Reverse Transformation Caused by Temperature Increase due to Deformation Heating

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1. Introduction

Austenite formation normally takes place due to a temperature increase induced by an heat source such as a furnace, induction, laser heating etc. The ferrite ($\alpha$) to austenite ($\gamma$) reverse transformation can also be induced by an internal heat source, for example a temperature increase due to deformation heating. Spontaneous reverse transformation (SRT)\cite{1-5} and transformed shear band (TSB)\cite{6-11} are two such cases. SRT occurs due to adiabatic heating caused by a deformation at temperatures close to the austenite phase field. It has been observed in rolling experiments\cite{3-5} as well as in uniaxial compression tests.\cite{1, 2} SRT has been developed as a microstructural control process to obtain ultrafine grained steels. Ultra-fine martensite ($\alpha'$) with a grain size of about 0.5 $\mu$m has been obtained through $\alpha \rightarrow \gamma \rightarrow \alpha'$ rapid phase transformation due to SRT in Fe–0.3C–9Ni wt% steel.\cite{1-5} On the other hand, transformed shear band (TSB), known as one of the morphologies of adiabatic shear bands,\cite{6, 6a} appears in many metals when they are deformed at high strain rates to large plastic strains, for example during high speed torsion and compression, ballistic impact, machining and explosive fragmentation. TSB characteristically etch white in optical microscopy and contrast of martensite.\cite{7-10} In the case of steels, the microstructure inside TSB is carbide-free fresh martensite with very fine grains, in the submicrometer range. Thus, its microstructural features are almost the same with those observed in SRT. The hardnesses of both TSB and SRT regions are higher than that of martensite of the same chemical composition, quenched after subjecting to ordinary austenitisation conditions. This is because of the extremely fine grain structure and possibly because the austenite is in a deformed state prior to transformation. In this note, characteristic features of SRT and TSB in steels were summarized and the differences between SRT and TSB are examined. The refinement mechanism in SRT and TSB is also discussed.

2. Deformation Conditions

Temperature increase due to the deformation causes rapid $\alpha \rightarrow \gamma$ phase transformation and the austenite is quenched very quickly by the surrounding cooler material or following water quenching to form martensitic structure. In this sense, the metallurgical phenomena occurring in SRT and TSB are identical.

Adiabatic shear bands can broadly be classified as either transformed shear band (TSB) or deformed shear band on the basis of their appearance in metallographic sections.\cite{5} A permanent change in structure is associated with the former, whereas the latter are manifested merely as zones of intense shear deformation of the original microstructure. In general, the formation of TSB appears to correspond to an advanced stage of adiabatic strain localization in a given metal, with a deformed shear band representing an earlier stage in this process. Flow localization in shear is attributed to the destabilizing effect of thermal softening which can outweigh the effects of strain and strain rate hardening in a deformation region when the local rate of heat generation resulting from the plastic flow exceeds its rate of dissipation into the surrounding material. There exists a critical shear strain to cause flow localization, expressed as a function of the strain hardening rate and the thermal softening rate\cite{6-11}; thus it depends mainly on the mechanical properties of the materials. In the case of alloy steels, AISI 4340, its value ranges from 0.1 to 0.5 depending on materials strength.\cite{11} The local shear strains usually range between 5 and 100\cite{10} and the local rate strain reach $10^7$–$10^8$ s$^{-1}$ within the shear band.\cite{6} The width of the shear bands ranges approximately from $10^{-2}$ to $10^{-1}$ mm.\cite{9} Temperature rises of several hundred degrees locally are experienced. Thus, once flow localization occurs, it is easy to bring about a reverse transformation in steels. Timothy\cite{10} claimed that TSB forms most readily in metals of low thermal diffusivity and low critical shear strain, e.g. alloy steels, titanium alloys and uranium alloys. Their low thermal diffusivity should cause the local temperature to rise rapidly at an early stage of deformation.

