MODEL OF HOT DEFORMATION RESISTANCE OF THE IRON ALUMINIDE OF THE TYPE Fe-40at.%Al

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Abstract
Iron aluminides with 40 at.% (which corresponds approx. 24 wt. %) of aluminium are advanced structural materials that are thanks to their low density and good resistance to high temperatures suitable as replacement of expensive high alloyed steels or nickel superalloys. Their more extensive industrial application is hindered by problems at their processing, since they exhibit an extremely low formability in as-cast state. Formation of surface cracks can be prevented by use of heated forming tools. Thanks to this fact it was possible to form successfully the samples from aluminide of the type Fe-40at.%Al by uniaxial compression with use of anvils that were locally heated on the plastometer Gleeble 3800 by the system of resistance heating. Stress-strain curves were obtained for temperatures from 800 to 1200 °C and strain rates from 0.05 to 30 s⁻¹. After the necessary smoothing of their course by an inverse method the activation energy at hot forming (236 kJ·mol⁻¹) was calculated from the coordinates of the stress peak, which was then used for mathematical description of deformation to peak in dependence on the Zener-Hollomon parameter. We managed to develop a phenomenological model, which describes with good precision deformation resistance of the investigated alloy in dependence on temperature, strain rate and deformation, with consideration of influence of dynamic recrystallization.

Keywords: iron aluminides, activation energy at hot forming, deformation resistance

1. INTRODUCTION
At present, efforts are being exerted to make existing production processes more efficient, as well as efforts to find eventual replacement of certain conventional structural materials, particularly such as high-alloyed and stainless steels, which are very expensive. That’s why efforts continue to find alternative materials, the service properties of which would be competitive and also cheaper. It is possible to include among such advanced materials selected types of intermetallics, such as iron aluminides or Fe 40at.%Al% [1, 2].
Iron aluminides of the type Fe-40at.Al%, became thanks to their properties a competitive material to chromium-nickel corrosion resistant steels. These properties include a relatively low density, high strength and very good resistance to oxidation and corrosion in aggressive environments thanks to creation of a surface layer of Al₂O₃. The products made of these materials are characterised moreover by favourable abrasion resistance, resistance to carburisation and sulphurisation. These materials exhibit, however, also some negative characteristics, such as low ductility and fracture toughness at room temperature (brittleness), low strength at high-temperatures and insufficient creep resistance at high temperatures [2, 3]. In general it can be stated that the production itself of intermetallics is relatively inexpensive, but their applications are often made more expensive due to problems associated with formability and machinability of these materials [4].
Physical simulations in the form plastometric tests are commonly used for investigation of the deformation behaviour of new materials at hot forming. Thermo-mechanical simulators (for example of the Gleeble type) are used for these purposes, as they enable simulation of the forming process in a very wide range of deformation conditions [5].
The object of investigation in this paper was creation of a phenomenological model that would be able to describe with sufficient accuracy the deformation resistance of the alloy Fe-40at.%Al% in dependence on temperature, strain rate and deformation. This model should include also the effect of dynamic recrystallization on the deformation behaviour of the studied alloy.

Resistance to deformation can be described by various mathematical models. These models differ by their mathematical structure and also by the fact, in what extent of deformation they can predict the resistance to deformation. According to the extent of deformation, in which the models are capable of prediction, these models can be divided into those that are able to really describe the resistance to deformation before reaching the stress peak, and models that are intended for description of the stress curve at deformation to the peak. Furthermore some other models exist, which can describe the whole stress curves [6, 7].

2. EXPERIMENT DESCRIPTION

The aim of the experiment was to develop a suitable mathematical model for description of the deformation behaviour of iron aluminate of the type Fe-40at.%Al, on the basis of results of test by uniaxial pressure. These tests were performed with use of the plastometer Gleeble 3800 under different thermo-mechanical conditions. For sufficient mapping of conditions for forming five temperatures (800, 900, 1000, 1100 and 1200 °C) were selected and four different strain rates (0.05, 0.4, 4 and 30 s\(^{-1}\)). The tests were carried out on rollers with a height of 15 mm and a diameter of 10 mm. All the samples were prior to forming pre-heated to the temperature of 1200 °C. The samples were after uniform reheating cooled down to the temperature of forming or they were formed right away. Formability was positively influenced by the tools (anvils) that were pre-heated to the temperature of forming. After completion of individual tests the measured data necessary for evaluation of plastometric tests were automatically recorded and stored. These data were, however, affected by considerable scatter, so it was therefore necessary to smooth them. Smoothing of the data was in this research performed by the method of inverse analysis. Subsequently the curves of dependence of stress on strain were plotted and values of the maximum (peak) stress and strain corresponding to the peak stress were determined from them. An example of this dependence is illustrated by the graph in Fig.1, which was plotted from the data obtained for the temperature of 1000 °C.

