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MATHEMATICAL DESCRIPTION OF THE STRAIN–RATE SENSITIVIT INDEX AT HOT FORMING OF STEEL

MATEMATYCZNY OPIS WSKAŹNIKA CZUŁOŚCI NAPRĘŻENIA NA PRĘDKOŚĆ ODKSZTAŁCENIA PODCZAS ODKSZTAŁCANIA PLASTYCZNEGO NA GORĄCO

The methodology of determination of strain-rate sensitivity index was developed, based on hot rolling of a set of samples with the same draft but different speed at defined temperature levels. It was proved that initial grain size had nearly negligible influence on the investigated variable, in contrast to phase composition whose influence was remarkable. Combined influence of strain rate and temperature on deformation resistance of various types of steel was studied. For a selected group of steels an universal equation was set up, which described with a good accuracy impact of reciprocal temperature and chemical composition, expressed simply by nickel equivalent, on strain-rate sensitivity in hot state.

Opracowano metodykę wyznaczania wskaźnika czułości naprężenia na prędkość odkształcenia bazując na wynikach walcowania na gorąco zestawu próbek dla zadanych temperatur i prędkości walcowania, przy zachowaniu stałego gniotu. Udowodniono, że początkowa wielkość ziarna praktycznie nie ma wpływu na wyznaczony wskaźnik w odróżnieniu do składu fazowego, którego wpływ jest znaczny. Badania realizowano dla zróżnicowanych wartości prędkości odkształcenia i temperatury dla różnych typów stali. Dla wybranych grup stali opracowano uniwersalne równania, które z dobrą dokładnością opisuje wpływ temperatury i składu chemicznego, wyrażonego przez równoważnik niklu, na wskaźnik czułości naprężenia na prędkość odkształcenia podczas walcowania na gorąco.

1. Introduction

Strain-rate sensitivity m of steels has been a traditional object of rich research activities. It can be applied at description of the hot and/or warm deformation behaviour (flow stress)

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– e.g. [1–3]. The efficiency of power dissipation given by $2m/(m + 1)$ can be plotted as a function of temperature and strain rate to obtain a processing map, which is interpreted on the basis of the dynamic materials model [4]. Precision strain-rate sensitivity measurements have been used to determine the solid solution component of interstitials in ferritic stainless steel [5]. High strain-rate sensitivity value plays a key role at superplasticity of duplex stainless steel [6] as well as superplastic-like deformation behaviour during creep deformation [7]. Of course there exist even some extraordinary functions of the m-value. The effects of strain hardening and strain-rate sensitivity on the plastic flow and deformation heterogeneity during equal channel angular pressing were studied [8]. Steel foams fabricated by a powder metallurgical process were subjected to compression tests to explore the dependence of defects on strain-rate sensitivity [9]. The influence of friction coefficient on material strain-rate sensitivity was assessed by dynamic friction measurements at sliding velocities representing the high-speed machining processes [10], etc.

In former experimental works [11,12] a combined influence of mean strain rate $\dot{\varepsilon}$ [s^{-1}] and temperature T [K] on mean equivalent stress (i.e. deformation resistance) σ [MPa] of various types of steel was studied. At the same time universal validity of a simple model for mean deformation resistance was verified, particularly of its member for stress-strain rate expression in the form of

$$\sigma \approx \dot{\varepsilon}^{\mathrm{m}}, \tag{1}$$

where m is strain-rate sensitivity, dependent on temperature according to the following proposed relationship

$$\mathrm{m} = \mathrm{D} - \mathrm{F/T}, \tag{2}$$

where D and F are material constants [13]. The laboratory rolling mill Tandem with computer-aided registration of experimental data was used for these experiments [14].

