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Light-weight isometric-phase steels with superior strength-hardness-ductility combination

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ABSTRACT

An optimal proportion of austenitic and martensitic phases is achieved in isometric-phase steels through meticulously designed and elaborately calculated surface nanotechnology. Such isometric-phase steels with nanolamellaed structures and nanograins, exhibit surpassing combinations of strength, hardness and ductility (with yield strength of 1215 MPa, surface hardness of 8.6 GPa, and favorable ductility of 31%). A microstructure-based constitutive model is developed to investigate the deformation mechanism and mechanical performance in isometric-phase steels. We believe the light-weight isometric-phase steels in this work can be regarded as a finer counterpart of dual phase steels for applications in automobile, aircraft and nuclear industry.

Steels are one of the most important structural materials [1, 2] and enable technological breakthroughs in various fields, such as energy, transportation, safety, and infrastructure [3, 4]. Researchers tried many ways to achieve better mechanical performance of steels in order for advanced applications, especially at extreme conditions [5–9]. Profound progresses in such fields have been achieved through the development of advanced high-strength steels (AHSS) [8], fueled by the demands of the automotive industry to simultaneously improve crash safety and fuel economy. As one of the earliest and most prominent examples of AHSS, dual-phase (DP) steel [10, 11] has been extensively studied in the last decade [3, 12] for its massive usage as materials for aircraft structural parts, automobile wheel covers and subway cars [13]. However, few people have studied how to reach a better proportion of the dual-phases in order to get peak performance of these steels. Currently, some of the major drawbacks of DP stainless steel are their low yield strength [14], usually being 150–300 MPa in the annealed states, and low hardness, from 180 HV to 210 HV [15], which limits their structural and technological applications [4, 16]. A great number of methods have been proposed to improve mechanical behavior of DP steels in the last decade. For example, Khondker [16] has applied alloying techniques to obtain the DP steel but his method changes the chemical composition of steels. Rocha [17] used hot and cold rolling to enhance the strength of DP steel while his process requires relatively high temperature of about 800 °C; Park [18] fabricated ultrafine grained DP steel by equal channel angular pressing (ECAP), but this process results in severe plastic deformation in DP and the inter-critical annealing is a relatively complicated method. Therefore, strengthening dual-phase steels without compromising its ductility and toughness is still highly challenging.

The aim of this work is to achieve optimum mechanical performance of DP steel by reaching a finer proportion of each phase through cautiously rectified and elaborately calculated surface nanotechnology process [19–22]. The optimized dual-phase steel with approximately equal-proportion of austenite (50.85% by volume fraction) and martensite phases (49. 15% by volume fraction) achieves a surpassing combination of strength and hardness, as well as ductility, with ultimate tensile strength of 1854 MPa, yield strength of 1215 MPa, surface hardness of 8.6 GPa and favorable ductility of 31%. Within the framework of micromechanical method, a gradient-nanostructure-based constitutive model is developed to describe the mechanical performance of this IPSS by considering the contribution of the nanolamellae in the flow stress. An excellent agreement between the simulations and the experiments is obtained. We believe this work has strong potential in modern industry since it opens another door to enhance mechanical properties of stainless steels.

Material used in this work was a light-weight AISI 301 stainless steel — as a typical kind of low stacking fault energy steel (7.3 mJ.m^{-2}) — in form of plate (70.0 × 50.0 × 1.0 mm^3 in size). The chemical compositions of this steel is (in wt.%): 15.4 Cr, 6.2 Ni, 0.5 Mo, 0.16C, 0.43 Si, 1.8

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Mn, 0.05 S, 0.06P and the balance Fe (all in mass%). The sample was annealed in vacuum at 1080 °C for 1 h with the grain size in a range of 110–170 μm. In the present study, both surfaces of the specimens were performed by one kind of surface nanotechnology, surface mechanical attrition treatment (SMAT), at room temperature for a specific period of time. The set-up and procedures of the SMAT were described in the previous papers [23–25]. The samples for the tensile tests were cut into dog-bone shapes with a gauge length of 28 mm and a width of 5 mm, and tested at room temperature at a strain rate of $7.7 \times 10^{-4}\ s^{-1}$. A group of specimens were tested to confirm the repeatability. X-ray diffraction (XRD) was carried out along the cross-sectional direction to determine the phase composition and the mean grain size at room temperature. Transmission electron microscopy (TEM) observations were carried out on a JEM2000 transmission electron microscope with operating voltage of 200 kV to explore the microstructures of tested samples. Scanning electron microscopy (SEM) observations were performed by a Hitachi S-4200 field emission scanning electron microscope to study the gradient distribution of microstructures. The plan-view TEM foils of the layers from certain depths were obtained by first polishing the corresponding surface layer, then mechanically polishing the sample from the untreated side until the sample reaches about the thickness of 20 μm, and finally thinning it by electro-chemical polishing.

