The Microstructure Prediction of Alloy720LI for Turbine Disk Applications

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Abstract

In order to reduce the lead time of developmental stage and increase the reliability of the forging process of turbine disk, it is effective to predict the transformation of microstructure during the forging stage. In this paper, the microstructure prediction procedure for cast/wrought form alloy720LI is introduced. To determine the parameters quantitatively, two kinds of tests were carried out. One was isothermal heating test, the other was isothermal compression test. The relational expressions between microstructure and various parameters e.g. time, temperature and strain rate were formulated for both static grain growth model and dynamic recrystallization model. Static grain growth model and dynamic recrystallization model represents preheating process prior to forging and forging process itself respectively. The models were coupled to finite element analyzing system. Furthermore pancake forging and generic shaped disk forging were carried out to verify the effectiveness of proposed prediction system. It was confirmed that the proposed prediction system has good accuracy to apply to the actual disk forging process.

Introduction

High performance alloys are used for turbine disks and the requirement for its properties and reliabilities are increasing for advanced aircraft engines. Alloy720LI is one of the most effective alloy for turbine disk applications because of its high creep strength and low cycle fatigue (LCF) property at elevated temperature. In fact, several engine adopt alloy720LI as turbine disk material.

Alloy720LI was developed as for both cast/wrought alloy and powder metallurgy (P/M) alloy. Many investigations were performed in both regions[1-4]. Each has advantages and disadvantages. Generally cast/wrought form is more desirable compared to P/M form from the viewpoint of cost. Advanced aircraft engine requires not only improvement of properties but also reduction of cost. Therefore cast/wrought form is worthy of being investigated further.

As for property, cast/wrought process can give excellent creep and LCF property, much the same to P/M process. But it is difficult to give such high properties in actual parts. Alloy720LI include higher alloying elements than conventional alloys e.g. alloy718 and has greater temperature and strain rate dependence on various behaviors. Especially deformation resistance and microstructure behavior are important to produce the disk. The former restricts disk size and shape, the latter is related to final mechanical properties. Various parameters e.g. temperature, strain rate, total strain etc. have to be controlled carefully to obtain desirable mechanical properties through out any portion of disk. In case of cast/wrought process, the control of such

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TABLE Ⅰ Chemical composition of the billet (mass%)

	Ni	Cr	Co	Mo	W	Al	Ti	Fe	Mn	Si	Zr	B	C
alloy720LI	Bal.	15.6	14.2	3.2	1.2	2.6	5.0	0.3	0.01	0.01	0.05	0.013	0.015

parameters is relatively difficult.

One of the effective ways to solve the problem is computer simulation. Generally computer simulation has been used to predict the load and deformed shape and to determine initial work size, preformed shape and so on. If the prediction of microstructure is possible, it enables to design the forging process that can obtain excellent and uniform properties through out any portion of disk and the reliability of the disk will be increased. Actually several microstructure modeling were proposed and reported in the past. But most of them were carried out on conventional alloys e.g. alloy718, Waspaloy[5,6]. In case of alloy720LI, large temperature and strain rate dependence on microstructure and dispersion of microstructure at billet condition make the prediction difficult. According to calculation of phase equilibria, the mole fraction of stable gamma phase changes about 10% under the range of temperature between gamma prime solvus and below that temperature by 40C, while only about 4% change is estimated in Waspaloy[7]. Such phase transition leads to drastic change of microstructure i.e. grain size, fraction of dynamic recrystallization and makes it difficult to recognize relationship between microstructure and various parameters. That is one of the reasons why accurate prediction in alloy720LI is difficult compared to other conventional alloys.

Furthermore, alloy720LI includes large amount of Al, Ti. Al and Ti are the major elements of gamma prime former and essential to obtain high strength but both elements tend to segregate in billet. Segregation of Al, Ti makes difficult to obtain complete uniform gamma prime distribution at billet stage. Actually two kinds of region are often observed. One has relatively high density of primary gamma prime particles i.e. gamma prime banding and the other has relatively low density of those. In case of disk production forging is carried out below the temperature of gamma prime solvus, the gamma prime distribution in billet condition effects strongly on the final microstructure. Therefore it is necessary to understand the behavior of each region for accurate prediction.

The objective of this investigation is to establish the microstructure prediction procedure of cast/wrought alloy720LI disk using computer simulation.

