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Deformation Resistance and Structure-Forming Processes of Iron Aluminides in Hot Rolling

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We have developed simple mathematical models of mean equivalent stress dependence on temperature and strain for selected iron aluminides. Four similar melts with 16.5–19.2 wt.% of Al, 4 wt.% of Cr and with various contents of Ti and B were studied and compared. Flat specimens graded by thickness were hot rolled. Deformation resistance was calculated from the roll force values obtained using a laboratory mill Tandem. Postdynamic structure-forming processes of the tested aluminides, as well as their cracking susceptibility, were investigated by metallography. The differences in the deformation behavior and formability of the tested aluminides were described.

Keywords: iron aluminides, hot rolling, deformation resistance, microstructure, formability.

Introduction. Fe_3Al-based iron aluminides have been an object of investigation for many years. These alloys feature low material costs and a lower specific weight. Compared with expensive corrosion-resistant types of steel, they guarantee savings in elements, such as Cr, Ni, and some others. Their tensile strength is comparable with that of many other steels. They have a high resistance in sulphidic and oxidic atmospheres, especially at high temperatures, and therefore, are promising materials for manufacturing, e.g., structural parts for aviation, heating elements, heat exchangers, equipment for chemical production, etc. [1].

A problem with Fe_3Al-based materials consists in their preparation and subsequent processing. They feature brittleness at the ambient temperature and a drop of strength above 600°C, which was the reason for not using them as structural materials. Attention has recently been focussed mainly on utilization of corrosion-resistant properties of iron aluminides at high temperatures. An essential step forward in their application is an increase in their creep resistance at temperatures above 600°C. This is achieved by the additives that form stable phases thus increasing the strength of the material at the temperatures of their operation. However, this strengthening may adversely affect the production of components, as the case may be, e.g., during hot forming. It is the introductory experiments involving determination of the deformation resistance of iron aluminides hardened for a later application as the materials exhibiting creep resistance at high temperatures that are the subject of this work.

Experimental. Four melts of iron aluminides with similar chemical compositions and various contents of Cr, Ti, and B (Table 1) were studied and compared. The chromium content in the range from 2 to 5 at.% has no effect on the basic mechanical properties of the aluminide, and its function is only to improve the formability at lower temperatures [1]. The experiment was divided in two parts. First, the mean equivalent stress (MES) was determined using a laboratory rolling mill Tandem, and then postdynamic structure-forming processes in the investigated aluminides rolled in a laboratory rolling mill K350 were studied [2].

Mean Equivalent Stress. Flat specimens graded by thickness, which have been prepared by water cutting and grinding, were hot rolled. Each specimen was carefully measured and afterwards directly heated in an electric resistance furnace to the rolling

temperature (900–1200°C). The heated specimen was immediately rolled down in the mill A of the laboratory mill Tandem [2] (roll diameter approx. 159 mm). The roll forces and actual revolutions of the rolls were recorded using a computer. After cooling down of the rolled stock, the width and thickness of individual specimens were also measured. All the recorded variables mentioned above were presented in the table and recalculated to obtain the values of the equivalent (logarithmic) height reduction e_h, strain rate $\dot{e}$ (in s^{-1}) and MES σ_m (in MPa) [3].

T a b l e 1

Chemical Composition of the Investigated Iron Aluminides in wt.%/at.%

Alloy	Al	Cr	Ti	B	C
M1	16.5/28.9	4.0/3.6	TiB_2 = 0.33/0.76	–	0.01/0.04
M2	19.2/32.8	4.9/4.3	0.68/0.65	–	0.04/0.12
M3	16.8/29.3	4.0/3.6	–	0.06/0.27	0.02/0.08
M4	18.4/31.7	4.9/4.4	0.61/0.59	0.07/0.30	0.02/0.08

The resulting equation for the description of the MES should make possible a quick prediction of the force parameters during adaptive control of the rolling mill. Based on previous experience, a simple model for the description of the MES of the investigated material in relation to strain (strengthening and dynamic softening are taken into account), temperature and strain rate, which is dependent on the deformation, was chosen [4]:

$$\dot{e} = \frac{2}{\sqrt{3}} \frac{v_r}{l_d} e_h , \tag{1}$$

where v_r (in mm/s) is the actual peripheral speed of the rolls with radius R (in mm), and l_d (in mm) represents the roll bite length. For calculation of the MES, the following relationship was chosen:

