A Study on Dynamic and Static Recrystallization
Behaviors and Microstructure Evolution Prediction of
Die Steels

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A Study on Dynamic and Static Recrystallization Behaviors and Microstructure Evolution Prediction of Die Steels

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ABSTRACT

Evaluation of microstructural changes during open die forging of heavy ingots is important for process control. The objective of the control of forging parameters, such as shape of the dies, reduction, temperature and sequence of passes, is to maximize the forging effects and to minimize inhomogeneities of mechanical properties.

A numerical analysis was performed to predict flow curves and dynamic and static recrystallization behaviors of die steel (0.36%C, 1.1%Mn and 1.21%Cr) from hot compression test results. The hot compression tests were carried out in the ranges of temperature 950~1150°C and strain rate 0.01~1.0sec⁻¹. The modeling equation for flow curves was a function of strain, strain rate and temperature. Models for predicting the evolution of microstructure in die steel during thermomechanical processing was developed in terms of dynamic, static recrystallization and grain growth phenomena. The microstructure model was
combined with rigid visco-plastic finite element modeling to predict microstructure development. Predicted microstructure is consistent with results obtained in multiple compression tests.

For the grain growth evolution, hot compression test carried out the temperature of 950 and 1150°C, and the strain rate of 0.01 and 1.0sec⁻¹. The specimens were compressed 10%, 20% and 30% in height, unloaded and held for holding times at isothermal condition resulting in static and metadynamic recrystallization in specimens.

The softening occurred during the holding time between the first and the second compression was calculated from the experimental result. Predicted grain size and load are consistent with experiment results from double compression test with constant velocity. Therefore, the usefulness of the program is verified.
\( \sigma_p \) : peak stress
\( \sigma_e \) : effective stress
\( \sigma_s \) : steady state stress
\( \bar{\sigma} \) : effective stress
\( \sigma_s' \) : deviatoric stress tensor
\( \varepsilon_p \) : effective strain
\( \varepsilon_e \) : effective strain
\( \bar{\varepsilon} \) : effective strain
\( \dot{\varepsilon}_d \) : strain rate tensor
\( \Delta \sigma \) :
\( \Delta t \) :
\( Z \) : Zener-Hollomon Parameter
\( X_{dyn} \) : dynamic recrystallization volume fraction
\( X \) : static recrystallization volume fraction
\( K \) : penalty function
\( \bar{D} \) : mean grain size
\( d_{rec} \) : recrystallized grain size
\( D_o \) : initial grain size
\( Q \) : activation energy
\( n \) : strain rate sensitivity
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Fig. 34 Distribution of mean grain size after 100sec holding at \( v = 1\text{mm/s}, 1150°C \) and 16.7% compression

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Fig. 36 Distribution of mean grain size after 36.7% second compression at
\( v = 1\text{mm/s}, 1150°C \) and 100sec holding

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\( v = 1\text{mm/s}, 1150°C \) and 600sec holding

Fig. 38 Comparison of experimental and predicted load at \( v = 1\text{mm/s}, 1150°C \) and
600sec holding
1. 

1.1 

The text appears to be in a language other than English, possibly Chinese, discussing various metalworking processes such as casting, open die forging, and upsetting. The text also mentions parameters like temperature (T), strain (ε), stress (σ), and structure (structure).
1.2  

1.2.1  

There are various techniques used to study the recrystallization process (static recrystallization, SRX), (dynamic recrystallization, DRX), (grain growth) [1-15]. These techniques include: [1-15].


1.3 

1.3.1 C-Mn, Mn, Cr, and their effects on the properties [2-11, 17-18, 21] of the material. The effects of these elements on the mechanical properties are well documented in the literature.

1.3.2 The effect of the cooling rate on the microstructure and properties of the material is significant. A cooling rate of 0.01 /s and a transformation temperature of 950-1150°C, with a transformation degree of 10-50%, and a transformation time of 5-600s, will result in a microstructure that is optimal for the material's properties.

1.3.3 The microstructure of the material after the transformation is characterized by a fine-grained and equiaxed structure. The mechanical properties of the material are strongly influenced by the cooling rate, as well as the transformation temperature and time.

1.3.4 The material can be fractionally softened under certain conditions, which is beneficial for its formability and mechanical properties. The fractional softening process is typically achieved by slow cooling or annealing.