Materials and Experimental Procedure

Materials

Original material in this study was the billet produced from triple melted ingot (VIM+ESR+VAR). Chemical composition and typical microstructure of the billet are shown in TABLE Ⅰ and Figure 1 respectively. The microstructure was controlled carefully to obtain equiaxed grain with average grain size of ASTM 10-11 but gamma prime banding was observed on whole billet.

Isothermal Heating Test

Isothermal heating test was conducted to understand the static grain growth behavior. The specimens were put into furnace in which was controlled at specific temperature and were kept for set time. The range of temperature is 1100-1180C. Microstructure observation was performed by optical microscopy and grain size was estimated in accordance with ASTM E112.

Isothermal Compression Test

Isothermal strain rate controlled compression tests were carried out to understand the essential relationship between temperature, strain rate, strain and dynamically recrystallized grain size, fraction of dynamic recrystalization. The specimens were cylindrical shape with 8mm in diameter and 12mm in height. These specimens were heated up to test temperature by induction heating and compressed isothermally. Each range of temperature, strain rate and total strain is 950-1180C, 0.01-0.2s^{-1} and 5-70% respectively. The specimens were cooled immediately or after keeping test temperature for definite time to achieve quench and dwelled condition. Microstructure observation was carried out by optical microscopy for specific area with 1/2 in height and 2/3 in radius. The area was selected by finite element analysis as desirable observation point in which uniform conditions e.g. strain rate, temperature were achieved through compression. The results of microstructure observation were associated to test temperature, revised strain rate and total strain.

Figure 1 :Typical microstructure of the billet.

Several kinds of heat treatment were done prior to machining of specimens to control grain size with care of remaining gamma prime banding. It is necessary to understand the effect of initial grain size on dynamic recrystalization behavior. Moreover the microstructure in as-billet condition is not always best to investigate dynamic recrystallization behavior. Stored strain to which was introduced through billet forging process will induce rapid grain growth during heat-up prior to compression and correct initial grain size will become indistinct. Excellent fine grain size may make it difficult to distinguish recrystallized grain from unrecrystallized grain and bring difficulty in correct measurement of recrystallized grain size and fraction of dynamic recrystalization.

Modeling

Static grain growth model which corresponded to preheating process prior to forging and dynamic recrystalization model which represented forging process itself were developed through quantitative analysis of the results which were obtained from isothermal heating tests and isothermal compression tests. Moreover constructed microstructure prediction models were coupled to the finite element analyzing system, DEFORM*. Estimation of average grain size and fraction of dynamic recrystallization in addition to general output e.g. temperature, strain and load on the whole area of disk was enabled by utilizing user subroutine developed under this study.

Pancake Forging

Hot die pancake forging were conducted with different three conditions to verify the effectiveness of proposed prediction system. Adopted forging conditions varied in temperature from 1125C to 1160C. Forged final shape had 200mm in diameter and 25mm in height.

Generic Shaped Disk Forging

For more accurate verification in practical shape and size, generic shaped disk forging were carried out with hot die condition. The component had 350mm diameter and 80mm height in boss region, 40mm height in rim region. Two kinds of preheating temperature condition, 1100C and 1120C were selected by proposed prediction system to obtain desirable grain size for disk applications.

Results and Discussion

Static Grain Growth Model

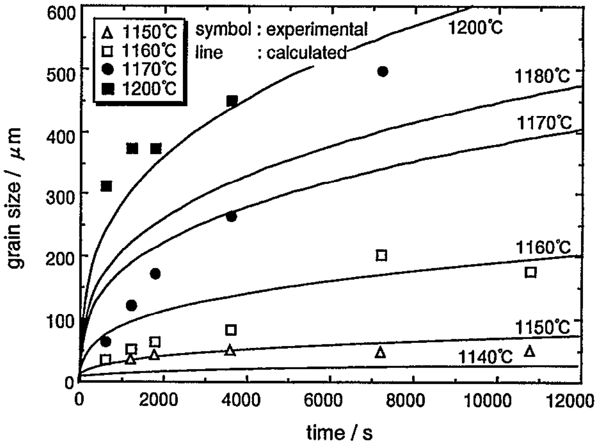

Figure 2: Temperature and time dependence of static grain growth.

