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# Effect of intercritical deformation on microstructure and mechanical properties of a low-silicon aluminum-added hot-rolled directly quenched and partitioned steel

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ABSTRACT

Here, we applied hot-rolling in conjunction with direct quenching and partitioning (HDQ&P) processes with different rolling schedules to a low-C low-Si Al-added steel. Ferrite was introduced into the steel by intercritical rolling and air cooling after hot-rolling. The effect of intercritcal deformation on the microstructure evolution and mechanical properties was investigated. The promotion of austenite stabilization and the optimization of the TRIP effect due to a moderate degree of intercritical deformation were systematically explored. The results show that the addition of 1.46 wt% of Al can effectively promote ferrite formation. An intercritical deformation above 800 °C can result in a pronounced bimodal grain size distribution of ferrite and some elongated ferrite grains containing sub-grains. The residual strain states of both austenite and ferrite and the occurrence of bainite transformation jointly increase the retained austenite fraction due to its mechanical stabilization and the enhanced carbon partitioning into austenite from its surrounding phases. An intercritical deformation below 800 °C can profoundly increase the ferrite fraction and promote the recrystallization of deformed ferrite. The formation of this large fraction of ferrite enhances the carbon enrichment in the untransformed austenite and retards the bainite transformation during the partitioning process and finally enhances martensite transformation and decreases the retained austenite fraction. The efficient TRIP effect of retained austenite and the possible strain partitioning of bainite jointly improve the work hardening and formability of the steel and lead to the excellent mechanical properties with relatively high tensile strength (905 MPa), low yield ratio (0.60) and high total elongation (25.2%).



## 1. Introduction

In recent years, quenched and partitioned (Q&P) steel composed of martensite and retained austenite has been widely investigated for its adequate combination of both high strength and high ductility [1–4]. The martensitic matrix results in high strength and the retained austenite leads to high ductility via the transformation induced plasticity (TRIP) effect. Previous studies show that conventional martensite–austenite Q&P steel generally exhibits high yield strength accompanied by high yield ratio and relatively low uniform elongation, leading to low forming limits [5–9]. To solve this problem, some microstructure concepts introduced ferrite into Q&P steels and proved that a certain amount of ferrite could further improve the mechanical properties by decreasing the yield ratio and increasing the uniform elongation [10–15]. However, some previous results also showed that the differences of hardness and work hardening ability between the soft ferrite and hard martensite accelerated the initiation and propagation of micro-cracks in the steel after necking, resulting in a reduction of post-necking elongation and total elongation of the steel [11,16,17]. By increasing the Si content and enhancing the ferrite by V-bearing precipitates, the hardness difference between ferrite and martensite was reduced and the elongation of the steel improved [16]. These results reveal that the deformation compatibility and the strain partitioning behavior among the different phases [18] can have a crucial effect on the ductility of ferrite containing Q&P steels. Recent work also showed that the introduction of ferrite can obviously affect the morphology and

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distribution of retained austenite [11]. So far, corresponding studies focused on the effect of ferrite on the thermal stability of the retained austenite but the associated effectiveness of such microstructures on the resulting TRIP effect has been rarely addressed. For a microstructure mixed with soft-phase and hard-phase, the deformation compatibility of the phases can directly influence the deformation homogeneity and the stress and strain state of local phases (especially near the soft/hard phase interfaces) in multiphase steels [19]. It is well known that the TRIP effect of retained austenite occurs under specific critical stress/strain conditions. Thus, one can infer that the introduction of soft phases must have an essential effect on the internal stress and strain partitioning [20] and hence on the effectiveness of the TRIP effect.

The conventional Q&P process usually contains a reheating procedure consuming a large amount of energy. Recently, for the purpose of removing the reheating procedure and saving energy, some studies proposed a new concept of a hot-rolling plus direct quenching and partitioning (HDQ&P) process combined with a thermo-mechanical controlled process (TMCP) technology and ultra-fast cooling (UFC) technology [11,21,22]. Another important difference of HDQ&P steel compared with conventional Q&P steel is that the austenite grains are deformed prior to quenching and that by suppressing austenite recrystallization the high-temperature residual strain state can be reserved to a low-temperature region because of the UFC process. Studies related to TRIP steel have shown that the deformation of austenite can increase the density of lattice defects such as unrecovered dislocations and sub-grain boundaries in the austenite and this conditioning of austenite retards the bainite growth and martensite transformation (so-called mechanical stabilization of austenite) [23,24]. Thus, the deformation of austenite should have a positive effect on its stabilization in HDQ&P steel. It is worth noting that the intercritical rolling process, which was used to develop dual-phase (DP) steel, TRIP steel and medium manganese steel [25–31], has rarely been involved in HDQ&P process design, except for some valuable results obtained from Gleeble thermo-mechanical simulator by Liu et al. [32]. Related results show that intercritical deformation can effectively increase the ferrite volume fraction and refine the ferrite grains according to different softening mechanisms, such as deformation induced ferrite transformation, recrystallization and recovery [23,33]. The acceleration of ferrite formation resulting from the intercritical deformation may promote the element partitioning from ferrite to austenite thus having a significant effect on the phase transformation behavior of austenite and retained austenite state in the steel. The deformation of both austenite and ferrite during the intercritical deformation may have a special effect on the austenite stabilization and element diffusion in the phases because of the increase of defect density. Since the element partitioning is the essence of the Q&P process [34,35], it is important to investigate the special effect of intercritical deformation on the microstructure evolution and mechanical properties of a HDQ&P steel.