2. Experimental procedure

The set of coincident samples is rolled with the same draft but various speed at selected temperature levels. For each draft mean values of rolling force F_R [kN] and/or revolutions of rolls N [rev/min] are evaluated; of course revolutions are not constant during the pass (Fig. 1). Variables σ and $\dot{\varepsilon}$ in equation (1) are substituted with variables F_R and N. In reference [15] mathematical proofs of justification of this simplifying procedure are given. This procedure assumes a linear relationship between strain rate and mean deformation resistance in the region of strengthening (at comparatively small strains).

Determination of material constants D and F requires that two types of regression have to be accomplished. First of all values of index m are found out for individual temperature levels by means of the procedure which is shown in Fig. 2 (an exponential relationship). Then temperature relationship of strain-rate sensitivity m is determined, after

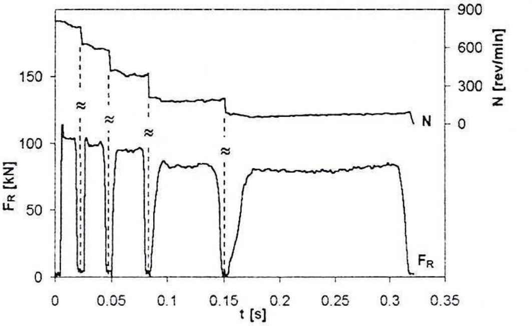

Fig. 1. Example of the course of rolling forces in relation to altering rolling speed – tool steel (see S24 in Table 1 below), identical height reduction of about 15 %, temperature 950 °C (in fact individual drafts do come after each other so quickly, long dwells have been removed in the plot)

plotting values m (acquired in this way) in the graph which is shown as an example in Fig. 3 (a linear regression).

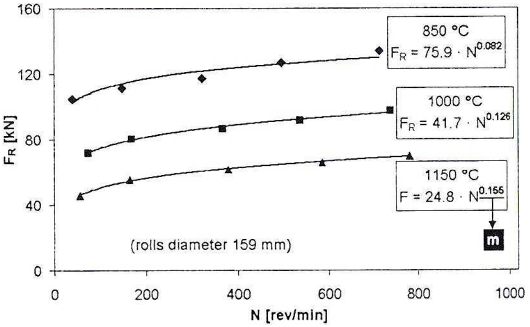

Fig. 2. Determination of strain-rate sensitivity values from rolling forces measured at individiual temperature levels (low-alloyed steel with Cr and Mn – see S13 in Table 1 below)

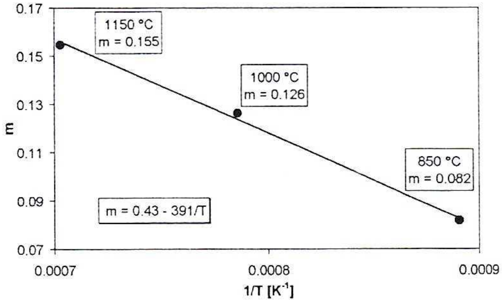

Fig. 3. Determination of temperature relationship of strain-rate sensitivity (values transferred from Fig. 2)

In total 35 selected types of steel (see steels S1 – S35 in Table 1) were hot rolled at strain rate in the range of ca 5 s^{-1} up to 120 s^{-1}. These steels feature considerable variability of both chemical composition and structure state – structural steels with different carbon content, microalloyed steels, low-alloyed steels, corrosion-resistant steels with austenitic or ferritic microstructure, carbon tool steels, and high-alloyed high-speed steels. The relationship of type $m = D - F/T$ was expressed in numbers for each material by means of procedure described above.

