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Influence of the Temperature and Strain Rate on the Deformability of Low-Alloy Carbon Steel

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Abstract—The influence of the temperature, strain, and strain rate on the deformability of low-alloy carbon steel is studied experimentally. Samples are tested on the STD 812 torsional plastometer at Czestochowa Technological University. The hardening of low-alloy carbon steel at different strain rates and temperatures is plotted on the basis of the results for its resistance to deformation. For all the curves, the rate of hardening is high in the initial section, with no relaxation processes. The influence of the strain rate and temperature on the maximum resistance to deformation is quantitatively determined; this is important for practical purposes. The resistance to deformation declines on account of relaxation. The influence of the strain rate and temperature on the mean hardening rate in the range $0 < \varepsilon_u < \varepsilon_u^*$ is also studied.

Keywords: rheological data, resistance to deformation, strain hardening, hot torsional tests, low-alloy carbon steel

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During high-temperature deformation, the deformability of steel depends on the hardening processes associated with the strain and strain rate and also on the dynamic polygonization and recrystallization determining the relaxation processes [1–3]. The process may be characterized by the relation

$$\sigma_s = \sigma_s(\varepsilon_u, \dot{\varepsilon}_u, \theta, p, \tau, X_w). \qquad (1)$$

It is evident from Eq. (1) that the resistance to deformation depends on two mechanical variables (the strain ε_u and strain rate $\dot{\varepsilon}_u$), two physical variables (the temperature θ and hydrostatic pressure p), one kinematic variable (the time τ), and one variable determining the steel's structural sensitivity X_w [1, 3–13]. The parameter p is only present in Eq. (1) when hydrostatic pressure acts on the deformable material. Usually, τ appears in the function $\varepsilon(\tau)$, which characterizes the development of deformation over time [1, 3–13].

In hot pressure treatment of metal (such as hot rolling), the resistance to deformation depends primarily on its temperature and the specified strain rate. The influence of these factors on σ_s at the onset of equilibrium between hardening and softening was investigated in [14]. In this case, the strain rate and temperature are selected so as to form fine-grain structure of the steel in pressure treatment [1, 3–13].

In the present work, we determine the influence of the strain, strain rate, and temperature on the resistance to deformation of low-alloy carbon steel; the composition of the steel is summarized in Table 1. Samples are tested on the STD 812 torsional plastometer at Czestochowa University of Technology, at temperatures of 800–1200°C, strain rates of 0.1, 1.0, and 10.0 s^{-1}, and strain values of 0–6.5. The samples for plastometric analysis are heated to 1250°C at 5°C/s, with 30 s holding at 1250°C to ensure uniform temperature over the working zone of the sample. Then they are cooled to the deformation temperature, held at that temperature for 10 s, and subjected to torsion at the required strain rate until the specified strain is attained, and finally cooled in air at 20°C/s. The rheological properties of the steel are investigated in vacuum at constant temperature and strain rate.

In the tests, specified strain rate and temperature are maintained with high precision. We calculate the strain and strain rate in torsion as follows

$$\varepsilon_u = \frac{2\pi r N}{\sqrt{3}L}(\tau); \qquad (2)$$

$$\dot{\varepsilon}_u = \frac{2\pi r \dot{N}}{\sqrt{3}\cdot 60L}; \qquad (3)$$

Table 1. Chemical composition of low-alloy carbon steel, %

C	Mn	Si	P	S	Cr	Ni	Cu	Al	Mo
0.21	0.97	0.10	0.014	0.009	0.26	0.07	0.17	0.024	0.014
N	Pb	Al_{met}	As	Cb	V	Ti	B	Zn	Sn
0.0119	0.001	0.020	0.007	0.002	0.004	0.047	0.003	0.018	0.012

We determine the resistance to deformation from the formula [2, 14, 15]

$$\sigma_s = \frac{\sqrt{3} \cdot 3M}{2\pi r^3}, \quad (4)$$

here r is the sample radius; L is its length; N is the number of turns in torsion; $\dot{N}$ is the speed; and M is the torque.

In Fig. 1, we show the strain hardening of the steel as a function of the strain and strain rate at 1200°C in tests on the STD 812 torsional plastometer at Czestochowa University of Technology.

