INFLUENCE OF HEATING REGIME AND PHASE TRANSFORMATIONS ON DEFORMATION RESISTANCE OF IF STEEL

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VLIV ZPŮSOBU OHŘEVU A FÁZOVÝCH PŘEMĚN NA DEFORMAČNÍ ODPORY IF OCELI

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Abstrakt

Cílem prací bylo popsat deformační odpory předem austenitizované IF oceli s titanem v širokém teplotním intervalu, a to jednou komplexní rovnicí. Střední přirozené deformační odpory byly zjišťovány originální metodou, založenou na laboratorním válcování plochých vzorků s odstupňovanou tloušťkou, měření a přepočtu válcovacích sil. Vzorky byly nejdříve ohřívány na jednotnou teplotu 1120 °C a poté volně ochlazovány na tvářecí teplotu. Jednotlivé modely popisující deformační odpor byly odvozeny pro tři teplotní oblasti – ferit, ferit + austenit, resp. austenit. Tyto modely popisují experimentální data získaná v širokém rozsahu deformačních podmínek s dobrou přesností. Jejich integrací do součtové funkce byl získán jednotný model středních přirozených deformačních odporů reflektující vliv tvářecí teploty, deformace, deformační rychlosti a fázového složení na deformační odpor zkoumané IF oceli. Jednotlivé členy v této funkci jsou násobeny koeficienty 1 nebo 0 v závislosti na aktuální teplotě. Výpočet těchto koeficientů musel reagovat na ostré přechody hranic jednotlivých fázových oblastí. Nová součtová funkce byla rovněž porovnána s obdobnou rovnicí získanou dříve po ohřevu vzorků přímo na tvářecí teplotu.

Odvozený jednotný model středních přirozených deformačních odporů může být využit při off-line predikci energosilových parametrů tváření dané oceli, a to pro tváření za tepla i polotepla. Získaná data potvrdila teoretické předpoklady o poklesu deformačního odporu nízkouhlíkových ocelí vlivem výskytu měkčího feritu. Nízký deformační odpor feritu ve srovnání s austenitem může být výhodně využit při feritickém válcování IF oceli.

Abstract

The goal was to describe by a complex equation deformation resistance of a preheated Ti-IF steel in the wide temperature range. The mean flow stress was determined by an original procedure, based on laboratory rolling of flat samples and measurement of the rolling forces. The samples were austenitized at temperature 1120 °C and then air-cooled to the forming temperature. Separate models describing deformation resistance were developed for three temperature regions – ferrite, ferrite + austenite, or austenite. These models describe experimentally obtained data in the applied wide range of deformation conditions with a good accuracy. By their integration in the cumulative function a unique model was developed that reflect influence of temperature, strain, strain rate and phase composition on deformation resistance of the investigated IF steel. Particular members in this cumulative function are multiplied by coefficient 1 or 0, in dependence on a specific temperature. Calculation of specific coefficients had to be proposed in such a way so that they could react to surpassing of temperature boundaries between individual phase regions. The new cumulative function was compared with those obtained after direct heating of samples to the forming temperature.

The integrated model can be used in off-line predictions of power/force parameters of forming of Ti-IF steel, in a wide range of conditions of hot and warm deformation. Achieved data confirmed theoretical assumptions about decrease in deformation resistance due to occurrence of the softer ferrite phase in low carbon steels. Relatively low deformation resistance of ferrite can be utilized favourably in ferritic rolling of IF steel.

Keywords: IF steel, deformation resistance, phase transformation, ferritic rolling

1. Introduction

Interstitial-free (IF) steels have become important materials in the automotive industry due to their very good pressability. At a glance at recently issued selected publications one can be assured that research works performed in the given area are up-to-date. Their topics are e.g. ferritic rolling [1,2], dynamic recrystallization of ferrite [3], investigation of deformation resistance [4], plastic properties in cold state [5], or special methods of forming such as accumulative roll-bonding [6]. The goal of own research was to develop a mathematical model describing influence of temperature, strain, strain rate and phase composition on deformation resistance of a Ti-IF steel. Unlike the former laboratory works, which were focused on deformation behaviour of this material after heating directly to the rolling temperature [7], this time samples were austenitized first of all.