Static grain growth model represents mainly preheating process prior to forging. The relationship between grain size and holding time is shown in Figure 2. The higher the temperature is, the larger the grain growth rate is. The tendency becomes obvious above gamma prime solvus temperature. Furthermore Figure 2 reveals that the relationship can be represented by following equation and the exponent n takes 3 in this case.

$$d_{i+1}{}^{n_{gro}}-d_i{}^{n_{gro}}=A_{gro}\,t\exp(-Q_{gro}/RT) \qquad (1)$$

where d_{i+1} is the grain size when time is t_{i+1}, d_i is the grain size when time is t_i, t is time, Q_{gro} is activation energy for grain growth, T is absolute temperature, R is gas constant and A_{gro}, n_{gro} are material constants. Generally the exponent n_{gro} varies from 2 to 4 with rate-controlling process of grain growth. In case of single phase structure, grain boundary migration controls the growth rate and the value n_{gro} takes 2. On dispersion structure condition in which dispersion particle plays as pinning of grain boundary, volume diffusion of atom which constructs dispersion particle controls not only growth of particle but also that of grain and n_{gro} takes 3. $n_{gro}=4$ is found in dual phase structure. According to differential thermal analysis, gamma prime solvus temperature varies from 1079C to 1164C in this material. Therefore primary gamma prime particle has great effect to grain growth at whole temperature range investigated. In addition to existence of gamma prime particle, carbide, nitride and boride are dispersed and remain in the structure even when the temperature is over gamma prime solvus. Consequently the estimated exponent 3 is supposed to be valid. However the equation (1) mentioned above represents essentially steady state grain growth with no internal strain. If the stored strain caused by billet forging process were extremely large or the distance among particles were extremely short compared to grain diameter, n_{gro} might not be the same. Actually activation energy Q_{gro} is effected by internal strain and initial dispersion of particles. As a result relatively large value is estimated while theoretical value is equivalent to activation energy for volume

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*DEFORM is the trade name of Scientific Forming Technology Corporation.

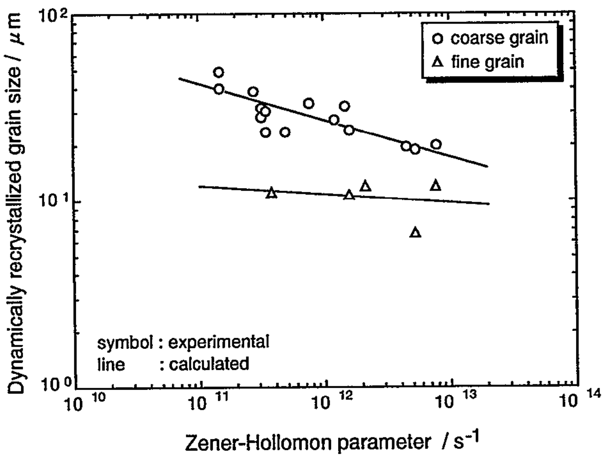


Figure 3 :The relationship between dynamically recrystallized grain size and Zener-Hollomon parameter.

diffusion of Ni or alloying element in Ni.

Dynamic Recrystallization Model

Dynamic recrystallization model corresponds to forging process itself. In case of cast/wrought forms, it is very important to control the occurrence of dynamic recrystallization. Dynamic recrystallization enables to bring desirable microstructure that consists of uniform, equiaxied and fine grain.

One of the most important factors to predict accurately is dynamically recrystallized grain size because dynamically recrystallized grain size has a great influence on average grain size. Average grain size is determined as mixture of initial grain size and dynamically recrystallized grain size. Figure 3 shows the relationship between dynamically recrystallized grain size and Zener-Hollomon parameter. Two kinds of relationship can be seen in Figure 3. One is observed in the area with relatively low density of primary gamma prime particles. The other is observed in the area with relatively high density of primary gamma prime particles i.e. gamma prime banding. The grain size tend to be coarse in the former condition and be fine in latter condition. Each relationship is represented with the following equation.