The hardening curves at other temperatures in the range 800–1150°C are similar. In all cases, the rate of hardening is high in the initial section, with no relaxation processes. Then, beginning at ε_u = 0.2–0.3, the rate declines. At some value $\varepsilon_u = \varepsilon_u^*$, on account of equilibrium between hardening and softening, the hardening rate falls to zero. Correspondingly, the resistance to deformation reaches a maximum value σ_s^{max}. When $\varepsilon_u > \varepsilon_u^*$, the equilibrium state is retained at 800–900°C, with a strain rate above 1.0 s^{-1}, but the resistance to deformation falls by $\Delta\sigma_{s1}$ with increase in temperature and decrease in strain rate. However, with some combination of deformation parameters, the strain rate then increases by $\Delta\sigma_{s2}$ (Fig. 2).

Table 2 presents values of ε_u^*, σ_s^{max}, the mean hardening rate $\sigma_s^{max}/\varepsilon_u^*$, and also $\Delta\sigma_{s1}$ and $\Delta\sigma_{s2}$ as a function of the strain rate and temperature; these results are obtained by analysis of Fig. 1.

The strain ε_u^* corresponding to equilibrium increases with increase in the strain rate over the whole temperature range: from 1.00 (when $\varepsilon_u^* = 0.1$) to 2.75 (when $\varepsilon_u^* = 10$) at 1200°C; and from 1.00 to 3.0 at 1100°C. With decrease in temperature to 800°C, ε_u^* rises to 3.5, regardless of the strain rate. The maximum resistance to deformation σ_s^{max} declines by a factor of 2.7 with increase in temperature from 900 to 1200°C, regardless of the strain rate; by a factor of 1.8 from 1000 to 1200°C, and by a factor of 1.4 from 1100 to 1200°C. Increasing the strain rate from 0.1 to 1.0 s^{-1} increases the resistance to deformation by a factor of 1.3–1.5, regardless of the temperature; the corresponding factor for increase in strain rate from 0.1 to 10.0 s^{-1} is 1.2–1.7.

Analysis shows that mean growth rate of the resistance to deformation $\sigma_s^{max}/\varepsilon_u^*$ with increase in ε_u from zero to ε_u^* is 35–50 MPa, at most values of the temperature and strain rate. At 800–900°C, however, it

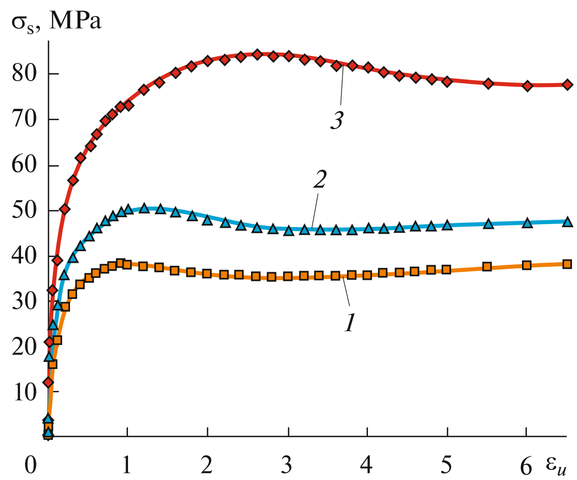

Fig. 1. Strain hardening of low-alloy carbon steel at 1200°C when the strain rate is 0.1 (*1*), 1.0 (*2*), and 10.0 (*3*) s^{-1}.

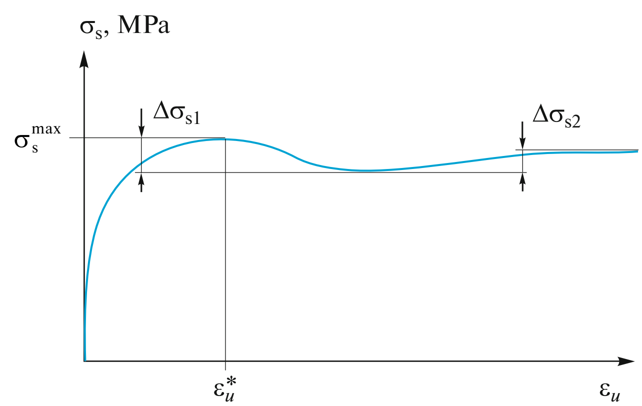

Fig. 2. Determining the characteristics of the hardening curve.