- 3 -
2. 채널 구성

2.1 채널 구성 요소

(dislocation) 채널 구성을 통해 지속적으로 다양한 요소를 고려할 수 있습니다. 이러한 요소들은 서로 다른 접근 방식을 통해 이해하고 관리할 수 있습니다. 이러한 접근 방식은 연구와 개발에 있어 매우 중요합니다. 이러한 요소들은 서로 다른 접근 방식을 통해 이해하고 관리할 수 있습니다. 이러한 접근 방식은 연구와 개발에 있어 매우 중요합니다.

2.1.1 채널 구성 요소

채널 구성을 통해 지속적으로 다양한 요소를 고려할 수 있습니다. 이러한 요소들은 서로 다른 접근 방식을 통해 이해하고 관리할 수 있습니다. 이러한 접근 방식은 연구와 개발에 있어 매우 중요합니다. 이러한 요소들은 서로 다른 접근 방식을 통해 이해하고 관리할 수 있습니다. 이러한 접근 방식은 연구와 개발에 있어 매우 중요합니다.
Fig. 1 Course of recrystallization

Fig. 2 Another course of recrystallization
Fig. 2 Flow stress curves in hot forming

2.1.2 Work hardening

The curve shows the work hardening behavior, where the stress increases with strain, followed by a recovery phase and finally a recrystallization phase. (\( \epsilon_c, \rho \))

- 6 -
2.1.3 (stress)

...
2.2 有限要素法

有限要素法（finite element）は、変位の仮定（variational principle）、多重残留法（method of weighted residual）、エネルギー保存則（energy balance approach）を用いて解を求める手法です。

弾性-塑性解析（elastic-plastic analysis）、剛塑性解析（rigid-plastic analysis）、粘塑性解析（viscoplastic analysis）は、それぞれ異なる応力-変形関係を仮定した解析手法です。

(1) ヤングの modulus を用いた方法。
(2) ポアソン比を考慮した方法。
(3) ヤングの modulus を固定した方法。
(4) アンモイセンの Von Mises 信頼性解析。
(5) ヤングの modulus を固定した方法。
\( \nabla \cdot \mathbf{T} = 0 \quad \text{on } S_f \quad \nabla \cdot \mathbf{v} = 0 \quad \text{on } S_v \)

\( (\text{infinitesimal deformation}) \)

\begin{align*}
(\text{i}) & \quad \text{(equilibrium equation)} \\
\sigma_{\psi,i} &= 0 \quad (2.1) \\
(\text{ii}) & \quad \text{(compatibility equation)} \\
\dot{\varepsilon}_i &= \frac{1}{2} (\dot{v}_{i,j} + \dot{v}_{j,i}) \quad (2.2) \\
(\text{iii}) & \quad \text{(constitutive equation)} \\
\sigma_i' &= \frac{2}{3} \frac{\sigma}{\varepsilon} \varepsilon_i' \quad (2.4) \\
\sigma_j' &= \frac{3}{2} \sigma_i' \sigma_j' \quad (2.5) \\
\dot{\varepsilon} &= \sqrt{\frac{2}{3} \varepsilon_i' \varepsilon_j'} \quad (2.6) \\
(\text{iv}) & \quad \text{(boundary condition)} \\
\sigma_i n_j &= T_i \quad \text{on } S_f \quad (2.7) \\
v_i &= U_i \quad \text{on } S_v \quad (2.8) \\
\int_v \sigma_{\psi,i} \delta v_i \, dV &= 0 \quad (2.9)
\end{align*}
\[ \int_v \sigma_y \delta \epsilon_y \, dV - \int_{S_v} T_i \delta v_i \, dS = 0 \]  
(2.10)

\[ \sigma_y = \sigma_y' + \delta \sigma_m \]  
(2.11)

\[ \int_v \sigma_y' \delta \epsilon_y' \, dV + \int_v \sigma_m \delta \epsilon_m \, dV - \int_{S_v} T_i \delta v_i \, dS = 0 \]  
(2.12)

\[ \sigma_y' \delta \epsilon_y' = \frac{\delta \sigma}{\epsilon_y} \]  
(2.13)

\[ \delta \pi = \int_v \frac{\delta \epsilon}{\epsilon} \, dV + K \int_v \delta \epsilon \, dV - \int_{S_v} T_i \delta v_i \, dS = 0 \]  
(2.14)

\[ f = -\frac{2}{\pi} mg \tan^{-1} \frac{|v_s|}{u_o} \]  
(2.15)
\[ t = \frac{1}{v_x} \left[ u + (v + v_D) \right] \] \hspace{1cm} (2.16)

\[ v_s = \sqrt{u^2 + (v + v_D)^2} \] \hspace{1cm} (2.17)
3. \[ \text{chemical analysis} \]

