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MATHEMATICAL DESCRIPTION OF DEFORMATION RESISTANCE OF IF STEEL INCLUDING INFLUENCE OF PHASE TRANSFORMATIONS

IVO SCHINDLER[1], JIŘÍ PLURA[2], VLADIMÍR JURKO[3], STANISLAV RUSZ[1], PAVEL SUCHÁNEK[1], MARCEL JANOŠEC[1]

[1] VSB – Technical University of Ostrava, Institute of Modelling and Control of Forming Processes, 17. listopadu 15, 708 33 Ostrava, Czech Republic
[2] VSB – Technical University of Ostrava, Department of Quality Control and Assurance, 17. listopadu 15, 708 33 Ostrava, Czech Republic
[3] U. S. Steel Kosice, s.r.o., Vstupny areal U. S. Steel, 044 54 Kosice, Slovak Republic

Abstract

The aim of work was to describe by a single equation deformation resistance of IF steel with titanium in the temperature range of 700 to 1200°C, in relation to the forming temperature T, logarithmic height strain e_h and mean equivalent strain rate $\dot{e}$. The mean equivalent stress σ_m [MPa] was determined by an original procedure, based on laboratory rolling of flat samples with graded in thickness in the computer controlled mill Tandem. Values of σ_m were computed from values of the registered roll forces by means of a specially developed methodology that uses knowledge of a particular equation for description of the forming factor of the mill Tandem.

Due to an intended application of results in rolling at very low temperatures (in the ferrite region), the samples were heated directly to the forming temperature, which influenced the temperature boundaries between the ferrite region, a two-phase region ferrite + austenite and the austenite region. Coefficients A, B, C and D were calculated in a simple equation of type $\sigma_m = A\, e_h^{\,B}\, \dot{e}^{\,C} \exp(-D \cdot T)$ for each of the given temperature ranges.

A top phase of the work was represented by an attempt to describe the deformation behaviour 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.

Relative deviations of values σ_m, calculated on the basis of the gained universal equation back for conditions of the laboratory rolling, from values of the mean equivalent stress expressed directly from roll forces do not surpass ±10 % which may be considered to be good accuracy.

Key words: IF steel, laboratory rolling, phase transformation, statistic software, model of deformation resistance

1. INTRODUCTION

Interstitial-free (IF) steels have become important materials in the automotive industry due to their very good capability of being shaped in press. 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 (Wang et al., 2005), dynamic recrystallization of ferrite (Kim et al., 2005), investigation of deformation resistance (Lino & Barbosa, 2005), plastic properties, in cold state (Gupta & Kumar,

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2006), or special methods of forming such as accumulative roll-bonding (Costa et al., 2005).

The target 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-based IF steel.

2. APPLIED EXPERIMENTAL METHODS

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 – 0.072 Ti. Determination of temperatures of phase transformations was based on measurement of roll forces in the course of forming samples with initial thickness of 21 mm and width 40 mm. Samples were heated to temperature 1150°C in the resistance furnace and afterwards rolled in a set of up to 13 passes (each draught with a height reduction of ca 12%) and simultaneously cooled in free air. The surface temperature T of the rolling stock was measured before each partial reduction by infrared pyrometer and computer registered and evaluated, together with roll forces F. Reversible rolling was performed in the computer controlled laboratory mill K350. Rolls with diameter 140 mm rotated with nominal speed 100 rpm. The obtained time dependencies F(t) and T(t) are presented in figure 1. It can be deduced that the two-phase ferrite+austenite region of the studied material exists in the temperature region 880–910°C (at the applied experimental conditions).

