METALS AND MATERIALS International, Vol. 9, No. 1 (2003), pp. 15~19

Prediction of Microstructure Evolution during High Temperature Blade Forging of a Ni-Fe Based Superalloy, Alloy 718

Young-Sang Na[1,*], Jong-Taek Yeom[1], Nho-Kwang Park[1] and Jai-Young Lee[2]

[1] Materials Processing Department, Korea Institute of Machinery and Materials
66 Sangnam-dong, Changwon 641-010, Korea
[2] Department of Materials Science and Engineering
Korea Advanced Institute of Science and Technology
373-1 Guseong-dong, Yuseong-gu, Daejeon 305-701, Korea

The mechanical properties of the Ni-Fe-based Alloy 718 depend very much on grain size, as well as the strengthening phases, γ' and γ". The grain structure of the superalloy components is mainly controlled during thermo-mechanical processes by the dynamic, meta-dynamic recrystallization and grain growth. In this investigation, the evolution of the grain structure in the process of two-step blade forging was experimentally and numerically dealt with. The evolution of the grain structure in Alloy 718 during blade forging was predicted using a 2-D FE simulator with implemented constitutive models on dynamic recrystallization and grain growth. The comparison of the simulated microstructure with the actual grain structure of the forged parts validated the prediction of the grain structure evolution. The effect of dynamic recrystallization on the evolution of grain structure is highlighted in this article.

Keywords : blade forging, dynamic recrystallization, meta-dynamic recrystallization, alloy 718, grain growth

1. INTRODUCTION

Alloy 718 is one of the most widely-used superalloys, and currently accounts for 45 percent of wrought Ni-Fe-based superalloy production. This alloy is widely used in the stationary and rotating parts of aircraft turbines and steam turbines due to its excellent combination of high temperature mechanical properties, formability and weldability. Final products are usually manufactured by adopting high temperature processing methods, such as hot forging, rolling and extrusion.

With the advent of advanced computer-hardware, software and numerical technologies, much effort has been made in predicting the microstructure change during metal forming processes. Microstructure prediction modules as well as the Bayesian neural networks and Gaussian method can be incorporated into the conventional FE code for the simulation of metal flow processes [1-4].

In this research, a microstructure prediction module is implemented into a conventional FE code, which is based on the metallurgical and mathematical understanding of the microstructural changes in Alloy 718 during deformation processing and subsequent heat treatment. Constitutive models were constructed and used for the prediction of grain structure in the forged Alloy 718. Grain growth, dynamic recrystallization and metadynamic recrystallization were taken into account. The simulation results were validated by comparing them with actual forging.

2. EXPERIMENTAL PROCEDURES

2.1. Compression tests

The material used in this study was the Ni-Fe-based Alloy 718 billet of 5.4 wt.% Nb+Ta. The initial grain size of the billet was chosen as 15-320 μm depending on usage. In order to evaluate the recrystallization behavior, compression specimens were induction-heated to a test temperatures 927 °C–1066 °C at a heating rate of 5 °C sec^{-1}, and held for 5 min; at the test temperatures to obtain a uniform temperature within the specimens. Compression tests were carried out in vacuum (~10^{-2} torr) up to the true strain 0.8 at strain rates between 5×10^{-4} sec^{-1} and 5×10^{0} sec^{-1}. To investigate meta-dynamic recrystallization, hold times were given to the compressed specimens of up to 60 sec after releasing the compression load. The specimens were quenched by purged N_2 gas as soon as the compression tests, with or without the hold-time, were completed.

*Corresponding author: nys 1664@kmail.kim.re.kr

2.2. Blade forging

Simple-shaped blades were forged using an 1800-ton screw press. A two-step blade forging route was employed, i.e. upsetting the cylindrical billets with a tapered end in the first step, and finish forging of the blade in the second step. In order to reduce die friction and get smooth deformation, graphite lubricant was spread on to the upper and lower dies. The upsetting temperature was 1010 °C and the forging temperature was varied between 982 °C and 1038 °C. The transfer time of the work piece from the furnace to the press and preparation time for forging was less than 10 sec.