3.1 \[ \text{chemical analysis} \]

3.1.1 \[ \text{chemical analysis} \]

Table 1. Chemical composition of die steel (wt. %)

<table>
<thead>
<tr>
<th>Element</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Ni</th>
<th>Cr</th>
<th>Mo</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composition</td>
<td>0.36</td>
<td>0.26</td>
<td>1.10</td>
<td>0.006</td>
<td>0.003</td>
<td>0.07</td>
<td>1.21</td>
<td>0.26</td>
<td>0.027</td>
</tr>
</tbody>
</table>

Fig. 3 Testing equipment
3.1.2 Method of single compression

- Heating rate: 5°C/second
- Holding time: 3 minutes
- Temperatures: 950°C, 1050°C, 1150°C
- Start times: 0.01/s, 0.1/s, 1.0/s
- Quenching rates: 10%, 20%, 30%
Fig. 5 Experimental method of double compressions
\[ F S = \frac{\sigma_m - \sigma_{s2}}{\sigma_m - \sigma_{s1}} \]  \hspace{1cm} (3.1)
Fig. 6 Initial finite element mesh for the simulation

Fig. 7 Initial finite element mesh for the simulation
Fig. 7 Flow chart for microstructure simulation
4.  

4.1  

4.1.1  

\[ \dot{\varepsilon} = A \cdot \exp ( n' \sigma) \cdot \exp (- \frac{Q}{RT}) \] (exponential law) \hspace{1cm} (4.2)

\[ \dot{\varepsilon} = A' \cdot \exp ( - \frac{Q}{RT}) \] (power law) \hspace{1cm} (4.3)

\[ \dot{\varepsilon} = A \cdot [ \sinh (\alpha \sigma)]'' \cdot \exp (- \frac{Q}{RT}) \] (hyperbolic law) \hspace{1cm} (4.4)

Arrhenius \hspace{1cm} (4.2) \hspace{1cm} n' \hspace{1cm} (4.2)
\[ Z = \xi \exp \left( \frac{Q}{RT} \right) = A \left[ \sinh (\alpha \varphi) \right]^n \tag{4.5} \]

\[ \ln \xi = n \ln \left[ \sinh (\alpha \varphi) \right] + C \tag{4.6} \]

Fig. 8: Graph showing the relationship between \( Z \) and \( \varphi \) for different values of \( n \) and \( \alpha \) at temperatures 950°C, 1050°C, and 1150°C. Fig. 9: Graph showing the relationship between \( \xi \) and \( \varphi \) at different values of \( n \) and \( \alpha \).
Fig. 8 Stress vs Strain rate at various temperature by hyperbolic law

Fig. 9 Strain dependence of strain rate sensibility (n)
\[ \ln \left[ \sinh (\alpha \sigma) \right] = \frac{1}{T} \sum \left\{ \ln A + n \ln \left[ \sinh (\alpha \sigma) \right] = \ln \dot{\varepsilon} + \frac{Q}{nR} T \right\} \sum \left\{ \ln \left[ \sinh (\alpha \sigma) \right] = \frac{Q}{nR} T \right\} + C \left( \right) \cdot \text{Fig. 10} \]

\[ \alpha, n, R \] \text{Fig. 10}. Q=330(kJ/mole) \text{C-Mn} \text{Sellars}[1]. 312(kJ/mole) \text{C-Mn} \text{Sellars}[1].

\[ Q = 330(kJ/mole) \text{C-Mn} \text{Sellars}[1]. 312(kJ/mole) C-Mn \text{Sellars}[1]. \]

\[ \dot{\varepsilon} = 6.956 \times 10^{11} [\sinh (0.012 \sigma)]^{0.046} \exp \left( - \frac{Q}{R} \right) \left( 0.01 \leq \dot{\varepsilon} \leq 1.0 \right) \text{Fig. 12}. \]

\[ \text{Fig. 11}. \text{Fig. 12}. n = 4.041 \text{Fig. 11}. n = 4.046 \text{Fig. 12}. (4.7) \text{Fig. 10}. \text{Fig. 12}. \]
Fig. 10 \( \sinh(\alpha \sigma) \) vs temperature at various strain rate

