Flow Stresses during Hot Deformation of Three Different Steels (C-Mn, Nb-Ti, Nb) and Ni Base Superalloys

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Using the Gleeble 1500, incremental and continuous hot compression straining tests were performed on C-Mn, Nb-Ti and Nb steels with test temperatures varying between 875 and 1100°C; strain rates between 0.5 and 20 s⁻¹. Maximum stresses obtained varied from 150 MPa for Nb-Ti at 1100°C to 330 MPa for C-Mn steel at 875°C. For comparison with hot compression tests, actual rolling was carried out on Hille reversible rolling mill on Ni₈₀Cr₂₀ and Ni₇₈Cr₁₆Fe₆ superalloys. The rolling reduction per pass was 10 and 30% at the predetermined rolling temperatures. The results indicate non-linearity relationship between rolling stresses and rolling temperatures, with rolling stresses increasing more sharply with decreasing rolling temperatures below 900°C. The highest rolling stress of 696 MPa was obtained for Ni₈₀Cr₂₀ at a temperature of 395°C for 10% reduction per pass. The relationship was observed to be linear for steels.

Existing and proposed stress peak models were applied to the experimental results in order to predict multistage flow stress curves from experimental single stage flow stress curves and vice versa. The results indicate fair accuracy of both the existing and proposed models. The stress restoration index k obtained from proposed stress peak model was found to be constant and unique to particular sets of experimental conditions.

Because of the peculiar differences in the cooling properties of steels and superalloys during rolling, the existing and proposed models were also applied to the experimental results obtained from rolling superalloys. The proposed stress peak model indicates fair accuracy in predicting the single stage curve from the multistage curve and vice versa. The existing models showed less accuracy as the rolling temperature dropped below 900°C. Stress strain equation constants have been obtained for single stage deformation of nickel-based superalloys.

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I. Introduction

Hot rolling involves deformation in predetermined strain increments with short time intervals between each strain increment during which some recovery and recrystallization occurs and the subsequent yield stress level is reduced. To calculate or predict the forming force and power under these conditions, it is necessary to know the yield characteristics for incremental straining. If the strain increments are small in relation to the strain hardening range of the corresponding continuous straining curve, the stress level achieved can vary widely depending on strain rate, temperature and holding time between strain increments. During the holding times, whether or not recrystallization is full or partial, influences considerably the shape of the overall flow stress-strain curves. Knowledge of the σ - ϵ curve is important in the evaluation of loads and stresses for hot working operations, which is, in turn, a prerequisite for control of dimensions and the shape of the worked product.

Resultant forming forces are as a result of the contributive effects of strain hardening on one hand and thermally activated softening processes of recovery, recrystallization and grain growth on the other, during holding times. Many investigations have been made employing incremental straining techniques in metallurgical studies of restoration processes, mainly in con-

nection with structure control in hot rolling. The use of the hot torsion test for such work has been described by Rossard and Blain⁽¹⁾, Vaughan⁽²⁾, Farag *et al.*⁽³⁾, and investigations using a cam plastometer for the two-stage compression tests have been reported by Evans and Dunstan⁽⁴⁾.

Computer-controlled hydraulic testing machines have been developed for simulating deformation in hot rolling schedules, as described by Kaspar and Rawelski⁽⁵⁾. Recently, models for calculating, flow stresses during incremental deformation from continuous flow curves, for austenitic stainless steel, have been reported by Roberts⁽⁶⁾.

In the present work, flow stresses have been predicted using the proposed stress peak model and newly constituted empirical equations; and prediction is also made using the theoretical models in Robert's paper⁽⁶⁾. The predicted or calculated flow stresses have been compared with the experimentally obtained test results. Because of the peculiar cooling properties of nickel-based superalloys, both the existing and proposed models have been applied to the hot rolling results obtained for these superalloys and compared with model application in steel deformation.