![Graph showing strain-stress at 1000 °C](image)

**Fig. 1** Curves strain-stress at the deformation temperature of 1000 °C and at strain rates of 0.05 - 30 s\(^{-1}\)

This graph confirms the considerable scatter of data recorded from Gleeble (smooth curve). **Fig. 1** shows furthermore the curves plotted with use of the inverse analysis (dashed curve). It is evident from comparison
of the curves for identical deformation conditions (strain rate and temperature) that the values obtained from the inverse analysis are lower than the values measured directly by the plastometer Gleeble. This phenomenon was caused by the fact that for technical reasons it is impossible to during to maintain constant temperature and strain rate during realisation of pressure tests, while in the case of the inverse analysis it is possible to choose a constant temperature and strain rate [8].

3. MATHEMATICAL PROCESSING AND DISCUSSION OF EXPERIMENTAL RESULTS

The values of peak stress and of corresponding strain were subsequently determined from the curves obtained by the inverse analysis. Afterwards the value of the activation energy at hot forming was determined with use of special software ENERGY 4.0, namely from the measured values of peak stress and of corresponding deformation. The software ENERGY 4.0 works on the principle of partial linear regressions, which gives a result, which will be made more accurate by application of the least squares method based on non-linear regressions [9]. The value of activation energy was calculated using a modified sine hyperbolic equation of Tegart and Sellars [10]:

\[ \dot{e} = C \cdot \exp \left( \frac{-\sigma}{R} \right) \cdot \sinh \left( \alpha \cdot \sigma_{\text{max}} \right)^n \]  

(1)

where \( \dot{e} \) is the strain rate [s\(^{-1}\)], \( R \) is the molar gas constant equal to 8.314 J.mol\(^{-1}\).K\(^{-1}\), \( T \) is temperature of deformation [K], \( \sigma_{\text{max}} \) [MPa] is the maximum deformation stress corresponding to the peak deformation, \( C \) [s\(^{-1}\)], \( \alpha \) [MPa\(^{-1}\)] and \( n \) are material constants. Methodology for determining material constants in the equation (1) is described for example in [11].

The value of activation energy at hot forming of the aluminide Fe 40at.Al\% was determined to be 236 kJ.mol\(^{-1}\), which in the case of this material is realistic value. At previous experiments we achieved on the same material similar values (235 kJ.mol\(^{-1}\)) in the case when the value of the activation energy was determined from the data obtained directly from the plastometer Gleeble [12], while in this case, this value was obtained from the regression analysis of the values obtained from the plastometer Gleeble.

Furthermore, thanks to the software ENERGY 4.0 material constants \( U \) and \( W \) calculated, which were subsequently used for prediction of kinetics of dynamic recrystallization, or of \( e_p \) on the basis of knowledge of the Zener-Hollomon parameter \( Z \) [s\(^{-1}\)]:

\[ Z = \dot{e} \cdot \exp \left( \frac{R}{K} \right) \]  

(2)

\[ e_p = U \cdot Z^W \]  

(3)

Two different models were used in this experiment describing the deformation behaviour of the investigated material. In the first case we choose the model Schindler et al. [13], and in the second case we used the Hensel-Spittel model [14], which is used in the simulation program FORGE. The model Schindler model et al. is described by the equation:

\[ \sigma = p_1 \cdot \sigma_0 \cdot \exp \left( -p_2 \cdot e_p \right) \cdot \exp \left( p_3 \cdot \frac{\dot{e}}{e_p} \right) \cdot \exp \left( -p_5 \cdot T \right) \]  

(4)

where \( p_{1,2,\ldots,5} \) are constants of the model, \( e \) is deformation, \( e_p \) is the strain corresponding to the peak stress and \( T \) is the temperature [K]. The equation (4) consists of altogether four members, two of which are deformation members. The first member of deformation of the model is formed by a power function reflecting the strengthening phase. The second deformation member formed by an exponential function reflects the influence of softening after the start of dynamic recrystallization. The third and fourth members then express the effect of strain rate and deformation temperature [13].
Material constants in the model (4) were determined by non-linear regression analysis of several variables with use of the statistical software UNISTAT. For achieving better accuracy of the calculation it was necessary to exclude from the processed file some data that exceeded the expected trends. This concerned especially start-up parts of some strain-stress curves, in which the method INVERS caused creation of significant "yield stress".

The final values of material constants $p_1$ to $p_5$ designated for non-linear regression with use of the program UNISTAT are given in Table 1. The determination coefficient of these constants $R^2$ is 0.9980, which shows already sufficient agreement. Theoretical values of resistances to deformation predicted with use of the constants from Table 1 for the model (4) were then compared with experimentally obtained values from smoothing by the inverse method, which is represented in Fig. 2, showing a comparison of experimental (measured) and predicted (model Schindler et al.) values of resistance to deformation for the temperatures of 1000 and 1200 °C.

**Tab. 1 Values of constants in the model Schindler et al.**

<table>
<thead>
<tr>
<th>Constant</th>
<th>$p_1$</th>
<th>$p_2$</th>
<th>$p_3$</th>
<th>$p_4$</th>
<th>$p_5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>391554</td>
<td>0.177</td>
<td>0.756</td>
<td>553.3</td>
<td>0.0059</td>
</tr>
</tbody>
</table>

![Graphs](image)

**Fig. 2** Graph plotted from the measured values of stress and the values determined by the model Schindler et al. in dependence on deformation for the temperatures of 1000 and 1200 °C.

