# THE EFFECT OF THERMOMECHANICAL PARAMETERS ON DEFORMATION BEHAVIOR OF P/M IRON ALUMINIDE ALLOY

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**Abstract**

Iron aluminides are one of the most attractive intermetallics for commercial applications due to their excellent corrosion resistance in combination with high specific strength. Proper design of thermomechanical parameters and precise control of the microstructural evolution are essential for successful processing of these alloys. This research evaluates the deformation behavior of P/M iron aluminide and discusses the importance of the processing parameters. Iron aluminide alloy powder was consolidated to full density by hot pressing. Cylindrical compression specimens were machined from the compacts and subjected to hot compression tests in order to characterize the material behavior under various thermomechanical conditions. Moreover, numerical simulations of the investigated alloy forging were performed. The boundary conditions for the simulations were prepared on the base of the experimental tests. Chosen results of the simulations were compared with the results of forging the investigated alloy performed in industrial conditions. The study showed good agreement of the experimental and numerical modeling results, what confirmed a proper design of the boundary conditions used in this study.

**Keywords:** Iron aluminide, deformation behavior, microstructure, numerical modeling

## 1. INTRODUCTION

Iron aluminides have been of great interest over the last several decades for possible use as moderate to high temperature structural materials. These alloys are especially attractive, because they combine low density with good strength, excellent corrosion and oxidation resistance at elevated temperatures, a wide range of chemical stability, and relatively low costs [1]. The densities of these materials, ranging from about 5.4 - 6.7 g/cm$^3$, are roughly 30 % lower than those of most commercial high-temperature structural materials such as superalloys and stainless steels offering better strength to weight ratios than these more conventional materials. Moreover, iron aluminides show strong resistance to catalytic coking, carburization, sulfidation, and wear. Despite the desirable properties mentioned above, FeAl alloys, like aluminide compounds in general, are known to have relatively high ductile-to-brittle transition temperatures (DBTT), on the order of half their melting point. This results in the limited ductility and toughness of these materials as one approaches ambient temperatures. Such limited ductility in the case of iron aluminides is thought to be the result of environmental embrittlement caused by the presence of moisture which, when it reacts with aluminum on the surface, causes the release of hydrogen. These limitations in ductility have greatly restricted the low-to-moderate temperature processing of these materials and subsequently, their general use to date. Thermal vacancies as well as yield anomaly of FeAl are also the reasons of such limited ductility of these alloys. Fracture behavior of hot processed cast FeAl-based intermetallic alloys have also been studied recently [2].

The deformation behavior of cast FeAl alloy has recently been investigated [3]. The flow stress was found to be strongly dependent on temperature and strain rate. Moreover, considerable strain rate sensitivity of the investigated alloy has been reported in [4]. Powder metallurgy (P/M) processing of low density alloys provides many advantages over more traditional casting techniques [5, 6]. The room temperature mechanical properties of these alloys, particularly ductility and strength, are microstructure sensitive. In this respect, powder metallurgy methods are very promising, since much finer microstructures can be produced. Recent studies have pointed out the importance of starting powder particle nature (particle shape, size or powder surface oxide content) in relation to the processing of P/M FeAl alloys [7, 8]. This research evaluates the possibility of FeAl alloys forging, with a special emphasis on the processing parameters.

## 2. EXPERIMENTAL PROCEDURE

-100/+325 mesh water atomized FeAl alloy powder (PM FeAl alloy) was used in this research. The chemical composition of FeAl powder is shown in **Table 1**.

**Table 1** Chemical composition (at.%) of FeAl alloy powder

| Al | Zr | Mo | Si | B | C | O | Fe |
|---|---|---|---|---|---|---|---|
| 39.3 | 0.05 | 0.19 | 0.31 | 0.02 | 0.22 | 0.85 | Bal. |

FeAl alloy powder was compacted to full density by hot pressing under an argon atmosphere at the temperature of 1100 °C. The density of the compacts was determined according to Archimedes method. **Fig. 1** shows FeAl alloy powder and the microstructure of powder compact.

Cylindrical specimens with a height of 12 mm and a diameter of 8 mm were machined from powder compacts and used for compression tests at strain rates of 0.1 $s^{-1}$ and 10 $s^{-1}$ at 100 °C intervals over the temperature range of 700-1100 °C. Gleeble thermomechanical simulator was used for compression testing. The load vs. displacement data obtained from the experiments were converted into experimental true stress-true strain curves. The nature of the microstructure of the compact (**Fig. 1b**), reflecting only the powder particle shape and size distribution, shows that hot compacting resulted only in densification without any further microstructural evolution.