TABLE 1

Chemical composition of studied steels S1 – S35 (wt %)

	C	Mn	Si	Cr	Ni	Mo	Al	other elements
S1	0.17	0.72	0.26					
S2	0.12	0.34	0.18					
S3	0.21	1.40	0.47					
S4	0.13	0.46	0.33					
S5	0.39	0.68	0.20				0.058	
S6	0.72	1.05	0.24					
S7	1.04	0.03	0.23	1.36				
S8	0.31	0.77	0.27	1.00		0.18		
S9	0.97	1.13	0.61	1.51				
S10	0.02	1.21	0.34	0.88				
S11	0.57	0.59	1.45	0.56				
S12	0.42	0.55	1.32	1.59				
S13	0.39	0.80	0.25	1.06		0.34		
S14	0.26	0.61	0.25	2.00			0.033	0.15 V
S15	0.33	0.65	0.29	1.36	1.65	0.29	0.030	
S16	0.39	0.82	0.99	0.89	1.51	0.20		
S17	0.21	0.51	0.43	12.1				
S18	0.15	0.49	0.36	13.1	0.64	0.15	0.046	
S19	0.12	0.43	0.52	25.5				0.42 Ti; 0.002 B
S20	0.05	1.70	0.20	19.1	8.67			
S21	0.01	0.84	0.50	17.0	8.89	0.20	0.146	0.31 Ti; 0.033 Nb
S22	0.05	0.91	0.42	17,4	11.3	2.32	0.054	0.044 N_2; 0.003 B
S23	0.85	0.23	0.25	0.11				
S24	1.58	0.38	0.32	11.2		0.66		0.94 V
S25	0.94	0.22	0.29	4.31		5.0		6.46 W; 1.96 V; 0.25 Co; 0.071 Nb
S26	0.06	1.52	0.46	17.8	8.97			0.25 S; 0.038 N_2
S27	0.13	1.04	0.03				0.035	0.016 Nb
S28	0.12	1.44	0.42				0.035	0.045 Nb; 0.04 V
S29	0.01	0.33	0.07					
S30	0.14	1.10	0.46	15.7	0.74	0.47		0.41 S
S31	0.11	0.22	1.16	18.9	0.58		0.790	
S32	0.21	1.15	0.21	0.81	1.22	0.73		0.37 W
S33	0.40	1.48	0.70	0.19				
S34	0.12	0.99	1.65	20.0	11.7	0.38	0.033	
S35	0.05	0.42	0.79	24.9	0.99	0.21	0.036	

3. Results and discussion

3.1. Impact of phase transformations

For evaluation of impact of structural state, ELC steel (see S29 in Table 1) has been chosen because it exhibited very strong changes in the temperature course of rolling forces in the region of transformation A_{r3} and A_{r1} [16]. In Fig. 4 impact of structure state on hot deformation resistance is demonstrated. When determining values of strain-rate sensitivity m, forming temperatures were selected in such a way that rolling with the same draft was always realized in the phase-defined region – austenitic, two-phase and purely ferritic. Data representing calculated values of strain-rate sensitivity were then added to the summary plot in Fig. 4

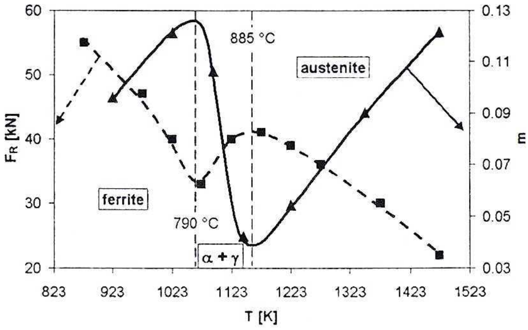

Fig. 4. Impact of temperature and phase composition of ELC steel on rolling forces F_R and values of strain-rate sensitivity m

The slope of the curve $m = f(T)$ in both mono-phase regions is qualitatively identical. On the contrary, the slope in the two-phase ferritic-austenitic region has the opposite value. Temperature relationships of strain-rate sensitivity for the given ELC steel in all three phase regions (concerning only linear sections of pertinent curves) could be described with following simple linear regressions:

austenite: $$m = 0.45 - 484/T \qquad (3)$$

austenite + ferrite: $$m = 1911/T - 1.64 \qquad (4)$$

ferrite: $$m = 0.39 - 272/T\,. \qquad (5)$$

From what was stated above follows the importance of selection of experimental temperatures at determination of strain-rate sensitivity m because data achieved at the temperature corresponding to another structural state will cause significant distortion of results.

