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The influence of deformation on the plasticity and structure of Fe3Al - 5Cr alloy

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Materials

ABSTRACT

Purpose: The major problem restricting universal employment of intermetallic phase base alloy is their low plasticity which leads to hampering their development as construction materials. The following work concentrates on the analysis of microstructure and plasticity of ordered Fe_3Al $D0_3$ - structured alloy containing 28% at. of Al and 5%Cr at. during hot plastic deformation process.

Design/methodology/approach: After casting and annealing, alloy specimens were subjected to axial-symmetric compression in the Gleeble 3800 simulator at temperatures ranging from 600 to 1200°C at 0.1, 0.01, 1.0, 10 s^{-1} strain rates. In order to analyse the processes which take place during deformation, the specimens after deformation were intensely cooled with water. Structural examination was carried out using light microscopy.

Findings: The processes of structural reconstruction such as dynamic recrystallization, which take place during hot - deformation, have been detected.

Practical implications: The research carried out enabled the understanding of the phenomena taking place during deformation and annealing of the investigated alloy. The results will constitute the basis for modelling the structural changes.

Originality/value: The results obtained are vital for designing an effective thermo - mechanical processing technology for the investigated Fe_3Al-5Cr alloy.

Keywords: Metallic alloys; Plastic forming; Microstructure; Compression test

1. Introduction

Intermetallic-phase-based alloys from Fe-Al system belong to the group of high-temperature creep resistant materials, which possess advantageous physical-chemical properties. The plastic working processes of these alloys are generally done at elevated or high temperatures. It is therefore essential to comprehend the phenomena occurring during those processes [1-4].

The unique properties of these alloys, such as their low density, good oxidation resistance and high endurance enable their applications in industry, for instance as elements of machines operating at high temperatures and corroding environments [5-9]. The major problem restricting their universal employment is their low plasticity and their brittle cracking susceptibility, which leads to hampering their development as construction materials. Consequently, the research of intermetallic-phase-based alloys focuses on their plasticising [10-14].

The following work concentrates on the analysis of microstructure and plasticity of ordered Fe_3Al $D0_3$-structured alloy containing 28% at. of aluminium during hot plastic deformation process taking place at 600÷1200°C, at strain rate equalling $\dot{\varepsilon}$ =0.1÷10s^{-1}. The displayed results may form the basis for designing the technology of plastic working of the investigated alloy.

2. Material and methodology

The bars composed of intermetallic-phase-based Fe-Al alloy, whose chemical content is presented in Table 1, were chosen as the material for the study. The alloy was prepared by casting in graphite forms. The following contents were used for smelting: ARMCO iron, aluminium 99,98% wt. minimum, amorphous boron and technically pure molybdenum powder compact. Having undergone the casting, the samples were introductorily heat-treated at 1000°C for 48h with furnace cooling.

Table 1.
Chemical composition of the Fe_3Al-5Cr alloy (at.- %)

	Al	Cr	Zr	C	B	Fe
At.-%	28.0	5.0	0.05	0.10	0.01	66.64

Following the annealing, the material was used for the preparation of the samples for the resistance trials, which consisted of axisymmetrical strain on GLEEBLE 3800 simulator, with simultaneous structure-freeze by rapid quenching. The samples were cylindrical, measuring ϕ=10 mm and h=12mm, as shown in Fig. 1. The compression trials were conducted at temperatures ranging from 600 to 1200°C at $\dot{\varepsilon}$ =0.1, 0.01, 1.0, 10 s^{-1} deformation rates, until the true strain values reached circa ε=1.0. The compression trials results, such as the sample temperatures T [°C], stresses σ [MPa], forces [N] and strains ε, processed with the calculation sheet, provided the means for determining the flow curves in the stress σ - strain ε system. Following the axisymmetrical strain trial, a microstructural analysis was conducted on the axis-parallel section of the sample, using bright field optical microscopy. The strain conditions, including the temperature and the strain rate for the Fe_3Al-5Cr alloy were described with Zener-Hollomon parameter:

$$Z = \dot{\varepsilon} \exp(\frac{Q}{RT}) \qquad (1)$$

where:

$\dot{\varepsilon}$ – strain rate, [s^{-1}];
T – deformation temperature, [K];
Q – activation energy of the plastic deformation process [kJ/mol];
R – molar gas constant [J/molK].