2. Research techniques

The IF steel, with the following chemical composition in wt. %, was investigated: 0.004 C, 0.13 Mn, 0.008 Si, 0.008 P, 0.009 S, 0.041 Al, 0.003 N, and 0.072 Ti. All calculations of MFS were realized on the basis of a methodology described earlier [8-10], based on the computer registration of forces that arise during rolling of flat samples with graded in thickness (4.6 mm, 5.4 mm, or 6.5 mm). The samples were austenitized at temperature 1120 °C and then air-cooled to the forming temperature, which was controlled by a pyrometer. Soaking of the sample on the required forming temperature followed. The samples heated in this way were rolled in the two-high stand A of the computer-controlled laboratory mill Tandem [11]. Rolls with diameter of 158 mm rotated with nominal speed in the range of 40 to 400 rpm. Roll forces and instantaneous revolutions of rolls were recorded by computer.

Mean flow stress is calculated from the measured roll force F [N] as follows [12]:

$$\sigma_m = \frac{F}{Q_{Fr} \cdot \sqrt{R \cdot (H_0 - H_1)} \cdot B_m} \tag{1}$$

where Q_{Fr} is a forming factor, corresponding to a specific rolling mill stand, and B_m [mm] is mean width of the rolling stock in a given place (an average value of the width before and after rolling). The member $\sqrt{R \cdot (H_0 - H_1)}$ represents contact length of the roll bite.

Credibility of calculation of MFS is influenced most of all by an exact estimate of the forming factor, which – as matter of fact – transfers deformation resistance to values of equivalent stress (i.e. of that which corresponds to a defined uniaxial stress state). Values of Q_{Fr} for both stands of the rolling mill Tandem were obtained by previous research and they are described in relation to aspect ratio l_d/H_m – see [10]; H_m [mm] is mean thickness in a given place. Model for mean flow stress (MFS) σ_m [MPa] was developed afterwards, in dependence on the temperature T [°C], equivalent strain ε and mean equivalent strain rate γ[s^{-1}] defined as [13]:

$$\varepsilon = \frac{2}{\sqrt{3}} \cdot \ln\left(\frac{H_0}{H_1}\right) \tag{2}$$

$$\gamma = \frac{2}{\sqrt{3}} \cdot \frac{v_r}{\sqrt{R \cdot (H_0 - H_1)}} \cdot e_h \tag{3}$$

where H_0, or H_1 [mm] is entry, or exit thickness of the rolling stock in a given place; v_r [mm/s] is real circumferential speed of rolls with radius R [mm].

3. Mathematical processing of experimental data

All values of σ_m achieved by rolling of described samples are plotted in a graph in Fig. 1 depending on temperature. The apparently huge scattering of experimental data is given by the fact that these values are significantly influenced also by various strains (from 0.23 to 0.72) and strain rates (from 14 to 100 s^{-1} in these specific experiments).

The mean flow stress could not be described in the whole temperature range by a simple equation. Therefore particular models for individual temperature regions had to be developed by means of a multiple non-linear regression analysis in the statistic software UNI-STAT 5.5 [14]. As a basis the proved model was chosen, which is of type as follows:

$$\sigma_m = A \cdot \varepsilon^B \cdot \gamma^C \cdot \exp(-D \cdot T) \tag{4}$$

where A ... D are material constants. The following final equations were reached:

$$\sigma_{m(F)} = 1520 \cdot \varepsilon^{0.24} \cdot \exp(-0.0027 \cdot T) \quad \text{(for the ferrite region)} \tag{5}$$

$$\sigma_{m(A)} = 2579 \cdot \gamma^{0.09} \cdot \exp(-0.0031 \cdot T) \quad \text{(for the austenite region)} \tag{6}$$

A part of the non-linear regression analysis was testing of statistic significance of determined parameters of the regression function. Applying the regression model in the ferrite region resulted in a conclusion that in the given temperature range the MFS is affected (and this influence is statistically significant) only by temperature and strain rate. At the same time this test proved that influence of deformation on variable σ_m is not on significance level α = 0.05 statistically significant, and therefore a relevant member was excluded from the regression model (see Eq. 5). The achieved value of correlation index for the final regression model was 0.979. Values of residua did not go beyond 8 % and they exhibited homoscedasticity in relation to temperature and strain rate.

