Original Article

Simulation of the Accumulative Roll-Bonding process through warm torsion test

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ABSTRACT

The objective of this work was simulating the process of severe plastic deformation, specifically the Accumulative Roll-Bonding process (ARB) in low carbon steel, by warm torsion test, using the typical ARB process parameters. The torsion test was performed at 500 °C, using a total equivalent strain of 4.0, with increment of 0.8 per pass and keeping the constant strain rate of 0.1 s⁻¹, as well as intermediate strains of 0.8, 1.6, 2.4 and 3.2. Along with the reduction of the average grain size there was an increase in the hardness of 43%. Torsion test was performed until failure, increasing the yield stress by about 380 MPa. After processing, the average grains size with 0.93 μm were obtained showing that the torsion test is an efficient tool for simulating ARB process.

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1. Introduction

One of the great challenges of the metallurgical industry is to increase the mechanical strength of its products without major changes in the chemical composition, this fact becomes more interesting in relatively cheap metals and produced in large scale, like low carbon content steels. An alternative of the great interest is to obtain a steel with ultrafine grain size, this is due to the fact that this process simultaneously increases mechanical strength and toughness. Thus, low carbon steels with ultrafine grains have great potential to replace carbon steels of high strength and low alloy, which has a higher industrial cost and difficult to recycle due to the presence of alloying elements, which would make the process more sustainable.

Ultra-fine metals are those in which the average grain size is between 1 and 2 μm in diameter, and their production methods are divided into two groups: methods based on advanced thermomechanical treatments and methods based on severe plastic deformation. The advanced thermomechanical treatments combine the solid state phase transformations with the application of controlled deformations to obtain the grain refining, whereas, the methods based on the severe plastic
deformation use the application of great cold or warm deformations [1].

Among the severe plastic deformation process are the Equal-Channel Angular Pressing, High Pressure Torsion and Accumulative Roll-Bonding. Furthermore, the Accumulative Roll-Bonding process is the only one that has better possibility of industrial application. The Accumulative Roll-Bonding-ARB process was initially developed in a commercial aluminum alloy an IF steel, and consists of the joint rolling of two metal sheets of the same size, chemically and mechanically treated to provide high weldability. The obtained strip is again sectioned in two equal parts, surface treated and again collapsed. This process is repeated continuously. Each pass of colimation performed a 50% reduction of the thickness, which represents 0.8 of true deformation [2]. Nowadays, the studies of ultrafine grains production by severe plastic deformation aim at a better understanding of the grain refining mechanism and the economic and technical viability for industrial scale production.

Another concern is due to the fact that despite the significant increase in mechanical strength and toughness, ultrafine grains show a considerable decreasing in ductility, which could limit their industrial application [3–5]. A solution studied to increase uniform elongation in ultrafine grain materials without great loss in mechanical strength would increase their hardening rate by some engineering device, such as dispersion of fine second phase particles in their matrix.

The torsion test is an efficient tool for a rolling processes simulation [6,7], where, with adequate temperature control and strain rate, it is possible to reproduce the conditions used in the industry. In this context, this work aims to study the ultra-fine grain of a low carbon steel (AISI 1020) simulating the Accumulative Roll-Bonding (ARB) by means of a warm torsion test.

2. Experimental

The chemical composition of low carbon steel used in this work was 0.20-C, 0.54-Mn, 0.17-Si, (mass %). Torsion test specimens which 20 mm length and 5 mm diameter were obtained from a commercial bar with 9.5 mm. The test specimens were first heated at 900 °C (1173 K) at a rate of 3 °C/s using an induction furnace and held for 5 min. After this process they were oven-cooled to room temperature. The samples were kept in a quartz tube with continuous passage of argon gas, to avoid corrosion. To obtain ultrafine grain, they were heated to 500 °C (773 K) at a rate of 1 °C/s, remaining for 5 min for homogenization, and submitted to five torsion passes, with equivalent deformation of 0.8 per pass, totaling 4.0 at the end of fifth pass with a strain rate of 0.1 s⁻¹. After each pass the specimens were cooled in the furnace turned off.

Aiming to evaluate the mechanical strength of the material after severe plastic deformation, torsion tests were performed from room temperature until its rupture, comparing with the annealed test specimen. The microstructural analysis was performed by scanning electron microscopy, and the grain size was obtained by the linear intercept method. The Vickers hardness test was performed using ten indentations with a load of 0.5 kgf. Torsion tests with intermediate deformations of 0.8, 1.6, 2.4 and 3.2 were performed to evaluate the grain refining process as well as the Vickers hardness evolution.

3. Experimental results

3.1. Torsion test

Fig. 1 shows the results obtained by torsion test at 500 °C (772 K), where it is found that with each pass the strength of the steel is increased. The curves have characteristics of metals that have been hardened during plastic deformation followed by dynamic softening, presenting a stress peak followed by a decrease of the same until its stabilization in a value denominated steady state stress.

