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# Experimental–numerical study on strain and stress partitioning in bainitic steels with martensite–austenite constituents

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ABSTRACT

To achieve safety and reliability in pipelines installed in seismic and permafrost regions, it is necessary to use linepipe materials with high strength and ductility. The introduction of dual-phase steels, e.g., with a bainite and dispersed martensite–austenite (MA) constituent, would provide the necessary ingredients for the improvement of the strain capacity (as required by a new strain-based linepipe design approach) and toughness. To fine-tune the alloy design and ensure these dual-phase steels have the required mechanical properties, an understanding of the governing deformation micromechanisms is essential. For this purpose, a recently developed joint numerical–experimental approach that involves the integrated use of microscopic digital image correlation analysis, electron backscatter diffraction, and multiphysics crystal plasticity simulations with a spectral solver was employed in this study. The local strain and stress evolution and microstructure maps of representative microstructural patches were captured with a high spatial resolution using this approach. A comparison of these maps provides new insights into the deformation mechanism in dual-phase microstructures, especially regarding the influence of the bainite and MA grain size and the MA distribution on the strain localization behavior.

## 1. Introduction

Recently, demand for greater efficiency in the transportation of oil and gas has driven the use of thinner but stronger linepipe steel for large-diameter pipelines. Furthermore, the reliability required for pipelines installed in seismic and permafrost regions necessitates high ductility and toughness. Therefore, the strain-based design approach has gained increasing acceptance in recent years, as this approach ensures high deformability to cope with the aggressive mechanical and thermal loads that act on pipelines constructed in such environments (Zhou et al., 2006). The deformability of linepipe steels in the strain-based design approach is parameterized by the yield-to-tensile strength ratio (Y/T), the strain hardening coefficient (n-value), and the uniform elongation (uEl). Generally, a low Y/T is desirable for linepipe steel and can be achieved in dual-phase microstructures containing both a high-strength phase (for high tensile strength) and a low-strength phase (for early yielding). These design constraints have lead to the use of ferrite–bainite pipeline steels (Ishikawa et al., 2005) because ferrite–martensite automotive steels (Calcagnotto et al., 2011; Kadkhodapour et al., 2011; Tasan et al., 2015) lack adequate low-temperature toughness. More recently, steels composed of bainite and martensite–austenite (MA) have been developed by applying an online heat treatment process in plate manufacturing (Shinmiya et al., 2008; Fan et al., 2014). During this treatment, deformed austenite (refined by controlled rolling) transforms partially into bainite after accelerated

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cooling. In the retained austenite islands, only partial martensitic transformation is observed as a result of carbon enrichment from the transforming bainite phase, creating a nano-dual-phase MA island structure (Morooka et al., 2012).

In dual-phase steels, damage-induced local softening may cause early failure when the volume fraction, phase distribution, grain size, and hardness of the phases are not optimized (Calcagnotto et al., 2010; Han et al., 2013; Gioacchino and Clegg, 2014; Minami et al., 2012; Morooka et al., 2012). However, deformation mechanisms governing the material properties of the bainite-MA steels have not been fully clarified. A few existing reports have discussed overall toughness. For example, Shinmiya et al. (2008) observed that finely dispersed MA islands do not affect the toughness of bainite–MA steels, whereas coarse MA islands observed in the heat affected zone are considered to reduce toughness (Ishikawa et al., 2006; Lan et al., 2014; Li et al., 2017).

To fill this gap in our understanding, in the present study, the local deformation behavior in bainite–MA dual-phase steel was investigated through a coupled experimental–numerical approach. The methodology employed here combines in-situ scanning electron microscopy (SEM) deformation experiments, microscopic digital image correlation (μ-DIC) analysis, electron backscatter diffraction (EBSD) analysis, and crystal plasticity (CP) simulations with a spectral solver to provide information on the local microstructure and strain and stress evolution of complex microstructured alloys (Tasan et al., 2014a, 2014b; Yan et al., 2015; Bertin et al., 2016; Guery et al., 2016; Guan et al., 2017). These techniques allow the examination of the effect of grain orientation, phase boundaries, and microstructural morphology on the strain localization of multi-phase steel. The heterogeneous plastic micromechanical deformation in bainite–MA steel used for linepipe was quantitatively investigated to evaluate its work hardenability with the ultimate goal of optimizing its mechanical response.

## 2. Methodology

### 2.1. Materials

The microstructure of grade X70 and X80 linepipe was investigated. Steel slabs with chemical compositions containing 0.06C–0.15Si–1.8Mn were produced in a laboratory vacuum furnace and cast into 150 kg ingots. Online heat treatment was applied to create the bainite–MA microstructure, as shown in Fig. 1. The ingots were reheated at 1150 °C and then hot rolled to 22 mm thick plates. The slab temperature was measured by inserting a thermocouple at the plate center at the midpoint in the thickness direction. Controlled rolling was applied at a temperature below the non-recrystallization temperature $T_{nr}$. Accelerated cooling of the plate was then performed from a temperature of 993 K, which is below the ferrite formation temperature $A_{r3}$, and stopped at a temperature of 773 K. An austenite microstructure refined by controlled multipass rolling initiated the bainite transformation during accelerated cooling. The microstructure after accelerated cooling was a composite consisting of bainite and untransformed austenite. Subsequent online heating to a temperature of 873 K, which is below $A_{c1}$, was applied after accelerated cooling. After online heating, the microstructure was air cooled to room temperature. The dislocation density in the bainite matrix decreased during subsequent online heating, and the supersaturated carbon contained in the bainite matrix became concentrated in the untransformed austenite. This tempering process softens the bainite matrix. However, untransformed austenite with supersaturated carbon is partially transformed into fine and isometric martensite during air cooling. Retained austenite is typically softer than other austenite phases, but the retained austenite in bainite–MA steel showed a carbon concentration about 10 times higher than the matrix (Ishikawa et al., 2014) and an intermediate hardness between those of bainite and martensite because of the presence of supersaturated carbon (Takahashi et al., 2012).

For the experiments, tensile specimens with gauge dimensions of 20 mm × 5 mm × 1 mm were cut parallel to the rolling direction from the plate center at the midpoint in the thickness direction. Table 1 gives the mechanical properties of the bainite–MA steel. The specimen surfaces were prepared using a conventional metallographic grinding and diamond polishing approach and finished with colloidal $SiO_2$ polishing. The microstructure was etched by nital and electrolytic etching. Fig. 2 shows SEM micrographs of the microstructure and the stress–strain curve obtained from the tensile test. In this figure, the black and red flow curves correspond to the curves obtained from the tensile test of the bainite–MA dual-phase steel and the stress–strain data used in the CP simulation, respectively. Details of the decomposition of the flow curves into the curves describing the individual phases will be

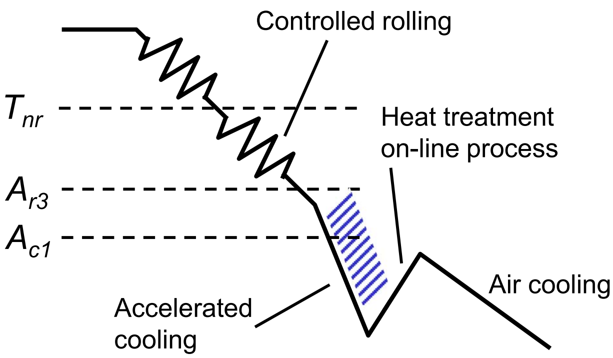


**Fig. 1.** Schematic of the rolling and heat treatment processes conducted at a laboratory scale.