II. Experimental

Specimens of 3 different steels; Nb-Ti, Nb and Plain carbon (C-Mn) steels, were machined to length 30 mm

and diameter 8 mm for the tests. They were then heated and subjected to 2- and 5-stage hot compression tests at temperatures between 875 and 1100°C with strain rates $\dot{\epsilon}$ varied between 0.5 and 20 s⁻¹. Strain ϵ increment for the 2-stage compression test was 0.3 for each stage while for the 5-stage test, it was 0.12. Holding times were varied between 0.5 and 30 s. Tests were carried out on the Gleeble 1500, a computer controlled machine capable of performing diverse thermo-mechanical tests and simulations, under vacuum conditions. Gleeble Computer programmes to effect 2- and 5-stage compression tests were developed, filed and used to carry out the tests. A 1-stage compression programme was also developed to obtain continuous stress-strain curves for comparison with the stress-strain curves of the 2- and 5-stage compression tests. Tests were often repeated and found to give the same results showing the accuracy of the Gleeble. During testing, force, holding times, and lengthwise strain measurements were automatically recorded and stored in the computer. These were retrieved after each test through the computer plotter system in the form of force-strain diagrams. Specimens were allowed to cool to room temperature at the rate of 40°C/s after tests. In addition, two superalloys Ni₈₀Cr₂₀ and Ni₇₈Cr₁₆Fe₆ were also hot rolled in five passes using a reversible Hille rolling mill at the predetermined rolling temperatures with 10 s holding time between passes. Reduction per pass was 10 and 30% at the predetermined rolling temperatures. Compositions of the Nb-Ti, Nb and C-Mn steels and the two superalloys are presented in Table 1. Summary of experimental results are presented in Tables 2-8.

III. Discussions

1. Single stage flow curves

With high deformation temperatures and deformation strains up to 0.90, the 1-stage compression test in the present work satisfies condition for the occurrence of dynamic recrystallization. Models exist to predict flow curves during such single stage deformation⁽⁶⁾⁻⁽⁸⁾. In cases where dynamic recrystallization contributes to softening, Roberts⁽⁶⁾ proposed the following equations to predict flow stress strain curves during hot working:

$$\sigma = C_1 \epsilon^p \quad \text{where } \epsilon < \epsilon_c \quad (1)$$

and

$$\sigma = C_1 \epsilon^p - C_2 \{1 - \exp[-K(\epsilon - \epsilon_c)^n]\} \quad \text{where } \epsilon > \epsilon_c \quad (2)$$

i.e. normal power-law hardening combined with a softening contribution when $\epsilon > \epsilon_c$ which is proportional to the extent of dynamic recrystallization. Experimental single stage compression test results have been drawn in Fig. 1 for Nb-Ti steel. Equations (1) and (2) combined have been used to calculate several stress points for increasing strain and points have been superimposed on the experimental curve (Fig. 1). Equations (1) and (2) combined appear to afford a very good fit up to strain 0.8. Calculated values of C_1 , C_2 , p , K , ϵ_c and n have been shown in the Figure. The test temperature and the strain rate were 875°C and 12.0 s⁻¹ respectively.

2. Multi-step flow curves

For practical evaluation of load/stress requirements for hot working, it is of interest to develop procedures whereby multi-step stress-strain curves can be calculated from single-step behaviour and *vice versa*.

(1) Stress peak model

In the present work, one such model is being proposed to enable single step flow curves to be obtained from multi-step flow curves. It is proposed that the maximum height of the second stress-strain increment be related to a corresponding point on the continuous curve by a stress restoration index (k). The procedure is shown in Fig. 2. 1-stage compression test is represented by the continuous curve OABC. The 2-stage incremental test, for example, is represented by OAD and DEF. OD and DF are equal strain increments. The difference between the peak stress of the second increment (DEF) at E and the corresponding point B on the continuous curve is represented by σ_a . σ_a is the stress reduction due to recovery and recrystallization during holding time. σ_b is the difference between the peak stress at E and peak stress (σ_0) of the first increment (OAD) at A. The stress restoration index is given by:

$$k = \left(\frac{\sigma_a}{\sigma_a + \sigma_b} \right) \quad (3)$$

The value of k can thus be determined for the first pair of strain increments. New values of σ_a and σ_b , hence k can also be determined for the 2nd and 3rd strain increments, (with σ_0 now being the peak stress of 2nd increment), the 3rd and 4th increments and so on. If the value of k remains reasonably constant for succeeding pairs of strain increments, it should be possible to predict continuous stress-strain curves from incremental stress-strain curves. Once the value of k is known, σ_b can be obtained for

Table 1

(a) Composition of steels.

