The operative dynamic recrystallization mechanism of austenite during the transient deformation in a Ni-30%Fe model alloy

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Abstract. Effect of strain rate and its discontinuous changes on dynamic recrystallization (DRX) behaviours of a Ni-30%Fe austenitic model alloy were investigated by hot compression tests. The results show that, during deformation at slow strain rates, DRX occurs with discontinuous nature, i.e. the DRX nuclei preferentially appear along initial grain boundaries followed by a quick growth through the strain-induced boundary migration (SIBM). Interestingly, during the further deformation after an abrupt increase in the strain rate, it can be found that the subgrains which developed in the first stage of deformation would gradually transform into new DRX grains. Therefore, in spite of the low stacking fault energy austenite, the continuous DRX (CDRX) is indeed possible to be activated during the transient deformation. The strain-induced sub-boundaries developed in the first deformation stages are believed to transform into higher-angle boundaries easily in further straining after abrupt increase of the strain rate. By this way, the CDRX mechanism in austenite is significantly promoted. Moreover, the local growth of new grains also plays an important role in this dynamic softening process.

1. Introduction

Dynamic recrystallization (DRX) process involves the formation of new strain-free grains on the deformation matrix during hot deformation, which plays a key role in tailoring the microstructure during the hot processing of steels. In general, there are two types of DRX that occur in metallic materials, which are closely related to the stacking fault energy (SFE) of the material [1]. The discontinuous DRX (DDRX) mechanism, usually takes place in metals of low to medium SFE, which has clear nucleation and growth stages. Continuous DRX (CDRX) mechanism, generally occurs in metals and alloys with high SFE, in which new DRXed grains with high angle boundaries (HABs) mainly formed by gradual coalescence of subgrains with minor boundary migration upon straining [2].

Up to now, a significant number of studies has been carried on to investigate the DRX mechanism in austenite under varying deformation conditions [3]. It recently has been proposed that the DRX mechanism is not only controlled by the deformation parameters, but also influenced by the initial grain structures. For instance, the fine initial grain size promoted CDRX in austenite [4]. However, limited attention has been given to the role of initial substructures on the DRX behaviors. In this study, the effect of strain rate as well as its discontinuous changes during the microstructural development in the austenite is considered. The aim of the present work is to investigate the evolution of pre-induced substructures under the transient change of deformation conditions.
2. Experiment

An austenitic model alloy with a composition of Ni-30.5Fe-0.02C-0.04Mn (wt.%) with an average grain size of about 300 µm has been used in the current study. This alloy has approximately the same SFE as the austenite phase in low carbon steels but does not undergo any phase transformation when quenched to the room temperature, which thus offers a facility to characterize microstructures of austenite from hot deformation [5]. Hot compression tests were performed on a Gleeble-3500 thermo-mechanical simulator. Cylindrical samples for compression tests have the length of 15 mm and the diameter of 8 mm. Uniaxial compression tests were performed both at constant deformation conditions with constant strain rates of 0.001 s\(^{-1}\) and 0.1 s\(^{-1}\) at 900 ºC and at transient deformation conditions with an abrupt increase of the strain rate from 0.001 s\(^{-1}\) to 0.1 s\(^{-1}\) at the strain of 0.3. The samples were water quenched immediately after the deformation to preserve the microstructure formed after the hot deformations.

The microstructures were analyzed by the electron backscattered diffraction (EBSD) and the transmission electron microscopy (TEM) on middle sections perpendicular to the compression axis of samples. EBSD scans were carried out using a FEI Nova NanoSEM 430 field-emission scanning electron microscope operated at 20 kV. The HKL Channel 5 software was used for the EBSD data acquisition and post-processing. Samples for EBSD were prepared by mechanical polishing and finished with Ion milling to remove the surface deformation layer. TEM foils were mechanically grinded to reduce the thickness followed by twin-jet electro-polished with a solution containing 10% perchloric acid and 90% ethanol at the temperature of about -30 °C and the voltage of 15 V. The TEM analysis was performed on a FEI Tecnai G2 F20 field-emission microscope at 200 kV.

