Note

Superplasticity in the Fe–6.7%Al–1.5%Cr–1.4%C Alloy

1. Introduction

Fine grained ultrahigh carbon steels, UHCS, can deform superplastically when tested in tension in the vicinity of the eutectoid point (727°C).^{1,2)} A uniform fine grain microstructure (less than about 10 µm) has been successfully obtained in the Fe–C binary system for a carbon content up to 2 by an appropriated thermomechanical process. This process includes the dissolution of the cementite particles in the matrix at 1100–1150°C, followed by continuous rolling during cooling through the γ -Fe + Fe₃C phase field.

Addition of Al alters the thermodynamics of the Fe–C system and a three-phase region (ferrite, asuttenite and κ -carbide) appears.³⁾ In this three phase region, austenite and ferrite inhibit mutual grain growth during deformation and better superplastic properties than UHCS can be expected. In addition, the carbide particles pin both austenite and ferrite grain boundaries. High tensile elongations (up to 1120%) have been reported for these materials, which indicates the possibility of forming into a near-net-shape.^{4,5)}

The aim of this paper is to study the superplastic behavior of an ultrahigh carbon steel containing 6.7%Al–1.5%Cr–1.4%C (mass%) after a thermomechanical process similar to that used in ultrahigh carbon steels.

2. Experimental

An ultrahigh carbon steel containing 6.7%Al–1.5%Cr–1.4%C was prepared by induction melting and cast in a mould. The as-cast ingot was homogenized at 1100°C for 30 min and then continuously rolled during cooling from 1100 to 750°C. After this process, the plates were annealed at 900°C for 10 min and then rolled around the Ac₁ transformation.

Microstructures were examined by optical and scanning electron microscopy (SEM). The microstructure was revealed by chemical etching with 5% nital or alternatively with a color reactive (10 g K₃[Fe(CN)₆], 10 g KOH, and 100 ml distilled water).

Tensile test specimens with a gage length of 15 mm were machined from the consolidated material. Two types of tensile test were conducted under a protective atmosphere of argon in the temperature range of 850 to 920°C. Strain-rate-change-tests were performed to determine the stress exponent, n , and monotonic tensile tests to failure were carried out at different strain rates.

3. Results and Discussion

3.1. Microstructure

The microstructure of the as-cast material consisted of large carbides. In order to refine this coarse microstructure, a thermomechanical process consisting of rolling continuously during cooling from 1100 to 750°C ($\epsilon = -2.8$) and then rolling around the Ac₁ transformation ($\epsilon = -1$) was conducted. **Figure 1** shows SEM images of the processed material. As shown in Fig. 1(a), the microstructure after the first step consists basically of ferrite grains surrounded by a lamellar eutectic, which consists of ferrite and κ -carbide. This microstructure transforms into a microstructure consisting of a dispersion of spheroidized carbides with a size ranging from 1 to 2 µm in a ferritic matrix of about 2 µm in grain size, as present in Fig. 1(b). A volume fraction of carbides of 31% was measured in the thermomechanical processed material.

3.2. Mechanical Properties

The high temperature behavior was analyzed using the following constitutive equation:

$$\dot{\epsilon} = K \exp(-Q_c/RT)(\sigma/E)^n \dots\dots\dots(1)$$

where $\dot{\epsilon}$ is the strain rate in the steady state, K is a material constant, n is the stress exponent, Q_c is the activation

Fig. 1. Microstructure of the Fe–6.7%Al–1.5%Cr–1.4%C steel rolled from 1100 to 750°C ($\epsilon = -2.8$) (a) and then around the Ac₁ transformation ($\epsilon = -1$).

energy for creep, R is the gas constant, T is the absolute test temperature, σ is the stress, and E is the Young's modulus. Therefore, n and the activation energy for creep can be evaluated from strain-rate-change tests, carried out in the temperature range of 850 to 920°C.

A plot of strain-rate sensitivity exponent, m (defined as $1/n$), as a function of the logarithm of the strain rate is shown in Fig. 2. At testing temperatures of 850 and 880°C was obtained a value of m higher than 0.3, which correspond to a grain boundary sliding deformation mechanism. At these temperatures the three-phases $\alpha + \gamma + \kappa$ coexist in equilibrium and smaller increase in grain size during deformation is observed. In the three-phase region, austenite and ferrite inhibit mutual grain growth, with the added benefit of carbide particles which pin both austenite and ferrite grain boundaries. Thus the better superplastic properties with elongation to failure as high as 800% are obtained in this region as observed in Fig. 3.