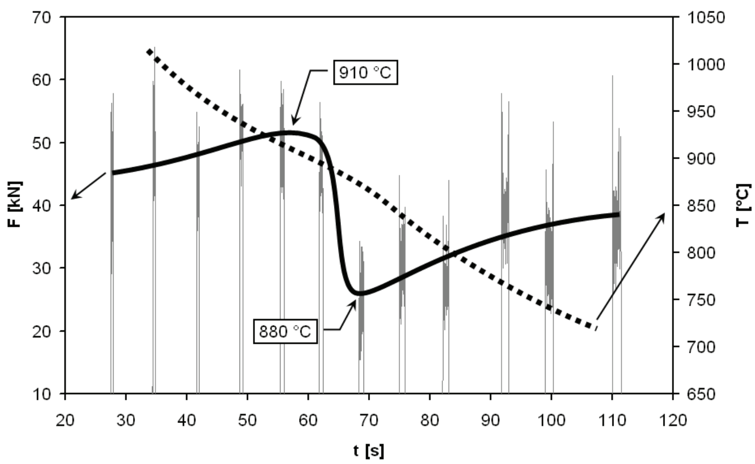

Fig. 1. *Influence of temperature and phase composition on roll forces (a dotted line – interpolated course of surface temperature; a thick solid line – interpolated course of roll forces).*

These results were verified by another method. The inner temperature of prisms with weight ca 1.5 kg and thickness 30–40 mm, which were cooled in free air, was computer registered. Holes with diameter max. 2.5 mm, reaching nearly a half of thickness, were drilled into these samples. Thermocouples of K type were inserted into the holes. After heating of samples, prepared in such a way, the samples with thermocouples were taken out of the furnace, put on a brick and their inner temperature was measured. The cooling speeds and temperatures of phase transformations, determined from changes in cooling curves, are given in graphs in figure 2 (where t is time [s], T is temperature [°C]). Agreement of the results obtained by both methods is notable.

Model for mean equivalent stress σ_m [MPa] was developed afterwards, in dependence on the logarithmic height strain e_h, mean equivalent strain rate $\dot{e}$ [s^{-1}] and temperature T [°C]. This development was realized on the basis of a methodology described earlier (Schindler et al., 2002; Schindler & Marek, 2004; Kratochvil & Schindler, 2004), based on the computer registration of forces F [kN] that arise during rolling of flat samples with graded in thickness. In this case the samples had the following dimensions: width of 25 mm, total length of 120 mm and thickness of individual stages of 4.6 mm, 5.4 mm, or 6.5 mm. The samples were heated in the resistance furnace directly to the forming temperature and subsequently rolled in the two-high stand A of the computer-controlled laboratory mill Tandem. Thorough information on the applied experimental technique can be found at web pages http://www.fmmi.vsb.cz/model/. During rolling the roll gap was differently adjusted in an appropriate way. 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. An example of registered roll forces is given in figure 3.

Deformation resistance was calculated from roll forces based on knowledge of a forming factor for a particular mill stand. For each step of the given sample, the roll force values were determined by the automated method. After cooling down of the rolling stock, width and thickness of individual steps were also measured; an advantage of the sample with thickness graded in size is the three times higher quantity of data achieved by its rolling at exactly defined temperature as compared with rolling of one flat sample with the constant thickness.

