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Formation of Ultrafine Ferrite by Dynamic Strain-Induced Transformation

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Abstract

In the current study, the role of dynamic strain induced transformation on ferrite grain refinement was investigated using different thermomechanical processing routes. A Ni-30Fe austenitic model alloy was also employed to study the evolution of the deformation structure under different deformation conditions. It was shown that the extreme refinement of ferrite is more likely due to the formation of extensive high angle intragranular defects in the austenite through deformation. Among the different thermomechanical parameters, the deformation temperature had a significant effect on the intragranular defect characteristics. There was a transition where the cell dislocation structure changed to laminar microband structures with a decrease in the deformation temperature. Moreover, the ultrafine grained structure was also successfully produced through static transformation using warm deformation process; in other words, concurrent deformation and transformation are not necessary for ultrafine ferrite formation.

Introduction

The refinement of ferrite grain size is the most commonly accepted approach to simultaneously improve the strength and toughness of steels. Ultrafine ferrite can be produced by a number of thermomechanical processing routes. These include simple processes, such as single deformation, dynamic strain induced ferrite transformation (DSIT) [1], through to more complex multistage processes involving hot and cold processing and complex heat treatments [2-4]. The simplicity and commercial potential of the DSIT route has encouraged research groups around the world to investigate this process. In addition, this method exhibits general insensitivity to variations in chemistry and can therefore be applied to a full range of steels for ultrafine grain refinement [5].

The DSIT route requires deformation within the Ae_3 to Ar_3 temperature range for a given alloy. While this process appears relatively simple it is in fact extremely complex compared with controlled rolling because the deformation is being applied in the two-phase region, which involves the interplay of a number of microstructural processes (i.e. transformation and deformation). So far, very different mechanisms have been suggested in the literature including continuous [6] or discontinuous [7] dynamic recrystallisation of the ferrite, dynamic recrystallisation of the austenite [2] and dynamic strain induced transformation of the austenite to ferrite [1]. The work to date has shown that it is necessary to control both the nucleation and growth phases to obtain uniformly fine ferrite. The most likely commercial exploitation of UFF would appear to rely on the formation of a critical volume fraction of dynamic strain induced ferrite followed by controlled cooling to ensure that this unique microstructure is maintained to room temperature [8]. Therefore, it is important to determine the critical condition in which UFF can be produced through the DSIT route. The authors have attempted to rationalize some of these requirements by the construction of a microstructure evolution map.

Microstructural Map for Ultrafine Ferrite Formation

Recent work has shown that there are two critical strains: one for the start of dynamic strain induced transformation $\varepsilon_{C,DSIT}$ [1], where the Ar_3 temperature intercepts the deformation temperature during straining, and one for formation of the ultrafine microstructure after cooling to room temperature $\varepsilon_{C,UFF}$ [1], where an appropriate volume fraction ferrite is formed during deformation. In reality, there will also be another strain for the completion of DSIT (i.e. $\varepsilon_{F,DSIT}$). The latter is not easy to detect during thermomechanical processing because it requires complete transformation to the equilibrium volume fraction of ferrite. However, for a given set of thermomechanical conditions, such as in a torsion experiment, the samples may have limited ductility and failure can occur before complete transformation has taken place.

The current authors have systematically studied the effect of the thermomechanical processing parameters on $\varepsilon_{C,DSIT}$ and $\varepsilon_{C,UFF}$ using hot torsion experiments [1]. It was shown that the thermomechanical parameters significantly affect these critical strains. Based on those results, a hot working microstructural map was developed for a 0.17C–1.5Mn–0.02V steel, which shows five regions representing: I – work hardening, II – dynamic strain induced transformation, III – ultrafine ferrite formation, IV – dynamic recrystallisation and V – warm deformation (Fig. 1) [8]. This study mainly focuses on the region between the Ae_3 and Ar_3 temperatures as this is the critical temperature range for UFF formation through the DSIT process. This shows how critical strains vary with temperature for austenite dynamic recrystallisation and the start of strain induced transformation and the level of strain required to obtain ultrafine ferrite at room temperature. These lines will differ with initial austenite grain size and strain rate (as well as the normal variation with composition); the ultrafine ferrite strain will also alter with the post deformation cooling rate.