3.2. Impact of grain size

Samples from free-cutting steel of type 18/9-S (see S26 in Table 1) were soaked on temperature 1275 °C, and then rolled with the same draft but various speed at temperature 1000 °C, or heated directly to the rolling temperature 1000 °C. The initial size of austenitic grain is demonstrated by micrographs in Fig. 5. Dark points or stretched aggregates in streaks are sulphides MnS. The equiaxed grains' mean diameter is ca 0.2 mm after heating to1275 °C, or 0.03 mm after heating to 1000 °C. The plot in Fig. 6 demonstrates the effect of initial grain size on strain behaviour of particular steel. The value of strain-rate sensitivity at forming temperature 1000 °C ($m_{1000} = 0.07$ or 0.08) fluctuates in the range of statistical error that is quite usual at hot testing used. Thus it is possible to take no account of the impact of grain size on the value of strain-rate sensitivity index at calculations of deformation resistance and rolling force in practice.

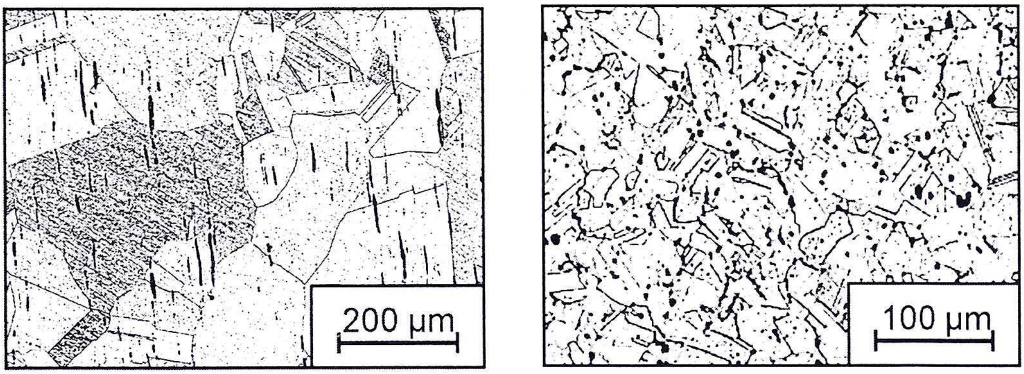

Fig. 5. Grain size of austenitic steel 18/9-S after heating to 1275°C (up) or 1000°C (down)

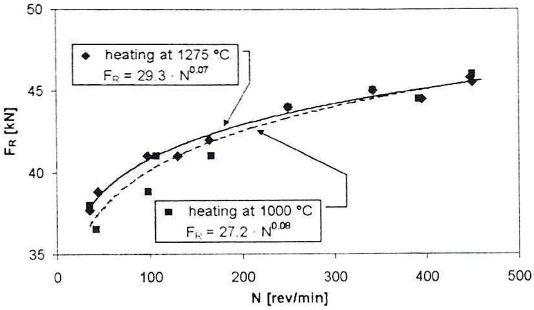

Fig. 6. Impact of initial grain size on rolling forces and value of strain-rate sensitivity m during forming of steel 18/9-S at temperature 1000°C

3.3. Impact of chemical composition on material constants D and F

During the experimental results processing it was confirmed that mathematical description of the studied relationship with one equation is possible only in case that the selected interval of forming temperatures at particular steel covers the region with analogous structure (characterized by occurrence of identical phases). That is why the range of temperatures $T_{min} - T_{max}$, in which test rolling of individual steels was performed, is stated in Table 2. The another quantities are as follows: nickel equivalent E_{Ni}, determined material constants *D* and *F* in the equation of type (2), and the value of m_{1000} (for 1000 °C) calculated according to equation (2) and based on knowledge of corresponding constants *D* and *F*.

