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Enhanced tensile properties of a reversion annealed 6.5Mn-TRIP alloy via tailoring initial microstructure and cold rolling reduction

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ABSTRACT

The feasibility of improving the overall performance of medium Mn steels was demonstrated via tailoring the initial microstructure and cold rolling reduction. The combined effects of cooling patterns after hot rolling (HR) and cold rolling (CR) reductions show: (1) as the cooling pattern varied from furnace cooling (FC) to oil quenching (OQ), the intercritically annealed microstructure was dramatically refined and the fraction of recrystallized ferrite dropped, regardless of CR reductions. This resulted in both high yield/ultimate tensile strengths (YS/UTS) but low total elongation to fracture (El); (2) as the CR reduction increased from 50% to 75%, the OQ-samples after annealing exhibited a more refined microstructure with relatively higher fractions of retained austenite and sub-structure, leading to higher YS and UTS but lower El; whereas the FC samples appeared to exhibit little difference in overall tensile properties in both cases. The differences in microstructural evolution with cooling patterns and CR reductions were explained by the calculated accumulated effective strain (ε_{AES}), which was considered to be related to degrees of recovery and recrystallization of the deformed martensite (α'). The optimal tensile properties of ~1 GPa YS and ~40 GPa·% UTS×El were achieved in the OQ-50%CR annealed samples at 650 °C for 1 h. This was quite beneficial to large-scale production of ultra-high strength steels, owing to its serious springback during heavy cold working.

1. Introduction

Medium manganese steel (3–12 wt% Mn), as a candidate of new-generation advanced high strength steels (AHSS) family, has become a focus of studies for its promising application in the lightweight automotive industry [1–3]. Medium Mn steel was usually subjected to hot-rolling (HR), cold-rolling (CR) and intercritical annealing (IA), in which the strain induced martensite reverse transformation (SIMRT) [4,5] was proposed to enhance the yield/ultimate tensile strength (YS/UTS) through grain ultra-refinement of a called M^3 microstructure [2] as well as improve the ductility through transformation-induced plasticity (TRIP) effect [6]. The resulting UTS values ranged from 800 to 1400 MPa with total elongations from 20% to 40%, which have been well reviewed by Suh and Kim [7].

Several microstructure-sensitive control principles associated with alloy compositions [8], IA parameters [9–12] have been suggested to optimize the overall tensile properties of medium Mn steels. Additionally, Han et al. [13] investigated the influence of the initial as-hot/cold-rolled microstructure on tensile deformation of Fe-9Mn-0.05C (wt%). It was demonstrated that the athermal martensite (α') transformed to the lath-shaped ferrite (α) and retained austenite (γ_R), resulting in a continuous yielding behavior; whereas the deformed α' transformed to the globular-shaped α and γ_R, leading to a notable Lüders band propagation (LBP) phenomenon. The difference in deformation behavior between HR and CR samples was considered to be related to strain partitioning between α and γ_R [14].

Another few studies confirmed the influence of rolling reduction on microstructural evolution during partial/fully austenitization of HSLA steels [15,16]. For example, increasing rolling reduction gave rise to further grain refinement owing to active recovery and recrystallization of the deformed α'. However, our preliminary work [17] demonstrated that more dozens of passes were required for ultra-

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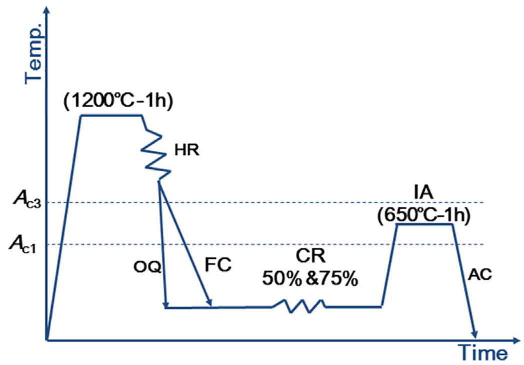

Fig 1. Schematic illustration of thermo-mehcanical process of a Nb-Mo microalloyed 6.5 Mn alloy. HR, CR, OQ, FC and IA represent hot rolling, cold rolling, oil quenching, furnace cooling and intercritical annealing, respectively.

high medium Mn steels with increasing rolling reduction from 50% to 75%, even in small-scale laboratory production. This was mainly due to the serious springback effect of ultra-high strength TRIP steels, eventually increasing dimensional uncertainty of structural components [18].

Therefore, it would be highly advantageous to the large-scale production of medium Mn steels if the overall properties can be optimized, mainly through controlling the initial as-hot-rolled microstructure rather than imposing an extremely heavy rolling reduction (e.g., 75%). The purpose of present work is to investigate the combined effects of cooling patterns after hot rolling and subsequent cold rolling reductions on the microstructure evolution and overall tensile properties of a novel Nb-Mo microalloyed 6.5Mn-TRIP steel [19].