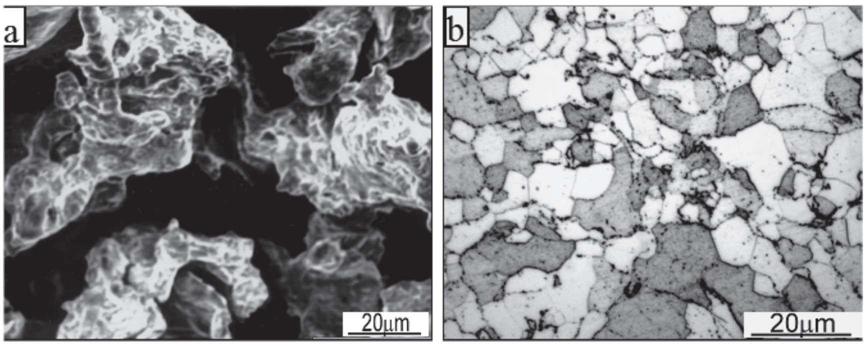


**Fig. 1** FeAl alloy powder (a) and microstructure of FeAl alloy powder compact (b).

Microstructures of the hot processed samples were observed at the center of longitudinally sectioned specimens (parallel to the axis of compression). **Figures 2** and **3** below show respectively the microstructures of fully dense FeAl alloy powder compacts, deformed to a total true strain of 1, at a strain rate of 0.1 $s^{-1}$ and 10 $s^{-1}$.

As can be seen in **Figs. 2b** and **2c** as well as in **Figs. 3b** and **3c**, the microstructure of powder material samples, deformed at the temperature lower than 900 °C consists of elongated grains, characteristic of highly deformed and un-recrystallized material. Regardless of the processing strain rate, compression at the temperatures higher than 900 °C resulted in dynamic recrystallization with subsequent grain growth, more evident in the case of the samples deformed at lower strain rate.

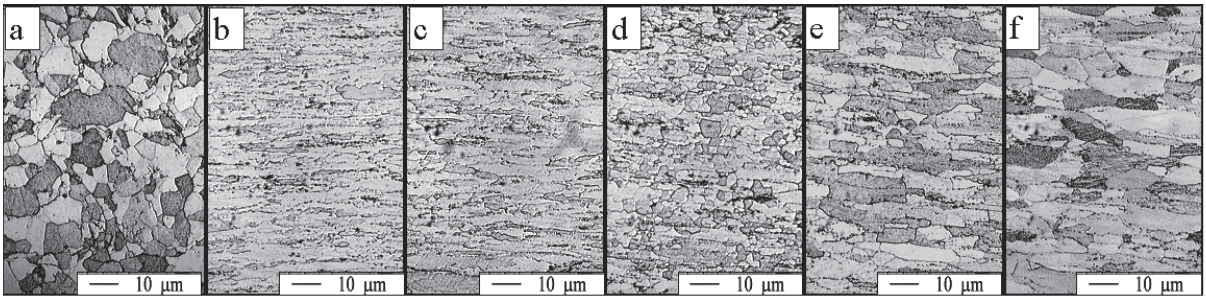


**Fig. 2** Evolution of the microstructure of PM FeAl alloy: powder compact (a) and powder compacts deformed in compression to a true strain of 1 at a strain rate of 0.1 $s^{-1}$ at the temperature of: 700 °C (b), 800 °C (c), 900 °C (d), 1000 °C (e), and 1100 °C (f)

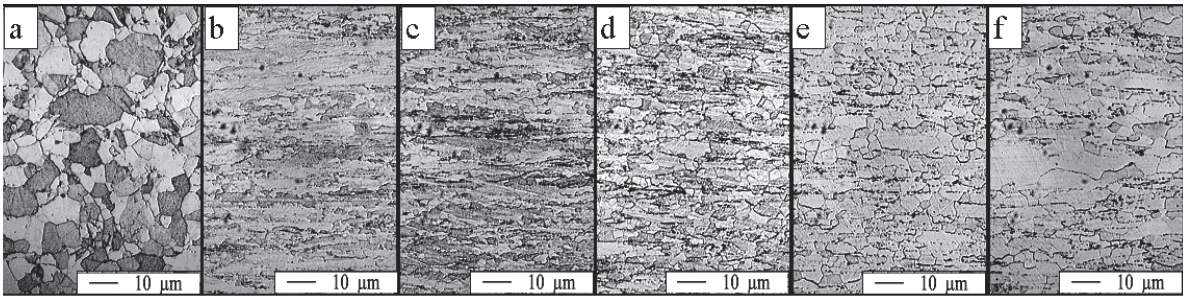


**Fig. 3** Evolution of the microstructure of PM FeAl alloy: powder compact (a) and powder compacts deformed in compression to a true strain of 1 at a strain rate of 10 $s^{-1}$ at the temperature of: 700 °C (b), 800 °C (c), 900 °C (d), 1000 °C (e), and 1100 °C (f)

## 3. INVERSE CALCULATIONS

Identification of rheological parameters is based on the results of plastometric tests, such as axisymmetrical compression or plane strain compression. Loads measured and monitored during the tests as a function of the tool displacement are the input data for the inverse model described in detail in [9]. In this study the inverse method was applied to interpret the results of the axisymmetrical compression tests performed for FeAl alloy samples on a Gleeble 3800 thermomechanical simulator. Calculated by the inverse method true stress - true strain curves for PM FeAl are shown in **Fig. 4**.