$$\sigma_{mc} = A e_h^B \exp(-C e_h) \dot{e}^D \exp(-GT), \tag{2}$$

where σ_{mc} (in MPa) is the mean equivalent stress (c means "as calculated"). During calculation of the material constants $A, \ldots, G$ (by means of the statistical software UNISTAT 5.5) appearing in the equation of type (2), an observation was made for all the materials studied (M1, M2, M3, and M4) that enabled us, without any registered loss of accuracy, to simplify this relation by exclusion of the strain member. The following models were the result of this mathematical processing:

$$\sigma_{mc} = 2017 \dot{e}^{0.032} \exp(-0.00225T) \quad \text{for M1,} \tag{3}$$

$$\sigma_{mc} = 6763 \dot{e}^{0.159} \exp(-0.00395T) \quad \text{for M2,} \tag{4}$$

$$\sigma_{mc} = 4954 \dot{e}^{0.040} \exp(-0.00311T) \quad \text{for M3,} \tag{5}$$

$$\sigma_{mc} = 8832 \dot{e}^{0.083} \exp(-0.00389T) \quad \text{for M4.} \tag{6}$$

The simplified models of the MES according to Eqs. (3)–(6) do not include the strain parameter e_h, which is sufficiently represented in the parameter of the strain rate $\dot{e}$ [see Eq. (1)], as it has already been found and verified by previous experiments [3].

The accuracy of the obtained models can be evaluated by a simply defined relative error (in %) according to the relation: $(\sigma_m - \sigma_{mc})/\sigma_m \cdot 100$, where σ_m and σ_{mc} are the observed and calculated values of the mean equivalent stress, respectively. Relative errors did not exceed approx. $\pm 10\%$ for alloys M1 and M3 or $\pm 7\%$ for alloys M2 and M4, which is quite sufficient for the given purposes.

The mathematical model of the MES calculated on the basis of the methodology mentioned above is capable to compare different deformation behaviour of the materials M1–M4. For this purpose, graphs in Fig. 1 were plotted. It follows from Fig. 1 that alloys M2 and M4, on the one hand, exhibit a sharper rise in the σ_m value with increasing strain as against alloys M1 and M3, and on the other hand, their deformation resistance is approx. 20 to 30 MPa lower. Moreover, for alloys M2 and M4, a decrease in the MES with increased forming temperature is more pronounced.

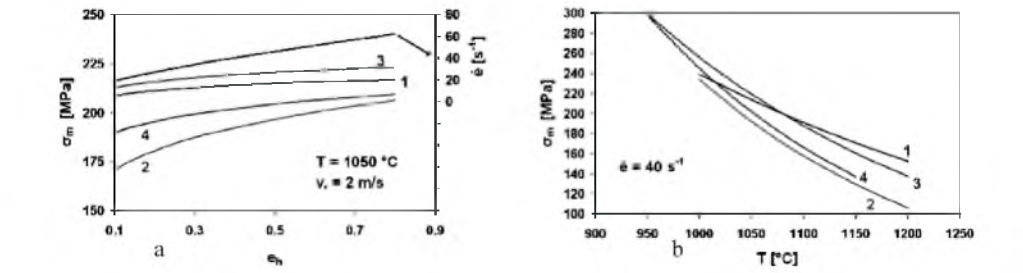

Fig. 1. Comparison of behavior of M1–M4 alloys in dependence on (a) height strain e_h [see Eq. (1) for dependence $\dot{e} = f(e_h)$] and (b) temperature T.

Evaluation of Microstructure. The forming temperatures used for all four aluminides were 900, 1100, and 1300°C, and for alloy M3 a temperature of 1200°C was used additionally. Specimens were rolled with one draught (height reduction) in the rolling mill K350, the rotation speed of the rolls was 80 rpm. The relative height reduction corresponded to a value of 33%.

Immediately after rolling, three modes of cooling were applied: quenching of the specimen in oil directly or after a dwell at the forming temperature during 1 minute or 5 minutes. The resulting microstructure was analyzed by means of optical metallography (Figs. 2 and 3).

Summary of Results. Figure 2 shows an example of the structure evolution depending on the mode of cooling for the chosen iron aluminide M3. This example proves the observation common for all four investigated materials that recrystallization proceeded only in during the temperature dwell. Hence, softening of the investigated alloys by static recrystallization has become apparent.

