1. Introduction

There has been considerable recent interest in the development of steel microstructures with a ferrite grain size of the order of 1 μm (e.g., Refs. 1–3). While a number of methods have been proposed, the simplest approach appears to be through Dynamic Strain Induced Transformation (DSIT). This approach has been given a number of names: Dynamic Induced Ferrite Transformation (DIFT), Dynamic Transformation (DT). The common feature in all cases is that a substantial amount of transformation occurs dynamically, or ‘during’ deformation. This contrasts with typical thermomechanical processing approaches to grain refinement where the transformation occurs statically, or ‘after’ deformation.

Interestingly, the ultrafine ferrite microstructure from within a single original austenite grain revealed a strong ferrite texture related to the transformation texture from heavily deformed austenite by the Kurdjumov–Sachs (K-S) relationship. Therefore, the ultrafine ferrite formed through DSIT route appears to be the result of transformation from heavily deformed austenite. However, as this ferrite should have also been deformed.

Generally, for a given level of strain applied to the austenite the level of refinement is much more intense if the transformation is dynamic rather than static. For example, high levels of strain can be stored (term ed retained strain) in the austenite by using strain induced precipitation to retard the recrystallisation kinetics. With retained strain levels of 1 to 2 the ferrite grain size can be reduced to around 5 μm, with some further refinement to 3 μm possible for more highly alloyed steels and higher cooling rates. However, for even simple low C steels that are air cooled after deformation it is possible to store as much and even more strain for static transformation processes in heavy controlled rolling schedules such as used on some hot strip mills. Although there is the potential lose some of this by recovery before transformation this is likely to be very low for austenite.

The following paper analyses some of the recent published work in conjunction with new results to develop a descriptive model to explain some of the key reasons for the development of these ultrafine microstructures. Firstly, the role of different process parameters and the initial microstructure are considered. This is followed by a consideration of the microstructure evolution during and after deformation with a final section considering multi-deformation conditions.

2. The Role of Process Variables in Dynamic Strain Induced Transformation

In hot deformation the main parameters that can be varied are the strain, strain rate and temperature. It is clear that increasing strain leads to an increase in the volume fraction of ferrite for a given alloy and deformation condition. However, this ferrite should have also been deformed.

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some evidence that the nature and rate of formation of these defects is a function of the deformation temperature. For example, decreasing the temperature has been shown\(^{10}\) to increase the rate of generation of internal defects in the model alloy (Fig. 1) and some recent work where there has been an ultrafine ferrite formed through static transformation was from an austenite that had been deformed at 570°C and then reheated to 750°C to allow transformation on a structure with numerous high angle intragranular defects.\(^{11}\)

Strain also appears to play a further role which is much less clearly understood at present. The ferrite maintains an equiaxed shape throughout the dynamic transformation reaction even though this may occur over a very large strain range (Fig. 2). This suggests some form of dynamic recrystallisation, or at least dynamic adjustment of the boundaries. This will be discussed in more detail below.

Changing the strain rate has been reported to have a variable effect on the dynamic transformation to ferrite. Generally where there is clear evidence for dynamic transformation as the major mechanism it would appear that strain rate has a minor effect for a given strain.\(^{12}\) However, the real effect of strain rate is probably more linked to the deformation time. The austenite to ferrite transformation involves nucleation and growth and the activation of different nucleation sites also requires different times at a given condition. At low strain rates it is possible that some sites will become active at an early stage and the ferrite formed there will grow to a large grain size before other sites are activated. For example, sites at the austenite grain boundary will be active from the start of deformation, whereas the intragranular sites require strain (and therefore time) to reach the required level of misorientation. These potential sites can be wiped out by ferrite growing into these spaces from the austenite grain boundary.

At higher strain rates the issue of time can mean there is inadequate time for any transformation to occur during deformation—for example at a strain rate of \(10\ s^{-1}\) there is only 0.1–0.2 s available for even very high strains. This is further exacerbated by the effects of deformation heating which will retard the rate of transformation.

The role of temperature is the same as in any austenite to ferrite reaction. Once below the \(A_e\), the driving force for transformation increases with decreasing temperature and the time for the start of transformation decreases. For most commercial structural steels this means that there is often only a small temperature range where there will be adequate levels of strain induced transformation, due to the fact that close to the \(A_e\) the equilibrium fraction is low, whereas at lower temperatures there is a strong driving force for transformation before deformation.

### 3. The Role of Microstructure Variables

The area that has received the greatest attention is the austenite grain size. One of the reasons is that a large austenite grain size is one method to allow higher levels of undercooling without substantial transformation prior to deformation. A large grain size can also promote a wide range of intragranular defects in the austenite and may increase the rate of generation of high misorientation structures, particularly near the austenite grain boundaries.\(^{13}\) However, there is an increase in the overall inhomogeneity of the ultrafine ferrite structure and there is now clear evidence that transformation from a finer grain size is preferable,\(^{13}\) assuming it is possible to avoid transformation before deformation.

