A NEW MATHEMATICAL MODEL DETERMINATING THE FORMING FACTOR

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NOVÝ MATEMATICKÝ MODEL URČUJÍCÍ TVÁŘECÍ FAKTOR

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Abstrakt

Tvářecí faktor Q_{Fv} charakterizuje vliv středního napětí působícího na stykové ploše mezi válcovaným kovem a pracovními válci v pásmu deformace a ve směru válcování na velikost válcovací síly. Tvářecí faktor Q_{Fv} umožňuje převést hodnotu přirozeného deformačního odporu σ_e, získanou například pomocí plastometrického měření, na válcovací sílu a predikovat zatížení při vlastním tváření. Všeobecně lze konstatovat, že hodnota Q_{Fv} je závislá na tvaru a geometrii provalku ve válcovací mezeře, na deformačních podmínkách a podmínkách tření mezi provalkem a pracovními válci. Třecí podmínky ve válcovací mezeře jsou ovlivňovány drsností a tvrdostí pracovních válců, povrchem zokujeného povrchu provalku, teplotou provalku, rychlostí válcování a dalšími faktory. U vyhodnocování pro konkrétní válcovací stolici předpokládáme, že hodnota součinitele tření μ_{vs} je v průběhu válcování konstantní a lze ji zanést přímo do hodnoty válcovacího faktoru Q_{Fv}. Pro tento experiment bylo nutné provést v plastometrické laboratoři Výzkumu a vývoje, Vítkovice spol. s r. o. spojité krutové zkoušky a válcování plochých vzorků na laboratorní válcovací stolici TANDEM v Ústavu modelování a řízení tvářecích procesů. Srovnáním takto získaných středních deformačních odporů mohl být odvozen nový model tvářecího faktoru na válcovací stolici s uvažováním geometrických parametrů válcování. Byly zkoumány dvě uhlíkové oceli dle normy ČSN 11 523, resp. 12 040 a dvě korozivzdorné oceli ČSN 17 251, resp.17 153. Nový model tvářecího faktoru byl odvozen v závislosti na širokém rozsahu geometrických poměrů l'_d / h_m.

Abstract

The forming factor Q_{Fv} highlights influence of the mean stress exerting on the contact surface between the rolled metal and work rolls in the roll bite and in the rolling direction on the roll force size. The forming factor Q_{Fv} enables conversion of the equivalent stress σ_e value, obtained e.g. by means of plastometric measurements, to the roll force and predict load in forming. Generally, the Q_{Fv} value is influenced by shape and geometry of the rolling stock in the roll gap, deformation conditions and friction conditions between the rolling stock and work rolls. Friction conditions are affected by roughness and hardness of work rolls, scaled surface of the

rolling stock, temperature of the rolling stock, rolling speed and other factors. In evaluation for a particular mill stand we suppose that a value of the friction coefficient μ_{vs} is constant in the course of the rolling process and may be directly integrated into the forming factor Q_{Fv}. For determination of the forming factor it was necessary to carry out continuous torsion tests in the plastometric laboratory of Research and Development of Vítkovice and rolling of flat samples in the laboratory rolling mill Tandem in the Institute of Modelling and Controlling of Forming Processes. Comparing the obtained values of mean stress, forming factor for the applied rolling mill could be developed as a function of geometrical parameters of rolling. The experiment was carried out with samples from steel grades ČSN 11 523, 12 040, 17 153 and 17 251. A new model for the forming factor was developed in dependence on a wide range of values of aspect ratio l'_d / h_m.

Keywords: hot flat rolling, forming factor, torsion test, mean equivalent stress, rolling force

1. Introduction

Deformation resistance is defined like internal resistance of the material, acting against effect of external forces which try to bring about a shape change of the given body. The given stress can be oriented towards the contact surface in both normal and tangential direction. As this stress varies along the whole contact surface, so called mean deformation resistance is determined for power and force calculations. The mean deformation resistance σ_m [MPa] may be expressed as a product of the mean equivalent stress σ_{em} [MPa] and the forming factor Q_F:

$$\sigma_m = \sigma_{em} \cdot Q_F \tag{1}$$

The equivalent stress σ_e is conventionally defined like resistance of the metal against its deformation in uniaxial tension state and monotonous strain. So for the given material it is a function of thermodynamic factors [1]

$$\sigma_e = f(T, \varepsilon, \dot{\varepsilon}) \tag{2}$$

where T [K] temperature, ε [-] strain size and $\dot{\varepsilon}$ [s^{-1}] strain rate, and further it depends on metallurgical factors (chemical composition, structural state, grain size).

