Iron aluminide alloys are promising advanced structural materials for high temperature applications. They offer a combination of such properties as excellent corrosion and wear resistance, lower density and cost advantage over the Fe-Cr or Fe-Cr-Ni stainless steels. The subject matter of this work focuses on studying characteristics of hot deformation of iron aluminides by using a compression test in the temperature range 600-1100°C and the true strain rate range 0.001-100 s⁻¹. The flow stress has been found to be strongly dependent on the temperature as well as on the strain rate. At strain rates higher than about 10 s⁻¹ or temperatures lower than 800°C, the materials exhibited flow softening type of stress-strain curves, while at lower strain rates and temperatures higher than 800°C, the flow curves were of steady-state type. At lower strain rates (<1 s⁻¹) and higher temperatures (>800°C) the material undergoes dynamic recrystallization to produce a fine-grained microstructure.

Keywords: Fe-Al alloys, hot deformation, microstructure, mechanical properties

1. Introduction

Fe-Al alloys with aluminum content from 16 to 50 at.% are usually called iron aluminides [1]. They are mainly based on Fe₃Al or Fe₅Al intermetallic compound. These materials are commercially attractive due to their low material cost, good wear and corrosion resistance, excellent oxidation and sulfidation resistance, low density and good mechanical properties [2-4]. However, structural applications of iron aluminides have been hampered by their low room temperature ductility due to environmental hydrogen embrittlement and by poor strength above 600°C. In order to overcome these problems a lot of efforts have been made so far in the area of their mechanical behavior at the room and high temperature with putting emphasis on the relationship between their microstructure and mechanical properties [see e.g., 5, 6]. It has been found that the room temperature ductility of iron aluminides can be essentially improved by the controlling of microstructure under thermomechanical treatment.

The present study is therefore directed towards assessing the temperature and strain state dependence of the flow stress of iron aluminides based on disordered (A2) Fe(Al) alloy and ordered (B2) Fe₃Al intermetallic alloy. A microstructural examination in the compression tested samples has been carried out to correlate their mechanical behavior with their microstructural features. It should be also mentioned that this work is a part of the research program being in progress in our research.

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group on the hot working behavior of iron aluminides [7].

2. Experimental procedure

The chemical compositions of the investigated iron aluminide alloys are listed in Table 1. Both alloys were prepared by induction melting in the argon atmosphere and casting into a cylindrical steel mold. Each ingot of 24 mm in diameter and 150 mm in length was homogenized at 1100°C for 10 h. Hot-hammering steps at about 1100°C were then carried out and rods of 7.8 mm in diameter were obtained. Compression specimens with nominal dimensions of 12 mm in height and 7.6 mm in diameter were cut by electrical discharge machining (EDM) from the hot-hammered rods. Isothermal, constant-strain rate compression tests were carried out on a Gleeble 3800 testing system over a range of strain rates (0.001-100 s⁻¹) and temperatures (600-1100°C). All the tests were performed in the argon atmosphere with the heating rate of 3°C s⁻¹. The specimens were annealed for 10 min at the testing temperature prior to deformation, deformed to a true strain of ~0.65 and water cooled to the room temperature after deformation. The microstructure was observed by an optical microscopy after etching the polished specimens in 33%CH₃COOH+33%HNO₃+33%H₂O+1%HF reagent. Grain size measurements were carried out by using an automatic image analyzer developed by Soft Imaging Software GmbH (SIS) attached to a Philips XL30 scanning electron microscope (SEM). The following parameters of the individual grains were measured: A, grain section area and $d_{eq}$, equivalent circle diameter of the grain ($d_{eq} = [4A/\pi]^{1/2}$).

<table>
<thead>
<tr>
<th>Material designation</th>
<th>Al</th>
<th>Cr</th>
<th>Mo</th>
<th>Zr</th>
<th>B</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>FAP</td>
<td>16</td>
<td>5</td>
<td>1.0</td>
<td>0.10</td>
<td>–</td>
<td>balance</td>
</tr>
<tr>
<td>Fe₃Al</td>
<td>28</td>
<td>5</td>
<td>–</td>
<td>0.08</td>
<td>0.04</td>
<td>balance</td>
</tr>
</tbody>
</table>

3. Results and discussion

The microstructures of the starting iron aluminide alloys are shown in Fig. 1a,b. As it can be seen both initial materials, FAP and Fe₃Al have an equiaxed grain structure with the average equivalent grain diameter of about 250 and 300 µm, respectively.

![Fig. 1. Starting microstructures of investigated iron aluminides: (a) FAP and (b) Fe₃Al and microstructures showing DRX: (c) FAP deformed at 900°C/0.001 s⁻¹ and (d) Fe₃Al deformed at 1100°C/0.01 s⁻¹](image-url)
The typical true stress – true strain curves recorded for both investigated alloys at the two selected temperatures, 800°C and 1000°C are shown in Fig. 2. The flow curves at strain rates lower than 10 s⁻¹ are essentially of steady state type. At higher strain rates (>10 s⁻¹) the flow curves of Fe₃Al intermetallic exhibit significant flow softening after reaching a peak in the flow stress in the initial stages of deformation (Fig. 2b, d). Moreover, some oscillations on the flow curves at temperatures higher than 800°C and strain rates lower than 1 s⁻¹ can be observed. Such oscillations generally suggest that dynamic recrystallization (DRX) may occur [8]. However, it is hard to attribute any specific deformation mechanism to the shapes of flow curves since different mechanisms lead to similar behavior, e.g. DRX, flow instability or globularization of lamellar structures. The investigations in this area are in progress in our research group.

Fig. 3. Temperature and strain rate dependence of flow stress for iron aluminides at 0.6 strain: (a) FAP and (b) Fe₃Al. Variation of flow stress with strain rate at 0.6 strain: (c) FAP and (d) Fe₃Al
Fig. 3a, b shows the effect of the temperature on the flow stress of both alloys at the 0.6 strain level. It is clearly seen that the flow stress at a given strain rate decreases with increasing the temperature in a normal manner. Similar trends are observed at a given temperature, the flow stress increases with the increasing strain rate (Fig. 3c, d). However, the variation of both parameters is less at high temperatures and lower strain rates. The above mechanical characteristics clearly indicate that the deformation of both alloys is thermally activated. Our results are in good accord with the results reported by Sundar et al. [9, 10], who also observed a strong dependence of the flow stress on the temperature and the strain rate.

Fig. 4 shows the variation of average grain size as a function of the temperature. There is no any visible grain growth before DRX in both alloys. The grain size is seen to be almost constant up to about 800°C, for FAP and about 900°C, for Fe₃Al. The grain refinement at temperatures higher than 900°C can be noticed, especially for Fe₃Al intermetallic. Moreover, the grain size in both alloys is finer at higher strain rates. Typical microstructures recorded on the FAP specimen deformed at 900°C at the strain rate of 0.001 s⁻¹ and Fe₃Al specimen at 1100°C and 0.01 s⁻¹ are presented in Fig. 1c, d, respectively. As it can be seen, both microstructures exhibited fine newly formed grains in the matrix of original grains.

4. Conclusions

In the present paper, the temperature and the strain rate dependencies of the flow stress were studied on the basis of the shapes of flow curves and microstructural analysis. Both investigated iron aluminides at temperatures lower than 800°C and higher strain rates (> 10 s⁻¹) exhibited the flow softening type of stress – strain curves, while at higher temperatures and lower strain rates (< 10 s⁻¹), the flow curves were of steady – state type. Both materials recrystallized at lower strain rates (< 1 s⁻¹) and higher temperatures (> 800°C) to produce a stable fine-grained microstructure.

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