At 825°C, the normal behavior of increasing ductility with decreasing strain rate is related with a more stable grain size of about 2–3 μm . By contrast, at testing temperatures of 850 and 880°C the ductility increases with decreasing the strain rate only up to a strain rate of 10^{-3} s^{-1} . This decrease in ductility was explained in basis to structural coarsening as the strain rate decreases (time of test increases). A grain size of about 3 and

10 μm were measured in the material tested at 880°C at a strain rate of 10^{-2} and 10^{-4} s^{-1} , respectively. In the specimen deformed at 920°C a grain size of more than 10 μm was found even at the highest strain rate tested.

On the other hand, Fig. 2 shows m values lower than 0.3 at testing temperature of 920°C. Now, a slip creep deformation mechanism is assumed to control the deformation in the whole range of strain rates used. In this region the number of carbide particles is reduced due to the large solubility of carbon in austenite. A lower volume fraction of carbides causes grain growth to occur more readily and diminishes the superplastic effect as observed in Fig. 3.

Microstructural changes during the superplastic deformation depend on the temperature and strain rate. At testing temperatures in the $\alpha + \kappa$ region the microstructure remains quite stable during the elongation to failure test. However, a strain-enhance dissolution of carbide has been observed when testing in the three phases $\alpha + \gamma + \kappa$ region. Figure 4 shows two optical micrographs of a sample tested deformed 530% at 880°C at a strain rate of $1 \times 10^{-2} \text{ s}^{-1}$. Figure 4(a) shows the grip region of the specimen, where no deformation took place, and Fig. 4(b) shows the region near the final fractured tip. A comparison between both figures reveals in Fig. 4(b) the presence of a lower number of coarse κ -carbide particles and some amount of pearlite, precipitated during cooling. The lower volume fraction of coarse carbides in Fig. 4(b) is explained in basis to a strain-enhanced dissolution of carbides. Grain growth occurs more readily in the deformed region because of the reduced number of carbide particles.

Fig. 2. Strain-rate sensitivity exponent as a function of the logarithm of the strain rate.

Fig. 3. Elongation to failure as a function of strain rate at different test temperatures.

Fig. 4. Scanning electron micrograph after a deformation of 530% in tension at 880°C at a strain rate of 10^{-2} s^{-1} . (a) is the undeformed grip region and (b) is the deformed region.

The results of this investigation show that the ultrahigh carbon steel containing 6.7%Al–1.5%Cr–1.4%C exhibits large elongation to failure, typical of superplastic materials, and a strain-rate sensitivity exponent higher than 0.3 at testing temperatures up to 880°C. On the other hand, a microstructural study of a superplastically deformed sample reveals an equiaxed structure of grains, as shown in Fig. 4(b) for a sample deformed 530%. All these results indicate that plastic deformation in this regime is controlled by a grain boundary sliding mechanism.

4. Conclusions

(1) The coarse as cast microstructure of the Fe–1.4%C–6.7%Al–1.5%Cr alloy is strongly refined by a thermomechanical process. The processed material consists of fine spheroidized carbides (1 to 3 μm) in a ferritic matrix with a grain size of about 2 μm .

(2) Elongation to failure up to about 800% with a stress exponent of about 2 were obtained when testing in the three-phases $\alpha + \gamma + \kappa$ field. This effect is associated with a smaller increase in grain size during deformation since austenite and ferrite inhibit mutual grain growth and, at the same time, carbide particles pin both, austenite and ferrite grain boundaries.

REFERENCES

- 1) D. W. Kum, T. Oyama, O. D. Sherby, O. A. Ruano and J. Wadsworth: Superplastic Forming, Metals Park, ASM, OH, (1984).
- 2) Y. Maehara and T. G. Langdon: *Mater. Sci. Eng.*, **A128** (1990), 1.
- 3) V. Raghavan: Phase diagram of Ternary Iron alloys, Part I, Metals Park, ASM, OH, (1987).
- 4) H. Fukuyo, H. C. Tsai, T. Oyama and O. D. Sherby: *ISIJ Int.*, **31** (1991), 76.
- 5) C. K. Teo, O. A. Ruano, J. Wadsworth and O. D. Sherby: *J. Mater. Sci.*, **29** (1994), 6581.

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