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Fabricating interstitial-free steel with simultaneous high strength and good ductility with homogeneous layer and lamella structure

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ABSTRACT

Annealed interstitial-free steel (IF steel) and deformed IF steel sheets were stacked alternatively into multi-layers to produce laminated IF steel through thermal-mechanical processing. After proper processing, a yield strength of 500 MPa, an ultimate tensile strength of 600 MPa (comparable to cold rolled one) and a uniform elongation around 17% can be realized. Microstructural observation by electron back-scatter diffraction revealed a characteristic hierarchical layer + heterogeneous lamella structure, namely L2 structure. The reasons for the good mechanical properties were discussed.

It is a challenge to produce metals and alloys with both high strength and good ductility. This is because a material may be either strong or ductile but rarely both at once. Recently, a series of breakthroughs have been realized by tailoring nanostructured grains to achieve decent ductility while keeping the high strength. Examples are bimodal (or multi-modal) grain size distribution in Cu and Ni [1,2], gradient nano-grained Cu, Ni and IF steel [3–7], heterogeneous lamella structured Ti [8] and laminated Cu/Cu composite [9]. It is realized that by introducing a heterogeneous structure into those metals, work hardening capability can be improved and thus higher uniform ductility can be achieved, with only a relatively small loss of strength [4].

Here, we report a new strategy for single phase IF steel with the aim to realize a superior combination of strength and ductility. The idea is to produce a heterogeneous lamella structure by introducing different initial structures namely stacking of deformed and annealed layers alternatively into multi-layers. The stacked plates were "welded" together by hot compression, followed by thermomechanical processing. It is shown that a good combination of strength and uniform tensile elongation in IF steel, together with good stability and reproducibility, was obtained by this strategy. Transmission electron microscope and electron back-scatter diffraction (EBSD) investigation were used to characterize the microstructure and the mechanical properties are discussed based on this characterization.

The initial material was 1 mm thick Ti-added commercial cold rolled (77.8% reduction in thickness) IF steel sheets. The chemical composition of the IF steel was 0.012 wt% C-0.005 wt% Si-0.1 wt% Mn-0.061 wt% Ti. One cold rolled sheet was annealed at 780 °C to complete recrystallization with an average grain size of about 20 μm. The cold rolled and the annealed sheets in the following are called CR and AR, respectively. The CR and AR steel sheets were cut into plates with a diameter of 15 mm. After surface cleaning by polishing with grinding papers and degreasing with acetone, the CR and AR steel sheets were stacked to 11 layers in an alternate sequence, as shown in Fig. 1(a) step 1. During the stacking, all plates were aligned along their original rolling direction (RD). The stacked multilayer plates were hot compressed to a thickness reduction of 40% at 500 °C by using a Gleeble 3800 thermo-mechanical simulator in vacuum to weld the layers together. The hot-compressed specimens were air cooled and then cold forged (CF) at room temperature to a thickness of about 1.6 mm by a hydraulic press, as shown in Fig. 1(a) step 2. After cold forging, the nominal deformation strains of the initial CR and AR layers are 96.8% and 85.5% corresponding to von Mises strains of 4.0 and 2.2, respectively. The interfaces between the original AR and CR layers can be recognized after hot compression, but cannot after cold forging (Fig. 1(a) step 3). However, the differences can be seen in the microstructure after etching with a 5% Nital solution. The elongated feature in the CR layers is more clear which relates to the higher nominal deformation strain in the CR layers than that in the AR layers. The cold forged specimens were then annealed at various temperatures ranging from 500 °C to 700 °C for different times. Tensile tests were performed along the original RD direction to evaluate the

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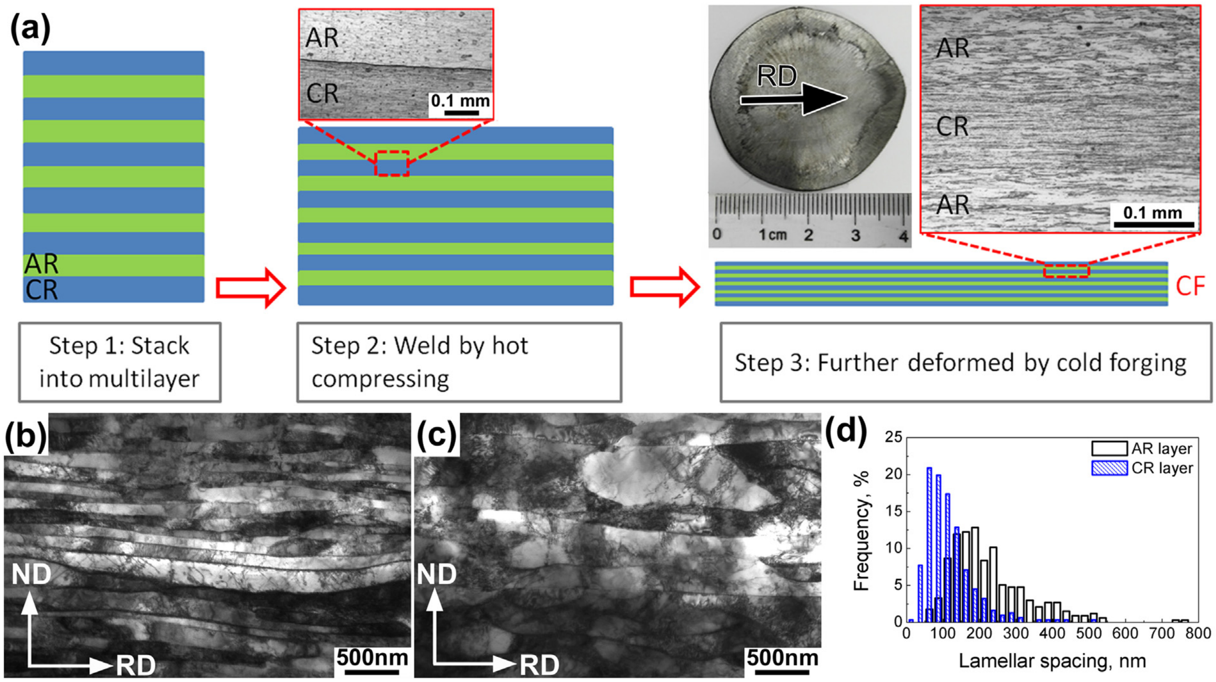