SRT has been observed in rolling experiments\cite{3-5} as well as in uniaxial compression tests.\cite{1, 2} In rolling experiments, the rolling reduction needed to cause SRT in Fe–0.3C–9Ni wt% steel was 70–90\% for a rolling speed of 50 m/min which corresponds to strain rate of around 10/s. Macroscopic shear bands such as TSB as a result of flow instability have not been observed in the rolled plate in which SRT took place all through the thickness.\cite{5} Deformation analysis incorporated with thermal analysis for the rolling processes revealed that SRT occurrence could be explained by temperature distribution along the plate thickness caused by deformation heating, calculated using equivalent stress and equivalent plastic strain, friction heating and roll chill.\cite{3, 4} The analysis successfully explained experimentally obtained reverse transformation behaviour along the plate thickness. This implies that the necessary condition for SRT occurrence is essentially a temperature rise to above the transformation temperature. There is substantial heat conduction and this causes more homogeneous and moderate reverse transformation behaviour. Temperature rise in SRT is not as rapid as in TSB and not large enough to cause instant reverse transformation.

*Adiabatic heating to high temperature is one of the most conspicuous features of adiabatic shear bands and set them apart from other types of shear bands observed typically in cold rolled steels.\cite{6}
The chemical driving force for the austenitisation, related to the chemical composition, plays an important role in promoting reverse transformation.5)

The difference in deformation conditions between TSB and SRT are summarized in Table 1. TSB corresponds to macroscopic shear bands formed as a result of flow localization which can be precursor for the fracture of the materials, while SRT does not show morphology of macroscopic shear bands but is associated with a stable deformation mode. SRT and TSB have different occurrence criteria. SRT is the first case to utilize adiabatic heating in controlling the microstructure of steels.

3. Ultra Refinement Mechanism

The microstructure inside TSB has been regarded as carbide-free fresh martensite with a very fine grain size. However, detailed observations inside TSB have only recently been made. Research background of TSB is materials fracture phenomena under a high strain rate condition, and TSB is regarded as a precursor for the fracture. Therefore, the formation mechanism, initiation and propagation behavior of TSB were often of more practical interest than the microstructure itself.12) There are two explanations for the microstructural development in TSB. Lee et al.13) claimed that the possible martensite refinement mechanism was strain-induced dynamic transformation from austenite to martensite after reverse transformation. On the other hand, Wittman et al.14) claimed that reverse transformation did not take place in ‘TSB’, even though the band showed white etching characteristics in optical micrographs, and martensitic features in transmission electron microscopy images. They observed \(\chi\) carbides in TSB which require a considerable amount of time to form. This was the main evidence of the claim, because \(\chi\) carbides could not precipitate during rapid quenching after the reverse transformation. Finally, they concluded that ‘the shiny, transformed appearance reported by many investigators in shear bands in steels is the result of a fine recrystallised structure with an associated dissolution of carbides, resulting in an increased resistance to etching’.15)

In the case of SRT, austenitisation was clearly observed.2) The refinement mechanism is due to the highly refined austenite transformed from deformed tempered martensite. Austenite grains nucleate at precipitated cementite on sub-grain boundaries of the deformed tempered martensite and grow by a diffusion mechanism.2) Intensive deformation at martensite phase region has an important effect on ferrite subgrain refinement, and thus on austenite nucleation.16)

As a consequence, there is no common interpretation for ultra refinement mechanism of SRT and TSB at the moment. However, it is established that both of them are formed as a result of temperature increase due to intensive deformation. Therefore, rational explanation on ultra refinement mechanism which covers both SRT and TSB could exist. As long as reverse transformation takes place, austenite grain must be refined by nucleation enhancement due to the deformation at ferrite phase field. Final martensitic structure in TSB might be refined through the dynamic martensitic transformation as well.13) However, the effect will not be as much as austenite grain refinement through the reverse transformation, because deformation and accompanying adiabatic heating take place simultaneously due to the flow instability, and deformation would take place mainly during heating rather than cooling. Presumably, ultra refinement mechanism in TSB would be same as in SRT, namely austenite grain refinement. Further study is indispensable on this point.

4. Summary

The metallurgical phenomenon occurring in SRT and TSB are intrinsically identical and ultra refinement mechanism would be likely the same. However, there is an explicit difference in deformation mode between SRT and TSB. TSB is macroscopic shear band formed as a result of flow localization which can be precursor for fracture, while SRT does not show the morphology of macroscopic shear bands but is associated with a stable deformation mode. SRT and TSB have likely different occurrence criteria.
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