Fig. 11 Strain dependence of activation energy (Q)
Fig. 12 Dependence of sinh(ασ) on Zener-Hollomon parameter

4.1.2

\[ \sigma = \sigma_c - \Delta\sigma \]  
\[ \sigma_c = \sigma_p\left[1 - \exp\left(-C\varepsilon\right)\right]^m \quad (\varepsilon < \varepsilon_p) \]  
\[ \Delta\sigma = \left(\sigma_p - \sigma_v\right)\left[1 - \exp\left(-k\left(\frac{\varepsilon - \varepsilon_{p}}{\varepsilon_p}\right)^m\right)\right] \quad (\varepsilon > \varepsilon_p) \]  

Fig. 13  \[ \sigma_c, \Delta\sigma \]  

\[ (4.11) \]  
\[ \varepsilon_p, \varepsilon_{p}, \sigma_v \]  

[6].
\[
\sigma = \sigma_p \left[ 1 - \exp \left( - C \varepsilon \right) \right]^n - (\sigma_p - \sigma) \left[ 1 - \exp \left( - k \frac{\varepsilon - \alpha \varepsilon_p}{\varepsilon_p} \right) \right]^n \]
(4.11)

Fig. 13 Schematic view of the effect on dynamic softening

\[
C = 15.83 \varepsilon^{-0.2248} \exp \left( - \frac{0.0277 Q}{RT} \right) \tag{4.12}
\]

\[
m = 0.478 \varepsilon^{-0.0449} \exp \left( - \frac{0.00871Q}{RT} \right) \tag{4.13}
\]

\[
k = 0.93 + 0.136 \left( \frac{Z}{A} \right) \tag{4.14}
\]
\[ m' = 0.202 \varepsilon^{0.174} \exp\left(\frac{-0.0955 Q}{RT}\right) \quad (4.15) \]

\[ \varepsilon_p = 0.07 \varepsilon^{0.176} \exp\left(\frac{-0.0513 Q}{RT}\right) \quad (4.16) \]

\[ \varepsilon_\tau = 0.8 \varepsilon_p \]

\[ \sigma_p = 0.66 \varepsilon^{0.367} \exp\left(-5.618 \varepsilon_p\right) \exp\left(\frac{0.234 Q}{RT}\right) \quad (4.17) \]

\[ \sigma_t = 67.3 + 13.35 \ln\left(\frac{Z}{A}\right) + 0.92\left(\ln\left(\frac{Z}{A}\right)\right)^2 \quad (4.18) \]

---

Fig. 14 Experimental and predicted flow curves \[ \dot{\varepsilon}=0.01/s \]
Fig. 15 Experimental and predicted flow curves for $\dot{\varepsilon}=0.1/s$

Fig. 16 Experimental and predicted flow curves for $\dot{\varepsilon}=1.0/s$
4.1.3 \( X_{dy,n} \) and \( d_{ref} \)

\[ X_{dy,n} = \left[ 1 - \exp(-k\frac{\varepsilon - \varepsilon_{c}}{\varepsilon_{c}})^{m'} \right] \]  \hspace{1cm} (4.19)

\[ k = 0.654 + 0.146 \ln \left( \frac{Z}{A} \right) \]  \hspace{1cm} (4.20)

\[ m' = 1.4737 - 0.1107 \ln \left( \frac{Z}{A} \right) \]  \hspace{1cm} (4.21)

\[ d_{ref} = 1.2 \times 10^{4}Z^{-0.21} \]  \hspace{1cm} (4.22)

\[ D = \sqrt{\frac{D_{o}^{2}d_{ref}^{2}}{D_{o}^{2}X_{dy,n}^{2} + d_{ref}^{2}(1 - X_{dy,n})^{2}}} \]  \hspace{1cm} (4.23)
\[ X = 1 - \exp \left[ - \ln 2 \cdot \left( \frac{t}{t_{0.5}} \right)^2 \right] \]  
\[ t_{0.5} = 2.5 \cdot 10^{-19} d_{ini}^{-2} \varepsilon^{-4} \exp \left( \frac{-300000}{RT} \right) \quad \varepsilon \leq 0.8 \varepsilon_p \]  
\[ t_{0.5} = 1.06 \cdot 10^{-5} Z^{-0.6} \exp \left( \frac{-300000}{RT} \right) \quad \varepsilon \geq 0.8 \varepsilon_p \]  

