J. Kliber; I. Schindler

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Description of Stress-Strain Curves on High Temperature Deformed Steels

J. KLIBER, I. SCHINDLER*)

Czechoslovakia

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Introduction

In response to the growing interest on the work hardening and softening processes of the metallic material under the heat loading in the zone of plastic deformation, a theoretical and laboratory study has been conducted to examine and to define in mathematical form the shape of stress-strain curve.

The stress-strain curve of a polycrystalline metal [1, 2] under any simple loading has the shape shown diagrammatically in current pictures. The three most usual types of test are the tension of a rod, the compression of a short cylindrical block, and the twisting of a thin-walled tube or a prismatic bar. The result of such a test is represented by plotting the mean stress σ (tensile, compressive or shear) acting over the current (initial) cross-sectional area, against some measure of the total strain. The amout of deformation is usually measured as equivalent (logharitmic = = true) strain.

Over the years, a number of investigations defined the overal response of a material in terms fo some generalized equation of state

$$\sigma = f(T, \varepsilon, \dot{\varepsilon}) \tag{1}$$

e.g. on the basis of relaxation's study proposed [3]

$$\sigma = \sigma_0 . B_1 \exp(n_1 T) . B_2 \varepsilon^{n_2} . \exp(n_3 \varepsilon) . \tag{2}$$

$$B_3 \dot{\varepsilon}^{n_4} . B_4 \tau^{n_5} . \exp(n_6 \tau)$$

where B, to B_4 nad n_1 to n_6 are constants, T, ε, $\dot{\varepsilon}$, τ are temperature (°C or K), strain, strain rate (s^{-1}) and dwell period between deformations in (s), respectively. Other possibility is [4]

$$\sigma = \sigma_0 . \varepsilon^n . \dot{\varepsilon}^m . \exp(C + A/T) . \tag{3}$$

At present the description resulted in [5]

$$\sigma = A . \varepsilon^b . \exp(-c\varepsilon^d) . \dot{\varepsilon}^{fT} . \exp(g/T) . \tag{4}$$

*) Faculty of Metallurgy and Material Eng., Ostrava, Czechoslovakia.

PEAK STRESS

Characteristic stresses (original σ_{ss} – stress at sready-state condition) may be correlated with temperature and strain rate. At low stresses ($\alpha\sigma_{ss} < 0.8$) and high stresses ($\alpha\sigma_{ss} < 1.2$) lead these equations in common form [6]

$$\dot{\varepsilon}_{ss} = A \exp\left(-Q/(RT)\right) \left[\sin\mathrm{h}\,(\alpha\sigma_{ss})\right]^n \tag{5}$$

where A, α, n are constants and Q is activation energy in (J/mol), and all data may be correlated using the Zener-Hollomon parameter $Z = \dot{\varepsilon} \exp\left(Q/(RT)\right)$. Relationship (5) has been applied successfully with σ_p – stress at peak (STRESSP) and transformed into [7, 8]

$$\sin\mathrm{h}\,(\alpha\sigma_p) = (Z/A)^{1/n} \tag{6}$$

$$\sigma_p = \frac{1}{\alpha} \arg\sin\mathrm{h}\left(\frac{\dot{\varepsilon}\,.\,\exp\left(Q/(RT)\right)}{A}\right)^{1/n} \tag{7}$$

PEAK STRAIN

Temperature compensated strain rate Z is related to time compensated strain rate W as [9]

$$W = A_p\,.\,Z^{-a_p}\,. \tag{8}$$

Hence, using $\varepsilon_p = W_p\,.\,Z$ [10] and eq. (8)

$$\ln \varepsilon_p = \ln A_3 + (1 - a_3)\ln \dot{\varepsilon} + (1 - a_3)\frac{Q}{RT} \tag{9}$$

is obtained where A_p, A_3, a_3 are constants, $W_p = t_p \exp\left(-Q/(RT)\right)$ and t_p is time to peak in (s). By gradual linear regression analysis we become the slope $(1 - a_3)$. For expressing the thermally and strain rate activated process on peak strain ε_p a newly suggested and verified form have been obtained as follows [10, 11]

$$\varepsilon_p = \dot{\varepsilon}^a\left(P + \sqrt{(P^2 + 1)}\right) \tag{10}$$

where P is temperature dependent, $P = Y + X/T$, Y, X are constants, a has the same meaning as $(1 - a_3)$ eq. (9) and with rearrangement is obtained

$$\varepsilon_p = \dot{\varepsilon}^a\,.\,\exp \arg\sin\mathrm{h}\,(Y + X/T)\,. \tag{11}$$