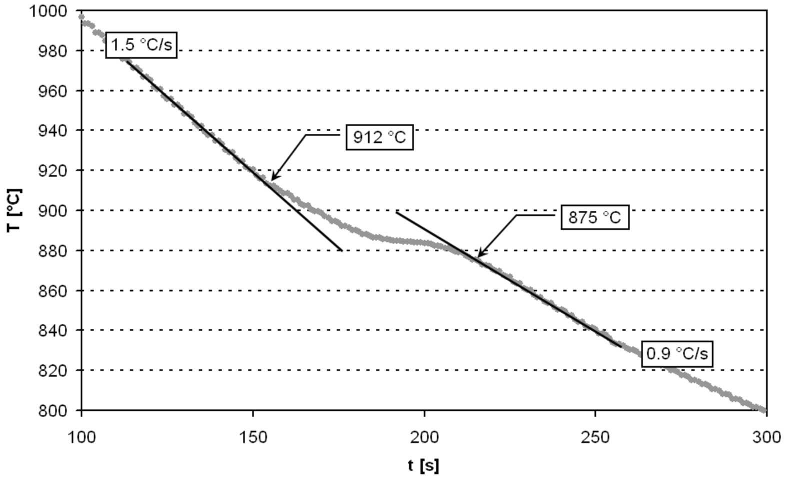

***Fig. 2.** Cooling curves for the IF steel, gained from the bored-in thermocouple.*

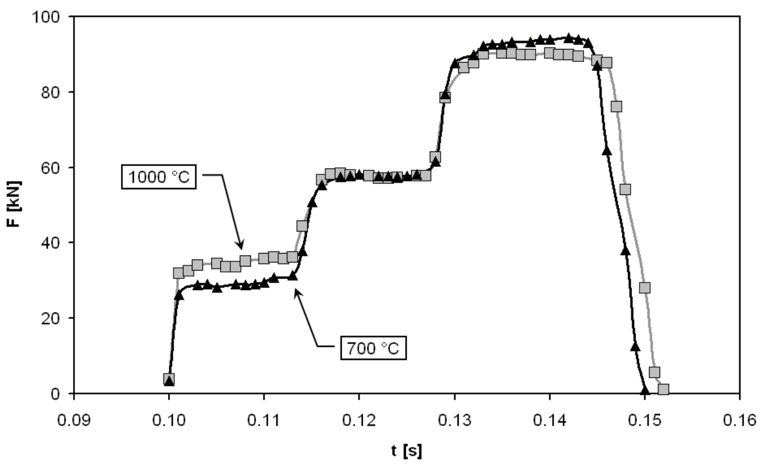

***Fig. 3.** Roll forces in relation to time during forming of two samples from IF steel (identical adjustment of roll gap 2.4 mm; rotation speed of rolls 400 rpm).*

All variables stated above were put down in the Excel table and recalculated by macros on values of strain and strain rate (according to Krejndlin, 1963). Mean equivalent stress σ_m [MPa] was calculated according to the equation

$$\sigma_m = \frac{F}{Q_{FR}\, l_d\, B_m} \qquad (1)$$

where Q_{FR} is forming factor corresponding to the particular mill stand, l_d [mm] is roll bite length and B_m [mm] is mean width in the given place of the rolling stock (the average of widths before and after rolling). Reliability of calculation of σ_m value is most influenced by accuracy of the estimate of the forming factor, which actually transfers pertinent values of deformation resistance to values of equivalent stress. Values of Q_{FR} for both stands of the mill Tandem were acquired and described by Rusz et al. (2005) in relation to geometric factor l_d/H_m by equation of type

$$Q_{FR} = J - K\, exp\left(-L\frac{l_d}{H_m}\right) + exp\left(M\frac{H_m}{l_d}\right) \qquad (2)$$

where J ... M are constants for the given facility, H_m [mm] is mean thickness of the rolling stock in the given place (the average of thicknesses of the given step before and after rolling).

3. MODEL OF DEFORMATION RESISTANCE

All values of σ_m achieved by rolling of described samples are plotted in a graph in figure 4. The apparently huge scattering of experimental data is given by the fact that these values are significantly influenced also by various strains and strain rates. Nonetheless, despite this fact a non-monotonous influence of temperature on deformation resistance, resulting from effects of various phase composition of the material, is obvious. The mean equivalent stress cannot be described in the whole temperature range by a single equation. Therefore particular models for three temperature regions had to be developed by means of a multiple non-linear regression analysis in the statistic software UNISTAT:

Ferrite (< 917°C):

$$\sigma_{m(F)} = 781 e_h^{0.22}\, \dot{e}^{0.064}\, exp(-0.0020T) \qquad (3)$$

Ferrite + Austenite:

$$\sigma_{m(F+A)} = 0.02 e_h^{0.19}\, exp(0.0098T) \qquad (4)$$

Austenite (> 959°C):

$$\sigma_{m(A)} = 639 e_h^{0.16}\, \dot{e}^{0.082}\, exp(-0.0015T) \qquad (5)$$

The temperature limits 917°C and 959°C (i.e. boundaries of the two-phase region, determined by mathematical analysis in the software Mathcad) do not exactly correspond to points of phase transformations, found out in cooling of the material because entry data for these models were gained after heating the steel immediately to the forming temperature. The virtually negligible dependence of deformation resistance on strain rate in the two-phase region represents an object of interest.

An idealized example of the temperature relationship of mean equivalent stress, computed according to equations (3-5), is also given in figure 4.

