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Development of precise load prediction system for free forging of Ni-based superalloy having softening

Shingo Sakurai[a], Takuma Okajima[a], Masanao Fujiwara[a],
Takuji Otake[b], Takashi Ishikawa[b]

[a]*Daido Steel, 2-30, Daido-cho, Minami-ku, Nagoya, 457-8545, Japan*
[b]*Nagoya University, Furo-cho, Chikusa-ku, Nagoya, 464-8603, Japan*

Abstract

Ni-based superalloys such as Alloy 706 that have high heat resistance are applied to gas turbine disks in electric power plant because. Free forging is one of the effective forging processes to form superalloy products, and forging simulation is quite useful method to optimize forging schedule. Softening behaviour at high temperature was not considered and implemented in conventional simulation, that induced the accuracy of load prediction. In this study, we investigated softening behaviour to improve the accuracy of forging simulation.

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Keywords : Free forging; Hot forging; Forging simulation; Softening

1. Introduction

In these days, improvement of efficiency is required for electric power plant. Especially at a gas turbine system, higher combustion temperature is required for higher efficient, so that requires endure the strength at higher temperature, Ni-based superalloys such as Alloy 706 are applied to gas turbine disks. Generally, Ni-based super alloys gas turbine disks are produced by closed-die forging or free forging; that is also called open-die forging, but they are hard to form because of their high heat resistance, and it is important to save forging energy in point of

Corresponding author. Tel : +81-052-611-9417; fax : +81-052-611-9559.
E-mail address : s-sakurai@ac.daido.co.jp

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view of energy save and economy.

Closed-die forging has an advantage to perform geometry, and it also has good repeatability of geometrical quality and mechanical property. But closed-die forging requires large forging energy with a huge press, and it also needs large size forging die for each product to control its shape.

Free forging doesn't need so large forging power because it uses anvil with simple shape. On the other hands, it has difficulty to control the shape of product. In general, forging passes' number increases more and more. To reduce the process time, forging schedule must be saved number of blow optimized to control the shape and within keep capacity of forging press.

Forging simulation is quite useful method to optimize the forging schedule to reduce trial cost. But the accuracy of commercial forging simulation in incremental multi-blow hot forging is not good enough, because softening behaviour that is caused by decrease of dislocation density at high temperature usually doesn't be considered between each blows. Softening behaviour is implemented into forging simulation for rolling in general. But, dynamic softening behaviour and semi-dynamic softening behaviour are considered only for rolling, static softening is not considered. The purpose of this study is following.

1) Evaluate softening behaviour in hot forging, and define the softening behaviour as the function of forging temperature and holding time.

2) Implement the softening behaviour formulation into forging simulation, and evaluate the prediction accuracy.

2. Evaluating softening behaviour

In this section, we investigated softening behaviour of Alloy 706. Alloy 706 is used at a high temperature over 923K environments such as turbine disks. Table 1 shows chemical composition of Alloy 706.

2.1. Experimental procedure

Softening behaviour is investigated by 2-blow compression test, the specimens are solution treated at 1253K/2hr and water quenched, and machined into the dimensions of ϕ 15 x 22.5. Fig.1 shows an experimental procedure. The specimen was heated by induction heating from 823K to 1273K, and after 30 sec., it was compressed as 20% reduction in height with strain rate was 0.5/sec. After 1st blow, there was a several holding time from 30 sec. to 10800 sec. Softening was occurred during this holding time, continuously, yield stress in 2nd blow was changed by softening during holding. After 2nd blows the specimens were water-quenched immediately to keep microstructure to measure fraction of recrystallization.

Stress-strain curves were calculated by measured forging load and displacement of press ram. Fig.2. shows schematic models of calculated stress-strain curve. Stress transfers within work-hardening and dynamic-softening or recrystallization after yielding. At the 2nd blow, the yield stress changes against holding temperature and holding time condition, and softening ratio is defined as Eqs. (1) and (2).

$$X_{softening}^{stress} = \frac{\Delta\sigma_{1-2}}{\sigma_{1f}} \quad , \tag{1}$$

$$X_{softening}^{strain} = \frac{\Delta\varepsilon_{1-2}}{\varepsilon_{1f}} \quad . \tag{2}$$

where σ_{1f} is stress at the end of 1st compression,$\Delta\sigma_{1-2}$ is released stress by softening, ε_{1f} is strain at the end of 1st compression and $\Delta\varepsilon_{1-2}$ is released strain by softening. At rolling model, softening ratio was defined by Eq. (1) [1]. But it has some difficulty to represent softening behaviour that is caused by recovery of stacked dislocations accurate. In this case, softening behaviour is defined as released ratio of strain (Fig. 2).