During normal (conventional) forming operations - e.g. in rolling - the formed metal is deformed by a variable reduction size with variable strain rate and often also with variable forming temperature – which means that various values of the local equivalent stress occur in each place of the contact surface. However, knowledge of the resulting effect, i.e. of mean equivalent stress, is required for obtaining force conditions. The mean equivalent stress is defined as follows:

$$\sigma_{em} = \frac{1}{e_1} \cdot \int_0^{e_1} \sigma_e(e) \cdot de \tag{3}$$

The mean equivalent stress represents deformation behaviour during the whole course of draught with size of e_1.

2. Materials and experimental methodics

2.1 etermination of equivalent stress by torsion test

The hot torsion test belongs to most used methods of determination of mean equivalent stress and formability of steels. Plastic properties of the material are deduced from a number of twists of the test bar leading to rupture, mechanical properties are deduced from the torque. The torsion test has advantages against other formability tests. It makes it possible to reach extreme degrees of deformation, with exclusion of an influence of the external friction. A wide use of this test is also beneficial.

Torsion test specimens have a cylindrical shape, one end is clamped in a fixed jaw, the other in a rotating jaw. The torque is detected from the fixed jaw. The rotary jaw is in longitudinal direction of testing either shiftable or firmly gripped. Requirements for investigation of metallurgical/physical processes in plastic deformation or simulation of forming processes cause increased demands on accuracy and stability of testing parameters and, above all, on control of processes in time. The high sensitivity to plastic properties enables use of the torsion test also for steels with high formability, where tension, impact or compression tests do not provide required results. The sample shape for the torsion test is illustrated in Fig. 1.

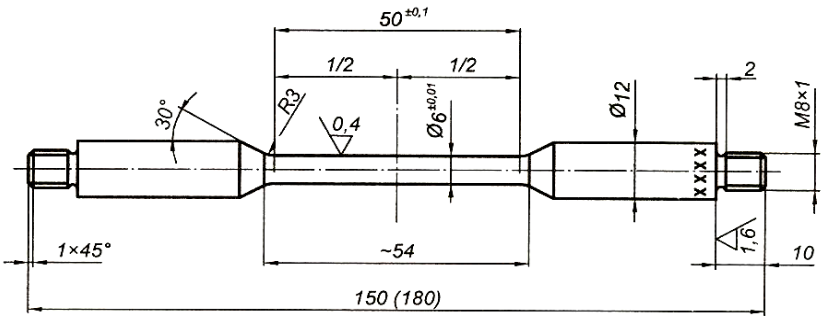

Fig.1 Shape and dimensions of samples used for hot torsion tests.

In collaboration with the plastometric laboratory at Vítkovice an original model for description of equivalent stress σ_e [MPa] of steel in hot forming was derived, taking into consideration dynamic softening [2, 3].

$$\sigma_e = A \cdot e^B \cdot \exp\left(-B \cdot \frac{e}{e_p}\right) \cdot \dot{e}^{\left(D - \frac{F}{T}\right)} \cdot \exp(-G \cdot T) \tag{4}$$

where e - true strain [-], e_p - strain to peak [-], $\dot{e}$ - strain rate [s^{-1}], T - temperature [K], A, B, D, F, G - material constants.

The term e^B represents hardening, the exponential term that includes variables e and e_p reflects dynamic softening processes (most frequently recrystallization). The deformation temperature influences the deformation resistance value twice. The direct temperature effect is expressed in the term *exp(-GT)*. The *T*-value appears also in the strain rate term because strain rate influences the s-value more markedly at high temperatures.