2.3. FEM simulation

A non-isothermal rigid-plastic FE code was used to simulate the effect of process variables on the distribution of state variables such as strain, strain rate and temperature. The upsetting and finish forging were simulated with 100 step increments in total, and the distributions of the state variables for each step were monitored to predict the grain structure.

Based on the constitutive equations for the dynamic recrystallization, meta-dynamic recrystallization and grain growth obtained from compression tests, grain distribution contour maps of the forged parts were constructed using a user-defined post-processor module implemented into FE code. For the simulation of the grain distribution of the forged parts, state variables obtained from FE simulations were used.

To estimate the variation in grain structure (grain size, recrystallized fraction, etc.) with deformation, the simulation results on local temperature, strain, and average strain rates within the forged parts were used. The total accumulated strain divided by the summation of the incremental times, not by the incremental strain rate at a specific simulation step, was employed as the average strain rate for the calculation of the grain structure.

3. RESULTS AND DISCUSSION

3.1. Dynamic recrystallization

From the true stress vs. true strain curves obtained under various strain rates and temperatures, one can obtain a variation in the hardening rate (dσ/dε) with strain. The critical strain for the onset of dynamic recrystallization can be obtained from the inflection point in the curves. The detailed experimental approach is presented elsewhere [5]. The critical strain is quite similar to the value of 0.8 times the peak strain [6]. In this research, the inflection point around 0.8 times the peak strain is selected as a criterion for the beginning of dynamic recrystallization. The critical strain for the onset of dynamic recrystallization increases by increasing the initial grain size and Zenor-Holloman parameter ($Z = \dot{\varepsilon}\exp(Q/(RT))$).

Dynamic recrystallization occurs typically near grain boundaries, forming a necklace microstructure. The volume fraction and sizes of the recrystallized grains were analyzed using an image analyzer. The volume fraction of dynamically recrystallized grains increases with strain, as fitted by an Avrami equation [6]. The change in recrystallization behavior with strain shows a different behavior below and above 1038°C because of the dissolution of the δ phase, which is known to be a grain boundary pinning phase. Recrystallized grain size can be expressed as a function of the Zener-Hollo-man parameter. The constitutive equations for dynamic recrystallization are given by the Eqs. 1, 2 and 3. The detailed process for obtaining the constitutive equations is presented elsewhere [7].

$$X_{dyn} = 1 - \exp\left(-\ln 2\left(\frac{\varepsilon}{\varepsilon_{0.5}}\right)^{1.7}\right)$$

$$\varepsilon_{0.5} = 0.037 \times d_0^{0.2} Z^{0.06} \quad \text{below } 1038\ ^{\circ}\text{C} \tag{1}$$

$$X_{dyn} = 1 - \exp\left(-\ln 2\left(\frac{\varepsilon}{\varepsilon_{0.5}}\right)^{1.9}\right)$$

$$\varepsilon_{0.5} = 0.029 \times d_0^{0.2} Z^{0.06} \quad \text{above } 1038\ ^{\circ}\text{C} \tag{2}$$

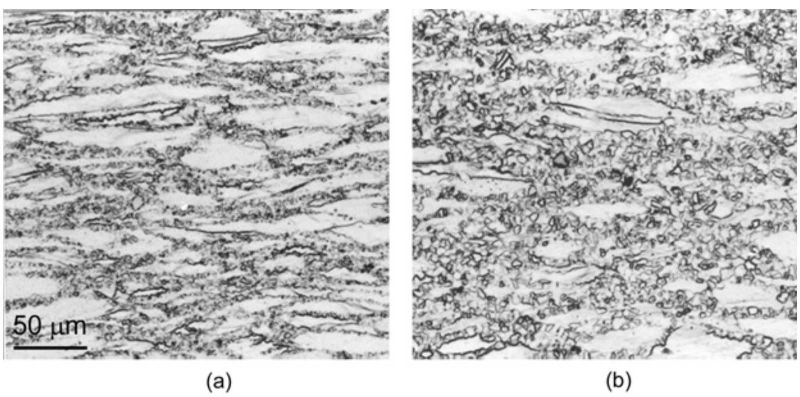

Fig. 1. Occurrence of metadynamic recrystallization during 5 sec holding. (a) 1020 °C, 1 sec^{-1}, 0 sec; (b) 1020 °C, 1 sec^{-1}, 5 sec.