This occurs because metals with high stacking fault energy such as ferritic carbon steels undergo continuous dynamic recrystallization at high strain rate, a phenomenon characterized by grain subdivision, recovery and migration of grain boundaries. The recrystallized microstructure is developed by the progressive transformation of subgrains into new grains within the original deformed grains. This occurs insofar as the high accumulated deformation causes an increase in the density of dislocations thus forming the low angle (subgrain) boundaries, which leads to the progressive increase of its misorientation angle and the formation of high angle boundaries. The transformation of low-angle into high-angle boundaries is apparently more effective when there is the presence of fine particles anchoring these [6,8,9].

Fig. 2 shows the stress-strain curves until the failure obtained by torsion test, at room temperature, of the steel in the annealed condition and steel processed by the ultrafine grain route. Comparing with the steel in the annealed condition, it was verified that after the deformation there was a 96% increase in the yield stress, from 400 MPa for the metal in the annealed condition and 783 MPa for the metal with a total deformation of 4, these yield stress were calculated by secant modulus (strain 0.002). Note also a reduction in ductility, an inherent characteristic in the production of ultra-fine grain materials, as the annealed steel deforms during the test to 0.71 and the processed steel undergoes a previous break at 0.46.
Fig. 2 – Stress–strain curves until the failure at the ambient temperature of the steel in the annealed condition and after severe plastic deformation at 500 °C for five passes (ε = 4).

Fig. 3 – Optical micrograph of the initial ferrite–perlite microstructure, after annealing at 900 °C.

The Vickers microhardness of the steel was also measured after the ultra-refining process, in which it showed an elevation from 140 to 200HV.

3.2. Microstructural characterization

Fig. 3 shows the optical microstructure after annealing at 900 °C. It was verified that before the torsion test, the steel had equiaxial ferrite grains with a small fraction of perlite, with an average grain size of 16.5 μm.

The scanning electron microscopy (SEM) image of the steel processed by the ultrafine grain route is shown in Fig. 4. There is a reduction in the ferrite average grain size, being the same after the torsion test of 0.93 μm, obtained from the linear intercept method. It is evident that the large accumulated strain caused the breaking of the perlitic lamellae and spheroidization of the cementite. This occurs because the warm deformation and consequent hardening causes an increase in the density of dislocation and the consequent

formation of subgrain boundaries, thus increasing the carbon diffusion rate in ferrite.

The plastic deformation involves the breaking of the perlitic lamellae into fine fragments, followed by the coalescing of these fragments in a competitive way. Fragments of cementite located in grain boundaries have a higher growth rate. The boundaries act as paths of greater mobility for the diffusion of carbon atoms, so the spheroidization occurs more rapidly at the triple grain boundary points, where the contact area is larger and there are more paths for diffusion [10–13]. It is also noted that the ferritic grains are approximately equiaxial, results similar to those of Song et al. [14] and Narayana Murty et al. [11].

Fig. 4 – SEM image of the ultrafine grained steel processed by the ultrafine grain route (with warm deformation, ε = 4).

Fig. 5 shows the microstructural evolution of the carbon steel obtained by scanning electron microscopy after each deformation pass. It is verified that in the first pass (ε = 0.8) the grains are cold-hardened and elongated in the deformation direction, also the presence of fine lines inside the ferritic grains indicates the beginning of the formation of grain substructures (arrow 1), after the second pass, the amount of subgrains is increased and the fragmentation of the perlitic lamellae and spheroidization of the cementite (arrow 2) begins. After equivalent deformation of 2.4 the cementite is totally spheroidized, but aligned in the direction of the deformation, also the formation of ultrafine grains is verified. After equivalent deformation of 3.2, the number of ultra-fine grains is increased, as well as homogenization of the cementite, becoming complete at the end of the fifth deformation pass (ε = 4.0).

Fig. 6 shows the evolution of the ferrite average grain size with the total equivalent deformation. It is found that in the first and second deformation passes there is a small reduction in the grain size, this is because, as shown in Fig. 5, there is only the formation of low angle grain boundaries inside the original ferrite grains, only from the third deformation pass the average grain size is effectively reduced, reaching the value of 0.97 μm.
Fig. 5 – SEM micrographs of the microstructural evolution of the carbon steel during deformation. ($\varepsilon = 0.8$) microstructure after a deformation pass at 500 °C, deformation rate of 0.1 s$^{-1}$, ($\varepsilon = 1.6$) after two deformation passes, ($\varepsilon = 2.4$) after three passes of ($\varepsilon = 3.2$) after four deformation passes and ($\varepsilon = 4$) after five deformation passes. Arrow 1: formation of grain subsets. Arrow 2: fragmentation of perlite and spheroidization of cementite.

4. Conclusions

1. Stress strain curves obtained by torsion test showed a behavior typical of steels subjected to continuous dynamic recrystallization, grain refining mechanism described by researchers of the process under study.

2. Microstructural analysis showed a microstructure similar to those found in ARB process with grain size reduction.

3. The grain refining showed that it directly affects the material mechanical behavior when it increases of the yield stress from 400 MPa until 783 MPa and the microhardness from 141 until 201HV.
4. The torsion test showed to be effective for simulation of the ARB process.

Conflicts of interest

The authors declare no conflicts of interest.

REFERENCES