Table 2. Values of ε_u^*, σ_s^{max}, $\frac{\sigma_s^{max}}{\varepsilon_u^*}$, $\Delta\sigma_{s1}$, and $\Delta\sigma_{s2}$ as a function of the strain rate and temperature and strain rate

θ, °C	Characteristic	$\dot{\varepsilon}_u$, s^{-1}		
		0.1	1.0	10
1200	ε_u^*	1.00	1.25	2.75
	σ_s^{max}, MPa	38	50	85
	$\frac{\sigma_s^{max}}{\varepsilon_u^*}$, MPa	38	40	30.9
	$\Delta\sigma_{s1}$, MPa	4	5	7
	$\Delta\sigma_{s2}$, MPa	0	2	4
1100	ε_u^*	1.0	1.5	3.0
	σ_s^{max}, MPa	50	70	105
	$\frac{\sigma_s^{max}}{\varepsilon_u^*}$, MPa	50	47	35
	$\Delta\sigma_{s1}$, MPa	4	8	10
	$\Delta\sigma_{s2}$, MPa	3	2	0
1000	ε_u^*	1.25	2.0	3.0
	σ_s^{max}, MPa	65	100	147
	$\frac{\sigma_s^{max}}{\varepsilon_u^*}$, MPa	52	50	49
	$\Delta\sigma_{s1}$, MPa	7	8	10
	$\Delta\sigma_{s2}$, MPa	2	0	0
900	ε_u^*	1.75	2.5	3.0
	σ_s^{max}, MPa	96	140	183
	$\frac{\sigma_s^{max}}{\varepsilon_u^*}$, MPa	55	56	61
	$\Delta\sigma_{s1}$, MPa	10	10	8
	$\Delta\sigma_{s2}$, MPa	2	0	0
800	ε_u^*	3.5	3.5	3.5
	σ_s^{max}, MPa	150	200	250
	$\frac{\sigma_s^{max}}{\varepsilon_u^*}$, MPa	43	57	71
	$\Delta\sigma_{s1}$, MPa	0	0	0
	$\Delta\sigma_{s2}$, MPa	0	0	0

increases to 70 MPa with increase in the strain rate to 10 s^{-1}. The softening of the steel $\Delta\sigma_{s1}/\sigma_s^{max}$ is around 10%, but declines to zero at 800–900°C. The subsequent increment $\Delta\sigma_{s2}$ is small and may be neglected.

CONCLUSIONS

On the basis of tests on the STD 812 torsional plastometer at Czestochowa University of Technology, we plot hardening curves for low-alloy carbon steel for different strain rates ($\dot{\varepsilon}_u$ = 0.1, 1.0, and 10.0 s^{-1}) and temperatures (θ = 800–1200°C).

For all the curves, the rate of hardening is high in the initial section, with no relaxation processes. On reaching some strain $\varepsilon_u = \varepsilon_u^*$, on account of equilibrium between hardening and softening, the hardening rate falls to zero. Correspondingly, the resistance to deformation reaches a maximum value σ_s^{max}. When $\varepsilon_u > \varepsilon_u^*$, decrease in the resistance to deformation by $\Delta\sigma_{s1}$ is observed with increase in temperature (θ > 900°C) and decrease in strain rate ($\dot{\varepsilon}_u$ < 1.0 s^{-1}). Regardless of the strain rate and temperature, $\Delta\sigma_{s1}/\sigma_s^{max}$ is around 10%, but it falls to zero at 800–900°C.

The influence of the strain rate and temperature on the maximum resistance to deformation σ_s^{max} is quantitatively determined; this is important for practical purposes. This resistance to deformation is reduced by $\Delta\sigma_{s1}$ under the action of relaxation processes. The influence of the strain rate and temperature on the mean hardening rate in the range $0 < \varepsilon_u < \varepsilon_u^*$ is also studied.

The increment $\Delta\sigma_{s2}$ observed at certain values of the strain rate and temperature is small and may be neglected.

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