The activation energy for Fe_3Al-5Cr alloy was determined with ENERGY computer program on the basis of tabular data containing stress values σ and strain values ε, which had previously been extracted from the flow curves.

3. Results

The structure of the investigated alloy following the annealing process is presented in Figure 1. The investigated alloy was characterised by coarse-grained structure, whose average grain measured circa 100µm.

The conducted axisymmetrical strain trials of Fe_3Al-5Cr alloy enabled the evaluation of the deformability in the form of deformation-hardening curves in the stress-strain system (Fig. 2). The stress-strain curves present a wide deformation hardening range.

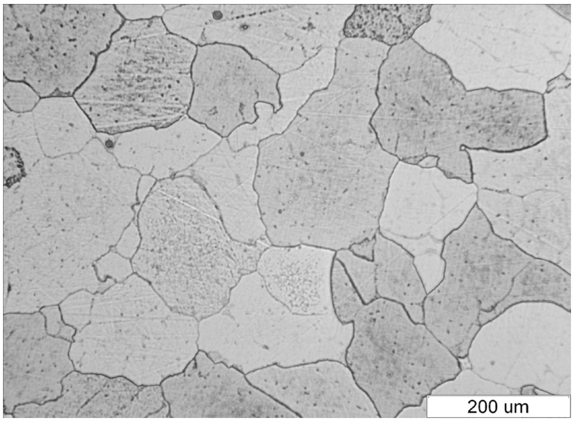

Fig. 1. Microstructure of the Fe-38%Al alloy after homogenization annealing at 1000°C for 48h, followed by cooling with furnace

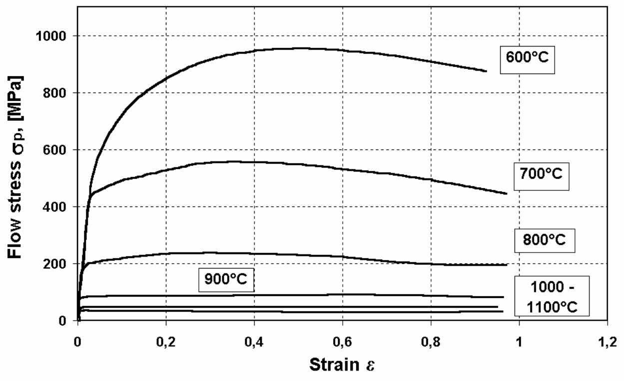

Fig. 2. The stress-strain curves of Fe_3Al-5Cr alloy deformed at the strain rate $0.1 s^{-1}$

The flow curves illustrating the impact of temperature and strain rate on the plasticising stress change as a function of the deformation of the investigated alloy during the hot-torsion trial were presented in Fig. 3. Calculated on the basis of the plastometric torsion trial results, the technological plasticity indicators of the investigated alloy are presented in Table 2. The results of these trials indicate that the increase in the strain temperature ranging from 600÷1100°C causes radical reduction in the maximal plasticising stress σ_p, as well as the decrease in the corresponding strain ε_p. The growth of the strain rate from 0.01 to 10 s^{-1} leads to the higher maximal plasticising stress σ_{pp}, which results in the increase of the corresponding strain ε_p, this refers to strain rates ranging from 0.01 to 1 s^{-1}. Further increase of the strain rate up to 10 s^{-1} leads to the decrease in the ε_p value.