Fig. 1. (a) Schematic illustration of the fabrication process of the IF steel before annealing. Optical microscopy images of the interfaces after compression and after cold forging are also included in step 2 and step 3. The cold forged plate has a diameter around 40 mm as shown in step 3. The original rolling direction of the CR plate is indicated by RD. TEM images of the CR layer (b) and the AR layer (c) obtained on the longitudinal section of a CF specimen. (d) Distance between lamellar boundaries measured along the original ND of the CF specimens. Totally more than 600 boundaries were counted in both the CR and AR layers.

mechanical properties. Dog-bone shaped tensile samples with a gage length of 12 mm and a width of 2.5 mm were used. Electron back-scatter diffraction (EBSD) using an Oxford Aztec detector attached to a JEOL 7800F scanning electron microscope (SEM) was applied to characterize the microstructures of the annealed specimens. Detailed microstructural characterization of the deformed sample were done in a JEOL 2100 transmission electron microscope (TEM). All the microstructural observations were conducted on the original longitudinal section (RD-ND plane).

The microstructures of the IF steel after cold forging is shown in Fig. 1(b) and (c). It is seen that both the original CR and AR layers have lamellar dislocation boundaries, which are typical for IF steel deformed to high strains [10]. The average boundary spacings along the original ND are 116 nm and 226 nm in the CR layer and the AR layer, respectively.

As an example, the EBSD maps of the 600 °C 1 h and 575 °C 3 h annealed samples are shown in Fig. 2. Four layers are included in Fig. 2(a), in which only high angle boundaries (≥15°) are shown. On

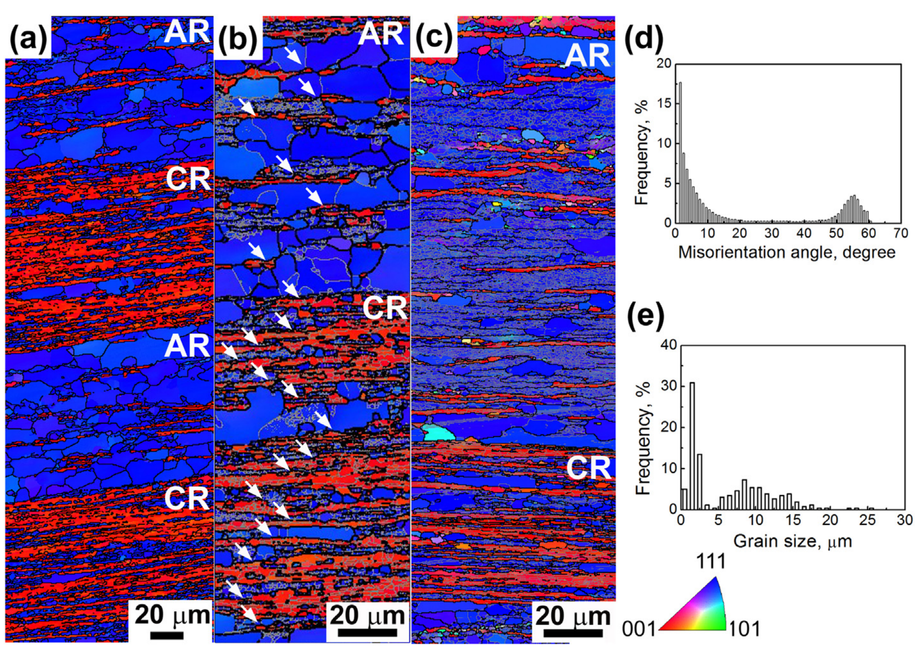

Fig. 2. Examples of EBSD mapping of the sample annealed at 600 °C for 1 h (a) and (b); and 575 °C for 3 h (c).Thick black lines represent high angle boundaries and thin white lines indicate low angle boundaries. (d) and (e) Corresponding misorientation angle distribution and grain size/boundary spacing distribution of the 600 °C annealed sample. In order to show the bimodal grain size distribution, same number of grains/boundaries was counted for coarse and fine grain size/boundary spacing.