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Microstructural Evolution of Nb–V–Mo and V Containing TRIP-assisted Steels during Thermomechanical Processing

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The microstructural evolution and precipitation behaviour of Nb–V–Mo and single V containing transformation induced plasticity assisted steels were investigated during thermomechanical processing. A plane strain compression testing machine was used to simulate the thermomechanical processing. Microstructures were characterised by optical microscopy, scanning-transmission electron microscopy and microanalysis, and X-ray diffraction analysis, and Vickers hardness was obtained from the deformed specimens. The resulting microstructure of both Nb–V–Mo and V steels at room temperature primarily consisted of an acicular/bainitic ferrite, retained austenite and martensite surrounded by allotriomorphic ferrite. The TEM analysis showed that a significant number of Nb(V,Mo)(C,N) precipitates were formed in the microstructure down to the finishing stage in Nb–V–Mo steel (i.e. 830 °C). It was also found that the V(C,N) precipitation primarily occurred in both ferrite and deformed austenite below the finishing stage. The results suggested that Nb–Mo additions considerably increased the temperature stability of microalloy precipitates and controlled the microstructural evolution of austenite. However, the microalloy precipitation did not cause a significant precipitation strengthening in both Nb–V–Mo and V steels at room temperature.

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1. Introduction

Hot rolled TRIP-assisted steel strip is frequently produced through hot rolling, followed by a rapid cooling after the final rolling pass to the bainite transformation range[1,2]. The cooling stage should be sufficiently rapid to minimise any transformation during cooling, allowing transformation to bainite at the isothermal hold[3]. The bainite transformation is associated with carbon partitioning into austenite. This increases the stability of austenite against martensite transformation, which leads to the retention of austenite at room temperature. A combination of hard phases, such as bainite and martensite, and soft ferrite in addition to the TRIP effect of retained austenite results in a steel with high strength and high formability.

Further improvements to the mechanical properties of these steels (strength and formability) are still sought, particularly with respect to adiabatic deformation due to the high strain rate deformation commonly occurring during passenger car collisions. Attention has focussed on the effect of microalloying element additions to manipulate the microstructure and improve the mechanical properties of these steels. Microalloy carbide precipitates with a higher temperature stability (e.g., Nb(C,N) and Ti(C,N)) can be widely formed in austenite, which are especially useful in controlling the microstructural evolution during thermomechanical processing at high temperatures[4–6]. The extensive microalloy carbide precipitation, in particular vanadium carbide/carbonitride, at lower temperatures can significantly increase the strength of steels[7,8].

Investigations in alloy design of microalloyed steels have shown the influence of a combination of Mo and other microalloying elements on dynamic precipitation and precipitate coarsening[9–13]. The Mo reduces the carbon activity in austenite, increasing the solubility of microalloying elements in austenite and facilitating finer precipitation in the ferrite temperature range. Precipitation at lower temperatures leads to denser and finer precipitates, which enhances steel strength. Additionally, the Mo could decrease the interfacial energy of carbides (e.g., Nb(C,N)), which subsequently enhances the precipitation and reduces the rate of precipitate coarsening.

Although many investigations have been carried out on the single microalloy addition during thermomechanical processing, relatively few works have been reported on the precipitation behaviour of multiple microalloy additions[14–17]. It has been documented in the literature that the multi-additions of microalloying elements can change the precipitation behaviour[7]. This is of particular importance in the context of microalloyed TRIP-assisted steels because

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Table 1
Chemical composition of the investigated steels (wt%)

Material	C	Mn	Si	V	Nb	Mo	N	S	P	Fe
Steel 1	0.12	1.47	1.54	0.16	0.04	0.08	0.0042	0.005	0.018	Bal.
Steel 2	0.12	1.49	1.51	0.16	–	<0.01	0.0042	0.005	0.017	Bal.

of the interaction between strong microalloy carbide/carbonitride formers and the evolution of microstructure. However, in multiple microalloyed steels, it is difficult to precisely predict the precipitation behaviour during thermomechanical processing due to the interaction between microalloying elements.