$$d_{dyn}=A_{dyn}\,Z^{n_{dyn}} \qquad (2)$$

where d_{dyn} is dynamically recrystallized grain size, Z is Zener-Hollomon parameter, A_{dyn} and n_{dyn} are material constants. Zener-Hollomon parameter means temperature-compensated strain rate and follows as

$$Z=\dot{\varepsilon}\,\exp(Q_{def}/RT) \qquad (3)$$

where $\dot{\varepsilon}$ is strain rate, Q_{def} is activation energy for deformation, T is absolute temperature, R is gas constant. Activation energy for deformation Q_{def} is estimated by following equation that represents deformation behavior at high temperature.

$$\dot{\varepsilon}=\sigma^{n_{def}}\exp(-Q_{def}/RT) \qquad (4)$$

where σ is peak stress or steady stress, n_{def} is material constant. In this study, peak stress is adopted to estimate n_{def} and Q_{def} in equation (4). The exponent n_{def} takes constant value of 4.6 at temperature above gamma prime solvus and is larger value below the temperature. Corresponding activation energy Q_{def} is 360kJmol^{-1} or larger. The value of estimated activation energy is apparent activation energy and includes the effect of non-thermally activated process. Generally, larger value is obtained compared to volume diffusion of Ni or alloying element in Ni and similar tendency is observed in this study.

It is interesting that two kind of different relationships are shown in Figure 3 even when various parameters except primary gamma prime distribution are equivalent to each other. Dynamic recrystallized grain size can be described as a function of Zener-Hollomon parameter in each region. But different constants A_{dyn} and n_{dyn} in equation (2) are obtained. The absolute value of n_{dyn} in the area with relatively high density of primary gamma prime particles is smaller than that of low density area. And the fitting curve for high density gamma prime region is positioned below the curve for low density area. This fact means that primary gamma prime particles act effectively as nucleation site and obstacle for grain boundary migration. Consequently Zener-Hollomon parameter dependence becomes relatively small in gamma prime banding.

Precise prediction is required for fraction of dynamic recrystallization too. Equation (5) is the most common form which represents the behavior of fraction change.

$$X_{dyn}=1-\exp(-kt^{n}) \qquad (5)$$

where X_{dyn} is fraction of dynamic recrystallization, t is time, k and n are constants. But another Avrami type equation (6) was maintained in this study.

$$X_{dyn}=1-\exp\{-\ln 2\,(\varepsilon/\varepsilon_{0.5})^{n_{dynx}}\} \qquad (6)$$

where ε is strain, $\varepsilon_{0.5}$ is strain for 50% dynamic recrystallization, n_{dynx} is constant. $\varepsilon_{0.5}$ is function of Zener-Hollomon parameter and initial grain size. This equation shows that fraction of dynamic recrystallization is affected by temperature, strain rate, strain and initial grain size. Figure 4 shows the relationship between fraction of dynamic recrystallization and strain when initial grain size is 73 μm, test temperature is 1130C and 1150C. Obtained fitting curve is able to trace the actual tendency quantitatively. The higher the temperature is and the smaller the strain rate is, the higher the fraction of dynamic recrystallization is. The exponent n_{dynx} which reflects the mechanism of nucleation and growth takes 1.7

