

The meta-dynamic recrystallized grain size in ASTM number versus strain under conditions with different as-preheated grain sizes, temperatures and strain rates is shown in Figure 8.

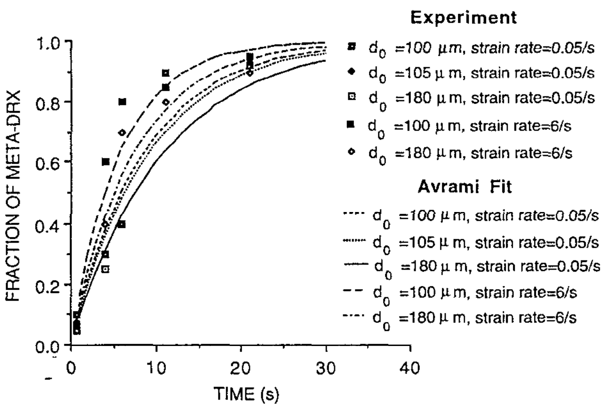
Grain Growth

Under high temperature deformation conditions grain growth happens rapidly after the completion of meta-dynamic recrystallization. Grain boundary energy is the driving force causing grain boundary motion at high temperature. Grain boundary energy is comparable to the surface energy, it tends to minimize itself whenever possible by decreasing the grain boundary area. In general, grain growth will continue to occur at elevated temperatures until the balance between the grain boundary energy and the pinning effects of precipitates (precipitate size and spacing) is reached.

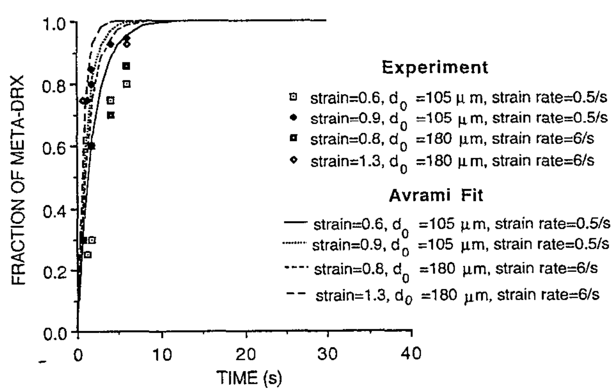
Grain growth is characterized by compression tests with different post-forging holding times. From the micrographs obtained from these tests, the microstructural evolution from partial dynamic recrystallization to full meta-dynamic recrystallization, and to grain growth were observed. The change in grain size versus time after the completion of meta-dynamic recrystallization is found to follow relationship:

$$d^3-d_1^3=2*10^{26}\ t\ \exp(-595000/[RT]) \qquad [18]$$

The form of the equation (18) is well known for the characterization of grain growth. The reason for emphasizing that the d_1 is the grain size after complete meta-dynamic recrystallization is that after the completion of meta-dynamic recrystallization the dislocations have essentially disappeared and the driving force for grain size changes is the grain boundary energy only.



(a)



(b)

Figure 7. Fraction of meta-dynamic recrystallization versus time at 1066°C with a strain of (a) 0.22 and (b) 0.6 to 1.3.

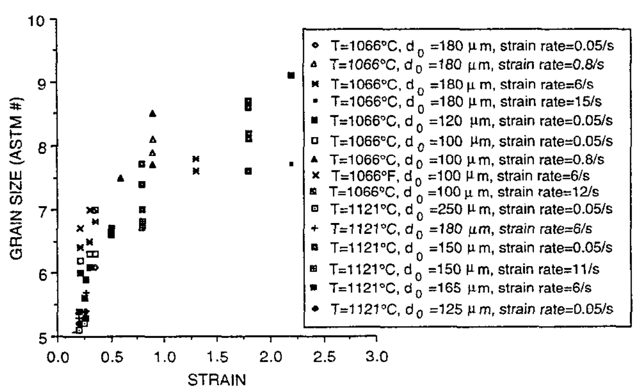


Figure 8. Meta-dynamically recrystallized grain size versus strain for various process conditions.

The experimentally obtained data and the model prediction for the short time grain growth are shown in Figure 9. It is seen from this figure that the grain growth at a temperature around 1121°C is very fast. There was not much difference in grain size after the completion of meta-dynamic recrystallization between the two samples obtained from compression tests at 1066°C and 1121°C (Figure 8). However, the grain growth results in a large difference in the final grain size for the two sets of tests conducted at 1066°C and 1121°C .