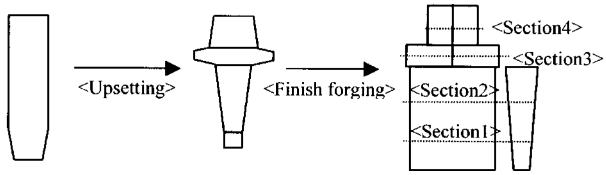

Fig. 2. Two-step blade forging process.

$$D_{dyn} = 1.301\times10^3\times Z^{-0.1243} \quad (3)$$

Meta-dynamic recrystallization takes place during the high temperature holding after the compression tests. A microstructure change during a holding time, 5 sec, is shown in Fig. 1. The recrystallization fraction increases with increasing hold time. The fraction of meta-dynamic recrystallization also depends on initial grain size, accumulated strain, temperature and strain rate. However,a meta-dynamic recrystallization model is not considered in this article because it can be neglected in blade forging because of rapid die chilling.

3.2. Blade forging and grain structure

A two-step forging route was employed for the blade forging as shown in Fig. 2. Before the upsetting and finish forging, the work-piece was heated to a forging temperature of around 982–1038 °C and held for about 15 to 30 min depending on the thickness of the work-piece to obtain a uniform temperature distribution. After upsetting at 1010 °C, a fully recrystallized grain structure was obtained in the blade platform area due to high strain, while the recrystallized microstructure was not formed in the root and airfoil region, as shown in Fig. 3. The average grain size in the blade platform region is about 6 μm, while about 37 μm in the blade airfoil region. The average grain size in the airfoil region is lower than that of the as-heated work-piece (50 μm) because the partial recrystallization occurred during the upsetting.

The grain structure of section 1 after finish forging at 1010 °C is shown in Fig. 4. Center part (A) shows the fully recrystallized grain structure, while the surface area (D) shows a partially recrystallized necklace structure due to the low temperature and limited strain caused by die chilling and friction. It should be noted that dynamic recrystal-

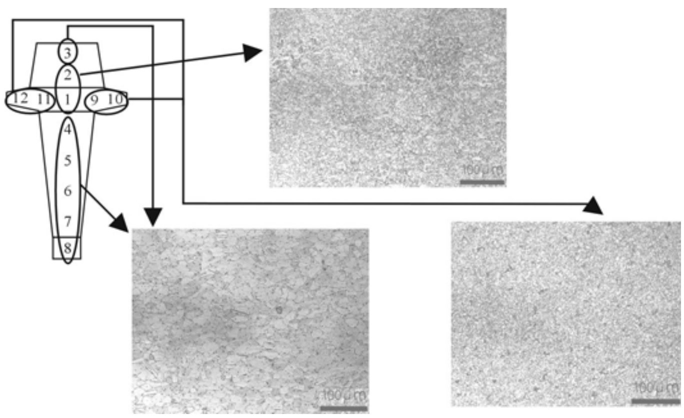

Fig. 3. Grain structure of upset forging forged at 1010 °C.

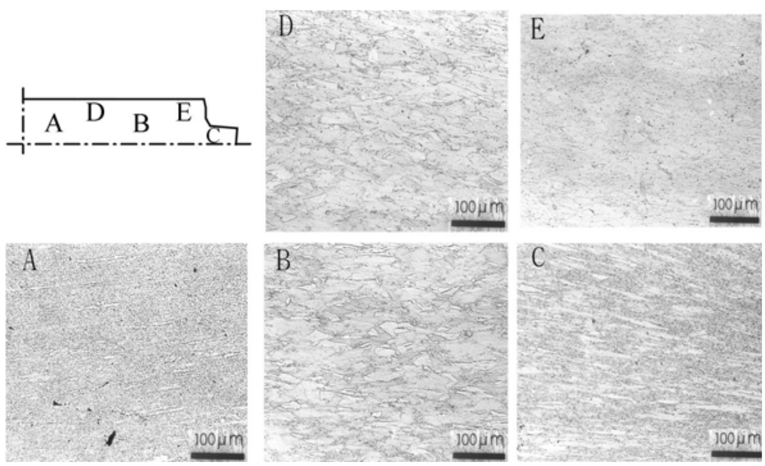

Fig. 4. Grain structure of section 1 of finish forging forged at 1010 °C.

lization hardly takes place in area B. A similar behavior is observed in section 2. Observation of the root and platform area in the finish forging indicated that dynamic recrystallization did not occur because the strain was not enough in the finish forging.