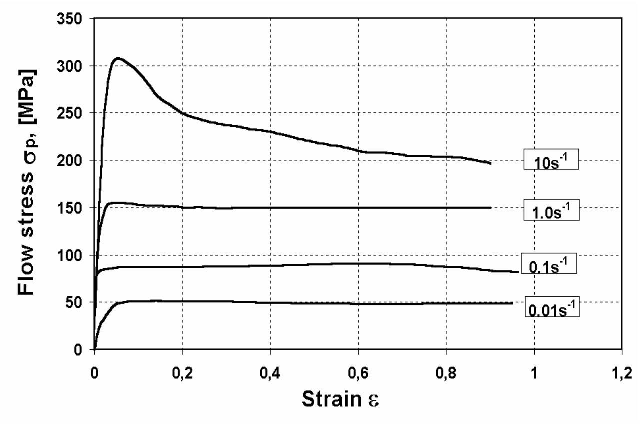

Fig. 3. The stress-strain curves of Fe_3Al-5Cr alloy deformed at the temperature 900°C

Table 2.
The indicators which characterise the technological plasticity of Fe_3Al-5Cr alloy

Temperature [°C]	Strain rate $\dot{\varepsilon}$	Flow stress σ_{pp}	Strain ε_p	Zener-Holloman Parameter Z
600	0.1	955	0.5	$2.66\ 10^{22}$
700	0.1	558	0.35	$1.04\ 10^{20}$
800	0.01	148	0.1	$1.148\ 10^{17}$
	0.1	210	0.05	$1.15\ 10^{18}$
	10	519	0.07	$1.15\ 10^{20}$
900	0.01	51	0.27	$2.72\ 10^{15}$
	0.1	87	0.1	$2.72\ 10^{16}$
	1.0	155	0.06	$2.72\ 10^{17}$
	10	304	0.04	$2.72\ 10^{18}$
1000	0.1	49	0.03	$1.16\ 10^{15}$
	1.0	83	0.05	$1.16\ 10^{16}$
	10	133	0.07	$1.16\ 10^{17}$
1100	1.0	60	0.01	$7.85\ 10^{14}$
	10	96	0.03	$7.85\ 10^{15}$
1200	1.0	42	0.03	$7.66\ 10^{13}$
	10	65	0.02	$7.66\ 10^{14}$

The relationship between the parameters of deformation process (Zener-Hollomon parameter) and the technological plasticity, determined during the compression trial, are displayed equations 2, 3. They testify that the impact of Zener–Hollomon parameter on the maximal plasticising stress σ_p and on the steady state flow strain σ_s may be demonstrated as a power function:

$$\sigma_{pp}=0{,}087\times Z^{0{,}188}\ [\mathrm{MPa}] \tag{2}$$

Similar relationship between the strain ε_p and Zener-Hollomon parameter in semi-logarithmic system $\varepsilon_{p=}f(\ln Z)$ is demonstrated by a power function, as presented by equation 3

$$\varepsilon_p = 0{,}003\times Z^{0{,}078} \tag{3}$$

The microstructures of Fe_3Al-5Cr alloy observed after heat deformation are presented in Fig. 4-6. The conducted hot deformation enabled the assessment of the microstructure of the investigated alloy, whose primary structure had been deformed and whose primary grains had been elongated.

The compression trial of Fe28Al-5Cr alloy performed at 600°C at strain rate $\dot{\varepsilon} = 0.1s^{-1}$ resulted in the change in the shape of the structural grains, though no dynamic re-crystallisation could be detected (Fig. 6). The analysis following the deformation of the samples at 700 and 800°C showed similar effects. However, at 900°C a clear intensification of dynamic re-crystallisation process became apparent. Intensive grain border migration and fine re-crystallised grains could be observed.

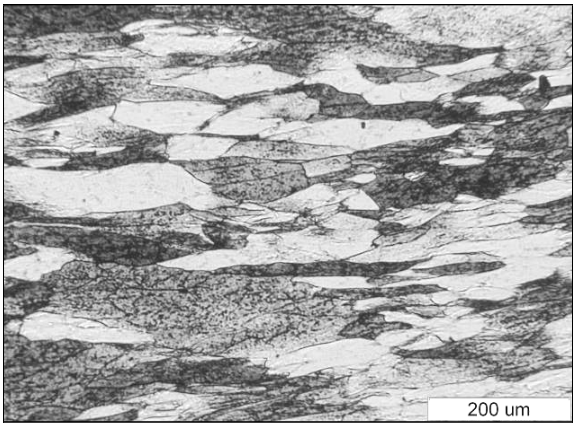

Fig. 4. The structure of Fe_3Al-5Cr alloy, following the deformation at 700°C at strain rate $0{,}1s^{-1}$