STRESS

For a fixed T, the stress-strain curves are progressively higher at medium $\varepsilon/\varepsilon_p$ for a higher strain rate. Although these curves are lower for decreasing Z value. The function which describes best the reduced flow stress is [12]

$$\ln\left(\frac{\sigma}{\sigma_p}\right) = c\left[\ln\left(\frac{\varepsilon}{\varepsilon_p}\right) + \left(1 - \frac{\varepsilon}{\varepsilon_p}\right)\right] \tag{12}$$

where c is a positive constant between zero and unity, which decreases as the curves are higher. The value of c is determined through plots of $[-\ln(\sigma/\sigma_p)]$ vs. $[-\ln(\varepsilon/\varepsilon_p) - (1 - \varepsilon/\varepsilon_p)]$. These should be linear but are never perfectly so.

The evaluation procedure

The result of continuous torsion tests are taken into the calculation – as torque moment and strain at various temperatures ($T \in (800;\ 1000)$°C and strain rates $\sigma \in (6;\ 1000)\ \mathrm{min}^{-1}$) from hot deformed HSLA steel. The specimens were 50 mm long having a diameter of 6 mm.

1. STRESSPC (STRESS at Peak Calculated)

The data can be fitted by

$$\sigma = 90 \arg\sin\mathrm{h} \left(\frac{\dot{\varepsilon} \exp \dfrac{365\,400}{RT}}{8 \,.\, 10^{13}} \right)^{0,2} \tag{13}$$

using personal computer AT.

2. STRAINPC (STRAIN at Peak Calculated)

$$\varepsilon_{PC} = \dot{\varepsilon}^{0,142} \,.\, \exp \arg\sin\mathrm{h} \left(-6,9 + \frac{7\,180}{T} \right) \tag{14}$$

3. STRESS (STRESS Experimental compared with STRESS Calculated)

$$\sigma_c = \sigma_{PC} \left[\frac{\varepsilon}{\varepsilon_{PC}} \exp \left(1 - \frac{\varepsilon}{\varepsilon_{PC}} \right) \right]^c . \tag{15}$$

Discussion

The value of exponent c, wich is variable, slightly complicate common use of equation (15). Taking into account that the resulting c is adequate for temperature,

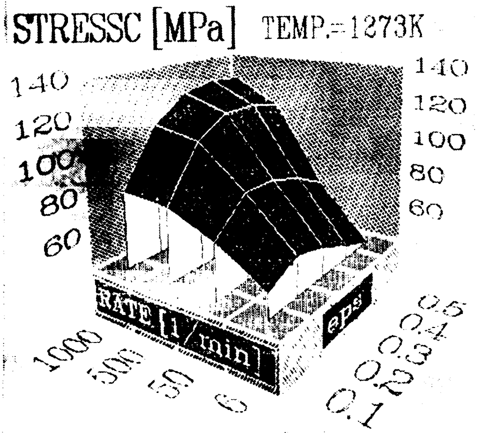

Fig. 1. Effect of strain rate from 6–1000 min^{-1} and true strain from 0.1 to 0.5 on STRESS Calculated (eq. 17).

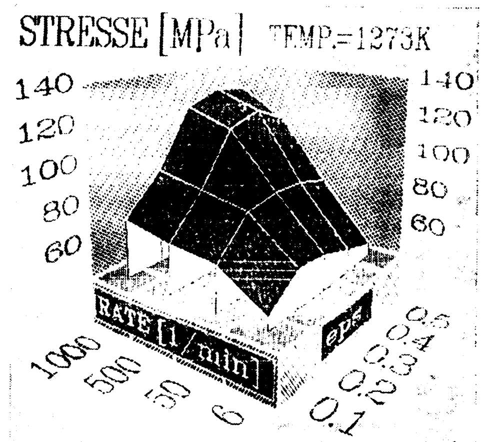

Fig. 2. Effect of strain rate from 6–1000 min^{-1} and true strain from 0.1 to 0.5 on STRESS Experimental.