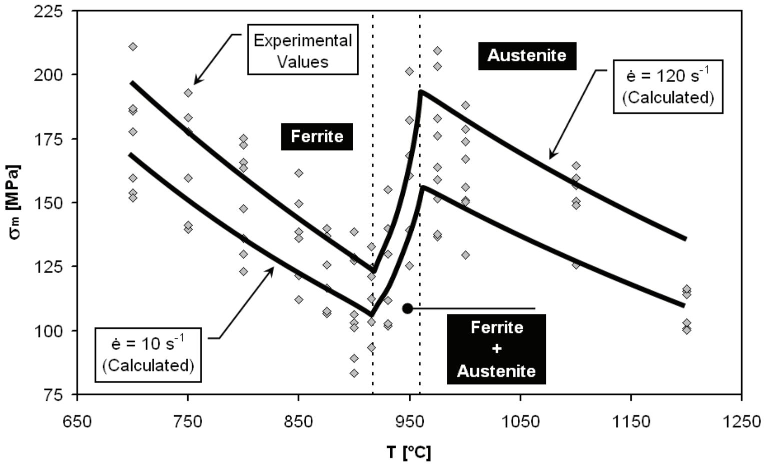

Fig. 4. *Temperature dependence of mean equivalent stress, gained by rolling of flat samples or by calculation according to equations (3-5) for strain* e_h *= 0.3 and selected values of strain rate* $\dot{e}$*.*

The final phase of the work was represented by an attempt to describe the deformation behaviour 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:

$$\sigma_m = \frac{(917-T)+|917-T|}{2(917-T)+1\cdot 10^{-10}}\sigma_{m(F)} + \left(\frac{(T-917)+|T-917|}{2(T-917)+1\cdot 10^{-10}} - \frac{(T-959)+|T-959|}{2(T-959)+1\cdot 10^{-10}}\right)\sigma_{m(F+A)} + \frac{(T-959)+|T-959|}{2(T-959)+1\cdot 10^{-10}}\sigma_{m(A)} \qquad (6)$$

where variables $\sigma_{m(F)}$, $\sigma_{m(F+A)}$, $\sigma_{m(A)}$ are deformation resistance values calculated according to equations (3-5) for individual phase regions; invariable $1\cdot 10^{-10}$ ensures that division by zero will not be possible.

Then values of „mathematical“ σ_m values according to equation 6 were recalculated for the given experimental conditions, including their relative errors Δ [%] in comparison with the „measured“ (i.e. from roll forces calculated) values:

$$\Delta = \frac{\sigma_{m(1)} - \sigma_{m(6)}}{\sigma_{m(1)}}100 \qquad (7)$$

where $\sigma_{m(1)}$ [MPa] is mean equivalent stress obtained from experimental results using equation (1); $\sigma_{m(6)}$ [MPa] is mean equivalent stress recalculated according to equation (6).

Using the values of relative errors reached in this way, their dependence on temperature, strain or strain rate could be designed and plotted in graphs in figure 5. From these graphs pertinent ranges of deformation conditions can be obtained: temperature 700–1200°C, strain 0.1–0.5 and strain rate 8–124 s^{-1}. Deviations of relative errors give good results of scattering. Calculated Δ values surpassed only exceptionally ±10%, which may be considered to be a good result in the applied wide range of deformation conditions.

4. CONCLUSIONS

Temperatures of phase transformations of the investigated IF steel with titanium were determined on the basis of measurements of roll forces during anisothermal and isothermal tests. Boundaries of the two-phase ferrite + austenite region correspond to temperatures 880°C and 917°C in the case of testing with continuously decreasing temperature of the sample (at average speed of 4°C/s), and to temperatures 917°C and 959°C after heating of the sample directly to a single forming temperature. Of course, these temperatures cannot be identical due to various experimental conditions.

Separate models describing the mean equivalent stress σ_m =f(e_h, $\dot{e}$, T) were developed for three temperature regions (ferrite, ferrite + austenite, or austenite) – see equations (3-5). These models describe experimentally obtained data in the applied wide range of deformation conditions with a very good accuracy. By their integration in the cumulative function – see equation (6) – a unique model was developed that describes influence of temperature, strain, strain rate and phase composition on deformation resistance of the investigated IF steel. This model does not reflect the possible complicating factor of deformation history (cumulative hardening due to incomplete softening during interpass pauses, etc.).

Due to complexity of the model its direct application in control systems of rolling mills is hardly presumable. With regard to the intended use of developed models in laboratory warm rolling (e.g. accumulative roll bonding), the experiments resulting in reaching of deformation resistance values were performed after heating the steel immediately to the forming temperature; this is hardly acceptable in the industrial rolling.