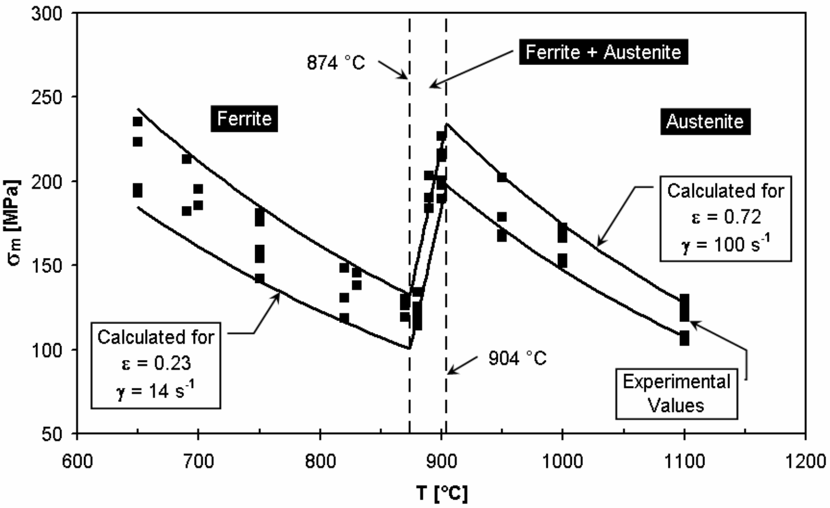

Fig.1 Dependence of MFS on temperature, gained by rolling of flat samples (see Eq. 1) or by calculation according to Eq. 9 for boundary values of strain and strain rate

Application of the regression model in the austenite region led to a conclusion that in the given temperature range the MFS is in a statistically significant way affected only by temperature and deformation. In this case the test proved that influence of strain rate on variable σm is not on significance level α = 0.05 statistically significant and a relevant member could be excluded from the regression model (see Eq. 6). The achieved value of correlation index for the final regression model was 0.969, which means again a very good degree of correlation. Values of residua did not surpass 9 % and again, they exhibited homoscedasticity in relation to temperature and strain rate.

A complicated task was finding an appropriate regression model for description of the relationship in the two-phase ferrite-austenite region. The regression model according to Eq. 4 proved to be inapplicable, even in a simplified form. Virtually the only suitable function in the given temperature region proved to be a linear dependence of deformation resistance on temperature; influence of other parameters proved to be statistically insignificant. However, this solution did not make it possible to take into account influence of these parameters, which was proved in the ferrite and austenite regions.

An appropriate solution of description of the relation of the variable σ_m to temperature and other parameters proved to be use of the interpolation function. The speech is essentially about the linear interpolation between values of MFS, calculated for lower boundary temperature T_1 [°C] and upper boundary temperature T_2 [°C] of the two-phase region according to relations valid for the ferrite and austenite regions:

$$\sigma_{m(F+A)}(T) = \sigma_{m(F)}(T_1) + (T - T_1) \cdot \frac{\sigma_{m(A)}(T_2) - \sigma_{m(F)}(T_1)}{T_2 - T_1} \tag{7}$$

In this expression the influence of not only temperature but also deformation and strain rate is reflected because values of σ_m for particular boundary temperatures are calculated with using Eqs. 5 and 6. It was found out that closeness of this relationship to measured data is sufficient, even though worse than in case of relationships in the ferrite and austenite regions (index of correlation reaches the value 0.719). It is caused mainly by large steepness of the relationship, when a small change of temperature results in a pronounced change of MFS. The boundary temperatures of the two-phase region were determined analytically and corresponding values were T_1 = 874 °C and T_2 = 904 °C. After their substitution into Eq. 7 and using Eqs. 5 and 6 the following model of MFS for the two-phase region was derived:

$$\sigma_{m(F+A)} = 143.4 \cdot \varepsilon^{0.24} + (T - 874) \cdot \left(5.26 \cdot \gamma^{0.09} - 4.78 \cdot \varepsilon^{0.24}\right) \tag{8}$$