Rolling at a temperature of 1100°C followed by a 1 or 5 min dwell at the same temperature (Fig. 2b, c and Fig. 3c) seemed to be the best way of forming from the viewpoint of the deformed structure. A more pronounced refining of the structure due to recrystallization occurred in the areas of more intensively formed edges of specimens. Rolling at a temperature of 900°C led to only average-level recrystallization processes, which can be seen from the photo in Fig. 3b). Rolling at a temperature of 1300°C did not result in grain refinement because, during subsequent temperature dwell, a complete recrystallization and subsequent grain coarsening occurred virtually to the original size corresponding to the initial state (compare the photos in Fig. 3a and 3d).

Based on laboratory rolling of flat specimens graded by thickness, the values of σ_m were obtained for iron aluminides M1, M2, M3, and M4 – after recalculation from roll forces – namely in the range of logarithmic height strain e_h from 0.20 to 0.76 and strain rate $\dot{e}$ from 20 to 96 s^{-1}. The rolling temperature T was in range from 960 to 1200°C.

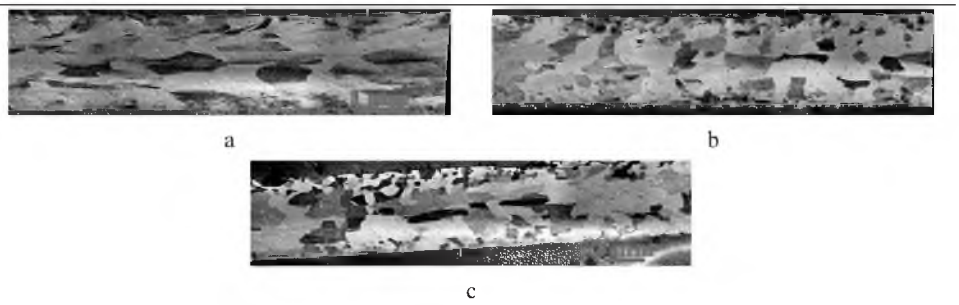

Fig. 2. Comparison of structure evolution in case of selected M3 samples depending on schedule of cooling from deformation temperature 1100℃: (a) 1100℃/oil quenching; (b) 1100℃/1 min, oil quenching; (c) 1100℃/5 min, oil quenching.

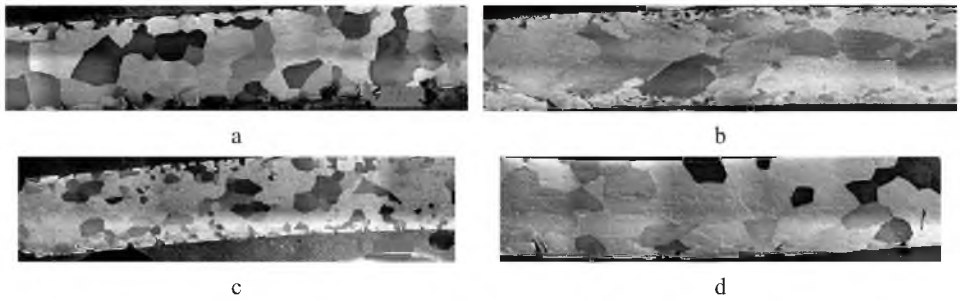

Fig. 3. Structure of selected samples of M2 alloy: (a) initial state; (b) 900℃/5 min, oil quenching; (c) 1100℃/5 min, oil quenching; (d) 1300℃/5 min, oil quenching.

As far as the accuracy of the derived models of the MES is concerned, for M1 alloy the root-mean-square error was 17.3 and the value of $R^2 = 0.91$; for M2 alloy the respective magnitudes were 6.1 and 0.97; for M3 alloy 9.9 and 0.95; and for M4 alloy 10.1 and 0.95. It may be concluded that the scatter of deviations between the values of σ_m obtained from the experiments and recalculated using Eqs. (3)–(6) is uniform in the whole range (and, moreover, these relative deviations do not exceed $\pm 10\%$ for M1 and M3 and $\pm 7\%$ for M2 and M4 alloys).

The MES models of iron aluminides – alloys M2 and M4 – exhibited a higher sensitivity to the changes in the forming conditions (deformation scale and forming temperature) compared to alloys M1 and M3 as demonstrated in Fig. 1. The cause for different deformation behavior can be found in the origin of various phases after the thermal history of each of the materials, i.e., in the presence and morphology of phases, whose formation is connected with the presence of the additives used. Those phases (which function as some obstacles) influence both recrystallization (by blocking the movement of the grain boundaries) and proper deformation during rolling. In case of M3 alloy, stresses along the grain boundaries, densely occupied by heterogeneous phases, initiate intercrystalline fracture.

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