2.2. Result

Fig. 3 shows the relationship between holding time and softening ratio. The plotted points indicate experimental data, and curves are approximated data by Avrami formulation [2] as following.

Table 1. Chemical composition of Alloy 706 [mass %].

Fe	Ni	Cr	Nb	Ti	Al
Bal.	40.0	16.0	3.0	1.7	0.2

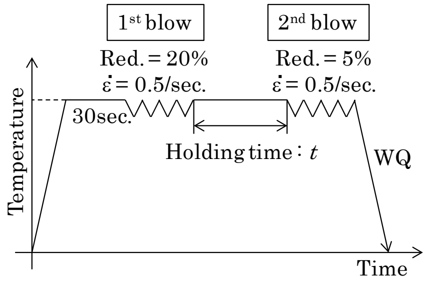


Fig. 1. Experimental procedure of 2-blow compression test.

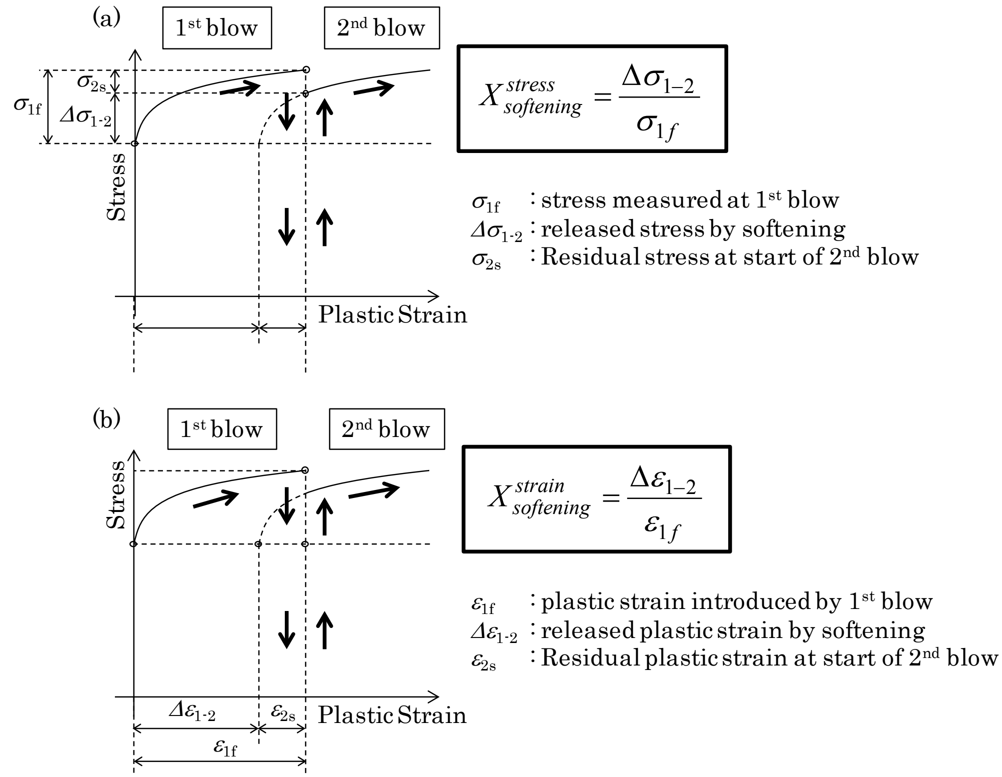


Fig. 2. Definition of softening ratio (a); based on stress (b); based on plastic strain.

$$X_{softening} = 1 - \exp\left\{-0.693\left(\frac{t}{C_1 \exp(Q/RT)}\right)^n\right\}. \tag{3}$$

where t is holding time, Q is activation energy, R is gas constant, T is holding temperature, C_1 and n is constant.

Table 2 shows the value of constant. Fig. 4 shows the microstructure of compressed specimen. Some recrystallized grains appeared on initial grain boundary.

Fig. 5 shows the relationship between holding time and fraction of recrystallization. Recrystallization starts above 1123K and increase of temperature accelerates its progress.

2.3. Discussion

Softening behaviour is considered to be caused by follow 3 mechanisms. Climbing of dislocations with opposite signs [3], recrystallization[4)] and phase transition[5)]. Recrystallization is caused by relocation of lattice in locally and phase transition causes relocation of lattice in entirely. In this case, matrix of Alloy 706 has no phase transition in the range from 823 K to 1273K, except for local gamma-gamma prime phase transition; this local phase transition causes only small effect for softening. Fig. 6 shows the contribution of recrystallization to softening ratio at 1173K / 300 sec. of holding condition. It became larger with increase of holding temperature above 1123K, and contribution of climbing of dislocations with opposite signs to softening ratio decreased. Both of them progress by consumption of dislocation. So it is considered that they are exclusive each other.

