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Effect of strain path on dynamic strain-induced transformation in a microalloyed steel

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Abstract

Dynamic strain-induced transformation (DSIT) in a low-carbon microalloyed steel was studied by hot cyclic torsion to understand the interactions between DSIT and strain path reversals, and the subsequent microstructure evolution when subjected to continuous cooling. The critical strain for DSIT ($\varepsilon_{c,DSIT}$) can be determined by analysing the dynamic softening of the flow stress–strain curves. When deformed to the same total accumulative strain of 2.0, deformation with a small strain amplitude in each pass and multiple strain path reversals led to the suppression of DSIT compared to the extensive DSIT ferrite produced by deformation with a large strain amplitude and a single strain reversal. The results reveal that the amplitude of monotonic strain, not the total accumulative strain, in relation to $\varepsilon_{c,DSIT}$ determines the occurrence of DSIT. The suppression or promotion of DIST can be attributed mainly to the increment of the austenite grain boundary area associated with deformation, especially the development of serration and bulging, and, to a lesser extent, to the generation of high-angle boundaries by austenite grain subdivision. The evolution of these planar defects, which are believed to be the primary ferrite nucleation sites, is strongly influenced by strain path changes, and lead to significantly different DSIT behaviours. DSIT ferrite also showed very limited coarsening after continuous cooling as the ongoing deformation produces further nucleation sites in the austenite matrix and causes orientation variation of the DSIT ferrite inherited from austenite parent grains. Based on these observations, it is believed that the transformation mechanisms for DSIT are essentially the same as the reconstructive mechanism during static phase transformations.

Keywords: Thermomechanical processing; Low-carbon steel; High-temperature deformation; Grain boundaries (GBs); Solid-state phase transformation

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1. Introduction

The most widely utilized method of achieving grain refinement through thermomechanical controlled processing (TMCP) of steels is to maximize the number density of nucleation sites in unrecrystallized austenite to produce a fine ferrite grain size after phase transformation. From a practical point of view, the ultimate ferrite grain size achievable by this method is approximately 5 μm [1]. In recent years, considerable international research and development efforts have been undertaken to develop novel processing methods for producing steels containing ultrafine ferrite (UFF, ~1 μm grain size) or "very fine" ferrite (VFF, 2–3 μm grain size) [2–4]. Heavy deformation of super-cooled thermodynamically metastable austenite, i.e. below the A_{e3} but above the A_{r3} temperatures, is a prominent example that has received significant attention because it requires only relatively simple TMCP routes [5,6]. It is generally believed that the formation of UFF/VFF is assisted by deformation-induced austenite-to-ferrite phase transformation [7,8]. Several names have been given to this refinement mechanism, including deformation-induced ferrite transformation, strain-induced transformation, strain-induced dynamic transformation

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and dynamic strain-induced transformation (DSIT). Some researchers used the term “dynamic” as the ferrite grains are believed to be formed dynamically during deformation of the austenite [7,9]. Work by Yada et al. [10–12] using in situ X-ray diffraction showed that the (1 1 0) α diffraction peak appeared concurrently with the (1 1 1) γ peak when deforming several Fe-Ni-C steels in torsion, at temperatures above the A_{r3} and near to the A_{e3}. This technique provided direct evidence that the $\gamma \rightarrow \alpha$ phase transformation occurred dynamically during deformation. Therefore, the term DSIT will be used in the present work for this type of phase transformation. Recently, several research groups reported that DSIT could even occur at temperatures above the A_{e3} [13,14]. This could be attributed to the plastic deformation effectively raising the A_{e3} temperature for deformed austenite by reducing the energy barrier for nucleation and increasing the driving force for transformation. Nevertheless, the dynamic nature of such transformation was confirmed by the observation of dynamic flow softening and microstructure deformation in ferrite grains [15].