The experiment was carried out with samples from steel grades ČSN 11 523, 12 040, 17 153 and 17 251, chemical composition of which is given in Tab. 1. For each of these materials a model of equivalent stress in the expression according to relation (4) was derived, based on continuous torsion tests. From these torsion tests values of mean equivalent stress σ_{em-t} may be calculated by integration and then compared with values of mean deformation resistance σ_{m-r}, obtained by rolling in analogous conditions.

Table 1 Chemical analysis of the investigated steels in wt. %

ocel ČSN	C	Mn	Si	P	S	Cr	Ni	Mo	V	Cu	Al
11 523	0,16	1,28	0,20	0,015	0,004	0,06	0,02	-	-	0,08	0,03
12 040	0,36	0,63	0,21	0,009	0,016	0,05	0,02	-	-	0,09	0,01
17 153	0,05	0,42	0,79	0,03	0,005	24,87	1,0	0,21	0,06	0,07	0,04
17 251	0,12	0,90	1,65	0,03	0,011	19,98	12,14	0,37	0,05	0,25	0,04

2.2 Rolling in Tandem mill

Flat samples were rolled with a various reduction size at various forming temperatures. The initial height of individual samples varied in the range of 4 - 30 mm. For reaching of a wide range of the aspect ratio l_d/h_m, height reductions in the range of 10 – 50 % were realized, according to power possibilities of the laboratory mill TANDEM [4]. The aspect ratio l_d/h_m includes roll geometry and adjustment of the roll gap and may be determined as follows:

$$\frac{l_d}{h_m} = \frac{2 \cdot \sqrt{R \cdot (h_0 - h_1)}}{h_0 + h_1} \tag{5}$$

where R - roll radius [mm], h_0 - initial height [mm], h_1 - height after rolling [mm].

Each sample was measured (height h_0, width b_0) and heated in an electric resistance furnace to a forming temperature (850 to 1200 °C). Heated samples were immediately after discharging the furnace rolled in one pass in stand A of the laboratory mill Tandem. Roll forces and the actual speed of roll rotation were computer-registered. After each pass also dimensions of the rolling stock were measured. In case of the carbon steel rolled at high temperatures a loss of scale was compensated by decrease in initial size of the sample.

For higher stress values the elastic flattening of work rolls has to be taken into account. This phenomenon results in the fact that the radius of roll on the contact surface will be enlarged from R to R' and the value of the length of contact l_d [mm] will be enlarged to l'_d. In hot rolling the impact of flattening is very high. For determination of the roll radius the roll flattening was considered according to formula [5]

$$R' = R \cdot \left(1 + \frac{16 \cdot \left(1 - 0{,}27^2\right) \cdot F_v}{\pi \cdot 170000 \cdot b_m \cdot \left(h_0 - h_1\right)}\right) \tag{6}$$

where F_v – roll force [N], R – roll radius [mm], b_m – mean width of the rolled stock.

Based on obtained data the strain e_h, mean strain rate $\dot{e}$ and mean deformation resistance σ_{m-r} were calculated (7).

$$\sigma_{m-r} = \frac{F_v}{l'_d \cdot b_m} \tag{7}$$

2.3 Determination of the forming factor

The mean equivalent stress σ_{em-t} was calculated by subsequent integration according to the equation (3).

The value of the forming factor Q_{Fv} (8) for each sample was calculated by means of the mean deformation resistance achieved from roll forces σ_{m-r} (7) and mean equivalent stress σ_{em-t} (3).

$$Q_{Fv} = \frac{\sigma_{m-r}}{\sigma_{em-t}} \tag{8}$$

By means of non-linear regression the relationship of the experimentally determined forming factor in relation to the aspect ratio l'_d / h_m was expressed:

$$Q_{Fv} = 1{,}35 \cdot \exp\left(-1{,}349 \cdot \frac{l'_d}{h_m}\right) + \exp\left(0{,}287 \cdot \frac{l'_d}{h_m}\right) - 0{,}67 \tag{9}$$

In Fig. 2 values of the forming factor related to aspect ratio for particular types of steel are seen, as well as dependence of Q_{Fv} based on the equation created by the authors of this paper for the mill stand A.

3. Conclusions

We determined values of the forming factor for mill stand A from values measured in rolling of flat products from steel grades ČSN 11 523 [6], 12 040, 17 251 and 17 153 in the laboratory rolling mill Tandem and from a model describing deformation behaviour of these steels on the basis of torsion tests.