TABLE 2

Selected parameters of studied steel S1 – S35

	E_{Ni}	D	F [K]	T_{min} [°C]	T_{max} [°C]	m_{1000}
S1	5.38	0.26	166	850	1150	0.12
S2	3.69	0.25	206	900	1200	0.09
S3	6.18	0.60	620	900	1150	0.11
S4	3.79	0.27	198	900	1200	0.12
S5	11.62	0.20	121	730	1130	0.11
S6	21.73	0.56	508	800	1050	0.16
S7 (+)	31.42	0.38	307	800	1050	0.14
S8	9.30	0.30	235	800	1120	0.12
S9 (+)	29.22	0.33	268	800	1050	0.12
S10	0.54	0.41	384	800	1080	0.11
S11 (+)	17.02	0.72	788	930	1130	0.10
S12 (+)	12.81	0.39	349	850	1120	0.12
S13	12.21	0.43	391	850	1150	0.12
S14	7.66	0.26	220	800	1180	0.09
S15	11.70	0.31	222	850	1150	0.14
S16	13.43	0.27	212	950	1150	0.11
S17 (+)	6.92	0.13	76	900	1100	0.08
S18 (+)	5.73	0.41	424	850	1120	0.08
S19 (+)	3.98	0.50	483	800	1050	0.12
S20 (+)	10.39	0.23	195	850	1150	0.80
S21 (+)	9.26	0.15	128	900	1100	0.05
S22 (+)	15.27	0.20	151	900	1200	0.08
S23 (+)	25.54	0.52	438	750	1050	0.18
S24 (+)	47.81	0.48	470	850	1050	0.11
S25 (+)	31.09	0.37	382	900	1100	0.07
S26 (+)	11.77	0.30	286	800	1200	0.07
S27	3.94	0.38	364	860	1150	0.10
S28	3.65	0.53	541	850	1150	0.11
S29	0.40	0.45	484	950	1200	0.07
S30 (+)	5.30	0.23	165	850	1150	0.10
S31 (+)	3.87	0.36	306	900	1150	0.12
S32	8.12	0.25	183	900	1150	0.10
S33	12.16	0.50	471	800	1120	0.13
S34 (+)	15.80	0.25	239	900	1200	0.06
S35 (+)	2,71	0.12	32	850	1150	0.09

It would be the best to find functional relations of constants D and F in equation (2) to chemical composition of studied steels and to acquire in such a way an universal mathematical description of strain-rate sensitivity at hot forming. Nevertheless, all attempts to relate values of variables D and F to chemical composition (expressed by % content of selected chemical elements or in various way selected synthetic indexes, e.g. the carbon, nickel, or chromium equivalent, their ratios, or in various way calculated liquidus temperature [17]) failed. This fact is demonstrated by a selected example – impact of the nickel equivalent E_{Ni} (Fig. 7), defined by the simple formula [18]

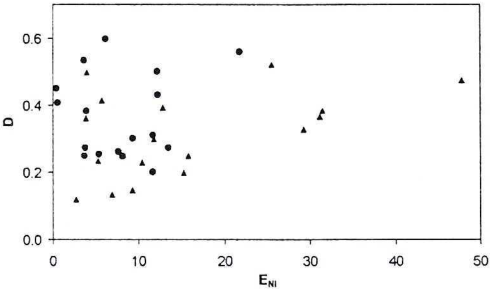

Fig. 7. Impact of chemical composition of steel on the value of constant D

$$E_{Ni} = [\%\ Ni] + 0.5 \cdot [\%\ Mn] + 30 \cdot [\%\ C] + 30 \cdot [\%\ N] \tag{6}$$

which counts with weight % of selected elements.

As we did not succeed in finding a suitable function for description of the whole complex of studied materials, we started to eliminate successively more complicated types of steel to be able to express mathematically sought-after relationships for a limited, but somewhat logically confined, group of steels. In Table 2 the eliminated steels are designated with „plus" – it follows from the procedure stated below that they are carbon eutectoid and hypereutectoid steels, low-alloy steels with increased silicon content, high-alloy corrosion-resistant steels (ferritic and austenitic) and tool steels.