The final phase of the work was represented by an attempt to describe the intricate deformation behaviour of the tested steel by a single equation. After a large analysis a certain way was proposed in the end, which uses a cumulative function in which particular members are multiplied by coefficient 1 or 0, in dependence on a specific temperature. Calculations of specific coefficients had to be proposed in such a way so that they could react to surpassing of temperature boundaries between individual phase regions. Thus the resulting cumulative function has a form as follows:

$$\sigma_m = \frac{874.01 - T + |874.01 - T|}{2 \cdot (874.01 - T) + 1 \cdot 10^{-10}} \cdot \sigma_{m(F)} +$$

$$+ \left(\frac{T - 874 + |T - 874|}{2 \cdot (T - 874) + 1 \cdot 10^{-10}} - \frac{T - 904 + |T - 904|}{2 \cdot (T - 904) + 1 \cdot 10^{-10}} \right) \cdot \sigma_{m(F+A)} + \frac{T - 904 + |T - 904|}{2 \cdot (T - 904) + 1 \cdot 10^{-10}} \cdot \sigma_{m(A)} \tag{9}$$

where variables $\sigma_{m(F)}$, $\sigma_{m(F+A)}$, $\sigma_{m(A)}$ are deformation resistance values calculated according to Eqs. 5, 6 and 8 for individual phase regions. Invariable $1 \cdot 10^{-10}$ ensures that division by zero will not be possible. The transition between the ferrite and two-phase region to be smooth, it had to be solved also by a modification of the boundary temperature in a relevant part of the model – see value 874.01 °C.

4. Discussion of results

Two curves were plotted in the graph in Fig. 1, representing values σ_m calculated in the temperature range of 650 to 1100 °C for boundary values of deformation and strain rate, obtained in the course of laboratory rolling. Values ε = 0.23 and γ = 14 s^{-1} are considered to be minimum ones, values ε = 0.72 and γ = 100 s^{-1} maximum ones. The experimentally found out values σ_m, plotted in the relevant graph, belong to the region limited by particular calculated curves with a good reliability. Accuracy of the resulting model is therefore respectable. Values of deformation resistance, gained from roll forces and calculated backwards, differ from each other by 10 % at the maximum.

Figure 2 represents a 3D-map of MFS according to the developed integrated model. Dissimilar deformation behaviour of the investigated steel in the ferrite or austenite region is evident.

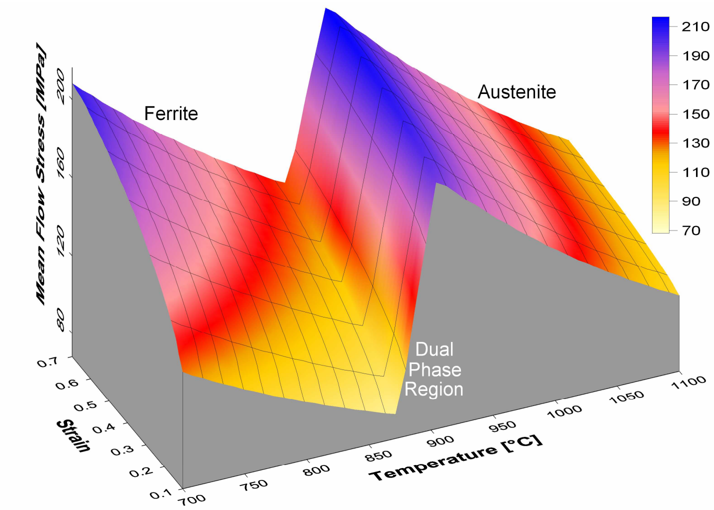

Fig.2 3D-map of MFS calculated according to Eq. 9 (circumferential speed of rolls with radius R = 160 mm was v_r = 1 m/s)