3.3. FEM simulation

Commercial 2D FE code was used for the axisymmetric simulation of the upset forging and plane strain finish forging. Heat dissipation during the transfer of the work-piece to the die and dwell on it was considered before the forging simulations. For the microstructure simulation, user-defined subroutines, which include the constitutive equations for grain growth, dynamic recrystallization and meta-dynamic recrystallization, were implemented into the commercial FE code. However, in the present simulation, meta-dynamic recrystallization after finish forging was considered to be negligible and ignored. Based on the experimental observation results, the grain sizes 50 μm and 70 μm were used as the initial grain sizes for the simulation of the upset forging and finish blade forging, respectively. Even if the recrystallization was concentrated in the blade platform region in the upsetting, the grain structure of the workpiece for finish forging became uniform due to the grain growth during holding at the forging temperature for 30 min before finish forging.

The axisymmetric simulation on strain and temperature distributions after upset forging indicated that the effective strain and temperature were the highest in the blade platform as expected. The dynamically recrystallized grain size and recrystallization fraction are very similar to the calculated results even if it is not presented here due to the limited space. However, the observed grain size is larger than the calculated one within the unrecrystallized region. As a matter of fact, it is difficult to observe the tiny recrystallized grains present near the original grain boundaries; i.e, the actual average grain size can be smaller than the measured one. An overestimation of the average grain size could be expected in the region where the calculated recrystallization fraction was lower than 0.3.

The effective strain in section 1 of the finish forging at 1010 °C does not show a uniform distribution. The maximum strain appears at one quarter away from the center axis along the horizontal line and the minimum strain at 3 quarters from the center axis. The non-homogeneous distribution of the strains leads to a different grain structure depending on the location within the blade. Fig. 5 shows simulation results quite similar to the measured results. At the center, the fully-recrystallized structure is predicted and confirmed by metallography, as shown in Fig. 4. At a location of 3 quarters away from the center, the simulation indicates that the recrystallized fraction is just about 0.25 as observed in area B of Fig. 4. However the recrystallization fraction of area E is overestimated in the simulation. The simulation indicates that the recrystallization fraction at E is over 0.5. However, recrystallization was hardly observed at area E in the forged blade. This seems to be related to the correctness of the metal flow simulations. In such high angle regions as area E in Fig. 4, the metal flow simulation is likely to be incorrect as the deformation variables are different from the actual values. The microstructure simulation for the platform area of the finish forging indicated that dynamic recrystallization did not take place in that area, as was experimentally validated. The average grain size was almost the same as that of the measured one in the platform area.