Table 2. Value of constant and activation energy in formulated softening behaviour.

Based on	C_1	Q (J)	n
Stress	5.0 x 10^{-45}	1000000 (≥1123K) 401067+533.3T (<1123K)	0.12
Strain	1.0 x 10^{-71}	1600000	0.10

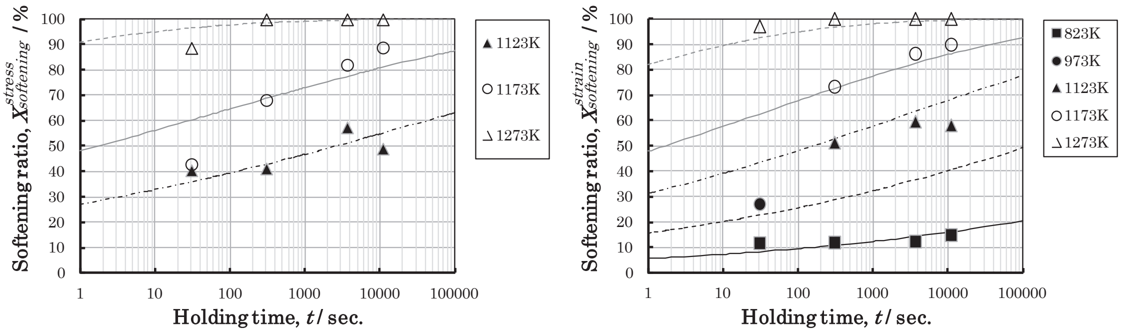
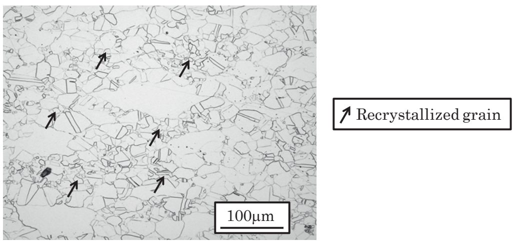


Fig. 3. Relationship between holding time and softening ratio (Temperature; from 823k to 1273K, (a); based on stress, (b); based on strain).



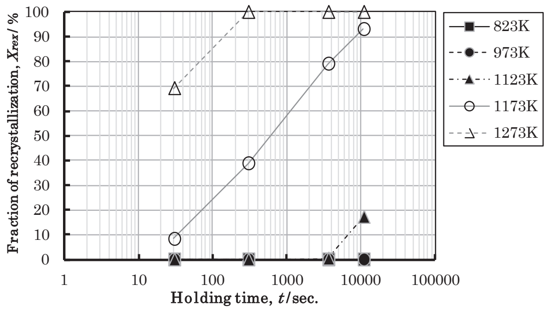


Fig. 4. Microstructure after compression test. Fig. 5. Relationship between fraction of recrystallization and holding time.

3. Evaluation test of softening behaviour prediction

3.1. Experimental procedure

To ensure the accuracy of formulated softening behaviour, actual forging and forging simulation were carried out, and their results were compared. Fig. 7 shows an experimental procedure of 4-blow compression test. The specimen were solution treated at 1253K/2hr and water quenched, and machined into dimensions of ϕ 15 x 22.5

mm. the specimens were heated by induction heating for 1123, 1173 and 1273 K. And after 30 sec. it was compressed as 20% reduction in height with strain rate was 0.5/sec. after 1st blow, there was a holding time for 300sec. 4-times of blow and holding are repeated, and after 4th holding, the specimens were water-quenched immediately. Softening ratio was calculated by stress-strain curves. Forging simulation by same forging pass was carried out with FEM by SimuFactForming11, and softening ratio was calculated.

3.2. Result and discussion

Fig. 8(a) shows the softening ratio, defined by released stress. In this case, softening ratio calculated at one stage differs from that of other stage. And, softening ratio decreased along to progress of compression stage at 1123K. These are unlike result for softening ratio to implement into forging simulation. On the other hands, softening ratio defined by released strain is shown in Fig. 8(b). In this case, softening ratio has only little difference between each compression stage at every holding temperature condition. Above mentioned softening ratio is defined by released stress and released strain, generally. But, softening is caused by recovery of dislocation, and dislocation density is proportional to the amount of strain. So variation of strain can represent the softening directly, but that of stress cannot. Fig. 9 shows the problem that there is deviation of increment of strain for same increment of strain.

Fig. 10 shows forging load, measured from the result of experiment and calculated from the result of forging simulation. They have good agreement each other, this indicates that softening behaviour implemented into forging simulation has good accuracy to predict forging stress.

