SIMPLE MODELS DESCRIBING HOT DEFORMATION RESISTANCE OF SELECTED IRON ALUMINIDES

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JEDNODUCHÉ MODELY POPISUJÍCÍ DEFORMAČNÍ ODPORY VYBRANÝCH ALUMINIDŮ ŽELEZA ZA TEPLA

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Abstrakt

Byly vyvinuty jednoduché modely deformačních odporů aluminidů železa s obsahem 16,5 a 18,4 hm. % Al; 3,96 a 4,90 hm. % Cr v závislosti na teplotě a velikosti deformace. Bylo použito dvou chemicky obdobných taveb s různými obsahy Ti (0,24 a 0,61 hm. %) a B (0,089 a 0,070 hm. %). Jedna obsahovala přídavek TiB_2 prášku (velikost jehliček do 10 μm) a druhá přídavek Ti a B. Ze stochiometrických vztahů vyplývá, že intermetalické sloučeniny obsahují 28,9 at. % Al (IMC 1) a 31,7 at. % (IMC 4). K experimentu byly využity ploché vzorky s odstupňovanou tloušťkou. Výhoda použití těchto vzorků s odstupňovanou tloušťkou spočívá v trojnásobném množství získaných dat pro jednu definovanou tvářecí teplotu v porovnání s válcováním jednoduchých plochých vzorků s konstantní tloušťkou. Každý vzorek byl proměřen a následně ohříván v elektrické odporové peci na tvářecí teplotu (900 – 1200 °C). Každému vzorku byly měněny následující parametry: válcovací teplota, nastavení velikosti mezery mezi válci (tj. konečná deformace jednotlivých stupínků vzorku), nominální otáčky válců – z nich je odvozena deformační rychlost. Po vychladnutí provalku se změří šířka i tloušťka pro jednotlivé stupně vzorku. Deformační odpory byly přepočítány z hodnot válcovacích sil, jež byly změřeny na laboratorní trati Tandem na Ústavu modelování a řízení tvářecích procesů. Konkrétní hodnoty konstant modelu byly stanovovány metodami vícenásobné nelineární regrese, a to za využití statistického programu Unistat 5.5.

Abstract

The simplified models of deformation resistance of iron aluminides alloyed with 16.5 and 18.4 wt. % Al; 3.96 and 4.9 wt. % Cr were developed depending on temperature and strain. Two chemically similar melts with different content of Ti (0.24 and 0.61 wt. %) and B (0.089 and 0.070 wt. %) were studied. One with addition of TiB_2 powder (needles up to 10 μm) and the other with addition of Ti and B. It results from stoichiometric relations that the speech is about intermetallic compounds with 28.9 at. % Al (IMC 1), or with 31.7 at. % Al (IMC 4). For experiment the flat samples with graded in size thickness were used. An advantage of the sample with thickness graded in size consists in a three times higher quantity of data achieved by its rolling at exactly defined temperature as compared with rolling of one flat sample with a constant thickness. Each sample was measured and afterwards directly heated in an electric resistance furnace to the rolling temperature (900 – 1200 °C). For each sample the following parameters were changed: temperature, roll gap adjustment (i.e. total deformation of the particular step of the sample) and nominal revolutions of rolls – they determine the achieved strain rate. After cooling down of the rolling stock, width and thickness of individual steps were also measured. Deformation resistance was calculated from the rolling force values which were measured on laboratory mill Tandem. By means of the statistical software Unistat 5.5 and thanks to his capability to treat experimental data to the form of suggested equation by method based on non-linear regression, the constants in the proposed equation were calculated.