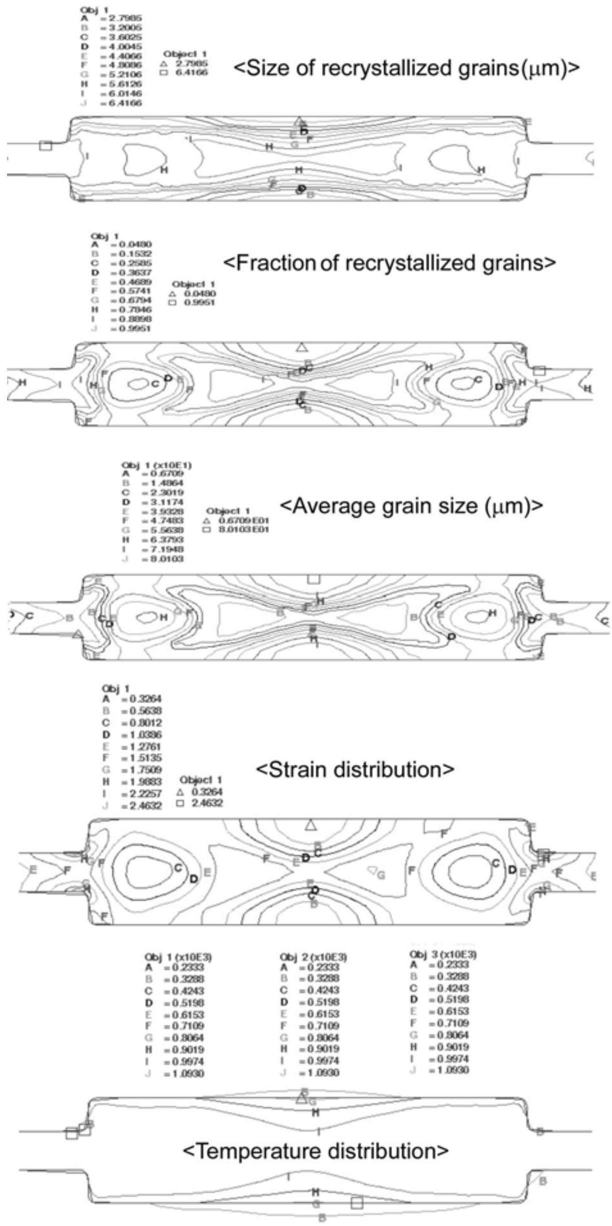

Fig. 5. Simulation results of state variables (strain and temperature) and grain structure at section 1 of finish forging forged at 1010 °C.

If minor errors are allowed in microstructure simulation, the 2D microstructure simulation model appears to be a useful tool for the forging process design. In this research, while the uniform grain structure is not obtained in the as-forged part, it may be possible to get a more uniform structure via post heat treatment because there still remains a driving force for meta-dynamic recrystallization. The simulation of meta-dynamic recrystallization using the FE code, including the grain structure simulation module, will help users to design forging and heat treatment processes.

The 2-D FEM simulation used in this research may not be satisfactory for the microstructure simulation of complex-shaped blades. However, the microstructure of forged blades can be easily predicted using the user-defined microstructure prediction module developed in this research by implementing it into the commercially available 3D FEM simulator.

4. CONCLUSIONS

Dynamic recrystallization and meta-dynamic recrystallization were modeled in the present study. The critical strain indicating the beginning of dynamic recrystallization can be expressed in numerical form as a function of strain rate, strain and temperature.

Numerical equations for the critical strain, dynamic recrystallization, meta-dynamic recrystallization and grain growth have been implemented into FE code to predict microstructure changes during deformation processes. The strain and temperature distribution simulated by FE code together with the implemented microstructure module can be effectively used to predict the evolution of microstructures of the work piece.

The comparison of the present 2D FE module with the actual microstructure of forged parts has successfully validated its effectiveness in the prediction of microstructures.

REFERENCES

1. G. Shen, J. Rollins, and D. Furrer, *Superalloys 1996* (eds., R. D. Kissinger, D. J. Deye, D. L. Anton, A. D. Cetel, M. V. Nathal, T. M. Pollock, and D. A. Woodford), p. 613, TMS, Pennsylvania, USA (1996).
2. C. A. L. Bailer-Jones, T. J. Sabin, D. J. C. MacKay, and P. J. Withers, *IPMM '97* (eds., T. Chandra, S. R. LeClair, J. A. Meech, B. Verma, M. Smith, and B. Balachandran), vol. 2, p. 913, Gold Coast, Australia (1997).
3. T. J. Sabin, C. A. L. Bailer-Jones, S. M. Roberts, D. J. C. MacKay, and P. J. Withers, *THERMEC '97* (eds., T. Chandra and T. Sakai), p. 1043, TMS, Wollongong, Australia (1997).
4. T. J. Sabin, S. M. Roberts, P. J. Withers, and C. A. L. Bailer-Jones, *Proc. of the Int. Conf. on Forging and Related Technology* (*ICFT '98*), p. 411, National Motorcycle Museum, Birmingham, UK (1998).
5. N. K. Park, J. T. Yeom, Y. S. Na, I. S. Kim, D. H. Kim, and S. J. Choe, *Superalloys 718, 625, 706 and Various Derivatives* (eds., E. A. Loria), p. 173, TMS, Pennsylvania, USA (1997).
6. G. Krauss, *Deformation, Processing, and Structure*, ASM, St. Louis, Missouri (1982).
7. J. T. Yum and N. K. Park, *J. Kor. Soc. Tech. Plasticity* **6**, 250 (1997).