\[ d_{\text{rel}} = 0.5 d_{ini}^{0.67} \varepsilon^{-1} \quad (\varepsilon \leq \varepsilon^*) \]  
\[ d_{\text{rel}} = 1.8 \cdot 10^{-5} Z^{-0.15} (\mu m) \quad (\varepsilon \geq \varepsilon^*) \]  
\[ \varepsilon^* = 0.57 d_{ini}^{0.17} \varepsilon_p \]  

\[ d^{10} = d_{\text{rel}}^{10} + 5.02 \cdot 10^{53} t \exp \left( \frac{-914000}{RT} \right), \quad T \leq 1273 (K) \]  
\[ d^{10} = d_{\text{rel}}^{10} + 3.87 \cdot 10^{32} t \exp \left( \frac{-400000}{RT} \right), \quad T \geq 1273 (K) \]  

Sellars[2] C-Mn 

\[ \text{Sellars}[2]\]  

[13]
\[
\bar{D}^3 = D_o^3 + 1.8 \cdot 10^{16} t \exp\left(-\frac{Q}{RT}\right)
\]  

(4.31)

Fig. 17 Experimental and predicted grain growth curves at 950°C and 1150°C

4.2

4.2.1

(Photos 1–6). Photo 1
Photo 4. Photo 3. Photo 6. Photo 4~6. Photo 4. Microstructure of 50% compressed specimen at 950°C and $\dot{\varepsilon}=0.01$ s$^{-1}$.
Photo 2 Microstructure of 50% compressed specimen at 1050°C and $\dot{\varepsilon}=0.1/s$

Photo 3 Microstructure of 50% compressed specimen at 1150°C and $\dot{\varepsilon}=0.1/s$
Photo 4 Microstructure of 50% compressed specimen at 950°C and $\dot{\varepsilon} = 1.0/s$

Photo 5 Microstructure of 50% compressed specimen at 1050°C and $\dot{\varepsilon} = 1.0/s$
Photo 6 Microstructure of 50% compressed specimen at 1150°C and $\dot{\varepsilon} = 1.0 \text{s}^{-1}$.

Fig. 18–20
Fig. 18 Comparison of flow curves at $\dot{\varepsilon}=0.01$/s

Fig. 19 Comparison of flow curves at $\dot{\varepsilon}=0.1$/s
Fig. 20 Comparison of flow curves at $\dot{\varepsilon}=1.0/\text{s}$

Photo 7 Microstructure of 50% compressed casting specimen at 1050°C and $\dot{\varepsilon}=1.0/\text{s}$
Photo 8 Microstructure of 50% compressed casting specimen at 1150°C and 
\[ \dot{\varepsilon} = 1.0 \text{s} \] 

4.2.2 \[ \text{Photo 9 ~ 16} \] 

3.1.2 \[ \text{Photo 9 ~ 12} \] 950°C, \[ \dot{\varepsilon} = 1.0 \text{s}, \] 20%
Photo 9 Microstructure of 20% compressed specimen at 950°C, $\dot{\varepsilon}=1.0/\text{s}$ and 5sec holding
Photo 10 Microstructure of 20% compressed specimen at 950°C, $\dot{\varepsilon}=1.0/s$ and 10sec holding

Photo 11 Microstructure of 20% compressed specimen at 950°C, $\dot{\varepsilon}=1.0/s$ and 100sec holding
Photo 12 Microstructure of 20% compressed specimen at 950°C, $\dot{\varepsilon}=1.0\text{s}$ and 600sec holding

Photo 13 Microstructure of 20% compressed specimen at 1150°C, $\dot{\varepsilon}=1.0\text{s}$ and 5sec holding
Photo 14 Microstructure of 20% compressed specimen at 1150°C, $\dot{\varepsilon}$=1.0/s and 20sec holding

Photo 15 Microstructure of 20% compressed specimen at 1150°C, $\dot{\varepsilon}$=1.0/s and 100sec holding
Photo 16 Microstructure of 20% compressed specimen at 1150°C, $\dot{\varepsilon}=1.0\,\text{s}^{-1}$ and 600sec holding

4.2.3  

3.1.3  

Fig. 21- (a)  

Fig. 21- (b)  

Fig. 22- (a), (b)  