In this work a systematic study was conducted through controlled thermomechanical processing to investigate the V(C,N) precipitation behaviour in TRIP-assisted steels with an expected microstructure of an acicular/bainitic ferrite matrix. There has been no study of microstructural evolution of Nb–V–Mo containing TRIP-assisted steels during thermomechanical processing. For the purpose of analysis, a comparison was made between Nb–V–Mo and V containing steels to better understand the effect of 0.04 wt% Nb and 0.08 wt% Mo additions on the microstructural evolution and subsequent properties of 0.16 wt% V microalloyed TRIP-assisted steels.

2. Experimental Procedure

2.1. Materials

The materials used in this investigation consisted of two as-cast microalloyed steels, prepared by laboratory melting. The chemical compositions of these steels are listed in Table 1.

The ingots were soaked at 1250 °C for 1800 s in an argon atmosphere and rough rolled from 30 to ~13 mm thick plates by 5–7 passes using a Hille-rolling mill with a finishing temperature of approximately ≥900 °C, followed by air cooling. Plane strain compression (PSC) testing machine equipped with a controllable heating–cooling system was used to systematically simulate thermomechanical processing. Standard PSC specimens with a size of 60 mm × 30 mm × 10 mm were machined from the rough rolled specimens. The PSC testing was carried out using the thermomechanical compression (TMC) machine at the University of Sheffield. 5-min soaking at 1250 °C was conducted before PSC testing to obtain a similar initial structure in all specimens and to dissolve the microalloy precipitates (Fig. 1(a)). Three deformation stages were applied at different temperatures with a finishing pass at 830 °C (designated “hot rolled”). In the second schedule, the specimen was held for 50 s at 900 °C to investigate the microstructural evolution and subsequent precipitation behaviour for two different microalloyed steels (designated “controlled rolled”). The effect of controlled rolling down to the end of the finishing rolling stage on the microalloy precipitation behaviour and austenite evolution was more specifically studied by water quenching the specimens immediately after the last finishing pass (designated “water quenched”). All three deformations within the PSC testing were performed at a strain rate of 10 s^{-1}. The PSC stress–strain curves were plotted after processing the recorded machine force-displacement data according to the measurement good practice guide[18].

2.2. Characterisation methods

Specimens after thermomechanical processing were cut (Fig. 1(b)), ground and polished according to standard methods (ASTM E3-11). The characterisation of microstructure, precipitation behaviour and mechanical properties at room temperature were undertaken by optical microscopy, scanning-transmission electron microscopy (SEM-TEM) and microanalysis, X-ray diffraction (XRD) and Vickers hardness testing.

To observe the prior austenite grain boundaries in water quenched specimens, the polished samples were etched with saturated aqueous

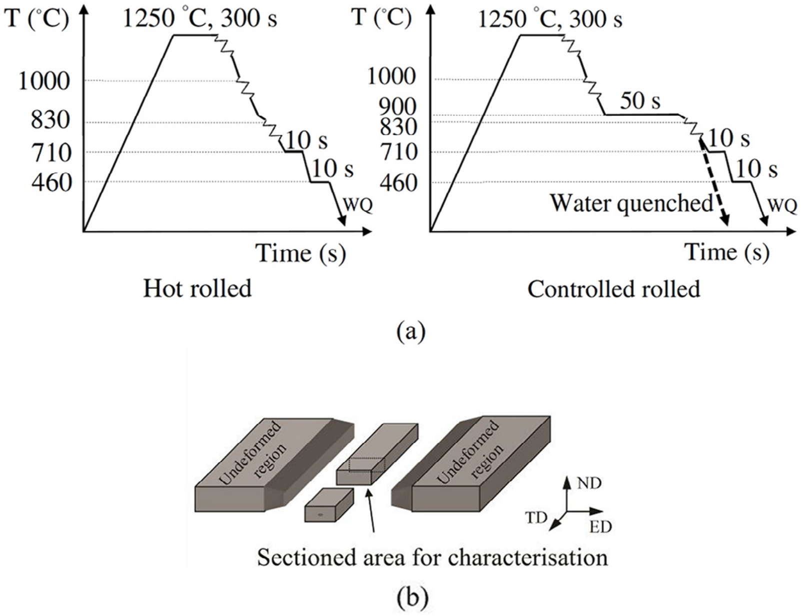

Fig. 1. (a) The thermomechanical processing schedules used to prepare the samples by PSC machine, (b) illustration of sectioned area from the deformed PSC sample for microstructural characterisation. ND: normal direction, ED: elongation direction, TD: traverse direction, WQ: water quenching.

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