Keywords: iron aluminides, laboratory hot rolling, rolling force, deformation resistance

1. Introduction

Iron aluminides are applied as structural materials due to their low material cost (as compared to corrosion- and heat-resistant steels, which contain a high quantity of additives – Cr, Ni, etc.), low specific mass, excellent resistance against oxidizing and sulphidizing environment at temperatures above 600 °C [1]. Mathematical models, which describe the rolling process of the intermetallic iron aluminide, are derived from the test results based on a methodology that is described in detail e.g. in [2]. The main point is to describe the mean equivalent stress in dependence on strain, temperature and strain rate. At the Institute of Modelling and Control of Forming Processes a method how to obtain and mathematically describe hot deformation resistance during laboratory hot rolling has been developed [3,4]. The aim of this work was to develop a mathematical model for prediction of hot deformation resistance of iron aluminides by a simple method, which will be described hereinafter.

2. Experiment

Chemical composition of the studied materials one with addition of TiB_2 powder (needles up to 10 μm) and the other with addition of Ti and B is in Table 1.

Table 1 Chemical composition of the studied materials

wt.%./at.%	Al	Cr	TiB_2	Ti	B	C
IMC 1	16.5/28.9	4.0/3.6	0.33/0.76			0.01/0.04
IMC 4	18.4/31.7	4.9/4.4		0.61/0.59	0.07/0.30	0.02/0.08

Determination of hot deformation resistance values was based on forces measured during rolling of flat samples with graded in size thickness. So firstly the input samples were prepared by milling to the required shape and dimension, as it can be seen in Fig. 1. An advantage of the sample with thickness graded in size consists in a three times higher quantity of data achieved by its rolling at exactly defined temperature as compared with rolling of one flat sample with a constant thickness.

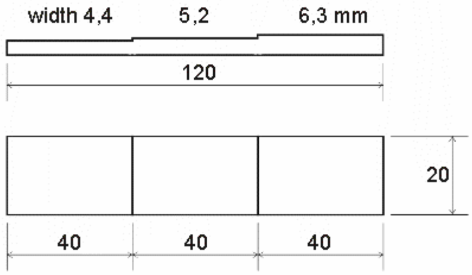


Fig.1 Initial shape of the graded in size Hample

Each sample was carefully measured and afterwards directly heated in an electric resistance furnace to the rolling temperature (900 – 1200 °C). The heated sample was immediately rolled down in stand A (roll diameter ca 159 mm) of the laboratory mill Tandem [5]. For each sample the following parameters were changed: temperature, roll gap adjustment (i.e. total deformation of the particular step of the sample) and nominal revolutions of rolls – they determine the achieved strain rate. Roll forces and actual revolutions of rolls (decreasing in relation to nominal speed in dependence on the total roll force or torque) were recorded by means of computer. Fig. 2 shows an example of recorded variables and comparison of selected samples from IMC 1 in dependence on the varying forming temperature. Afterwards the total roll force F [N] (a sum of forces measured under both adjustment screws) and corresponding variable N [rpm] (a mean value) were determined for each step of the given sample after rolling. After cooling down of the rolled stock, width and thickness of individual steps were also measured; spread of samples was dependent mainly on amount of the height reduction, thickness was influenced by amount of the roll force ("springing" of rolls).

All recorded variables mentioned above were put down in the Excel table and recalculated on values of equivalent (logarithmic) height reduction e, strain rate $\dot{e}$ and rolling temperature T. Mean equivalent stress σ_m [MPa] can be calculated from the F-value only if the forming factor, corresponding to the particular mill stand, is known (depending on a geometric factor). Equation for the mean equivalent stress σ_m [MPa] calculated according to experimental values is as follows:

$$\sigma_m = \frac{F}{Q_{Fr} \cdot l_d \cdot B_m} \tag{1}$$

where l_d [mm] is roll bite length, B_m [mm] is mean width in the given place of the rolling stock (the average of width values before and after rolling), and Q_{Fr} is forming factor corresponding to the particular mill stand.

$$Q_{Fr} = J - K \cdot \exp\left(-L \cdot \frac{l_d}{H_m}\right) + \exp\left(M \cdot \frac{H_m}{l_d}\right) \tag{2}$$

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 thickness values of the given step before and after rolling). Values of Q_{Fr} corresponding to geometric factor l_d/H_m for both stands of the mill Tandem were acquired during previous research [6].