3. Results and Discussion

True flow stress curves for the Ni-30%Fe alloy at different strain rates are displayed in figure 1a. At the constant strain rate condition, the flow curve shows a stress peak followed by gradually softening to the steady-state stress regime during the deformation at a low strain rate of 0.001 s\(^{-1}\). This type of flow behavior displays a typical feature of metals undergoing DRX. Increasing the strain rate to 0.1 s\(^{-1}\) leads to a broader plateau and a much high stress level on the flow curve, which implies the dynamic softening is hindered at this condition. In the case of the transient deformation condition with strain rate changed from 0.001 s\(^{-1}\) to 0.1 s\(^{-1}\), the flow stress is adjusted immediately according to the imposed strain rate and finally approached the same stress level appearing in the constant deformation of 0.1 s\(^{-1}\).

EBSD maps exhibit the microstructures of samples deformed to a strain of 0.8 at varying strain rates (as shown in figures 1b-d). These images revealed that the fraction and size of DRX grains are quite different under various deformation conditions. The deformed grains were completely replaced by newly coarse DRX grains in the sample deformed at a constant strain rate of 0.001 s\(^{-1}\). On the contrary, only a few of fine DRX grains can be observed at the original boundaries at the higher strain rate of 0.1 s\(^{-1}\). It is suggested that the DRX is suppressed by the increase of strain rate due to the shorter duration of deformation. However, it is noteworthy that, under the transient deformation condition, the DRX is accelerated significantly, which with a larger DRX fraction than that at the constant high strain rate deformations, but the average DRX grain size is approximately the same as that at the constant high strain rate condition. This implies that the DRX behavior has been changed due to the strain rate variation.

3.1. DRX behaviour at the constant low strain rate

Figure 2 shows a typical microstructure of samples deformed to strain of 0.3 with the strain rate of 0.001 s\(^{-1}\). It can be seen that new DRX grains preferentially develop along initial grain boundaries, and the nucleation of DRX resulted from bulging of pre-existed grain boundaries associated with the formation of annealing twins or strain-induced sub-boundaries. Some Σ 3 annealing twin boundaries can be observed within new DRX grains, which usually indicates that the development of the DRX grain is assisted by the migration of grain boundaries over a large distance [3,6]. The presence of annealing twins within the new grains, therefore, is widely recognized as an indicator for the occurrence of DDRX.
The highly cumulative (point-to-origin) misorientations estimated by EBSD reveal that a large strain gradient developed within the deformed matrix, which would generate the driving force for the DRX grain growth by the migration of grain boundaries (figure 2b). TEM observation reveals that the substructures within the deformed grains displays a complex character with varieties of subgrain/cell morphologies (figure 2c). In spite of long duration of the test at low strain rate, the local angular misorientations across sub-boundaries are not exceed 3°, which implies that the substructure development is stunted. It then implies that the CDRX mechanism which new grains form through the gradually evolution of sub-boundaries can hardly operate in this austenitic alloy at the current deformation condition.

Figure 1. (a) Stress-strain curves of the Ni-30%Fe alloy obtained from the constant deformation tests (dash lines) and transient deformation test (solid line) at 900°C. Typical OIM maps of samples deformed to strain of 0.8 at (b) 0.001s⁻¹; (c) 0.1s⁻¹; (d) 0.001s⁻¹ to 0.1s⁻¹. The silver, green, black, red and magenta lines represent boundaries with 1° < θ < 5°, 5° < θ < 15°, 15° < θ, ∑3 and ∑9 twin boundaries respectively.

Figure 2. (a) OIM map of the Ni-30%Fe alloy deformed to a strain of 0.3 at a strain rate of 0.001s⁻¹ at 900 °C; (b) misorientation profiles along the corresponding arrow L₁; (c) TEM image of deformed matrix corresponding to (a). The silver, green, blue, black, red and magenta lines represent boundaries with 0.8° < θ < 2°, 2° < θ < 5°, 5° < θ < 15°, 15° < θ, ∑3 and ∑9 twin boundaries respectively.