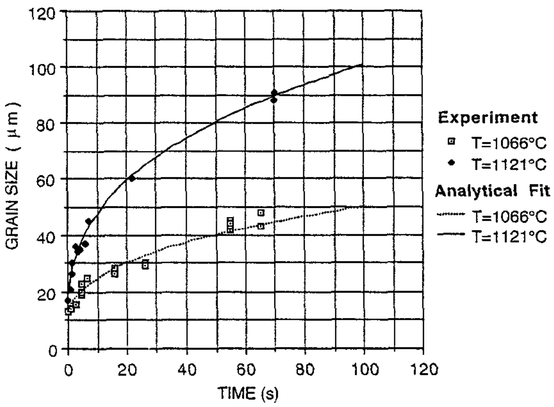


Figure 9. Grain growth versus time after the completion of meta-dynamic recrystallization in Waspaloy.

Summary of Equations Developed - It is seen from these equations that the major factors in the control of the grain size in the forging of Waspaloy are strain, temperature compensated strain rate and the as-preheated grain size.

Strains create localized high densities of dislocations. To reduce their energy, dislocations rearrange into subgrains. When the subgrains reach a certain size the nuclei of new grains form. The higher the strain, the greater the amount of dislocations and the greater the number of cycles of recrystallization. This results in a higher percentage of recrystallization.

The reason for deformation under high Z condition giving finer grain size is that an increase in Z results in the increase in the subgrain density which gives a higher density of nuclei. There are also more cycles of recrystallization present under high values of Z. Thus, the size of the recrystallized grains decrease [10].

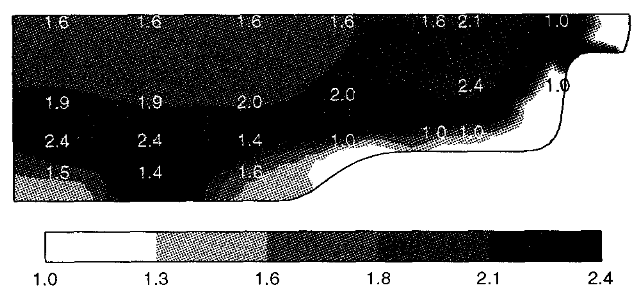
At a given strain, the reason for as-preheated grain size playing an important role in the determination of the fraction of recrystallization and recrystallized grain size is that when polycrystalline metal is deformed, the grain boundaries interrupt the slip processes. Thus, the lattice adjacent to grain boundaries distort more than the center of the grain. The smaller the as-preheated grain, the larger the grain boundary area and the volume of distorted metal. As a consequence, the number of possible sites of nucleation increases. The rate of nucleation increases, and the size of the recrystallized grains decreases. Moreover, the uniformity of distortion increases with the decrease in as-preheated grain size. Therefore, having a fine as-preheated initial grain size is very important for obtaining a fine recrystallized final grain size.

INTEGRATION OF THE MICROSTRUCTURE MODEL WITH FEM CODES TO PREDICT FORGING MICROSTRUCTURAL RESULTS:

The equations developed were integrated with a non-isothermal visco-plastic finite element software code for microstructure prediction. The grain growth model was applied to billet preheating processes. The as-preheated grain size is predicted based on starting grain size and time at temperature. The as-preheated grain size is then used as the starting grain size for the deformation processes. The dynamic and meta-dynamic recrystallized grain size is calculated for a given forging and post-forging cooling condition. Grain growth in post forging cooling is modeled upon the completion of meta-dynamic recrystallization and the time at temperature.

These modeling tools were used to predict different Waspaloy forging processes. Examples of model implementation for a sub-solvus and a super-solvus generic forging and subsequent evaluation results are outlined below.

Sub-Solvus Forging: The model predictions and actual measured microstructure results from a generic part forged at sub-solvus temperatures were compared. The results of this effort are shown in Figures 10(a) -10(c). Figure 10(a) compares the average grain size observed from the actual forging and the model prediction. Figure 10(b) compares the ALA grain size observed from the actual forging and the model prediction. Figure 10(c) compares the fraction of recrystallization observed from the actual forging and the model prediction. Overall, the model predictions agree very well with the actual measured forging results. Necklace structures are predicted with these modeling tools and can be seen in the plots of the prediction of fraction recrystallization shown in Figure 10(c). The region where the fraction of recrystallization is between 0.2-0.8 has a necklaced structure. This prediction of necklaced structures was shown to be very accurate, and is being used in the design of the forging processes.