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 fer-

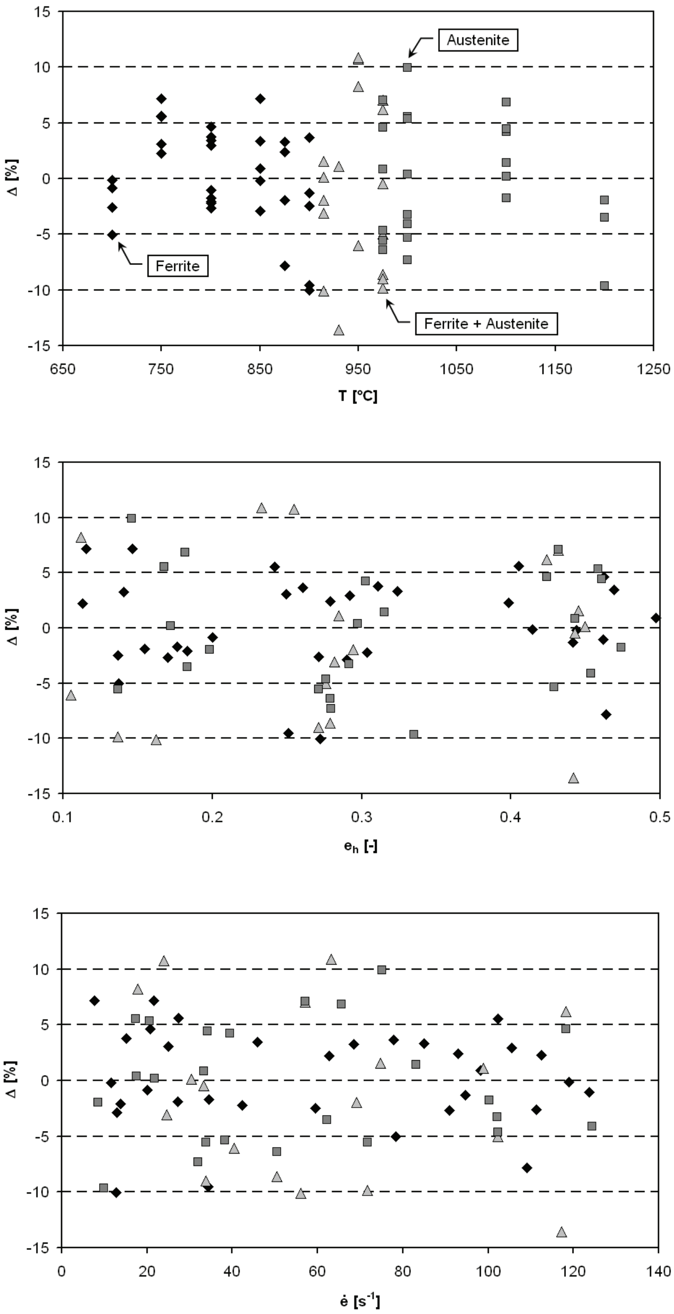

Fig. 5. Relative errors Δ of deformation resistance values calculated according to equation (7) and plotted in relation to temperature, logarithmic height strain and mean equivalent strain rate.

rite (see figure 3 for example) can be utilized favourably in warm (ferritic) rolling of IF steel.

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MATEMATYCZNY OPIS OPORU ODKSZTAŁCENIA STALI IF Z UWZGLĘDNIENIEM WPŁYWU PRZEMIAN FAZOWYCH

Streszczenie

Opracowanie pojedynczego równania opisującego opór stali IF z dodatkami tytanu w różnych temperaturach (od 700°C do 1200°C) z uwzględnieniem wpływu temperatury procesu, odkształcenia logarytmicznego e_h i średniej wartości intensywności odkształcenia ė jest tematem niniejszej pracy. Średnie wartości intensywności naprężenia σ_m zostały wyznaczone z testów walcowania próbek płaskich o zróżnicowanej wysokości na walcarce Tandem, bazując na zmierzonych siłach. Do obliczenia wartości σ_m z sił zastosowano opracowaną metodę wykorzystującą odpowiednie równania opisujące poszczególne parametry walcowania na walcarce Tandem.

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