3.2. Microstructure evolution at the constant high strain rate

The microstructures of the sample deformed to a strain of 0.5 at the strain rate of 0.1 s⁻¹ are displayed in figure 3. Similar to the deformation at low strain rate, new grains preferentially appear at the original grain boundaries due to bulging of the boundaries in this condition. It should be noted that an abundance of sub-boundaries is forming around the original grain boundaries (blue lines in figure 3a). The boundaries are impeded by the drag force derived from attachment of the various strain-induced sub-
boundaries, leading to the limited growth of new DRX grains. It indeed indicates that the DDRX process is inhibited at the high strain rate condition.

Figure 3. (a) OIM map of the Ni-30%Fe alloy deformed to a strain of 0.5 at a strain rate of 0.1s\(^{-1}\) at 900 °C; (b) misorientation profiles along the corresponding arrow L\(_2\); (c) TEM image of deformed matrix corresponding to (a). The silver, green, blue, black, red and magenta lines represent boundaries with 0.8° < \(\theta\) < 2°, 2° < \(\theta\) < 5°, 5° < \(\theta\) < 15°, 15° < \(\theta\), \(\Sigma\) 3 and \(\Sigma\) 9 twin boundaries respectively.

The microstructure within the deformed grains mainly shows regular arrays of sub-boundaries delineated as elongated bands. The misorientation angles across the band boundaries measured by EBSD are almost below to 5°, and the cumulative misorientation across the band tends to systematically alternate across the consecutive but extended sub-boundaries (figure 3b). The TEM image reveals that the band boundaries could be considered as dense dislocation walls, which separate the deformed grains into parallel segments with relatively low dislocation densities (figure 3c). This kind of dislocation boundaries are always considered as micro-shear bands, as suggested by previous reports for the deformation of metals under high strain rates or at low temperatures [7]. It then indicates that some of slip systems can be activated by increasing flow stress under the applied high strain rate condition.

Figure 4. OIM maps of microstructures evolved in the transient deformations: deformed with strain rate jumping from 0.001s\(^{-1}\) to 0.1s\(^{-1}\) at strain of 0.3 and further straining to total strains of 0.4 (a), 0.5(c) and 0.8 (e). (b), (d) and (f): misorientation profiles along the corresponding arrows L\(_3\), L\(_4\) and L\(_5\) respectively. The silver, green, blue, black, red and magenta lines represent boundaries with 0.8° < \(\theta\) < 2°, 2° < \(\theta\) < 5°, 5° < \(\theta\) < 15°, 15° < \(\theta\), \(\Sigma\) 3 and \(\Sigma\) 9 twin boundaries respectively.
3.3. Variation of DRX mechanisms under the transient deformation

During the transient deformation, after the strain rate changed from 0.001 s\(^{-1}\) to 0.1 s\(^{-1}\) at the strain of 0.3, the substructures formed in the first straining stage can be reasonably considered to do not alter immediately. The preformed microstructures have to evolve continuously to adapt to the imposed new strain rate in further deformations. Figure 4 shows the typical microstructures within the original grain interior after the strain rate jumps from 0.001 s\(^{-1}\) to 0.1 s\(^{-1}\). Under continued straining to 0.4 after the strain rate changing, the microstructures evolved into an elongated subboundary network, these subboundaries generally with small to medium misorientation angles (figure 4a). The misorientations of some sub-boundaries are observed sharply increasing to about 7–15° (figure 4b). With the further straining to 0.5 and 0.8, the point-to-point misorientations of some segments in the subgrain boundary network are continuously increasing to above 15°, leading to the development of HABs during the deformation (figure 4d and 4f). The appearance of incomplete HABs confirms progressive transformation of sub-boundaries towards general grain boundaries during the deformation [8]. Furthermore, many fine DRX grains delimited partly by low angle boundaries (LABs) and partly by HABs are developed within the subgrain network (figure 4c and 4e). It thus provides a strong evidence to support the operation of the CDRX under the present transient deformation condition. The occurrence of the CDRX in austenite under current condition is in good agreement with the model suggested by Gourdet and Montheillet [2] who have proposed that during CDRX, LABs become increasingly transformed to higher-angle boundaries by absorbing dislocations.