In plot in Fig. 7 values corresponding to eliminated steels (designated with „plus" in Table 2) are designated with triangles. It is evident that also values of constant D (as well as constant F) in the remainder of steels do not show any undoubted, mathematically formulated relationships.

3.4. Mathematical description of the strain-rate sensitivity

During following analyses we gave up the effort to describe strain-rate sensitivity for all studied steels with a common equation, by using earlier found out variables D and F. Further attention was focused on the relation of coefficient m, expressed in numbers for selected materials and particular levels of forming temperatures, based on knowledge of material constants D and F. Selected steels which remained after the successive elimination were considered only. These are hypoeutectoid carbon steels (surprisingly also with addition of microalloying elements) and low-alloy steels, of course with silicon content below 1.3 %.

In Fig. 8 values of strain-rate sensitivity of all 35 studied steels, expressed in numbers for temperature 1000 °C, are plotted in relation to the nickel equivalent. Points designated with smaller triangles correspond to successively eliminated types of material. High-alloy austenitic and tool steels show distinctly lower sensitivity to strain rate in hot state than other materials. That is why they were explicitly excluded from the following mathematical processing. A bit more complicated situation occurred in case of other materials. Unalloyed steels with carbon content above 0.8 %, as well as unalloyed steels with silicon content above 1.3 % and high-alloy ferritic steels, could be included with some tolerance in the data file, on condition that their values m generally followed the basic trend (indicated with a dashed line). This line arose as a result of the linear regression of points $m = f(E_{Ni})$ for non-eliminated steels (see bigger points in the form of circlets in the plot in Fig. 8). These steels could be on the whole included in the mathematical processing, but accuracy of the following regressions would be decreased and some doubt would be thrown on physical substantiation of the corresponding mathematical description. The group consisting of the remainder of steels (carbon hypoeutectoid steels or low-alloy steels with total content of alloying elements below 5%), defined in such a way, represents namely from the material viewpoint a comprehensive group of steels with similar deformation behaviour.

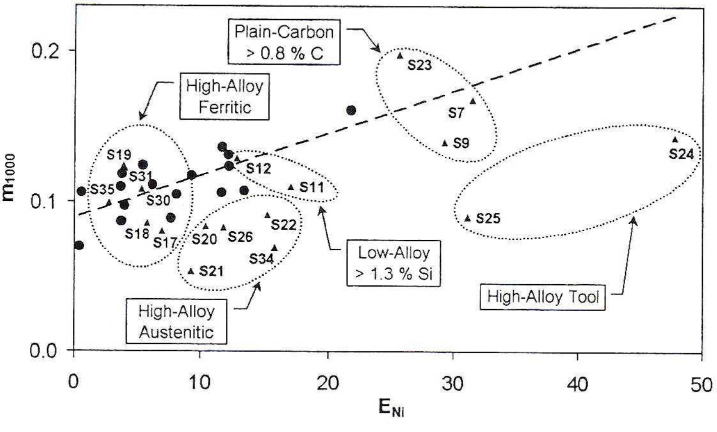

Fig. 8. Coefficient *m* at temperature 1000°C in dependence on chemical composition of steels

Based on relations of type (2), experimentally determined for temperature levels 900°C, 1000°C and 1100°C, strain-rate sensitivity values for all steels left after the previous elimination were calculated. The data file achieved was analyzed using methods of multiple regression by means of statistical program Unistat. The reciprocal temperature and impact of chemical composition, expressed with miscellaneous formulae, were chosen as independent variables. For this purpose also formulae for prediction of temperature of liquidus, as a function of contents of selected chemical elements in steel, were used. It was proved that these functions were closely associated with the nickel equivalent, which was chosen in the end as the second independent variable because of its simple construction as well as for the highest attained closeness of predicted results to initial data. The resulting regression model has then the form as follows:

$$m = 0.344 - 325/T + 0.00276 \cdot E_{Ni}, \tag{7}$$

where T [K] is forming temperature and the nickel equivalent is defined by relation (6).