Steel designation	Mass percentage									
	C	Si	Mn	P	S	V	Ti	Nb	Cr	Mo
Nb-Ti	0.084	0.23	1.4	0.013	0.002	0.006	0.018	0.031	0.018	0.006
C-Mn	0.18	0.2	0.8	0.04	0.045	0.09	—	—	—	—
Nb	0.081	0.26	1.43	0.014	0.003	0.009	0.003	0.030	0.021	0.003

(b) Super alloys Ni₈₀Cr₂₀ and Ni₇₈Cr₁₆Fe₆

Table 2 Summary of results of continuous or 1-stage compression tests.

Temp. (°C)	Strain rate $\dot{\epsilon}$ (s ⁻¹)	Stress values at $\epsilon=0.3, 0.6$ and 0.9								
		Nb-Ti			C-Mn			Nb		
		$\epsilon=0.3$	$\epsilon=0.6$	$\epsilon=0.9$	$\epsilon=0.3$	$\epsilon=0.6$	$\epsilon=0.9$	$\epsilon=0.3$	$\epsilon=0.6$	$\epsilon=0.9$
875	1.0	220	205	190	263	240	210	212	194	185
	9.5	260	244	200	318	296	267	230	233	228
	12.0	262	255	230	324	330	288	245	244	234
950	9.5	235	223	195	265	259	231	224	209	200
	12.0	243	237	200	270	262	240	220	216	190
	20.0	245	230	199	268	287	271	225	224	214

Table 3 Summary of results of '2-stage' compression tests.

Temp. (°C)	Strain rate $\dot{\epsilon}$ (s ⁻¹)	Holding time (s)	Peak stresses (MPa)					
			Nb-Ti		C-Mn		Nb	
			$\epsilon=0.3$	$\epsilon=0.6$	$\epsilon=0.3$	$\epsilon=0.6$	$\epsilon=0.3$	$\epsilon=0.6$
875	1.0	0.5	220	192	264	240	212	183
		0.5	258	239	315	290	224	209
	9.5	1.0	262	222	321	258	235	221
		0.5	258	243	326	296	238	229
	12.0	1.0	257	223	322	255	245	215
		3.0	262	207	322	252	242	203
		10.0	267	218	326	254	252	210
		30.0	263	220	324	253	248	210
	9.5	0.5	235	229	264	239	225	215
		1.0	237	209	273	219	222	199
		3.0	236	186	265	213	224	184
		10.0	251	207	271	210	226	199
950	12.0	0.5	242	214	268	239	215	205
		1.0	241	202	279	222	219	196
		3.0	239	187	268	210	214	184
		10.0	252	203	274	214	229	189
		30.0	246	204	271	210	228	189
	20.0	1.0	236	205	264	223	227	200
		3.0	245	202	270	210	226	189
		10.0	248	204	270	211	220	190

Table 4 Summary of results of '5-stage' compression tests.

Temp. (°C)	Strain rate $\dot{\epsilon}$ (s ⁻¹)	Holding time (s)	Peak stresses (MPa)														
			Nb-Ti					C-Mn					Nb				
			$\epsilon=0.12$	$\epsilon=0.24$	$\epsilon=0.36$	$\epsilon=0.48$	$\epsilon=0.60$	$\epsilon=0.12$	$\epsilon=0.24$	$\epsilon=0.36$	$\epsilon=0.48$	$\epsilon=0.60$	$\epsilon=0.12$	$\epsilon=0.24$	$\epsilon=0.36$	$\epsilon=0.48$	$\epsilon=0.60$
1100	0.5	2.0	110	122	114	105	99	120	131	121	100	92	103	112	100	88	82
1100	3.0	2.0	126	148	138	124	121	140	152	135	115	106	120	139	126	112	110

2nd, 3rd, etc. strain increments from incremental stress-strain curves. σ_a values can then be calculated for 2nd, 3rd, etc. strain increments from eq. (3), hence points are plotted to correspond to the continuous stress-strain curve of the material.

The variation of stress restoration index is plotted against the testing temperature for incremental tests

strain rates of 3–20 s⁻¹ in Fig. 3. The results indicate negligible variation in k with incremental or cumulative strain.