It is evident from the graphs in Fig. 2 that a comparatively good agreement between the results from the inverse analysis and the results predicted by the model was achieved (4). We can see here, however, that some complications arise at prediction of the resistance to deformation at high temperatures in combination with higher strain rates. Some minor complications also occur at description of the stabilised state at combination of low temperature with high strain rate. These complications, however, are definitely not essential.

The purpose of use of the second Hensel-Spittel model was to investigate, whether the predictions made by both models would be identical. The shape of the model is described by the equation (5), which is much more complex compared to the equation (4), and moreover this model is based on the physical foundation, but this is purely a universal mathematical interpretation [14].

$$
\sigma = p_1 \cdot \exp(p_2 \cdot T) \cdot T^p_3 \cdot \exp\left(\frac{E_\sigma}{\kappa}\right) \cdot \left(1 + \frac{\varepsilon}{\varepsilon_f}\right)^{(p_4 \cdot \varepsilon_f)} \cdot \exp(p_7 \cdot \varepsilon) \cdot \varepsilon^{p_8} \cdot \exp(p_9 \cdot \varepsilon_f)
$$

(5)

The model (5) contains more deformation members than the model (4), but it also contains a power member and exponential member. It contains even two deformation members based on exponential function. It...
contains also speed and temperature members. However, in contrast to the model (4), this model does not contain deformation to peak.

The calculation procedure itself ran similarly as in the model (4). The values after the performed selection used at creation of the model (4) were used here as input values of experimental deformation and resistance to deformation. After substituting these input values the approximate model constants $p_1$ to $p_9$ were substituted from the model developed within the frame of another solution. After that new constant of the model were obtained on the basis of non-linear regression. The regression was performed here only once. The resulting values of the constants $p_1$ to $p_9$ for the model (5) are shown in Tab. 2. The correlation coefficient $R^2$ of the constants $p_1$ to $p_9$ was calculated to be 0.9981, which is a value very similar to that in case of use of the model (4). The values of resistance to deformation predicted with use of the constants from Tab. 2 of the model (5) were compared with the values obtained by calculation of the model (4) and with the values from the inverse analysis. This comparison is shown in Fig. 3, which shows a comparison of resistances to deformation at the temperatures of 900 and 1100 °C.

<table>
<thead>
<tr>
<th>Constant</th>
<th>$p_1$</th>
<th>$p_2$</th>
<th>$p_3$</th>
<th>$p_4$</th>
<th>$p_5$</th>
<th>$p_6$</th>
<th>$p_7$</th>
<th>$p_8$</th>
<th>$p_9$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>8494</td>
<td>-0.0062</td>
<td>0.397</td>
<td>0.269</td>
<td>0.0041</td>
<td>-0.0019</td>
<td>0.295</td>
<td>-0.0613</td>
<td>0.00039</td>
</tr>
</tbody>
</table>

Fig. 3 Graph comparing the measured values of stress, the values determined by the model Schindler et al., and the values determined by the model Hensel-Spittel in dependence on deformation for the temperatures of 900 and 1100 °C

It is evident from Fig. 3 that prediction performed by both models is virtually identical, with some exceptions. The first proposed model (4) is slightly more accurate at higher temperatures. The accuracy of the second model (5) is, again with some exceptions, slightly better at lower temperatures.

4. CONCLUSIONS

Models for mathematical description of resistance to deformation of the iron aluminide Fe-40at.% Al at hot forming were proposed on the basis of a series of experimental tests by hot pressure performed on the thermo-mechanical simulator Gleeble. These experimentally measured data were due to considerable scatter of values and due to impossibility of maintaining constant temperature and constant strain rate subjected to smoothing by the inverse method. The value of activation energy was determined for hot forming with use of the software ENERGY 4.0. It was established that the value of 236 kJ·mol$^{-1}$ is practically identical with the value of the activation energy determined for the same material, but with use of of non-smoothed plastometric data (235 kJ·mol$^{-1}$) [12].
The model Schindler et al. and Hensel-Spittel model, which is used in the simulation program FORGE, were chosen for mathematical description of the resistance to deformation of the iron aluminate Fe-40at.%Al. It was found out that prediction made according to the Hensel-Spittel model is with few exceptions identical with prediction made by the model Schindler et al., with very similar determination coefficient. The model Schindler et al. is slightly more accurate at prediction at higher temperatures, while the Hensel-Spittel model is on the contrary more accurate at lower temperatures. This second model has, however, bigger problems at description of the resistance to deformation at the combination of the highest temperature with the highest strain rate. It was therefore determined that for description of the resistance to deformation of the aluminate Fe-40at.%Al in the given range of deformation conditions the first proposed model, i.e. the model Schindler et al., is more suitable. Nevertheless, it should be possible to use it with sufficient accuracy also for possible simulation of resistance to deformation of the aluminate Fe-40at.%Al for the purposes of computer simulation in the program FORGE.

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REFERENCES