2. Experimental procedures

2.1. Rolling and intercritical annealing procedures

The material studied is a TRIP steel with composition of Fe-0.17C-6.6Mn- 1.1Al-0.05Nb-0.22Mo-0.03N (wt%). The as-received ingot was solution-heat-treated at 1200 °C for 1 h, and hot-rolled to a plate of 6 mm in thickness, followed by oil quenching (OQ)/furnace cooling (FC) to ambient temperature, as shown in Fig. 1. Afterwards, the surface decarburized layers were removed from the as-hot rolled plates by machining, and a series of multi-pass rolling with reductions of approximately 50% and 75% was performed at room temperature.

2.2. According to thermodynamic and experimental results [19], an IA process at 650 °C for 1 h, as shown in Fig. 1 was employed to maximize the γ_R amount of

Meanwhile, these samples for IA treatment were wrapped in a foil bag and a stainless steel tube furnace was used at an Ar protective atmosphere to minimize the surface oxidation.

2.3. Tensile testing

Tensile samples were prepared parallel to the rolling axis with a gauge length of 25 mm with cross-section of 1 mm × 10 mm, according to the ASTM E-8 M sub-size standard [20]. Room-temperature tensile tests were performed on an INSTRON 5967 30 kn machine at an initial strain rate of 1.0×10^3 s^{-1}.

2.4. Microstructural characterization

Specimens for angle-selective backscatter (AsB) and electron backscatter diffraction (EBSD) were prepared following standard mechanical polishing and final finishing with a colloidal silica attack-polishing agent (OPS). Microstructural characterization was performed using a field emission gun scanning electron microscope (FEG-SEM; Zeiss-Supra 55 VP) integrated with both AsB and EBSD detectors. EBSD maps were scanned on the longitudinal section of the as-annealed samples using a step size of 50 nm. Data acquisition and post-processing were performed using HKL Channel 5 software.

Further microstructure analysis was done on a field-emission transmission electron microscope (FE-TEM, Tecnai G2 F20, operated at 200 kV). TEM specimens were mechanically ground and then punched into 3 mm round disks. The disks were electro-polished in a solution of 95% CH_3COOH and 5% $HClO_4$ at a voltage of 45 V and about 16 °C using a Twin-Jet polisher (Struers, Tenupol-5).

X-ray diffraction (XRD) analysis was used to determine the volume fraction of γ_R, based on a direct comparison of the integrated intensities of all diffraction peaks [21]. After proper electro-polishing, these samples were scanned in the angular range of 40°–100° with a speed of 2°/min in a D/MAX-550 diffractometer with Cu*Kα* radiation.

3. Results

3.1. As-hot/cold-rolled microstructures

Two types of the initial as-hot-rolled structures were expected when varying cooling patterns after HR process, i.e. OQ and FC, as shown in Fig. 2. It was found that the OQ microstructure was composed of very fine lath α' of ~200 nm in width (Fig. 2(a)), and only

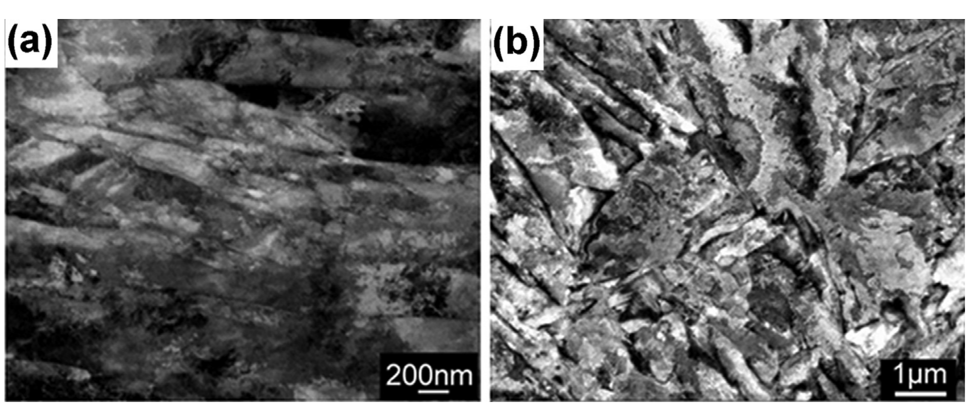

Fig. 2. SEM micrographs of Nb-Mo microalloyed 6.5 Mn alloy after hot rolling and different cooling patterns: (a) oil-quenching (OQ) and (b) furnace-cooling (FC).

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