The model has been applied to incremental tests obtained for Nb-Ti steel, $\dot{\epsilon}=3$ s⁻¹, $H.T.=2$ s, $T=1100^\circ\text{C}$ and the resultant continuous or 1-stage flow stress curve obtained shown in Fig. 4. Stress restoration index k was

Table 5 Dependence of rolling stresses on strain and rolling temperatures for $\text{Ni}_{80}\text{Cr}_{20}$. (10% reduction per pass)

Temp. (°C)	Strain ϵ	($\bar{\sigma}$) Rolling stresses (Calculated using Sim's equation ⁽⁹⁾) $\text{Ni}_{80}\text{Cr}_{20}$
982	0.1	256
759	0.18	373
664	0.26	418
494	0.34	556
395	0.41	696

Table 6 Dependence of rolling stresses on strain and rolling temperatures for $\text{Ni}_{78}\text{Cr}_{16}\text{Fe}_6$. (10% reduction per pass)

Temp. (°C)	Strain ϵ	Rolling stresses (Calculated using Sim's equation ⁽⁹⁾) (MPa) ($\bar{\sigma}$) $\text{Ni}_{78}\text{Cr}_{16}\text{Fe}_6$
982	0.1	404
759	0.18	334
664	0.26	470
588	0.34	520
518	0.41	560

Table 7 Dependence of rolling stresses on strain and rolling temperatures for $\text{Ni}_{80}\text{Cr}_{20}$. (30% reduction per pass)

Temp. (°C)	Strain ϵ	Rolling stresses (Calculated using Sim's equation ⁽⁹⁾) (MPa) ($\bar{\sigma}$) $\text{Ni}_{80}\text{Cr}_{20}$
1035	0.26	263
800	0.47	461
701	0.64	557

Table 8 Dependence of rolling stresses on strain and rolling temperatures for $\text{Ni}_{78}\text{Cr}_{16}\text{Fe}_6$. (30% reduction per pass)

Temp. (°C)	Strain ϵ	Rolling stresses (Calculated using Sim's equation ⁽⁹⁾) (MPa) ($\bar{\sigma}$) $\text{Ni}_{78}\text{Cr}_{16}\text{Fe}_6$
1070	0.26	240
881	0.47	408
778	0.64	510
683	0.80	672

found to be approximately constant at 0.429.

(2)

Other workers have also proposed models that predict multistep flow curves from single step ones. It should be noted that stress-strain response in multistage deformation is controlled to a great extent by the degree of softening during holding times. Static recovery proceeds simultaneously with recrystallization and strain is concentrated to the softer recrystallized regions⁽⁶⁾.

Barracough and Sellers⁽⁷⁾ have presented a description for multi-step flow which is based on softening derived from flow heterogeneity in partially recrystallized material. For a two-step test, the applied strain rate is transmitted via a faster deformation of recrystallized

Fig. 1 Experimental and calculated (eqs. (1) and (2)) flow stresses against strain for Nb-Ti steel. $T=875^\circ\text{C}$, $\dot{\epsilon}=12\text{ s}^{-1}$. Fig. 2 Incremental σ - ϵ curve prepared for measuring stress restoration Index k .

× : Nb-Ti, $\dot{\epsilon}=3\text{ s}^{-1}$, $\epsilon=0.12$ per increment
 ○ : C-Mn, $\dot{\epsilon}=20\text{ s}^{-1}$, $\epsilon=0.2$ per increment
 △ : Nb steel, $\dot{\epsilon}=12\text{ s}^{-1}$, $\epsilon=0.2$ per increment

Fig. 3 Variation of stress restoration index k with testing temperatures.

regions and slower straining in unrecrystallized material, i.e.

$$\bar{\epsilon} = \dot{\epsilon}_R X + \dot{\epsilon}_u (1 - X) \quad (4a)$$

If the strain rates in recrystallized and unrecrystallized material are related to flow stress through Robert's equation⁽⁶⁾,

Fig. 4 Continuous σ - ϵ curve obtained from the actual incremental curve for Nb-Ti steel, $\dot{\epsilon}=3 \text{ s}^{-1}$, $H.T.=2 \text{ s}$, $T=1100^\circ\text{C}$. k value=0.429.

$$\dot{\epsilon} = J \sigma_s^m \quad (4b)$$

then the average flow stress is given, for a 2-stage test, by

$$\frac{1}{(\bar{\sigma})^m} = \frac{X}{(\sigma_R)^m} + \frac{1-X}{(\sigma_u)^m} \quad (4c)$$

where X is the statically recrystallized fraction, m a constant of the material, σ_R is the yield stress of the first increment and σ_u the peak stress of the first increment at the point of unloading.