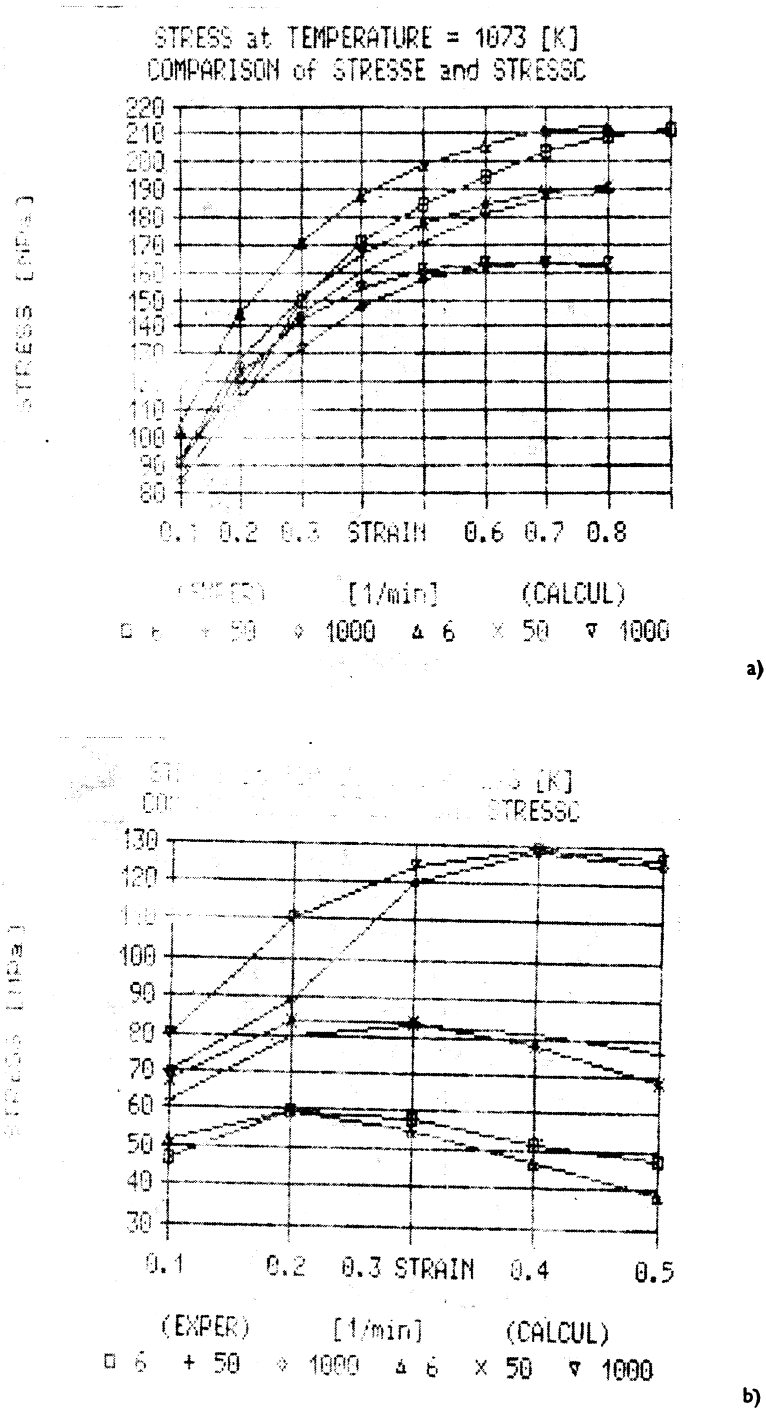

Fig. 3. Comparison of STRESSE and STRESSC for *a* ... $T = 1073$ K, various strain and strain rates *b* ... $T = 1273$ K.

TEMPERATURE T = 1123 /K/ RATE o = 6 /min-1/

eps= .1	STRESS (EXPER.) = 68 /MPa/	(CALCUL.) = 78 /MPa/
eps= .2	STRESS (EXPER.) = 96 /MPa/	(CALCUL.) = 100 /MPa/
eps= .3	STRESS (EXPER.) = 105 /MPa/	(CALCUL.) = 107 /MPa/
eps= .4	STRESS (EXPER.) = 104 /MPa/	(CALCUL.) = 106 /MPa/
eps= .5	STRESS (EXPER.) = 98 /MPa/	(CALCUL.) = 100 /MPa/
eps= .6	STRESS (EXPER.) = 94 /MPa/	(CALCUL.) = 93 /MPa/
eps= .7	STRESS (EXPER.) = 89 /MPa/	(CALCUL.) = 84 /MPa/
eps= .8	STRESS (EXPER.) = 88 /MPa/	(CALCUL.) = 76 /MPaú