Again the role of prior austenite grain size can be rationalised on the basis of those factors that can assist the transformation, such as the higher undercooling and greater deformation inhomogeneity, and those factors that retard the transformation. In the latter case this again relates to the fact that there is a hierarchy of nucleation potential sites that is exacerbated at the larger grain sizes by differences between neighbouring grains or within grains. So if a large strain is required to create a homogenous intragranular deformation structure for all grains then there is again time for some grains to grow and wipe out potential nucleation sites. This is the likely cause of the much greater inhomogeneity in the ferrite grain size distribution from coarse austenite.

### 4. Transformation Behaviour during Cooling

During cooling to room temperature there is the potential for the formation of more ferrite. This will depend on the fraction formed during the deformation compared with the equilibrium volume fraction at room temperature. It is clear that there is coarsening of the ferrite if only a low volume fraction of strain induced ferrite is formed and this has led to the concept of a critical strain to maintain an ultrafine microstructure during cooling to room temperature, with this often much larger than the strain to initiate dynamic transformation (Fig. 3). In essence this relates to the formation of close to the equilibrium volume fraction during de-
formation and/or to the extensive 3 dimensional impingement of ferrite grains.\textsuperscript{13)} This latter point is based on observations that 2 dimensional impingement is not adequate to stop significant coarsening during cooling\textsuperscript{13)} whereas it would appear that areas of ferrite that have 3 dimensional impingement are very stable during cooling to room temperature, even though other areas in the microstructure will show coarsening.\textsuperscript{14)}

5. The Role of Dynamic Recrystallisation or Adjustment

The actual role of ferrite dynamic recrystallisation (DRX) in the refinement through dynamic strain induced transformation (DSIT) process is still one of the major areas of debate. Because the stacking fault energy of ferrite is high, it is expected that dislocations will easily migrate through cross-slip and climb processes during deformation and will form low angle substructures. However, there are some reports using TEM\textsuperscript{15)} and EBSD\textsuperscript{16)} that conventional DRX (i.e. nucleation and growth) occurs in ferrite.

DRX of ferrite is believed to require high levels of purity, a low $Z$ (Zener–Hollomon) condition and high strain levels.\textsuperscript{17)} However, the $Z$ condition is relatively high during the deformation conditions associated with the DSIT route and most steels contained a wide range of alloying elements. In this case, the mechanism of high angle grain boundary formation in ferrite under high $Z$ conditions is believed by most researchers to be completely different from conventional DRX. This involves a continuous DRX reaction where high angle boundaries evolve with increasing strain. One study of the evolution of DSIT ferrite during deformation using TEM showed that DSIT ferrite grains were continuously refined (from 5 to 2 $\mu$m) as the strain increased during a single compression deformation. The authors proposed the continuous DRX process as a part of the ferrite refinement mechanism in the DSIT route.\textsuperscript{18)}

In recent work the present authors have studied the multi deformation behaviour of strain induced ferrite microstructures and it was found that if the grain size during the interdeformation period did not increase by more than a factor of 2 then the next pass would maintain the ultrafine ferrite—even if more ferrite formed during this pass (Fig. 4). This suggests some form of restoration process (e.g. dynamic grain size adjustment) occurring during further deformation in which the ferrite grain size is ‘locked in’ so that it does not grow and maintains its equiaxed shape.\textsuperscript{19)} This relates to the earlier comments related to the dynamic recrystallisation process that may also be an essential component of this process. However, if the grain size coarsened by more than a factor of 2 then the grains fragmented in the following pass, showing clear evidence of continuous dynamic recrystallisation (Fig. 5).

6. Overall Model

Based on the above it is possible to develop a descriptive framework for the formation of ultrafine ferrite through strain induced transformation in a specific sense and through thermomechanical processing in a more general sense. In some ways this is almost trivial; if the nucleation density is distributed three dimensionally through the austenite with a spacing of 1 $\mu$m and the growth can be controlled so that nuclei are not wiped out by the growth from adjacent nuclei then an ultrafine structure will result. However, the practical achievement of this is extremely difficult.

From a practical perspective it is necessary to avoid transformation to ferrite prior to the start of deformation. Then during deformation the growth of the ferrite that forms first must be controlled so that there is sufficient time/strain for the introduction of the intragranular defects. It may be possible to partially build-up this defect structure through controlled rolling above the transformation start temperature,\textsuperscript{10)} but this also appears to have limited potential. It is clear that some form of dynamic adjustment is occurring during deformation, although at the lower strain rates it also appears that too much growth can take place before this occurs leading to very large grains. At more typical strain rates this adjustment or recrystallisation stops the ferrite from growing. It is interesting to note that this ferrite
grain size is very similar to the steady state subgrain size based on extrapolation of other work on IF steels to these Z (Zener–Hollomon) conditions.\textsuperscript{20} In a similar way even static transformation can lead to an ultrafine structure if a) all the deformation features are introduced before transformation and transformation then occurs rapidly,\textsuperscript{11} or b) there is 3 dimensional impingement of the ultrafine ferrite or close to the equilibrium volume fraction has formed or c) in a multi deformation continuous scenario the time is controlled so that there is little growth of the ferrite between intervals of deformation.

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