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Effects of hot/cold deformation on the microstructures and mechanical properties of ultra-low carbon medium manganese quenching-partitioning-tempering steels

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A B S T R A C T

The mechanical properties and designed microstructure evolution have been investigated in ultra-low carbon medium Mn steels for enhanced strength, plasticity and toughness, after an innovative quenching-partitioning-tempering (QPT) treatment with different initial conditions, cold rolling (CR) and hot rolling (HR). The transmission electron microscopy (TEM) combined with 3D atom probe tomography (APT) observed plenty of block austenite (30%) with dispersed precipitation in CR-QPT steels, while less amounts of film austenite (18%) with a higher density of nanoprecipitates were found in HR-QPT steels. The controlled multiphase microstructure evolution strongly depends on the Mn diffusion and segregation process. The overall strength-ductility combinations of two QPT-steels from the contribution of combined nanoprecipitation hardening and transformation-induced plasticity (TRIP) effects, are strongly influenced by the varying austenite mechanical stability connected with the volume fraction, grain size, morphologh and dislocation density of CR and HR-QPT samples. The unloading-reloading tests reveal the respective roles of precipitation hardening and TRIP effect in the overall mechanical properties according to the Baushinger effect (BE): the nanoprecipitation results in a higher back stress strengthening, while the deformation-induced martensite transformation in a wide strain regime degrades the large stress concentration in grain boundaries (GB), leading to a back stress softening but effective stress hardening in the later deformation stage. In addition, CR-QPT samples show a significant higher value of impact toughness than HR-QPT samples. The QPT treatment of CR-QPT steels can not only eliminate the susceptible prior austenite grain boundaries, but also drive Mn enrichment at the phase boundaries diffusing into the pre-existing austenite interior due to a low migration rate of austenite/ferrite interfaces impeded by the nanoprecipitations in ferrite, contributing to a homogeneous Mn distribution and removing the grain boundary embrittlement.

1. Introduction

With manufacture and safety consideration, an increasing demand in automotive application is focused on medium Mn steels [1–3] of lean alloy system designed with enhanced strength, plasticity and toughness as the third-generation of advanced high strength steels (AHSS). The good plasticity mainly origins from a large fraction of ultrafine-grained (UFG) austenite providing various transformation-induced plasticity (TRIP) and twinning-induced plasticity (TWIP) effect [4–6]. However, the addition of carbon as an austenite stabilizer element is always limited due to the weldability performance and detrimental Portevin-LeChatelier (PLC) effect [7], thus restricting the strength. Currently, one of the effective solutions is to adopt the combination of nanoprecipitation hardening and TRIP concepts to improve both strength and ductility simultaneously without the expense of massive alloying. The introduction of intragranular nanoscale precipitations act as strong obstacles to impede dislocation motion without initiating cracks at grain boundaries (GB) [8], thereby substituting for traditional strength enhancement such as grain refinement and cold

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deformation without compromising plasticity [8,9].

Intercritical annealing [10] was demonstrated to be capable of obtain enough amounts of austenite by sufficient element partitioning into transformed austenite for stabilizing. A new approach of mediate temperature tempering for long time, revealing the enrichment of atoms in crystal defects such as dislocations [4], also makes it possible for stable austenite reversion with adjacent simultaneous nanoprecipitation. It is urgently demanding that the microstructure optimization [11,12] of nano-sized particles and retained austenite contributes mostly to the overall mechanical performance of medium Mn steels. However, the morphology, grain size and mechanical stability of reversed austenite can be controlled by the element diffusion process while uniform precipitation of nano-sized particles are closely connected with the segregation proceeding. As illustrated in a low carbon system, experiments and modeling [13–15] have been performed to study the interaction of ferrite-to-austenite transformation kinetics with Mn partitioning process. The interface migration rate of the kinematic growth mode [14] is dominantly governed by Mn diffusion across the austenite/ferrite phase boundaries. In addition, the Mn segregation favorably to precipitates [16] could decrease the concentration in solid solution and lower the stacking fault energy (SFE) of austenite, thus strongly influencing TRIP effects.