The experimental multistage stress-strain curve for Nb steel $\dot{\epsilon}=12 \text{ s}^{-1}$, $T=875^\circ\text{C}$ and 10 s holding time is shown in Fig. 5. Equation (4c) has been used to calculate varying mean flow stresses for varying strain for the 2nd strain increment and these points have been superimposed on the experimental curve in Fig. 5. Calculated points appear to fit in with the profile of the experimentally obtained curve. X was determined experimentally for the calculations and the value was 0.144. High accuracy of X is essential for accurate utilization of eq. (4c). Roberts⁽⁶⁾ also proposed a similar model for predicting the 2nd strain increment of a 2-stage deformation test based on static recovery. Recovery in unrecrystallized areas reduces the retained strain from ϵ_1 , the pass strain in the first step, to $\epsilon_{\text{eff},1}$:

$$\epsilon_{\text{eff},1} = \frac{\epsilon_1}{2M\tau\psi t\epsilon_1 + 1}, \quad (5)$$

where τ is the dislocation line Energy, M a dislocation mobility, ψ the ratio of the dislocation density ρ_0 and current strain ϵ , and t is the holding time between passes.

The flow stress at any strain ϵ during the second pass is given by:

$$\bar{\sigma}(\epsilon) = X \cdot \sigma_R(\epsilon) + (1-X) \cdot \sigma_u(\epsilon + \epsilon_{\text{eff},1}) \quad (6)$$

X , σ_R and σ_u have the same definition as for eq. (4c).

Experimental multistage stress-strain curve for Nb steel, $T=875^\circ\text{C}$, $H.T.=10 \text{ s}$, $\dot{\epsilon}=12 \text{ s}^{-1}$ has been shown in Fig. 6. Equation 6 has been used to calculate varying

$$\sigma_R = \sigma_0 = 130 \text{ MPa}, \quad \sigma_u = \sigma_1 = 252 \text{ MPa},$$

$$\times \text{ determined experimentally} = 0.144, \quad m = 5.5$$

Fig. 5 Comparison of calculated and experimental flow stresses during 2nd stage of a 2-stage compression test on Nb steel, $\dot{\epsilon}=12 \text{ s}^{-1}$, $T=875^\circ\text{C}$, $H.T.=10 \text{ s}$ using eq. (4c).

mean flow stresses for varying strains for the 2nd strain increment and these points have been superimposed on the experimental curve in Fig. 6. The points appear to fit in with 2nd stage experimental curve although slight variations could be attributed to values of M , τ , ψ and X obtained experimentally.

3. Nickel-based superalloys

Nickel-based superalloys are reactive metals that possess much higher compressive stresses at high temperatures than alloy steels. Hence their common use in high temperature service environments in the electrical and aeronautical industries. The relationship between rolling or compressive stresses and rolling temperatures is non-linear with rolling stresses increasing more sharply with decreasing rolling temperatures below 900°C . This is in contrast to steels which possess a linear relationship between rolling stresses and decreasing rolling temperatures (No reheating between passes). Because of the peculiar cooling properties during rolling of these superalloys, it is necessary to re-examine the applicability of the models earlier discussed in the present work to these superalloys.

Experimentally obtained rolling stresses dependence on temperature and strain has been presented in Fig. 7, for $\text{Ni}_{78}\text{Cr}_{16}\text{Fe}_6$ (10% reduction per pass). Stress peak model (eq. (3)) has been applied to this incremental curve, and the continuous curve (indicated in Fig. 7) has been obtained. The approximate constant value of stress restoration index k was 0.75. The model appears to apply equally well to the steels and superalloys. Stress-strain equation for the continuous straining curve obtained using the stress peak model (Fig. 7) fits in well with Inouye's Equation $\sigma = \sigma_0 \dot{\epsilon}^n \exp(A/TK)$ assuming constant experimental strain rate⁽⁸⁾. From Fig. 7, for $\text{Ni}_{78}\text{Cr}_{16}\text{Fe}_6$, $n=0.4$, $\sigma_0=300 \text{ MPa}$ and $A/TK=2.05$.