As a matter of fact, temperature influence at all selected steels was averaged out and the initial function of type (2) was enlarged by simply expressed influence of chemical composition. Table 3 gives evidence for justification of this procedure. In this table only values of coefficient m for selected steels, determined based on experiment or calculated according to equation (7), are given. It is evident that accuracy of the resulting equation is quite sufficient for the purpose of prediction of deformation resistance in relation to changing strain rate.

TABLE 3

Comparison of experimentally determined and predicted values of coefficient m for steels S1 – S33 (after elimination of selected types of steel – see designation (+) in Table 2)

	E_{Ni}	m (900 °C)		m (1000 °C)		m (1100 °C)	
		experiment	Eq. (7)	experiment	Eq. (7)	experiment	Eq. (7)
S1	5.38	0.118	0.082	0.130	0.104	0.139	0.123
S2	3.69	0.074	0.078	0.088	0.099	0.100	0.118
S3	6,18	0.071	0.084	0.113	0.106	0.148	0.125
S4	3.79	0.101	0.078	0.114	0.100	0.126	0.118
S5	11.62	0.097	0.099	0.105	0.121	0.112	0.140
S6	21.73	0.127	0.127	0.161	0.149	0.190	0.168
S8	9.30	0.100	0.093	0.115	0.115	0.129	0.133
S10	0.54	0.083	0.069	0.108	0.091	0.130	0.109
S13	12.21	0.097	0.101	0.123	0.123	0.145	0.141
S14	7.66	0.072	0.089	0.087	0.110	0.100	0.129
S15	11.70	0.121	0.100	0.136	0.121	0.148	0.140
S16	13.43	0.089	0.104	0.103	0.126	0.116	0.145
S27	3.94	0.070	0.078	0.094	0.100	0.115	0.119
S28	3.65	0.069	0.077	0.105	0.099	0.136	0.118
S29	0.40	0.037	0.068	0.070	0.090	0.097	0.109
S32	8.12	0.094	0.090	0.106	0.112	0.117	0.130
S33	12.16	0.098	0.101	0.130	0.123	0.157	0.141

4. Conclusions

a) It is necessary to alert that the equation (2) may always be applied only to description of strain behaviour of particular steel in the region of qualitatively identical phase composition, most often in the region of austenite. In case that the given steel exhibits the phase transformation (e.g. austenite/ferrite), validity of the derived relation is principally limited to the temperature region above temperature A_{r3}. It was proved by research of strain behaviour of ELC steel that the tendency of temperature relationship $m = f(T^{-1})$ is analogous in the austenitic and ferritic region, but quite opposite in the two-phase region of co-existence of austenite and ferrite.

b) Experiments showed only very weak impact of grain size on strain behaviour of corrosion-resistant austenitic steel. Adaptive control of rolling mills can normally work with deviations of real vs predictable values of mean deformation resistance or rolling force by more than 10 %. From this point of view it is rightful to neglect at calculations in practice the impact of grain size on the value of strain-rate sensitivity and forming force as well.

c) Constants in the equation of type $m = D - F/T$, describing impact of reciprocal forming temperature on strain-rate sensitivity, were expressed in numbers for totally 35 various types of steel by means of hot rolling. On one side general validity of the relationship formulated in such a way was confirmed, but on the other side efforts to express influence of chemical composition on material constants *D* and *F* failed. Nevertheless, it is interesting that these two variables are closely connected with each other – see the plot in Fig. 9.