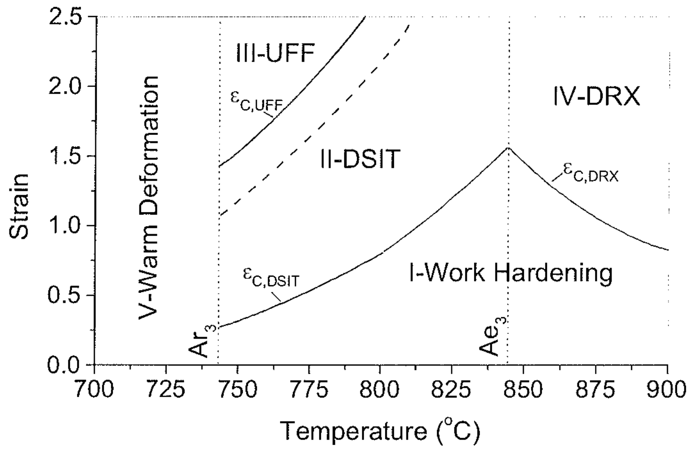

Figure 1: Microstructural map for 0.17C-1.5Mn-0.02V (in %wt) steel at strain rate of 1 s^{-1} and cooling rate of 3 °C/s for austenite grain size of 84µm (broken line represents $\varepsilon_{C,UFF}$ at cooling rate of 5 °C/s) [8]

The map clearly shows that the deformation window for UFF microstructure formation is very narrow. It appears that very large strains and low deformation temperatures are required to produce UFF microstructures. These are the main issues that have been raised as obstacles to industrial implementation. The following examines how to extend the UFF deformation window through optimizing the thermomechanical parameters.

Multiple Deformations on the UFF Formation

To overcome the aforementioned barrier, one concept is to precondition the austenite in the nonrecrystallization region to establish potential nucleation sites. The final deformation is then applied in the intercritical region (i.e. between Ae_3-Ar_3) to activate the dynamic transformation process. A recent work by the current authors [9] revealed that the multiple deformations on a Nb microallyed steel can significantly reduce the critical strain for UFF formation if the thermomechanical processing is designed to avoid any restoration process (i.e. recrystallization) between passes. $\varepsilon_{C,UFF}$ was reduced from 2.5 to 1 using multiple deformations. However, the sum of pass strains at different temperatures was much higher than the critical strain required for single pass deformation.

It is well known that the enhancement of nucleation sites in deformed austenite is the main reason for the remarkable refinement in ferrite grain size for most thermomechanical processes [10]. Therefore, it could be proposed that either the recovery has reduced the potential of intragranular defects during controlled cooling (before the final straining) compared with the single-pass deformation, or the nature of the intragranular defects were altered through partial deformation in the non recrystallization region. The study on an austenitic Ni-30Fe model alloy at a similar thermomechanical condition revealed that the deformation induces laminar microband structures, but the deformation temperature has a strong effect on their characteristics [9]. At a given strain, the microbands are refined (Fig. 2) and the overall misorientation angle distribution increases with a decrease in the deformation temperature (Fig. 3). In the case of multiple deformations, there is some contribution from strains at higher temperatures to the formation of high angle microbands, but the strain contributions are not completely additive.

This finding suggests that the deformation temperature can play a key role in ferrite refinement in conjunction with the dynamic strain induced transformation, but the individual contribution of deformation transformation and transformation in DSIT route is not clear yet.

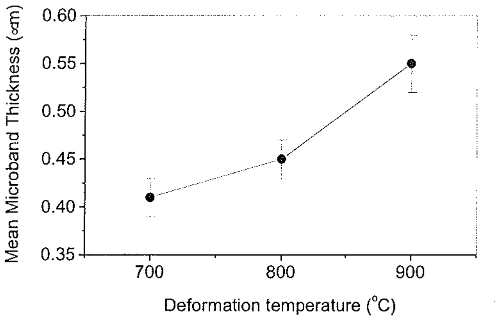

Figure 2: Mean microband thickness as a function of deformation temperature at strain of 1 and strain rate of $1s^{-1}$ for the Ni-30Fe alloy [9]