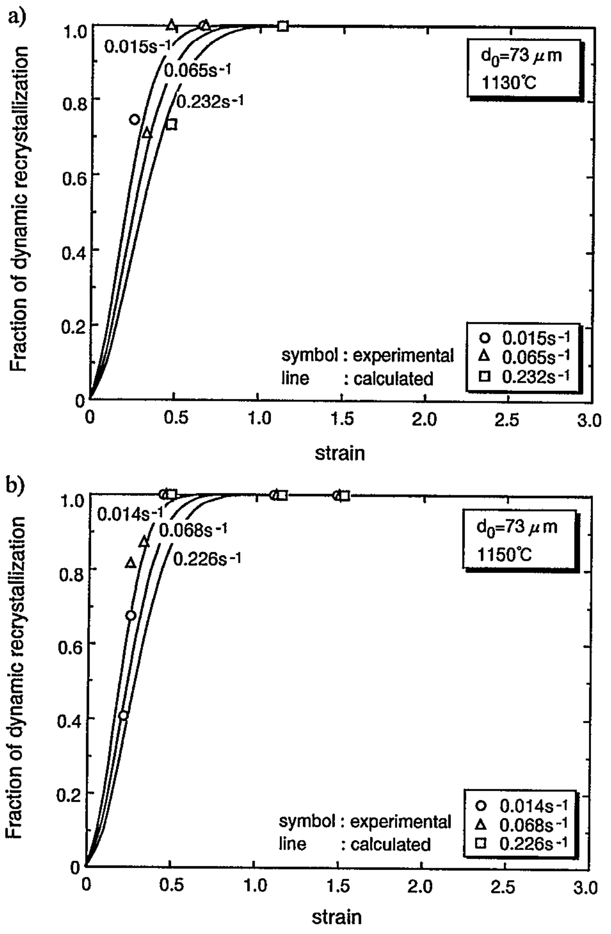


Figure 4 :The relationship between fraction of dynamic recrystallization and stain a)initial grain size; 73 μ m, test temperature; 1130C b)initial grain size; 73 μ m, test temperature; 1150C.

in 1130C and 1.9 in 1150C. However, the value of n_{dynx} changes as strain strictly. The change corresponds to various phenomena. Dynamic recrystallization occurs not only in unrecrystallized region but also in recrystallized region at the latter stage whereas it occurs only in unrecrystallized region at the early stage. Recrystallized grain is able to grow relatively free at early stage but the growth is restricted by next grains at later stage. Hence the estimated n_{dynx} is average value for prediction and dose not always represents the strict behavior at particular stage.

There are some amounts of possibility that grain growth occur in actual parts due to the deformation heat and stored strain. Therefore it is important to suppress the grain growth during and after forging in order to obtain the fine grain structure in whole disk. Moreover the degree of grain growth has to be predicted quantitatively when temperature exceeds the critical temperature. Hence accurate prediction of grain growth phenomena just after forging is required in particular. Figure 5 shows the grain growth behavior of dynamically recrystallized grain after isothermal compression. Very rapid grain growth tendency is observed. The relationship between grain size and dwell time is described with following equation (7) similar to equation (1).

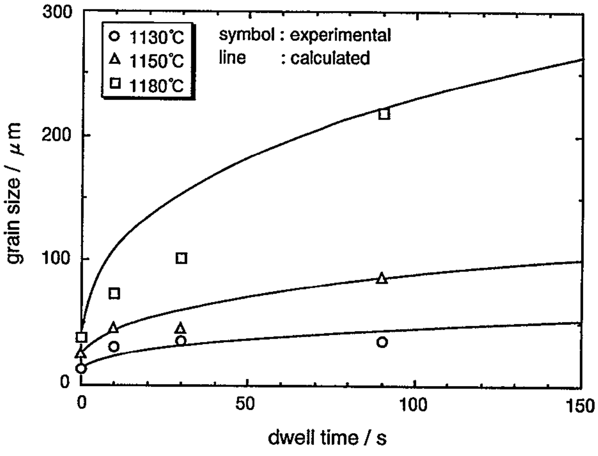


Figure 5 :Grain growth behavior after forging.

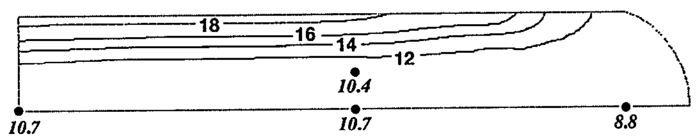
$$d_{dwc}^{n_{dgr}} - d_{com}^{n_{dgr}} = A_{dgr}\, t \exp(-Q_{dgr}/RT) \qquad (7)$$

where d_{dwe} is the grain size after dwell, d_{com} is the grain size just after compression, Q_{dgr} is activation energy for grain growth in dwell condition, T is absolute temperature, R is gas constant and A_{dgr}, n_{dgr} are material constants. The exponent n_{dgr} takes 3 which is identical value in equation (1).

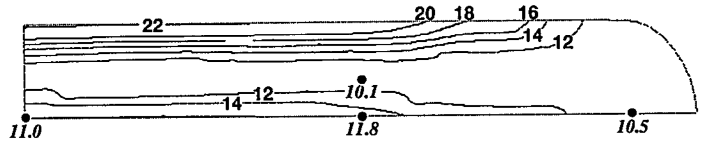
Pancake Forging

Figure 6 shows the predicted average grain size and actual observed one in case of pancake forging. The work shape is simple in this case, but the deformation is not uniform. For example, the strain distribution varied from low strain area near the die contact surface to high strain area at the center of the work. Therefore, distribution and history of temperature, strain rate and total strain seem to be complicated too. But in any forging temperature, the difference between predicted average grain size and observed one is relatively small and predicted values have good agreement with observed ones in spite of the large temperature dependence of microstructure change on alloy720LI. It does not need to say that precise prediction is required when the forging temperature is relatively low i.e. sub-solves temperature. However, it is also important to predict the degree of grain growth quantitatively when temperature exceeds the gamma prime solvus because there are some amount of possibility that grain growth may occur partially in actual large and complicated portion due to the deformation heat even if preheating temperature is sub-solvus one.