In particular, the precursor plays a crucial role in the microstructure evolution with Mn partitioning. The cold deformation prior to the austenite reversion treatment [17] has been adopted in medium Mn steels to obtain metastable austenite with varying micro-mechanical stability, which is a consequence of non-uniform distribution [18] of element content such as Mn and austenite grain size. As is all known, the mechanical stability of austenite depends on not only the element content, but also the development of the deformation microstructure correlated with the grain size, morphology, dislocation density of austenite [19,20]. It has been found that grain refinement [21] can result in a transition of deformation mechanism from martensite transformation to mechanical twinning, while other research showed that smaller nanoscale austenite grains (<200 nm) exhibited a lower stability against transformation with less pronounced in-grain deformation substructures [22]. What's more, the different initial microstructure of martensite before intercritical annealing can result in a totally different morphology [23] of reversed austenite, which also plays an important role in the mechanical stability of austenite. Thus, the effects of hot and cold deformation before heat treatment are investigated with different number density of dislocations as nucleation sites for austenite reversion and precipitation. In extraordinary, it's demonstrated that adopting a double-step heat treatment [5] is conductive to prevent the grain boundary Mn segregation which always results in a brittle failure [24–26]. However, recent works [27] in medium Mn steels have little focused on the multistage aging procedure due to an obvious distinction of diffusion rate between manganese and carbon, which strongly affects the mechanical stability of austenite and precipitation condition.

Although the combination of two strengthening and toughening mechanisms has been investigated in some alloy systems, the respective role of precipitation hardening and TRIP effect on the work hardening and overall mechanical properties have not yet received much attention in medium Mn steels. The precipitation strengthening effect strongly depends on the precipitate size which determine the shear mechanism or Orowan mechanism [28]. On the other hand, almost all the articles [29,30] come to the conclusion that the work hardening in medium Mn steels originates from the TRIP effect. However, it is also reported that the work hardening is absent in UFG (~200 nm) material due to the pronounced dynamic recovery of dislocations even though martensite transformation occurs. The previous research [31] has demonstrated that a large plasticity is unlikely predominantly caused by individual stimulation-induced martensite transformation because the newly martensite can also results in good strain hardening as strong inclusions [32]. Besides, the overall mechanical properties of multiphase are closely related to the deformation modes of constituent phases [33] and the stress partitioning resulting from the microstructural heterogeneity [34] during deformation. In medium Mn steels, it was found that softer austenite phase deformed easily while a shift of strain localization to ferrite occurred in the later deformation stage due to mechanically-induced transformation to α'-martensite [35]. As reported in TRIP steels [36], long range internal stresses or back stresses arising from the plastic heterogeneity and dynamic martensite transformation lead to the generation of geometrically necessary dislocations [37–39] (GND), contributing to a significant strain hardening and affecting the final ductility. What's more, the intragranular nanoprecipitation in ferrite can help with the generation and storage of dislocation without initiating cracks at grain boundaries [8], also resulting in a high back stress increment and work hardening in the initial deformation stage. As Baushinger effect [40–42] (BE) can provide a method to determine the respective contributions of the back stress and dislocation hardening to the flow stress, the kernel average misorientation [43,44] (KAM) can also show the deformation-induced local orientation gradients inside grains indicating the GND contribution. Consequently in this study, the respective roles of nanoprecipitation hardening and TRIP effect have been investigated by the evolution of flow stress components determined by the combination of the KAM characterization and modified BE methods.

In this paper, an ultra-low carbon medium-Mn system was studied, with some additions of Al to introduce coherent B2-ordered NiAl nanoparticles as a reinforcing component. The multiphase microstructure evolution during QPT process, mechanical properties and deformation mechanisms have been investigated. Based on the evolution of back stress and effective stress components, the respective roles of nanoprecipitation hardening and TRIP effect have been evaluated. Finally, the damage and failure mechanisms of multiphase microstructures were discussed in guide for design of ultra-low carbon medium Mn steels with enhanced strength, plasticity and toughness.

2. Experimental procedures

2.1. Materials

The alloy system of Fe–Mn–Ni–Al–C was used in this study. The alloys were melted and cast to round billets of 1 kg in vacuum. After homogenization at 1473 K for 60min, Hot-forged swaging was conducted in eight passes between 1000 and 1300 K and then water quenching to room temperature, resulting in hot-rolled plates size of 300 mm × 240 mm × 25 mm. A one-step aging of partitioning and two-step aging of partitioning and tempering for various periods of time were respectively marked with “QP” and “QPT” process, and then water quenching. In comparison, an extra cold rolling for multiple passes for a total reduction of ~75% before QPT procedure was applied to introduce more nucleation sites for austenite reversion. The nominal compositions and corresponding aging procedure in this study are listed in Table 1.

2.2. Mechanical property tests

Plate-type sub-sized (the gage section