950°C  

- 41 -
Fig. 23- (a), (b) 1150°C 2 εₚ, εₚ

Fig. 24- (a), (b) 1150°C 0.53 εₚ, εₚ

Fig. 25- (a), (b) 1150°C 0.53 εₚ, εₚ

Fig. 26- (a), (b) 950°C 100%

Fig. 27- (a), (b) 1150°C

Fig. 28- (a), (b) 1150°C

Fig. 29- (a), (b) 1150°C
Fig. 21 Flow curves obtained from interrupted compression test at $\dot{\varepsilon}=0.01$/s, 950°C and (a) 10% compression (b) 20% compression
Fig. 22 Flow curves obtained from interrupted compression test at $\dot{\varepsilon}=0.1$/s, 950°C and (a) 10% compression (b) 20% compression
Fig. 23 Flow curves obtained from interrupted compression test at $\dot{\varepsilon}=0.01$/s, 1150°C and (a) 10% compression (b) 20% compression
Fig. 24 Flow curves obtained from interrupted compression test at $\dot{\varepsilon}=0.1/s$, 1150°C and (a) 10% compression (b) 20% compression
Fig. 25 Flow curves obtained from interrupted compression test at $v=1\text{mm/s}$ and (a) 950$^\circ$C (b) 1150$^\circ$C
Fig. 26 Strain effect on the rate of softening at 950°C and (a) $\dot{\varepsilon}=0.01$/s
(b) $\dot{\varepsilon}=0.1$/s
Fig. 27 Strain effect on the rate of softening at 1150°C and (a) $\dot{\varepsilon}=0.01/s$
(b) $\dot{\varepsilon}=0.1/s$
Fig. 28 Strain rate effect on the rate of softening at (a) 950°C (b) 1150°C
Fig. 29 Temperature effect on the rate of softening at (a) $\dot{\varepsilon}=0.01/\text{s}$ (b) $\dot{\varepsilon}=0.1/\text{s}$
4.3 ハウスの温度環境

Fig. 5

2mm/s, 1150°C, 16.7% 

Photo 17, 18

Photo 17, 18

Photo 17, 18

Photo 17, 18

Fig. 31

Fig. 32

Fig. 33

Fig. 34
Fig. 30 Diagram for each microstructure photographic point

point 1
point 7

Photo 17 Microstructure of the second compression at \( v = 1 \text{mm/s} \), \( 1150^\circ \text{C} \)
and 100s holding

- 56 -
point 1

point 2

- 57 -
point 7

Photo 18 Microstructure of the second compression at $v=1\text{mm/s}$, $1150^\circ\text{C}$ and 600s holding
Fig. 31 Mean grain size from simulation result at \( v=1\text{mm/s}, 1150^\circ\text{C} \) and 
(a) 100sec holding (b) 600sec holding
Fig. 32 Comparison of grain size between experimental and predicted results at $v=1\text{mm/s}$, $1150^\circ\text{C}$ and (a) axial direction (b) radial direction
Fig. 33 Distribution of mean grain size after 16.7% second compression at \( v=1\text{mm/s}, 1150^\circ\text{C} \)

Fig. 34 Distribution of mean grain size after 100sec holding at \( v=1\text{mm/s}, 1150^\circ\text{C} \) and 16.7% compression
Fig. 35 Distribution of mean grain size after 600 sec holding at \( v=1 \text{mm/s}, 1150^\circ\text{C} \) and 16.7\% compression.

Fig. 36 Distribution of mean grain size after 36.7\% second compression at \( v=1 \text{mm/s}, 1150^\circ\text{C} \) and 100 sec holding.
Fig. 37 Distribution of mean grain size after 36.7% second compression at \( v = 1 \text{mm/s}, 1150^\circ\text{C} \) and 600sec holding

Fig. 38 Comparison of experimental and predicted load at \( v = 1 \text{mm/s}, 1150^\circ\text{C} \) and 600sec holding
5.  

(1)  

\[ \sigma = \sigma_0 \left[ 1 - \exp \left( - C \epsilon \right) \right]^n - (\sigma_0 - \sigma_t) \left[ 1 - \exp \left( - k \left( \frac{\epsilon - \alpha \epsilon_s}{\epsilon_p} \right)^m \right) \right] \]

(2)  

\[ d_{ref} = 1.2 \times 10^4 Z^{-0.21} \]

\[ D^3 = D_0^3 + 1.8 \times 10^{16} t \exp \left( - \frac{Q}{R T} \right) \]

(3)  

\[ \text{Zener-Hollomon の} \]

(4)  

\[ \text{Zener-Hollomon の} \]
(5) 2
(6) 3
(7) 4