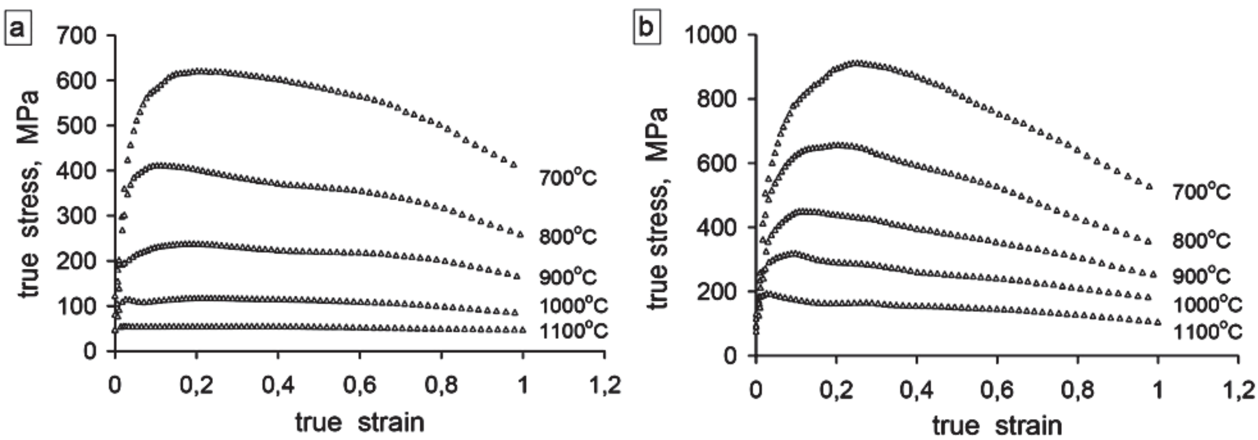


**Fig. 4** True stress - true strain curves for FeAl alloy powder compacts deformed in compression at a strain rate of 0.1 $s^{-1}$ (a), and 10 $s^{-1}$ (b)

All flow stress curves indicate a rapid increase in true stress at the very beginning of deformation. After reaching the peak flow stress, softening starts, indicating the development of the microstructure of the deformed materials. Microstructural observations confirmed that in the case of the investigated materials softening was connected with recovery (lower processing temperatures: 700 °C, 800 °C) and dynamic recrystallization (higher processing temperatures).

Validation of the inverse analysis was performed next. Flow stress data in a tabular form were implemented in the FE code and all compression tests were simulated. Selected example of comparison of measured and calculated load is shown in **Fig. 5**. Very good agreement between measurements and calculations was obtained for all the tests.

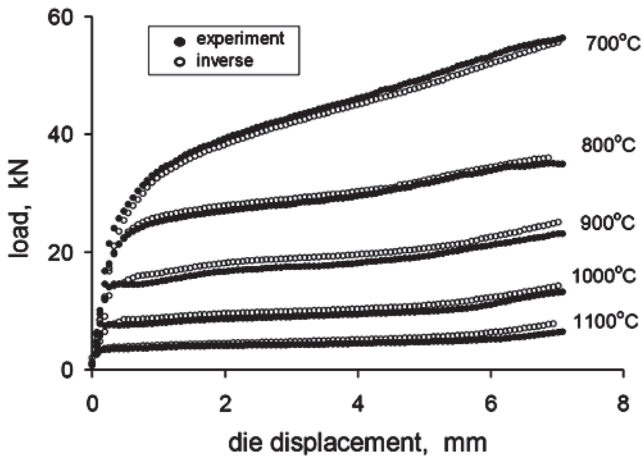


**Fig. 5** Load - displacement curves for PM FeAl alloy deformed in compression at a strain rate of 0.1 $s^{-1}$

## 4. NUMERICAL MODELING

Numerical modeling of the investigated forging process was performed using Simufact.forming 8.0 software. Calculated by inverse method flow stress curves were applied to numerical simulations as one of the boundary conditions. **Fig. 6** shows the geometry of the dies and forged workpiece.

