Heterogeneous multi-layered IF steel with simultaneous high strength and good ductility

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Abstract. Multi-layered IF steel samples were designed and fabricated by hot compression followed by cold forging of an alternating stack of cold-rolled and annealed IF steel sheets, with an aim to improve the strength of the material without losing much ductility. A very good combination of strength and ductility was achieved by proper annealing after deformation. Microstructural analysis by electron back-scatter diffraction revealed that the good combination of strength and ductility is related to a characteristic hierarchical structure that is characterized by layered and lamella structures with different length scales.

1. Introduction
In the past several years, achieving simultaneously high strength and good ductility has been realized by utilizing combinations of length scale, such as multi-layered materials, and bimodal (or multimodal) grain size distributions [1-9]. The results of these studies have shown that it is possible in some cases to do better than just a simple trade-off between strength and ductility (i.e. sacrificing some strength for ductility). Recently, Wu et al. reported a heterogeneous lamella structure (a special case of a bimodal structure, with soft micro-grained lamella embedded in a hard ultrafine-grained lamella matrix) in Ti produced by asymmetric rolling and partial recrystallization that possesses an unprecedented property combination: as strong as ultrafine-grained metal and at the same time as ductile as conventional coarse-grained counterpart material [10]. In the cases above, the metals with bimodal structure have a mechanical incompatibility due to the bimodal grain size distribution, inducing a strain gradient and complex stress state, which generates geometrically necessary dislocations (GNDs) to accommodate the strain gradient and promote the generation and interaction of dislocations [10]. Furthermore, interfaces in the multi-layered materials are believed to be responsible for the observed high strain hardening and ductility, across which there were heterogeneities in...
chemical composition, grain size, hardness and texture [1]. Some researchers have found that gradient distribution of stress near the interface significantly contributes to working hardening in multi-layered metals. Yang et al. [11] proposed that a strain gradient and back stress strengthening caused by the pileup of GNDs played a critical role in the observed high stress and high strain hardening. Therefore, it is promising that multi-layered metals with heterogeneous structure may yield a good combination of strength and ductility by combining both bimodal structure and interface effects.

In the present study, we tried three methods to obtain multi-layered IF steel sheets with an aim to improve the strength of the material without losing much ductility, including accumulative roll bonding (ARB), hot compression followed by hot rolling (HR) and cold forging (CF). The results of the last method will be discussed in detail. Different to other reported multi-layered materials, such as copper with bronze [1], Cu–10Zn with Cu [4], and Nb with Cu [5, 12, 13], single phase IF steel sheets with different initial structures (deformed and annealed) were stacked alternatively into multi-layers in the present experiment. The stacked plates were "welded" together by hot compression, followed by hot/cold deformation. A heterogeneous lamella structure was obtained by this strategy and a very good combination of strength and ductility was achieved by adjusting the heat treatment schedule after hot compression plus cold forging deformation. A characteristic hierarchical structure that is defined by two types of layered or lamella structures with different length scales has been fabricated, referred to hereafter in this work as a L2 structure (layer + lamella), and is discussed in detail.

2. Experimental

The initial material is 1 mm thick Ti-added (0.012 wt% C - 0.061 wt% Ti) commercial cold-rolled (78% reduction in thickness) IF steel sheet. One cold rolled sheet was annealed at 780°C to achieve complete recrystallization with average grain size about 20 µm. For the multi-layered heterogeneous sheets, the cold rolled (CR) and the annealed steel sheets (referred to hereafter by AR) were cut into plates with a diameter of 15 mm. The sample surfaces were ground and then degreased with acetone. Then, the CR and AR steel sheets were stacked in an alternate sequence into 11 layers, along the original rolling direction (RD). To weld the layers together, the stacked multilayer plates were hot compressed at 500°C by using a Gleeble 3800 thermo-mechanical simulator in vacuum. The hot-compressed specimens were air cooled and then cold forged (CF) at room temperature to a thickness of about 1.6 mm using a hydraulic press. 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. Note that unless otherwise specified CR and AR indicate the initial CR and AR layers in the specimens. The cold forged specimens were then annealed at 625 °C for 0.5 hour or 1 hour. Tensile tests were performed along the original RD direction to evaluate the mechanical properties. Dog-bone shaped tensile samples with a gage length of 12 mm and a width of 2.5 mm were used. An Oxford Aztec electron back-scatter diffraction (EBSD) detector attached to a JEOL 7800F scanning electron microscope (SEM) was used to characterize the microstructures of the specimens. All the observations were conducted on the original longitudinal section (RD-ND plane).

3. Results and discussion

The microstructure of the 0.5 hour annealed sample is given in figure 1. Figure 1 (a) shows an inverse pole figure map and (b) shows a boundary map in which black lines represent high angle grain boundaries and red lines indicate low angle grain boundaries. It is seen that the mapping area contains an AR layer and a CR layer. In the AR layer, there are dominantly coarse (recrystallized) grains seen in blue (with ND aligned along the <111> direction). Within this layer, there are also fine-grained (deformed) lamellae (indicated by white arrows), approximately parallel to RD. In contrast in the CR layer, the microstructure is composed of fine-grained (deformed) matrix with mixed red color (with ND aligned along the <001> direction) and blue color. Within this layer, there are also coarse grains (indicated by yellow arrows). The red and blue regions also form heterogeneous lamellae similar to those seen in Ti [10]. The coarse grains are distributed only in the blue region so that the blue regions are the coarse lamellae in the CR layer, while the red regions are the fine lamellae. This characteristic
hierarchical layer structure combined with a heterogeneous lamella structure differs from previously reported heterogeneous structures, including a heterogeneous lamella structure [10], a bimodal structure [14], a harmonic structure [15] and a gradient structure [16]. A bimodal distribution of misorientation angle and grain size are shown in figures 1c and 1d. The average grain sizes of the small grains and coarse grains based on the EBSD measurements are 1.6 μm and 11.1 μm, respectively.