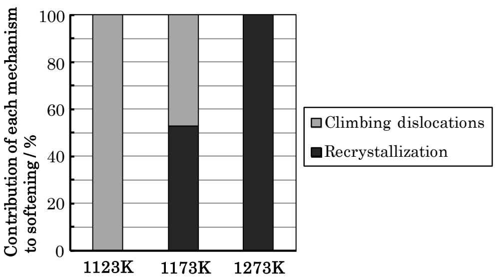


Fig. 6. Contribution of recrystallization to softening ratio.

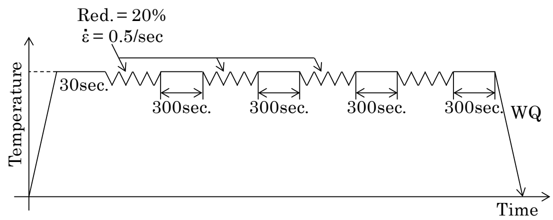


Fig. 7. Experimental procedure of 4-blow compression test.

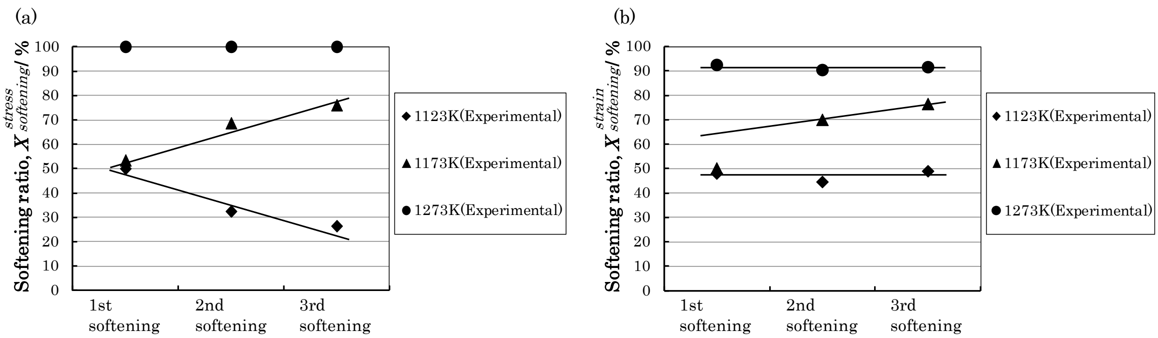


Fig. 8. Softening ratio measured by compression test and calculated by forging simulation. (a) Based on stress and (b) based on strain.

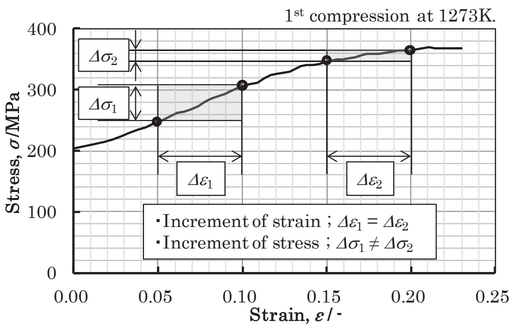


Fig. 9. Deviation of increment of stress for same increment of strain.

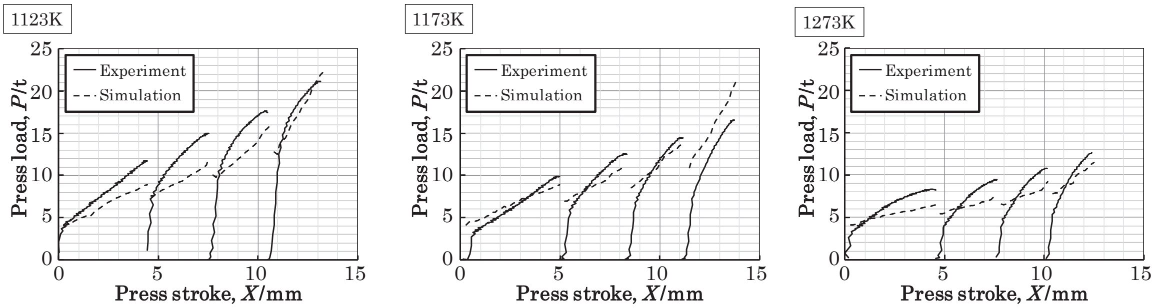


Fig. 10. Stress in forging measured by compression test and calculated by forging simulation.

4. Conclusions

Softening behaviour was investigated and defined as softening ratio, and it was implemented into forging simulation. Softening ratio was defined as ratio of released strain in holding at higher temperature and that was formulated from the result of 2-blow compression test from 823 to 1273K.

To validate the prediction accuracy of formulated softening behaviour in forging simulation, 4-blow compression test was carried out at 1123, 1173 and 1273 K, and then, measured stress was compared to calculated stress. They had good agreement each other, this result proves the accuracy of forging load prediction with softening behaviour.

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