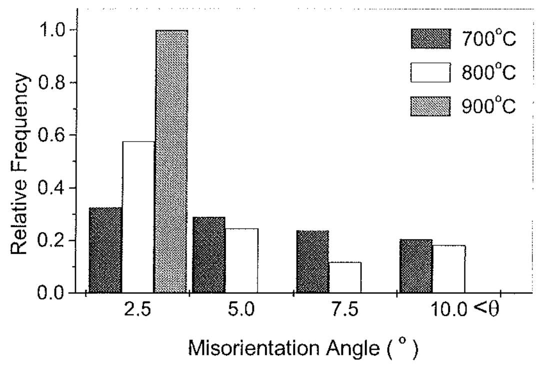

Figure 3: The misorientation angle distribution as a function of deformation temperature at a strain of 1 for the Ni-30Fe alloy [9]

UFF Formation through Static Transformation

A novel approach was then employed to provide insight into the relative contributions of deformation temperature and transformation to microstructure refinement through static/dynamic transformation. This process involved a 0.2C-2Mn steel with high quench hardenability, which underwent warm deformation of the supercooled austenite (i.e. ~570°C) followed by reheating in to the austenite region to statically ferrite followed by cooling [11]. A ferrite grain size of 1.5 μm was successfully formed through static ferrite transformation. The Ni-30Fe model alloy revealed that there is a transition temperature below which the cell dislocation structure changed to laminar microbands. Interestingly, this temperature regime corresponds with deformation temperature for most processes that have produced ultrafine ferrite by DSIT in carbon steels. Indeed, another explanation for the enhancement of the ferrite refinement in the thermomechanical route using relatively low deformation temperatures (i.e., <700°C) is the formation of extensive intragranular defects in this region (Fig. 4). This significantly increases the ferrite nucleation rate for a given thermomechanical condition and will result in extreme ferrite refinement.

This result leads us to conclude that it is possible to achieve an ultrafine ferrite microstructure through transformation, if an appropriate density and nature of intragranular nucleation sites is formed, regardless of whether it is a dynamic or static transformation process.

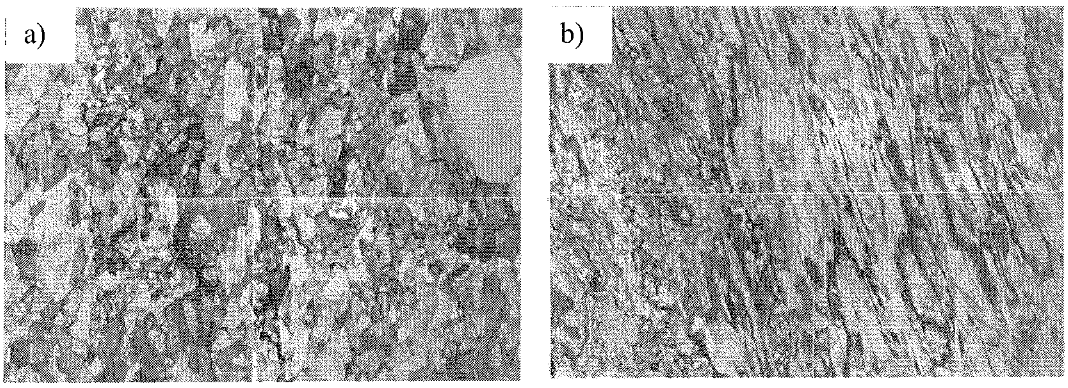

Figure 4: Microstructures of Ni-30fe alloy at different deformation temperature at 70% reduction: a) 800 °C and b) 530 °C [11]

Conclusions

A series of thermomechanical processes were reviewed to examine whether the dynamic transformation process is the only key factor in ultrafine grained ferrite formation in steels or whether other elements are involved in this process. Hence, the individual contribution of the thermomechanical parameters in the DSIT route was investigated in conjunction with a Ni-30Fe model alloy. It was revealed that the deformation temperature plays a key role in the development of intragranular defects characteristics and there is a transition temperature below which the defects structure is significantly changed. It was shown that the UFF structure can also be developed through static transformation if an appropriate intragranular defect structure is formed by low deformation temperature.

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