Of interest is comparison of deformation behaviour of the investigated IF steel after the former uniform austenitization, or after direct heating of samples to the forming temperature – see [7]. In another case the boundary temperatures of the two-phase region 917 °C and 959 °C were found out. This range is hence a little bit broader than in case of experiments described here, which enabled to define the relation of deformation resistance to temperature in the ferrite-austenite region by a regression relationship. Values σ_m after direct heating to rolling temperature could be described by the following equations:

$$\sigma_{m(F)} = 757 \cdot \varepsilon^{0.22} \cdot \gamma^{0.06} \cdot \exp(-0.0020 \cdot T) \quad \text{(for the ferrite region)} \qquad (10)$$

$$\sigma_{m(F+A)} = 0.02 \cdot \varepsilon^{0.19} \cdot \exp(0.0098 \cdot T) \quad \text{(for the two-phase region)} \qquad (11)$$

$$\sigma_{m(A)} = 619 \cdot \varepsilon^{0.16} \cdot \gamma^{0.08} \cdot \exp(-0.0015 \cdot T) \quad \text{(for the austenite region)} \qquad (12)$$

Influence of strain could not be neglected in any of these equations. Models of deformation resistance obtained after the uniform austenitization (see Eqs. 5, 6 and 8) exhibit more pronounced relations to temperature and nearly coincidentally mild relation to strain rate. Influence of heating of the material to the austenitization temperature 1120 ° resulted in an anticipated shift of transformation temperatures, as well as in change of deformation behaviour obviously by the different initial grain size as compared to the material which was heated directly to the forming temperature – see Fig. 3.

In the case of newly derived models an interesting chance for their simplification occurred, specifically for neglecting of the strain rate member in Eq. 5 or the strain member in Eq. 6. Similar results were registered previously, e.g. in rolling of HSLA steel [15] or various iron aluminides [16]. Evidently, the functional relationship between variables ε and γ is manifested here – see Eq. 3.

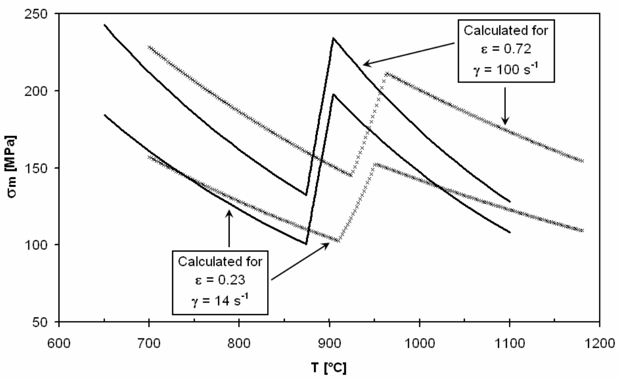

Fig.3 Comparison of MFS calculated according to the integrated model (Eq. 9 – solid lines) and Eqs. 10-12 (x-marks)

5. Summary

Separate models describing the MFS σ_m = f(ε, γ, T) were developed for three temperature regions (ferrite, ferrite+austenite, or austenite) – see Eqs. 5, 6 and 8. These models describe experimentally obtained data in the applied wide range of deformation conditions with a good accuracy. By their integration in the cumulative function – see Eq. 9 – a unique model was developed that reflect influence of temperature, strain, strain rate and phase composition on deformation resistance of the investigated IF steel.

The models of MFS applied according to Eqs. 5 and 6 could not be so simple when they should reflect even very small values of strain (in the area of sharp increase of the stress-strain curve). It is important as well that values of mean, and not actual, stress are described. Mainly thank to this fact a member representing influence of dynamic softening could be neglected.

The integrated model can be used with good results in off-line predictions of power/force parameters of forming of Ti-IF steel, in a wide range of laboratory and operational conditions of hot and warm deformation. So, knowledge of deformation behaviour of the investigated steel after its heating directly to rolling temperature [7] was completed in a suitable way.

Achieved data confirmed theoretical assumptions about decrease in deformation resistance due to occurrence of the softer ferrite phase in low carbon steels. Relatively low deformation resistance of ferrite can be utilized favourably in ferritic rolling of IF steel.

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