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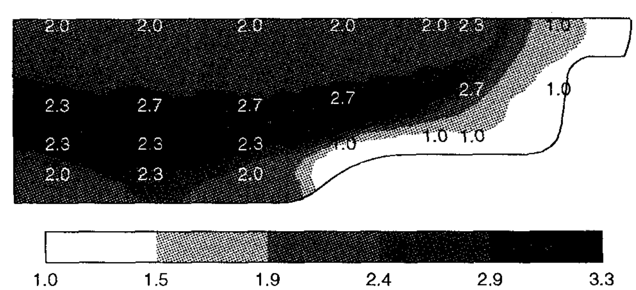

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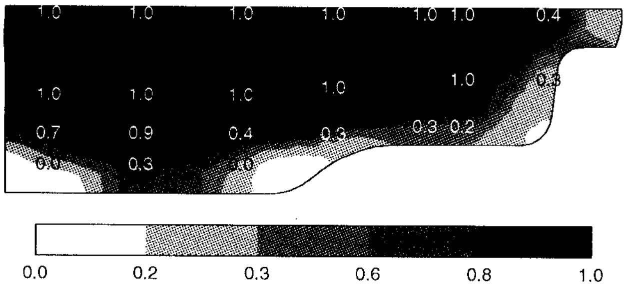
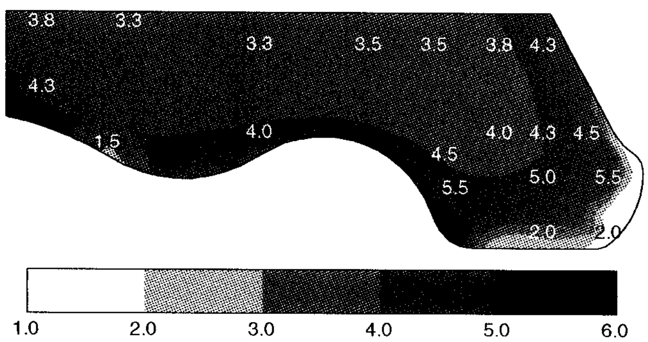


(c)

Figure 10. Partial component cross-sectional plots of predicted and observed microstructures for a generic sub-solvus forging: (a) average grain size, (b) ALA grain size, and (c) fraction of recrystallization. The microstructure values are normalized.

Super-Solvus Forging: The model predictions and actual measured microstructure results from a generic part forged in the super-solvus temperature range were also compared and evaluated. Results from this comparison effort are shown in Figure 11(a) - 11(c). Again the comparison is made in terms of average grain size, ALA grain size, and fraction of recrystallization. The predictions are again in very good agreement with the measured results.



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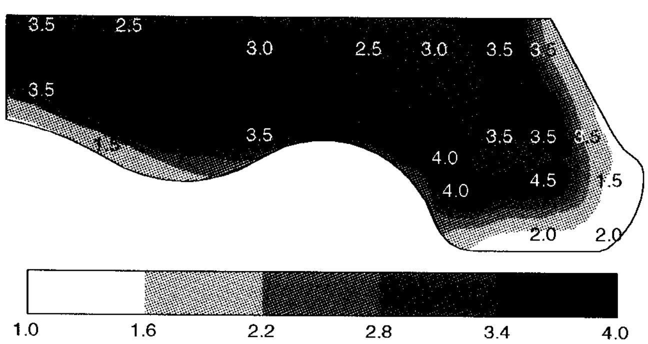

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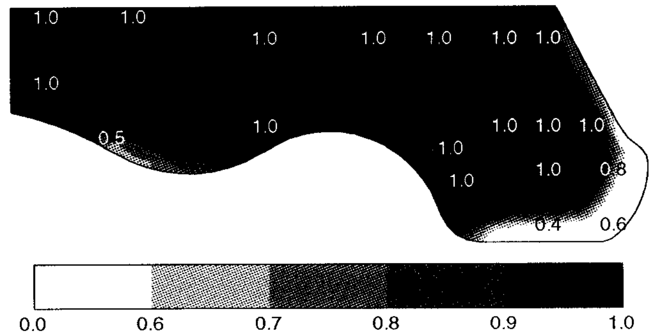

(c)

Figure 11. Partial component cross-sectional plots of predicted and observed microstructures for a generic super-solvus forging: (a) average grain size, (b) ALA grain size, and (c) fraction of recrystallization. The microstructure values are normalized.

Extensive efforts to further study the implementation and application of computer models to the prediction of microstructure results of forged Waspaloy under various processing temperature regimes, and numerous processing methods, has allowed considerable growth and refinement of this predictive model. The overall goal of this effort, for the real-world manufacturing environment, is to develop tools which are practical, but provide the best possible shop-floor correlation.

Efforts to refine the model have included developing an understanding and identifying the differences between material suppliers, and ingot-to-billet conversion methods (ie., mill-to-mill differences, and billet size differences). Significant differences between mills and billet sizes have been found, and these differences are defined accordingly in the model for an accurate prediction of the as-preheated microstructure and evolution during deformation processing.

Conclusions

Microstructure development in terms of dynamic recrystallization, meta-dynamic recrystallization and grain growth has been formulated. These equations were developed using preheating and compression tests. The integration of the microstructure model with finite element simulation codes made it possible for microstructure prediction of production parts with different shapes and different thermomechanical histories. The model was validated by generic experimental and actual production forging comparisons. Confidence in the refined model equations is at a level where the predictions are currently being used to guide all new part and existing part optimization efforts.

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