DSIT phenomena were reported as early as the 1980s by various researchers [17–20]. More recently, the potential for utilizing the DSIT mechanism to produce UFF steels was exploited in strip rolling by Hodgson et al. [21,22]. This sparked extensive systematic studies of the DSIT mechanisms and the effects of processing parameters such as deformation mode, strain, strain rate, deformation temperature and post-deformation cooling rate on the formation of UFF through the DSIT process. Two very recent review papers, by Beladi et al. [7] and Dong et al. [23], have summarized the latest understanding of the DSIT process. One common agreement is that there are two critical strains: $\varepsilon_{c,DSIT}$, the threshold strain for the onset of DSIT, which has physical meaning as the starting point of dynamic transformation; and $\varepsilon_{c,UFF}$, which is the minimum strain needed to obtain a UFF microstructure after continuous cooling. This latter critical strain is related not to any physical event but, rather, to processing parameters, specifically cooling rate.

Most of the published work on DSIT has been conducted in the laboratory using large monotonic compression or torsion. The required low deformation temperatures, coupled with large deformation (50–80% reduction), present enormous challenges for the industrialization of DSIT to produce UFF steels. For example, the required rolling force to achieve such monotonic deformation far exceeds the capability of current hot rolling technologies [24]. Therefore, practical industrial approaches inevitably require multi-pass deformations which involve strain path changes. To maximize the DSIT effect on grain refinement through multi-pass deformation, it is necessary to gain a fundamental understanding of the interaction between the strain path changes and the DSIT mechanism.

In the present study, the effect of strain path reversals on DSIT was studied using an API grade X70 microalloyed steel deformed under DSIT conditions with single and multiple strain path reversals. By drawing parallel comparisons with the observations made on austenite model alloys in previous studies [25,26], insights were gained that help to understand the role played by strain path reversal on influencing the evolution of austenite grain boundaries and subgrain boundaries and, thus, the final transformed microstructure through the DSIT process.

2. Experimental

The material used in the present study is a commercially produced low-carbon microalloyed pipeline steel (API grade X70) supplied by Tata Steel RD&T, UK. This X70 steel, with a chemical composition of 0.036C–1.56Mn–0.31Si–0.16Cr–0.16Ni–0.16Cu–0.039Nb–0.029Al–0.014Ti–0.005Mo–0.004V–0.008P–0.0006S (wt.%), was received as a hot-rolled plate with a thickness of 19 mm. The as-received plate was solution heat treated at 1250 °C for 3 h in a nitrogen atmosphere, followed by immediate water quenching to maintain the solute elements present at 1250 °C in solid solution. As shown in Fig. 1, an austenite microstructure consisting of equiaxed grains of fairly uniform diameter was achieved after the solution heat treatment. The austenite grain size measured by the mean interception length was 65.1 ± 3.7 μm in the rolling direction and 65.6 ± 4.3 μm in the transverse direction (errors represent 95% confidence limit). Solid-bar torsion specimens of 20 mm gauge length and 10 mm diameter were then machined according to the geometry described elsewhere [16].

Hot torsion tests with single and multiple strain path reversals were conducted using the servo-hydraulic Arbitrary Strain Path (ASP) testing rig at The University of Sheffield. Samples were heated by an induction method at 12 °C s^{-1} to 1250 °C, held for 2 min then cooled to the deformation temperature of 820 °C at 5 °C s^{-1}. This deformation temperature is believed to be below the A_{e3} temperature of the heat-treated and undeformed X70 steel, which

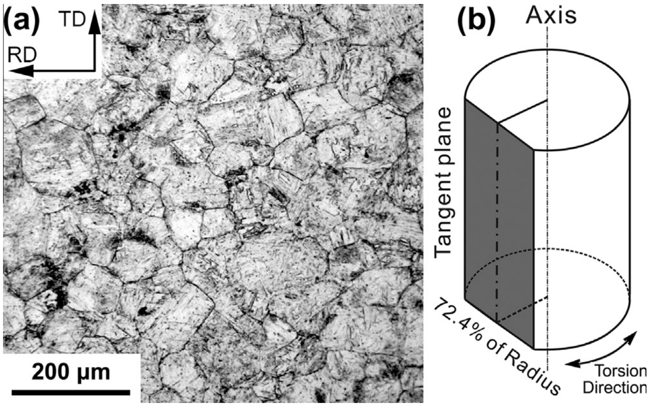

Fig. 1. (a) Optical micrograph of a uniform austenite microstructure achieved after heat treatment at 1250 °C for 3 h in a nitrogen atmosphere; (b) the position of the effective radius within the gauge section of a solid bar torsion specimen.