TEMPERATURE T = 1123 /K/ RATE o = 50 /min-1/

eps= .1	STRESS (EXPER.) = 78 /MPa/	(CALCUL.) = 86 /MPa/
eps= .2	STRESS (EXPER.) = 105 /MPa/	(CALCUL.) = 117 /MPa/
eps= .3	STRESS (EXPER.) = 128 /MPa/	(CALCUL.) = 133 /MPa/
eps= .4	STRESS (EXPER.) = 137 /MPa/	(CALCUL.) = 139 /MPa/
eps= .5	STRESS (EXPER.) = 139 /MPa/	(CALCUL.) = 140 /MPa/
eps= .6	STRESS (EXPER.) = 135 /MPa/	(CALCUL.) = 137 /MPa/
eps= .7	STRESS (EXPER.) = 130 /MPa/	(CALCUL.) = 132 /MPa/
eps= .8	STRESS (EXPER.) = 124 /MPa/	(CALCUL.) = 125 /MPa/

TEMPERATURE T = 1123 /K/ RATE o = 500 /min-1/

eps= .1	STRESS (EXPER.) = 80 /MPa/	(CALCUL.) = 90 /MPa/
eps= .2	STRESS (EXPER.) = 120 /MPa/	(CALCUL.) = 127 /MPa/
eps= .3	STRESS (EXPER.) = 138 /MPa/	(CALCUL.) = 148 /MPa/
eps= .4	STRESS (EXPER.) = 155 /MPa/	(CALCUL.) = 161 /MPa/
eps= .5	STRESS (EXPER.) = 165 /MPa/	(CALCUL.) = 168 /MPa/
eps= .6	STRESS (EXPER.) = 168 /MPa/	(CALCUL.) = 170 /MPa/
eps= .7	STRESS (EXPER.) = 168 /MPa/	(CALCUL.) = 169 /MPa/
eps= .8	STRESS (EXPER.) = 160 /MPa/	(CALCUL.) = 166 /MPa/

TEMPERATURE T = 1123 /K/ RATE o = 1000 /min-1/

eps= .1	STRESS (EXPER.) = 100 /MPa/	(CALCUL.) = 93 /MPa/
eps= .2	STRESS (EXPER.) = 142 /MPa/	(CALCUL.) = 133 /MPa/
eps= .3	STRESS (EXPER.) = 162 /MPa/	(CALCUL.) = 158 /MPa/
eps= .4	STRESS (EXPER.) = 175 /MPa/	(CALCUL.) = 173 /MPa/
eps= .5	STRESS (EXPER.) = 182 /MPa/	(CALCUL.) = 183 /MPa/
eps= .6	STRESS (EXPER.) = 186 /MPa/	(CALCUL.) = 187 /MPa/
eps= .7	STRESS (EXPER.) = 189 /MPa/	(CALCUL.) = 189 /MPa/
eps= .8	STRESS (EXPER.) = 186 /MPa/	(CALCUL.) = 188 /MPa/

TABLE

COMPARSION OL EXPERIMENTAL AND CALCULATED RESULTS

t [C]	o [min^{-1}]	STRESSPE	STRESSPC
1000	6	59.7273	59.8895
1000	50	85.456	84.985
1000	500	117.617	118.151
1000	1000	129.256	129.024
900	6	92.507	96.2548
900	50	120.986	128.329
900	500	147.327	166.37
900	1000	164.48	178.114
850	6	107.203	121.149
850	50	139.976	155.578
850	500	169.993	194.926
850	1000	188.983	206.872
800	6	142.12	150.634
800	50	164.48	186.434
800	500	192.046	226.309
800	1000	213.487	238.773

PEAK STRAINS

temperature [K]	rate of twisting [min^{-1}]	strainp STRAINPE	STRAINPC
1273	6	.197537	.1903
	50	.251786	.257165
	500	.366307	.35636
	1000	.413775	.393024
1173	6	.261415	.266365
	50	.315296	.359915
	500	.461657	.498369
	1000	.549565	.549144
1123	6	.329538	.334584
	50	.466217	.451474
	500	.621253	.624558
	1000	.70535	.687928
1073	6	.443752	.441804
	50	.666054	.594724
	500	.875773	.820567
	1000	.840429	.906523

thus a mathematically correct relationship should be of the form

(16) $$c = A - B/T \qquad c = 1{,}5157 - 998/T$$

and eq. (15) transformed to

(17) $$\sigma = \sigma_p \left[\frac{\varepsilon}{\varepsilon_p} \exp\left(1 - \frac{\varepsilon}{\varepsilon_p}\right)\right]^{A - B/T}.$$

Conclusion

Comparison of experimental – STRESSPE – and calculated – STRESSPC – values are given in tables together with STRAINPE and STRAINPC results. The delivered figures 1 to 3 ilustrate differences between STRESSPE and STRESSPC according equations (15), (17), respectivelly.

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