Experimentally obtained rolling stresses dependence on temperatures and strains for $\text{Ni}_{80}\text{Cr}_{20}$ (30% reduction

Nb steel, $\sigma_R = \sigma_0 = 130$ MPa, $\sigma_u = \sigma_1 = 252$ MPa,
 $\times = 0.144$, $\epsilon_{eff} = 0.145$

Fig. 6 Comparison of calculated and experimental flow stresses during 2nd stage of a 2-stage compression test on Nb steel, $\dot{\epsilon} = 12 \text{ s}^{-1}$, $T = 875^\circ\text{C}$, $H.T. = 10 \text{ s}$ using eq. (6).

per pass) is also presented in Fig. 8. Barraclough and Seller's Model (eq. (4c)) has been used to calculate varying mean flow stresses for varying strain (for 2nd and 3rd strain increments) and these points have been superimposed on the experimental curve in Fig. 8. X was obtained experimentally as 0.075. Calculated points deviated from the experimental curves mainly because of the cooling and hardening effect of the superalloy as an isothermal condition was not possible during rolling and no reheating was involved.

IV. Conclusions

(1) To ensure wider acceptability of model analysis, variations in temperature ($875\text{--}1100^\circ\text{C}$), strain rate ($0.5\text{--}20 \text{ s}^{-1}$), Holding time ($0.5\text{--}30 \text{ s}$) and strain increments (0.12 to 0.3) have been carefully chosen to reflect actual conditions during typical hot working processes *e.g.* open die forging, plate and strip rolling.

(2) Negligible variation in the stress restoration index

Fig. 7 Dependence of rolling stresses on temperature and strain for $\text{Ni}_{78}\text{Cr}_{16}\text{Fe}_6$ (10% reduction per pass). (10 s holding time between passes).

Fig. 8 Dependence of rolling stresses on temperature and strain for $\text{Ni}_{80}\text{Cr}_{20}$ (30% reduction per pass). (10 s holding time between passes).

ensures that accurate prediction of the continuous σ - ϵ curve from the incremental σ - ϵ curve and *vice versa* can be obtained.

(3) Predictions from models may serve as a basis for more accurate calculations of load/stress requirements for hot working, which in turn are a prerequisite for the improved process control in industrial plants.

(4) Rolling stresses encountered during deformation of superalloys are much higher than those of steels and using models to predict in advance such high rolling stresses will help to predict safe working loads.

(5) In view of the wide ranging process parameters (σ , T , ϵ , $\dot{\epsilon}$) involved in the present work, continuous σ - ϵ equation for steels, could best be described by Inouye's equation⁽⁸⁾ of the form:

$\sigma = \sigma_0 \epsilon^n \dot{\epsilon}^m \exp(A/TK)$ where σ_0 , n , m , A and K are constants.

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REFERENCES

- (1) C. Rossard and P. Blain: Flat rolled products, Metals Soc. Conf. A.I.M.E. **16** (1962), 3.
- (2) T. V. Vaughan: Special Report 108, Iron and Steel Institute, (1968).
- (3) M. M. Farag, C. M. Sellars and McG. Tegart: Special Report 108,

Iron and Steel Institute, (1968).

- (4) R. W. Evans and G. E. Dunstan: J. Inst. Metals, **99** (1971), 4.
- (5) A. Kaspar and A. Pawelski: Mechanical Properties at High Rates of Strain, Institute of Physics Conference, Series No. 47, (1979).
- (6) W. Roberts: *Strength of Metals and Alloys*, ed. by J. J. McQueen *et al.*, Pergamon Press, Oxford, (1986), p. 1859.
- (7) D. R. Barraclough and C. M. Sellars: Met. Sci., **13** (1979), 257.
- (8) K. Inouye: Tetsu-to-Hagané, **41** (1955), 593.
- (9) R. Sims: Proc. Inst. Mech. Engrs., **168** (1954), 191.

Nomenclature

- σ : stress (MPa)
 ϵ : strain
 $\dot{\epsilon}$: strain rate (s^{-1})
 T : Temperature ($^{\circ}C$)
 t , $H.T.$: Holding time (s)
 ϵ_c : critical strain
 K , P , n : strain hardening exponents (eqs. (1) and (2))
 C_1 , C_2 : stress proportionality constants (MPa) (eqs. (1) and (2))
 k : stress restoration index
 m , J : material constant (eqs. (4b) and (4c))
 X : recrystallized fraction
 M : dislocation mobility (eq. (5))
 ψ : ratio of dislocation density to current strain (eq. (5))
 σ_0 : initial yield stress (MPa)
 n : strain hardening exponent
 m : strain rate exponent
 A , K : Exponential temperature constants (Inouye's eq. (8))
Fig.: Figure
eq.: Equation
 σ_s : steady state stress
 $\dot{\epsilon}_R$: strain rate in recrystallized material
 $\dot{\epsilon}_U$: strain rate in unrecrystallized material.