![Figure 5](image)

**Figure 5.** Typical TEM micrographs of (sub)structures evolved in the transient deformations: deformed with strain rate jumping from 0.001 s\(^{-1}\) to 0.1 s\(^{-1}\) at the strain of 0.3 and further straining to the total strain of 0.4 (a), 0.5 (b) and 0.8 (c).

TEM micrographs in Figure 5 show the evolution of sub-boundaries during the transient deformation. When the strain rate changes, the preformed substructures become elongated along the deformation direction. At the same time, abundant dislocations are generated and further accumulated around the sub-boundaries due to rapid strain hardening concomitantly with the instant strain rate jump (figure 5a). Furthermore, these newly formed dislocations will be effectively trapped and absorbed by the existing sub-boundaries or be rearranged to form new strain-induced sub-boundaries, leading to a rapid increase in their misorientations. Therefore, new CDRX grains will be preferentially developed from the existing sub-boundaries (figure 5b). It should be noted that the new grains formed by the CDRX generally have a relatively finer grain-size. Other than the CDRX grains in materials within high SFEs, these new grains in this austenitic alloy might be able to further grow by the migration of grain boundaries due to the high density of dislocations around them (figure 5c). The annealing twins can also be clearly observed inside many of new DRX grains (figure 4c and 4e), which also provides evidences for the occurrence of grain growth during this softening process, albeit most of new grains are forming by the CDRX mechanism.

In this study, it should be noted that the substructures formed during the transient deformation are quite different from the low-angle shear bands developed under the condition with constant high strain rates. It is easy to found that preserved substructures developed at former deformation stages will
enhance the transformation of strain-induced subboundaries towards higher-angle boundaries in further straining after the abrupt jump of the strain rates. High density of preserved sub-boundaries can effectively absorb new generated dislocations. Meanwhile, some additional slip systems should be activated by the increased flow stress, which can induce rotations of individual crystallites towards different stable orientations during the deformation [9]. Both reasons can lead to quick increase in misorientations of the sub-boundaries, which can contribute to the occurrence of the CDRX in austenite [10]. It seems that the CDRX provides partially softening by the rearrangement of lattice dislocations to low-energy configurations (i.e. LABs to HABs) due to the absence of grain boundary migration inside the deformed coarse grains. The CDRX mechanism, however, cannot consume the lattice dislocation sufficiently because of the limited mobility of the dislocation in austenite. Hence, it can be expected that the newly formed CDRX grains would eliminate dislocations further by the local migration of new formed HABs. It can be reasonably speculated that the apparent acceleration of the DRX observed after the strain rate transition in Fig.1 is ascribed to the beneficial effect of the occurrence of CDRX and the subsequent grain growth.

4. Conclusions

In summary, although the austenitic alloy is of low SFE, two types of dynamic recrystallization might operate in the Ni-30\%Fe austenitic model alloy, depending on the deformation conditions. At a slow strain rate, dynamic softening of the austenite takes place through a DDRX mechanism, whereas the DRX process was remarkably limited at the high strain rate condition. The transient deformation during which the strain rate jumps from low to high strain rates, however, can significantly promote occurrence of the CDRX in the low SFE austenitic alloy. The microstructure behaviours during the transient deformation are strongly affected by the deformation history. The preserved substructures are found significantly facilitate the strain-induced sub-boundaries increasingly transforming to higher-angle boundaries by continuing straining after the strain rate jumps, which promotes the occurrence of the CDRX in the low SFE austenitic alloy. Furthermore, the formation of new CDRX grains may further promote the dynamic softening of austenite by the subsequent grain growth.

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