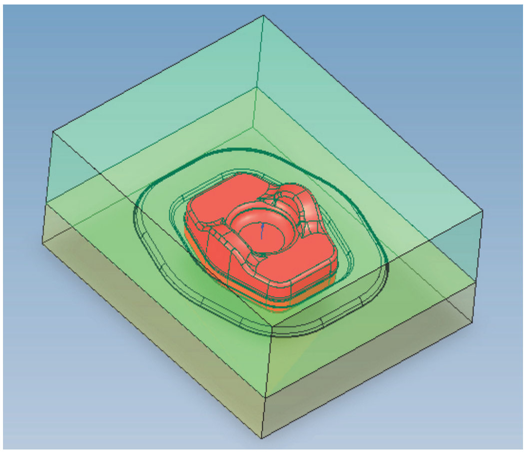

**Fig. 6** Model of the forging dies and forged part

The simulations revealed local increases of the effective strain rate in certain parts of the material forged at 1100 °C (**Fig. 7a**), which can cause local gradients of stresses leading to surface cracking of the forgings at certain stages of deformation. This observation was confirmed during forging tests in industrial conditions performed at ATI ZKM in Stalowa Wola. The forging was performed on 1000 t crank press. P/M FeAl alloy billets were forged. An average ram speed of the forging press was 1 m/s. The billet was heated up to 1100 °C in induction furnace, transferred from the furnace into the die cavity and then forged. The temperature of the dies and P/M FeAl alloy billet was constantly monitored using optical pyrometers. After processing, the forged part was cooled down to room temperature with forced air.

Due to the characteristics of the crank press, the forging process was performed with relatively high strain rate, which caused surface cracks at certain areas of the forged at 1100 °C materials (**Fig. 7b**). These areas - the areas of most intense material flow - were confirmed in the numerical simulations, what proved a proper selection of boundary conditions used in the simulations.

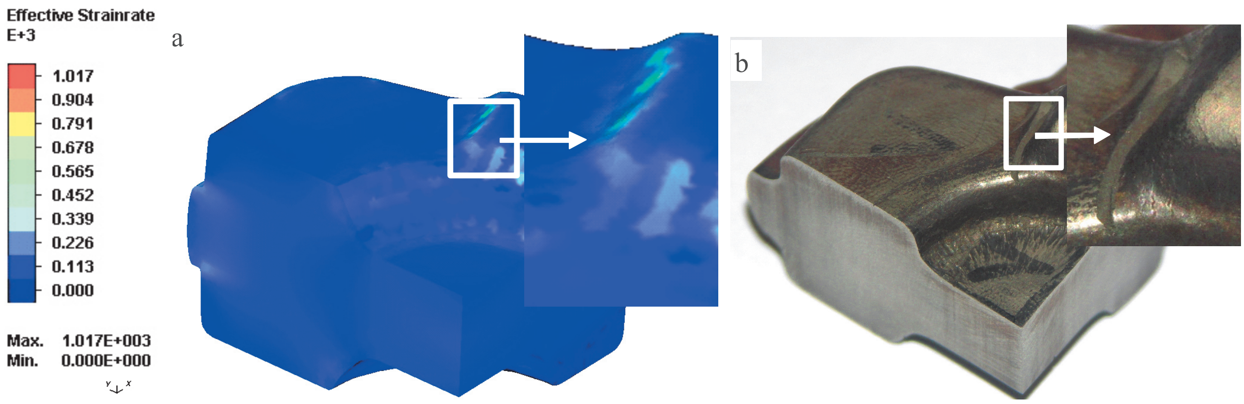


**Fig. 7** Strain rate distribution obtained from the simulation with revealed area of strain rate gradient (a) and surface crack in FeAl alloy part forged at 1100 °C (b)

Further simulations were performed to determine proper thermomechanical parameters of FeAl alloy forging. The simulations showed, that for obtaining good quality part the temperature of forging for the assumed strain-strain rate conditions should be lower. These observations were applied in industrial conditions and P/M FeAl alloy was successfully forged at 900 °C (**Fig. 8**).

**Fig. 8** P/M FeAl alloy part forged at 900 °C

## 5. CONCLUSIONS

Basing on experimentally designed parameters of thermomechanical processing of P/M FeAl alloys, numerical simulations of forging process and on experiments performed in industrial conditions, the following conclusions can be drawn:

- The investigations showed that proper design of thermomechanical parameters and precise control of the microstructural evolution are essential for successful processing of P/M FeAl alloys.
- Numerical simulations of P/M FeAl alloy forging showed, that high strain rate and high temperature processing of such alloy could lead to local increases of the effective strain rate in certain parts of the

forged material. Such strain rate gradients can cause local gradients of stresses leading to surface cracking of the forgings.

- Forging P/M FeAl alloy performed in industrial conditions confirmed, that processing with high strain rates (1 m/s ram speed of the forging press) at relatively high processing temperatures (1100 °C) can lead to surface cracking of the forgings.
- Moreover, the performed research on FeAl alloys forging showed good agreement of the experimental and numerical modeling results, what confirmed a proper design of the boundary conditions used in this study.

## ACKNOWLEDGEMENTS

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