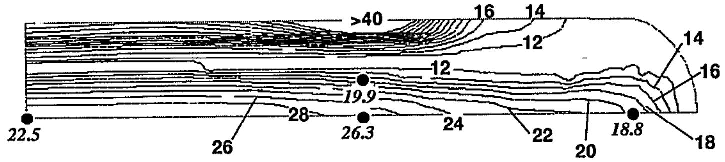
Generic Shaped Disk Forging



(a) temperature 1125C／ram speed 3.1mms^{-1}



(b) temperature 1140C／ram speed 3.1mms^{-1}

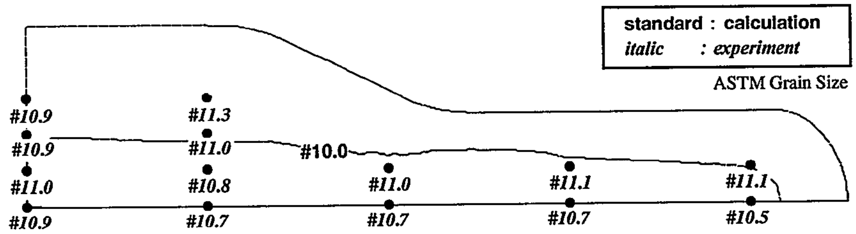


(c) temperature 1160C／ram speed 3.1mms^{-1}

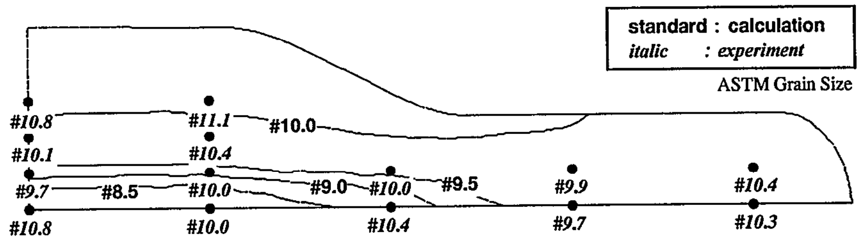
[µm]

standard : calculation
italic : experiment

Figure 6 : Comparison between predicted and observed average grain size distribution in case of pancake forging (a)1125C with 3.1mms^{-1} ram speed (b)1140C with 3.1mms^{-1} ram speed (b)1160C with 3.1mms^{-1} ram speed.



(a) temperature 1100C／ram speed 3.5mms^{-1}



(b) temperature 1120C／ram speed 3.0mms^{-1}

Figure 7 : Comparison between predicted and observed average grain size distribution (a)1100C with 3.5mms^{-1} ram speed (b)1120C with 3.0mms^{-1} ram speed.

The deformation is more complicated in this actual disk shape than in pancake one. Two forging conditions were chosen due to proposed simulation system. One gives the best microstructure distribution for disk, around ASTM No.10 at any portion of the work. The other gives some amount of distribution, from ASTM No.8.5 to 10. Figure 7 shows the comparison of prediction and observation in two conditions mentioned above. In each condition, good agreement between predicted values and observed ones was obtained in spite of complicated deformation.

Conclusions

The microstructure prediction procedure of cast/wrought form alloy720LI for turbine disk production has been developed. The essential relationship between microstructure and various parameters, e.g. temperature, strain rate, strain was revealed through isothermal heating tests and isothermal compression tests. Obtained relationship was formulated as static grain growth model and dynamic recrystallization model. The models were coupled to finite element analyzing system. In order to verify the effectiveness of proposed prediction system, pancake forging and generic shaped disk forging were conducted. It was confirmed that accuracy of prediction was enough to apply to practical forging process.

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Unpublished Mitsubishi Materials data.