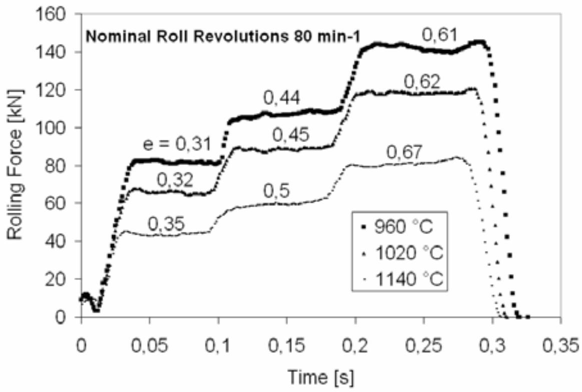


Fig.2 Comparison of roll forces in case of selected IMC 1 for various forming temperatures (revolutions of rolls 80 rpm, roll gap 2.5 mm)

3. Mathematical model

By means of the statistical software Unistat 5.5 and thanks to its capability to treat experimental data the suggested equation was obtained. By method based on non-linear regression the constants in the proposed equation were calculated. For calculation of mean deformation resistance the following relationship was chosen [3,4]:

$$\sigma_{mc} = A \cdot e^{B} \cdot \exp(-C \cdot e) \cdot \dot{e}^{D} \cdot \exp(-G \cdot T), \tag{3}$$

where σ_{mc} [MPa] is mean equivalent stress (c means "as calculated"), A ... G are material constants, T is temperature [°C].

During calculation of material constants A ... G in the equation of type (3) an observation was made that it was possible – without registered loss of accuracy – to simplify this relation by exclusion of the deformation member. The following simple models were the result of mathematical processing:

IMC 1: $\sigma_{mc} = 2017 \cdot \dot{e}^{0.032} \cdot \exp(-0.00225 \cdot T)$ (4)

IMC 4: $\sigma_{mc} = 8832 \cdot \dot{e}^{0.083} \cdot \exp(-0.00389 \cdot T)$ (5)

The simplified models of mean equivalent stress according to relations (4) and (5) do not include the deformation parameter e, which is sufficiently represented in the parameter of strain rate $\dot{e}$, see formula (6), as it was already found out and verified by previous experiments [7].

$$\dot{e} = \frac{2}{\sqrt{3}} \cdot \frac{v_r}{\sqrt{R \cdot (H_0 - H_1)}} \cdot e \tag{6}$$

where v_r [mm/s] is actual (real) peripheral speed of rolls with radius R [mm]. The member $\sqrt{R \cdot (H_0 - H_1)}$ represents the roll bite length.

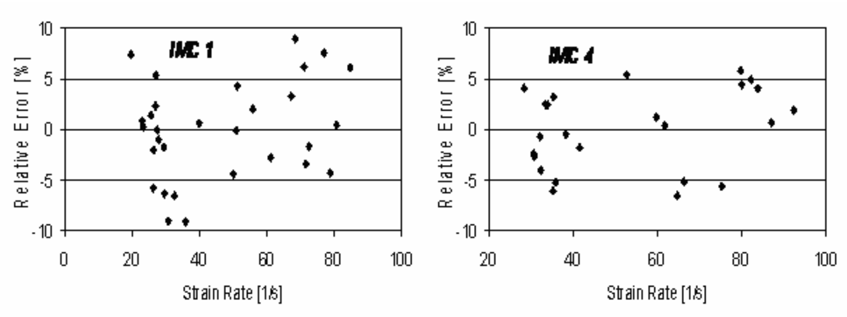
Accuracy of the achieved models may be evaluated by a simply defined relative error [%] according to the relation:

$$\text{Relative Error} = (\sigma_m - \sigma_{mc}) / \sigma_m \cdot 100 \tag{7}$$