Additionally, traditional Q&P steel generally contains a high Si content for the purpose of inhibiting cementite formation and insuring sufficient austenite stabilization [36,37]. Unfortunately, a high Si content can also lead to surface oxides and seriously deteriorate the surface quality [38]. Since Al can also retard cementite formation, which is similar to Si, it is feasible to replace Si by a limited amount of Al. Al is a typical ferrite formation element and its increase in the alloy usually can expand the intercritical region of a low carbon alloyed steel [39]. Thus, it is more pertinent to investigate the intercritical deformation effect in an Al-added steel.

In this paper, HDQ&P processes with different finish intercritical rolling temperatures and pre-quenching temperatures were applied to a low-C low-Si Al-added steel, and the effect of intercritical deformation on the microstructure and the mechanical properties of the steel were investigated by analyzing the phase component, elemental partitioning, austenite stabilization, TRIP effect and tensile properties.

## 2. Experimental details

A low-C low-Si Al-added steel was investigated. The chemical composition (wt%) is 0.18C, 0.53Si, 1.95Mn, 1.46Al, 0.08P, and balance Fe. The steel was first vacuum-melted into a 150 kg ingot and then forged into slabs with thickness of 60 mm. The $A_{c1}$, $A_{c3}$, $A_{r1}$, $A_{r3}$, $M_s$ and $M_f$ temperatures, which were detected by a Formastor-FII(FTF-340) dilatometer (temperature accuracy within $\pm 2$ °C), are about 712 °C, 1037 °C, 634 °C, 914 °C, 421 °C and 172 °C, respectively.

Five different thermo-mechanical processes were designed to produce different microstructures. The 60 mm thick slabs were first fully austenized at 1200 °C for 2 h and then two slabs (Nos. 1 and 2) was hot-rolled to 4 mm through 7 passes on a $\Phi$450 mm rolling mill with finish rolling temperatures of about 910 °C. Subsequently, the No. 1 sheet was directly ultra-rapidly cooled (about 200 °C/s) to 380 °C, then isothermally partitioned at 350 °C for 5 min in a resistance heating furnace and finally air-cooled to room temperature. The No. 2 sheet was air-cooled to about 760 °C, thereafter directly ultra-fast cooled to 370 °C and finally isothermally partitioned at 350 °C for 5 min followed by air-cooling to room temperature. Three other slabs (Nos. 3, 4 and 5) were first hot-rolled to 10 mm thickness through 4 passes with rolling temperatures above 1000 °C. After being air-cooled to 950 °C, the sheets were again hot-rolled to 4 mm with finish rolling temperatures respectively of about 800 °C (No. 3), 780 °C (No. 4) and 785 °C (No. 5) and then the sheets were air-cooled to about 760 °C. Subsequently, the sheets were directly ultra-fast cooled to 360 °C (No. 3), 400 °C (No. 4) and 260 °C (No. 5) and then isothermally partitioned at 350 °C for 5 min and finally air-cooled to room temperature. Hereafter, the sheets are referred to as: No. 1: 910–380 °C; No. 2: 910–760–370 °C; No. 3: 800–760–360 °C; No. 4: 780–760–400 °C; and No. 5: 785–760–260 °C.

Tensile tests were conducted on specimens with gauge length of 25 mm and width of 5 mm at a crosshead speed of 1 mm/min using a CMT5105-SANS machine. The specimens were cut with their longitudinal axes parallel to the rolling direction and three specimens were used for each sheet.

To characterize the microstructures, secondary electron (SE) imaging, energy-dispersive X-ray spectroscopy (EDX), Electron Back-Scattered Diffraction (EBSD) and electron channeling contrast imaging (ECCI) techniques were employed [40–42]. For these analyses, JXA-8530F electron probe micro-analyzer (EPMA) (for SE imaging), JEOL JSM-6500F SEM (for EBSD), Zeiss-Crossbeam XB 1540 FIB-SEM (for EBSD) and Zeiss-Merlin-SEM (for ECCI) were used. The specimens for EPMA observation were ground and polished mechanically then etched with 4% nital for 20 s. The specimens for SEM analysis were ground and polished in diamond suspension and finally polished in colloidal silica suspension. EBSD measurements were carried out at 15 kV with a step size of 40 nm or 50 nm.

Characterization of the different phases was also performed on selected specimens in a TECNAI G220 transmission electron microscope (TEM) at an operating voltage of 200 kV using 40 μm thick $\Phi$3 mm thin foils, which were twin-jet polished using a solution of 5% perchloric acid alcohol at about $-20$ °C.

For the purpose of investigating the austenite stabilization and retained austenite's mechanical stability in the sheets, X-ray diffraction (XRD) with Cu Kα radiation was applied on both undeformed and deformed specimens to estimate the volume