Figure 1. Example EBSD maps of the specimen annealed for 0.5 h: (a) inverse pole figure map, (b) boundary map. Thick black lines represent high angle grain boundaries and thin red lines small angle grain boundaries. The interfaces are indicated by yellow dashed lines in (b). (c) and (d) are misorientation angle distribution and grain size distribution based on the EBSD mapping. In order to show the bimodal grain size distribution, same number of grains were counted for the coarse and fine grains.

Figure 2. Schematic illustration of the L2 structure.
Figure 2 shows schematically the structure of present steel after annealing. The structure contains alternating layers, labelled here as fine-grained layers and coarse-grained layers. In the fine-grained layers, some coarse-grained lamellae are distributed approximately along the RD; meanwhile, fine-grained lamellae decorate the coarse-grained layers. As a result this combination of features is defined as a L2 (layer + lamella) structure.

Figure 3 shows the microstructure of the 1 hour annealed sample. A similar structure can be seen in this sample, especially in the CR layer. However, due to the longer annealing time, the red lamellae in the AR layer are consumed completely, leaving some small angle grain boundaries. The average grain sizes do not change too much. However, the misorientation distribution in the AR layer is clearly more random, as shown in figure 3c.

Figure 4 gives the true stress - true strain curves (S-S curve) for the annealed samples. The S-S curves of the CF, AR and CR samples are also plotted for comparison. The S-S curve of the AR sample has the largest uniform elongation with a yield strength of about 150 MPa, which is typical for annealed IF steel. The heavily deformed samples, such as the CF sample and CR sample, have almost no uniform elongation. The strength of the CF sample is higher than that of the CR sample, due to its deformation strain. After heat treatment at 625°C for 0.5 h, the uniform elongation is about 30%, and the yield strength is twice that of the AR sample. Annealing for 1 h results in a decrease in strength, but still higher than that of the sample fabricated by accumulative roll bonding (ARB) to a similar strain followed by annealing, as shown in the "ARB-1.6 μm" curve [17]. The average grain size of the fine grain layer in the 1 hour annealed sample is about 1.6 μm, comparable to the grain size in Ref. [17], but the present results show that a heterogeneous lamella structure can yield better strength than a homogeneous ultra-fine grain structure. Furthermore, the ARB fabricated homogeneous IF steel shows a yield drop phenomenon, which is not observed in the present study. It is also seen that longer annealing time can result in a less typical L2 structure. This might be the reason why the uniform elongation of the 1 hour annealed sample does not increase, as it seems that it does not follow the same trend as that of the 0.5 hour annealed sample.
Figure 4. True stress - true strain curves of the cold forged and annealed samples. S-S curves of the AR, CR samples and a 1.6 μm grain size sample (reproduced from Ref. [17]) are also plotted for comparison.

Figure 5 gives the yield strength and uniform elongation combinations obtained in the present study as well as those reported in other references [17-21]. It is clear that the combination of strength and ductility in the present study is superior to those of previously reported data, for example homogeneous ultra-fine grained IF steel prepared by equal-channel angular pressing/extrusion [19, 21] and ARB [17] and heterogeneous structure by asymmetric rolling (AsyR) [20]. It is thus speculated that the ultra-fine grains impart high strength while the large grains stabilize the tensile elongation of the material, accommodating the mechanical incompatibility due to the interfaces between layers and lamellae with different grain sizes and orientations within the layers. The mechanical incompatibility induces a strain gradient and complex stress state, which can generate geometrically necessary dislocations (GNDs) to accommodate the strain gradient and promote the generation and interaction of dislocations. Consequently, a high strength and good ductility can be achieved in the present steel.

Figure 5. Comparison of yield strength and uniform elongation combinations between the present study and other data obtained from references [17-21] as indicated in the figure.

Important parameters that may affect the L2 structure and mechanical properties are the initial material, layer thickness, sample stacking sequence, welding process, deformation strains, heat treatment parameters, etc. Systematic studies the effects of these afore-mentioned parameters on microstructures and mechanical properties, underlining mechanisms and large-scale production are necessary in the future. It is believed that further improved mechanical properties can be achieved by tailoring the L2 structure. Also, the plausibility of this strategy on other material systems is worth of
investigation. The results of the present study nevertheless form a good basis for further studies in this research area.

4. Summary
An IF steel with a characteristic hierarchical layer + lamella structure (L2 structure for short) was produced by interleaving cold rolled and annealed commercial IF steel sheets prior to cold deformation followed by an appropriate post-deformation annealing. Compared to homogeneous fine structured IF steels, it is shown that the L2 structured IF steel exhibits a superior combination of strength and uniform elongation. Both the yield/ultimate strength and ductility in uniaxial tension are improved compared to previous studies, and it is proposed that this enhanced combination of mechanical properties is attributed primarily to the effect of mechanical incompatibility across both layer interfaces and the micro-scale lamella structure with different grain sizes. By tailoring the processing parameters, and thus the L2 structure, still better properties may be achieved.

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