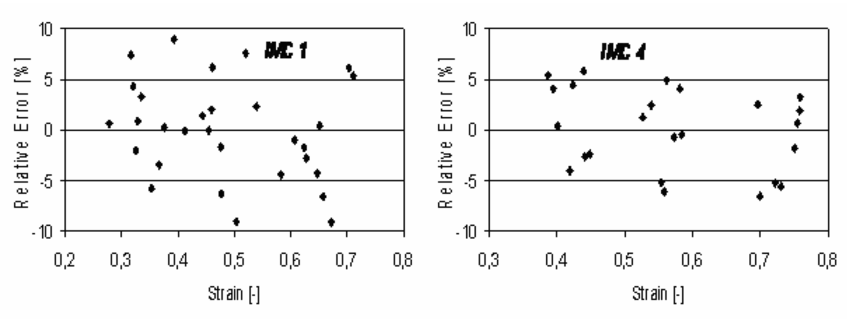
where σ_m is an observed and σ_{mc} a calculated value of the mean equivalent stress.

Evaluation of accuracy of the achieved mathematical model σ_m is based on comparison of the relative error on dependence on temperature, strain or strain rate.

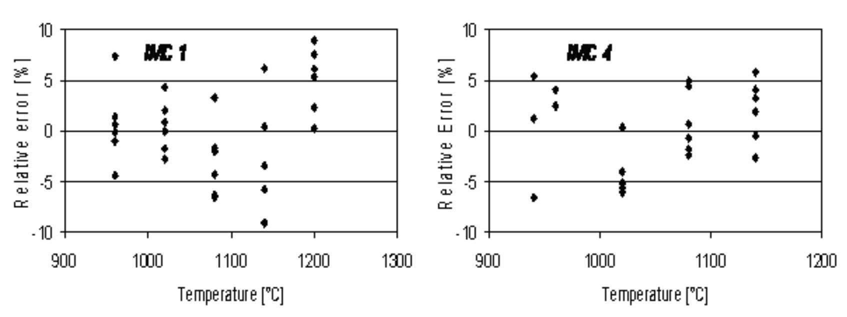
Graphs in Fig. 3 demonstrate comparison of experimentally obtained σ_m values with those calculated retrospectively according to Eqs. (4,5) using the relative error in %. It results from the given graphs that these errors do not surpass ca 10 % in case of IMC 1, or 7 % in case of IMC 4. Such accuracy is quite sufficient from viewpoint of utilization and original determination of the methodology for obtaining mean equivalent stress values for control of rolling mills determined for hot rolling of sheet and strip.



a) Dependence of relative error of model σ_m on strain rate é [s^{-1}]



b) Dependence of relative error of model σ_m on strain e [-]



c) Dependence of relative error of model σ_m on temperature T [°C]

Fig.3 Relative errors of the mean equivalent stress calculated according to Eqs. (4,5)

4. Conclusions

For experiment were used flat samples with the graded in size thickness. Values of σ_m of iron aluminides IMC 1 and IMC 4 were obtained – after recalculation from roll forces – namely in the range of actual (logarithmic) strain e from 0.28 to 0.71 (IMC 1) and from 0.39 to 0.76 (IMC 4), strain rate $\dot{e}$ from 20 to 85 s^{-1} (IMC 1) and from 28 to 92 s^{-1} (IMC 4), rolling temperature T from 960 to 1200 °C (IMC 1) and from 940 to 1140 °C (IMC 4).

Experiments were carried out in the wide range of temperatures (900 to 1200 °C) but we did not succeed in mathematical description of their results in the whole range of experimental conditions. Deformation behaviour of both materials varied significantly particularly at the lowest temperatures, obviously due to impact of the proceeding phase transformations.

As far as accuracy of both models is concerned, the root of the mean square error was 17.28 and 10.1 and the value of R^2 = 0.91 and 0.95 for IMC 1 and IMC 4, respectively. It is possible to welcome that scattering of deviations between values of σ_m that follow from experiments and recalculated from equations (4) and (5) is uniform in the whole range. These relative deviations do not surpass ±10 % in case of IMC 1 and ±7 % on case of IMC 4. An exception is the mild temperature trend of these deviations, which was mostly observed, however, in description of mean equivalent stress by the given type of the equation [3,4,7].

Acknowledgements

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