X-ray diffraction (XRD) profiles of the isometric-phase steel and as-received dual-phase steel (AISI 301 steels) are shown in Figs. 1(a) and 1(b), respectively. The as-received dual-phase steel is mainly composed of mainly γ-austenite (fcc) and a small amount of α'-martensite (bcc).

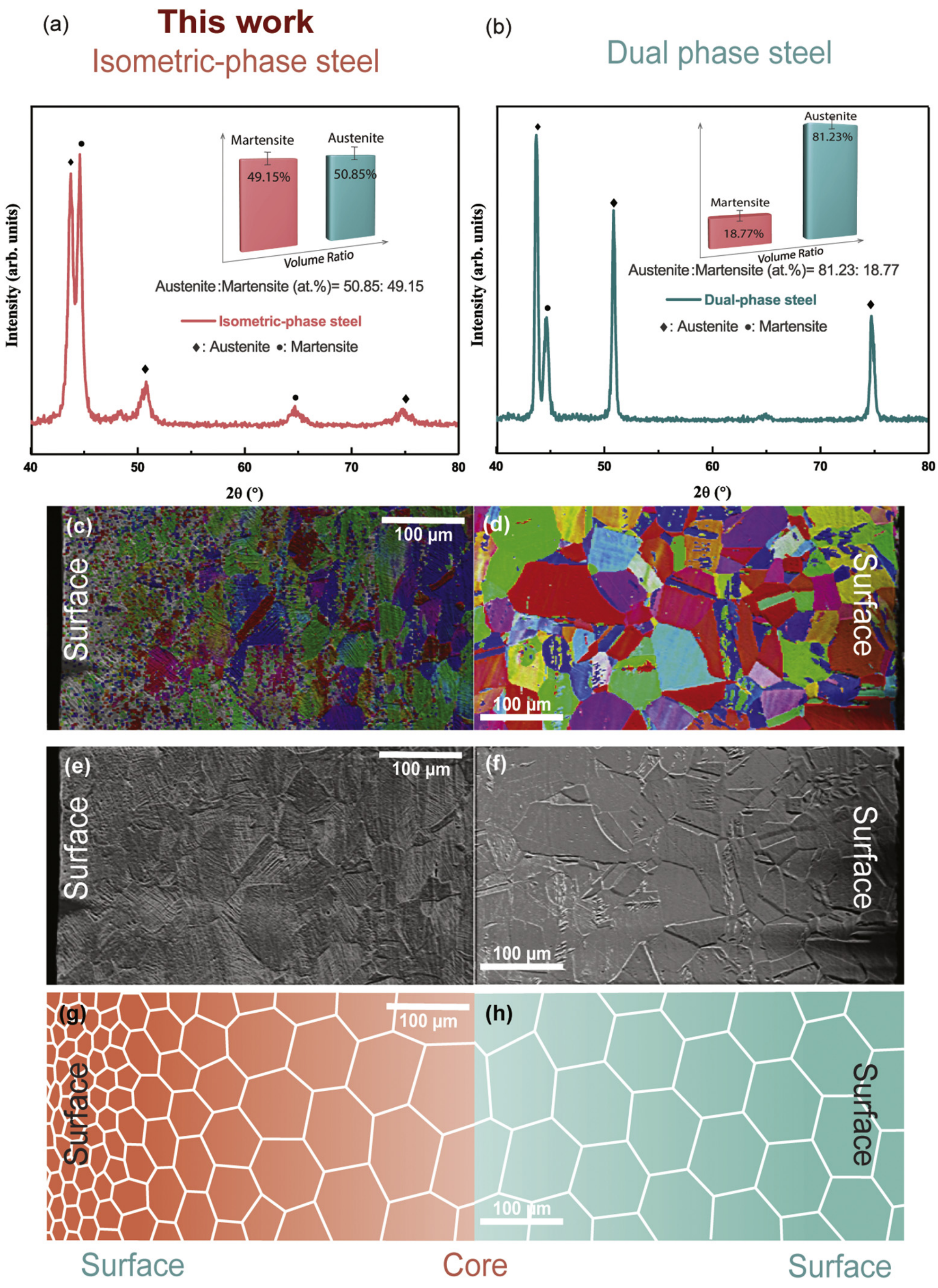

Fig. 1. Structure comparison: isometric-phase steel vs dual-phase steel. Volume fraction of austenite and martensite phases in isometric-phase steel (a) and dual-phase stainless steel (b) by XRD patterns. Cross-section EBSD and SEM images of isometric-phase steel (c) and dual-phase stainless steel (d). Cross-section SEM images of isometric-phase steel (e) and dual-phase stainless steel (f) and the schematic drawing for both steels in g and h.