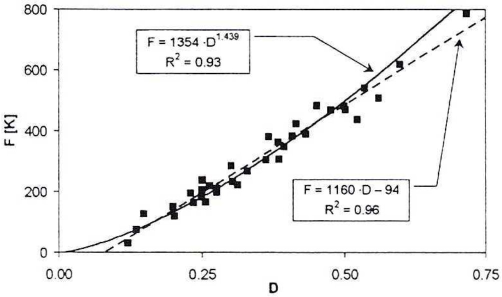

Fig. 9. Some mathematical formulations of the relation between variables *F* and *D* in equation (2)

d) It was shown that no universal equation describing the dependence of coefficient m on temperature and chemical composition can be found. Nevertheless, after elimination of certain types of steel from the initial data file, the relation of type $m = f(T^{-1}, E_{Ni})$ was formulated, in which chemical composition of the given material is represented by the simply defined nickel equivalent. The E_{Ni}-value represents the aggregative content of the austenite-forming elements in steel.

e) The resulting equation $m = 0.344 - 325/T + 0.00276\ E_{Ni}$ makes it possible to predict strain-rate sensitivity of deformation resistance of wide range of steels and can make a contribution to more precise calculations of forming forces, e.g. at computer control of rolling mills. The advantage of this equation consists in the fact that it was derived based on high-speed laboratory hot rolling tests. Strain rates up to 120 s^{-1} achieved during the tests (calculated simply according to [19]) were enabled thanks to application of newly built laboratory rolling mill Tandem [20].

f) It should be emphasized that equation (7) may be applied only to description of deformation behaviour of carbon steels (hypoeutectoid, including microalloyed) and low-alloyed steels (with total content of alloying elements up to 5 %, but with silicon content below 1.3 %). In case that the given steel exhibits phase transformation (e.g. austenite/ferrite), validity of the derived equation (7) is exclusively limited to the region above temperature A_{r3}.

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REFERENCES

[1] Y. Maehara, Scripta Metallurgica et Materialia **26**, 11, 1701 (1992).
[2] J. Jaipal et al., The Biennial Materials Conference of The Institute of Materials Engineering. Wollongong University Press **2**, 541 (1998).
[3] A. Gilat, X. Wu, International Journal of Plasticity **13**, 6–7, 611 (1997).
[4] S. Venugopal, S.L. Mannan, Prasad, YVRK. Materials Science and Engineering A A160, 1, 63 (1993).
[5] WD MacDonald, GJC Carpenter, S. Saimoto, Materials Science and Engineering **A 190**, 1–2, 33 (1995).
[6] JL Song, PL Blackwell, Materials Science and Technology **15**, 11, 1285 (1999).
[7] SC Lee, YH Kim, YD Lee, Journal of Materials Processing Technology **123**, 1, 185 (2002).
[8] H. Kim, SI. Hong, MH. Seo, Journal of Materials Research **16**, 3, 856 (2001).
[9] C. Park, SR. Nutt Materials Science and Engineering A **323**, 1–2, 358 (2002).
[10] HD. Espinosa, AJ. Patanella, M. Fischer, Journal of Tribology (Transactions of the ASME) **122**, 4, 834 (2000).
[11] M. Radina et al., FORMING 99. Katowice Silesian Technical University; 1999.
[12] I. Schindler, et al. Hutnicke Listy **56**, 6–7, 67 (2001).
[13] I. Schindler, E. Hadasik, Journal of Materials Processing Technology 106, 1–3,132 (2000).
[14] I. Schindler, et al. The 6th International Conference on Technology of Plasticity. Berlin : Springer-Verlag, 1, 449 (1999).
[15] M. Radina, et al. FORMING 2000. Katowice Silesian Technical University, 137 2000.
[16]I. Schindler, et al. METAL 2000. Ostrava 58, Tanger; 2000.
[17] L. Smrha, Tuhnuti a krystalizace ocelovych ingotu. Praha. SNTL, 1983.
[18]V. Pilous, K. Löbl, K. Stransky, Navary a svarove spoje konstrukcnich oceli. Vodni stavby Praha. Plzen, 1993.
[19] NN. Krejndlin, Raschot obzhatij pri prokatke. Moskva, Metallurgizdat, 1963.
[20] http://www.fmmi.vsb.cz/model/

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