These values were related to the aspect ratio l'_d / h_m. The resulting equation describes with good accuracy the function $Q_{Fv} = f(l'_d / h_m)$ in the whole range of applied temperatures and deformations, regardless of friction coefficient.

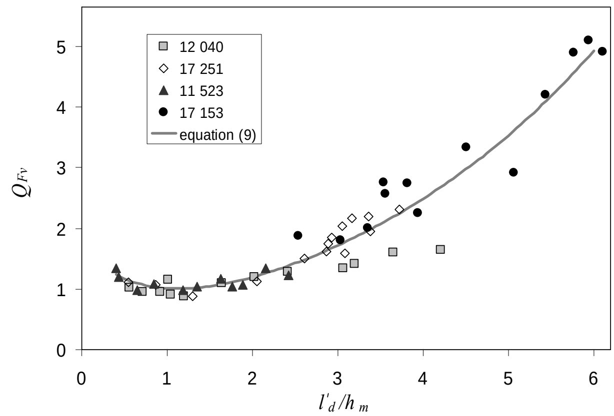

Fig.2 Graphic expression of the relationship between the forming factor of the stand A of laboratory mill Tandem and aspect ratio l'_d / h_m

A new mathematical model that includes a wider range of aspect ratio l'_d / h_m was created, up to values of $l'_d / h_m = 6$. For values of $l'_d / h_m > 4$ the experiment was implemented with stainless steel grades 17251 and 17153, namely for the reason of lesser extent of scaling of thinner samples.

The newly derived equation (9) was compared with the equation (10) mentioned below, which had been derived earlier [7] for the range of lower values of the aspect ratio l'_d / h_m. As it can be seen in Fig. 3 both equations give very similar results for the range of l'_d / h_m 1.1 to 2.4. Just this range of the geometric factor (aspect ratio) we use for rolling of samples with graded-in-size thickness in the mill Tandem.

$$Q_{Fv} = 4{,}0483 - 4{,}7198 \cdot \exp\left(-0{,}0842 \cdot \frac{l'_d}{h_m}\right) + \exp\left(0{,}2475 \cdot \frac{h_m}{l'_d}\right) \qquad (10)$$

This rolling serves for recalculation of roll forces to mean equivalent stress and their subsequent description in dependence on deformation conditions [8].

It stands to reason that the older model (10) describes the forming factor better for values of parameter $l'_d / h_m < 1$. On the other side, its accuracy is adversely influenced by values of $Q_{Fv} = f(l'_d / h_m)$ determined earlier during rolling of thin samples from carbon steel ČSN 12040. In these cases influence of scaling of samples was pronounced relatively stronger than in rolling of samples with bigger thickness.

Accuracy of description of the relationship $Q_{Fv} = f(l'_d / h_m)$ by one equation in such wide range is worse and therefore it is better to derive the equation for narrower ranges of the given geometric factor, which correspond to specific conditions of the given rolling mill.

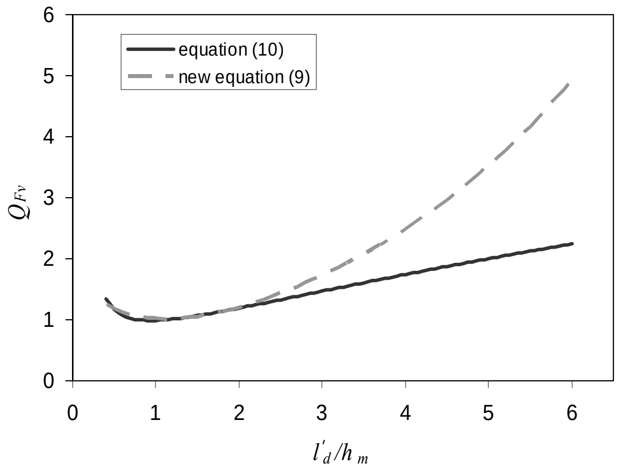

Fig.3 Graphic comparison of two equations for determination of the forming factor value for $l'_d / h_m < 6$

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