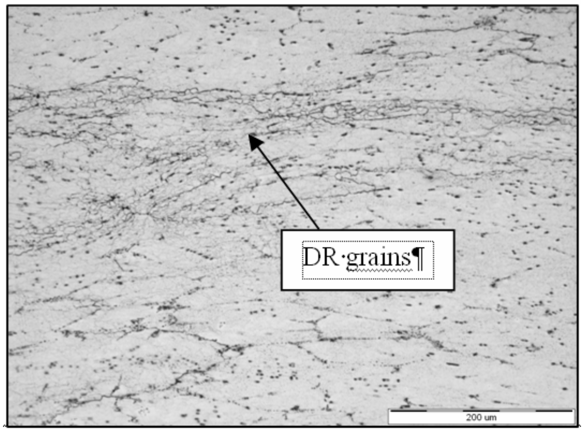

Fig. 5. The structure of Fe_3Al-5Cr alloy, following the deformation at 900°C at strain rate $0{,}1s^{-1}$

At 1000°C and 1100°C, completely recrystallised structure and the development of new grains were noted in the investigated Fe_3Al-5Cr alloy (Fig. 6).

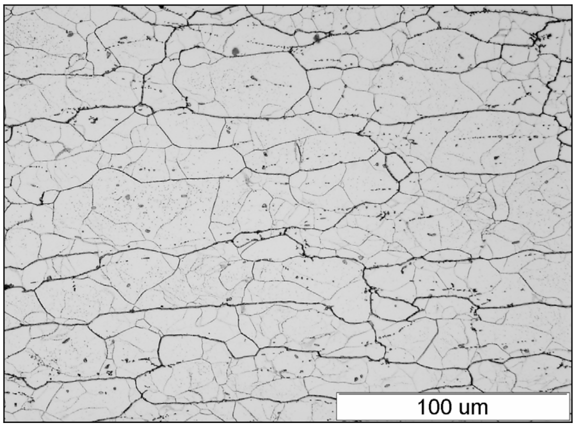

Fig. 6. The structure of Fe_3Al-5Cr alloy after the compression at 1000°C, at compression rate 0,1s^{-1}

4. Conclusions

The Fe_3Al-5Cr ordered-solid-solution-based alloy, having undergone the heat treatment in the form of homogenising annealing at 1000°C, possessed a single-phase coarse-grained structure prior to the deformation process. The activation energy for the heat deformation process of Fe_3Al-5Cr alloy was determined to equal 391 kJ/mol. The activation energy value is comparable to the value for austenitic steel of X3CrNi18-9 type [15]. It is significantly lower, nevertheless, than the activation energy of Fe-Al alloys of B2 type structure. The temperature and the strain rate is, in practice, expressed in the form of Zener-Hollomon parameter. In the investigated range of strain parameters, two characteristic types of flow curves were observed. While compressing at 600÷900°C, at rates ranging from 0.01 to 10s^{-1}, after the deformation had exceeded the peak stress, a gradual decrease in stress can be detected, up to the destruction of the sample. The samples of the investigated alloy deformed at temperatures reaching and exceeding 1000°C exhibited a stable level of stress σ_p for the entire range of analysed strain rates, after the strain had exceeded ε_p.

Having undergone compression at temperatures ranging from 600 do 800°C until the strain equalled ε=1, the samples of the investigated alloy did not exhibit any structure changes denoting dynamic re-crystallisation, regardless of the strain rate. When deformed at temperature 1000°C or higher, in the entire analysed range of strain rates, the structural changes related to the dynamic recrystallisation process become apparent. Additionally, the sub-grain borderlines become apparent ins the grain microstructure. At 1100°C and 1200°C, a completely recrystallised structure occurs and the development of the re-crystallised grains can be noted.

The information obtained from the conducted study of alloy will form a basis for the plastic working technology design of this group of materials. Further research into this matter is going to focus on recognising the mechanisms of strain, employing electron microscopy. The quantitative analysis of the grain size and the changes in the density of defects are also planned.

Acknowledgements

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