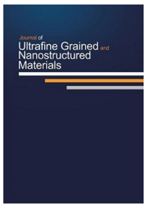

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Enhancement of mechanical properties of low carbon steel based on heat treatment and thermo-mechanical processing routes

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ABSTRACT

Thermal treatments and thermo-mechanical processing routes were applied on a conventional structural steel (st37 steel: 0.12C-1.11Mn-0.16Si) for improvement of tensile properties and enhancement of work-hardening behavior. Full annealing resulted in a sheet with coarse ferrite grains and pearlite colonies arranged alternatively in distinct bands, which showed high ductility, low strength, and the presence of the yield point elongation at the beginning of the plastic flow. The cold-rolled sheet, however, showed poor ductility but much higher strength level. The dual phase (DP) sheet, resulted from intercritical annealing in the austenite plus ferrite region, showed a remarkable strength-ductility balance, which was related to the excellent work-hardening behavior. A bimodal-sized ferritic structure with the appearance of a poor strain hardening regime after experiencing a high yield stress was obtained from the subcritically annealed cold-rolled DP microstructure. The ultrafine-grained sheet was processed by applying the abovementioned route on a martensitic microstructure, which resulted in low ductility but high strength at ambient temperature. These results demonstrated the ability to control the properties of conventional steels by simple thermal and thermo-mechanical treatments.

Keywords: *Low carbon steel, Grain refinement, Mechanical properties, Strain hardening rate.*

1. Introduction

Grain size effects on the tensile properties of metallic materials are well-known. Therefore, large plastic straining [1,2], mechanical alloying [3], thermo-mechanical processing [4], and thermal treatments [5] are commonly used for grain refinement.

Regarding low-carbon steels, remarkable grain refinement can be achieved by cold deformation and annealing (CRA) of martensite [6-8]. The effect of intercritical annealing on the enhancement of tensile properties of low carbon steels has been also taken into account, which results in the formation of ferritic-martensitic dual phase (DP) microstructure [9,10]. By consideration of a DP microstructure, the CRA process results in a bimodal sized ferrite structure, where large grains originate from ferrite and finer grains develop from martensite [11]. This can result in a good ductility-strength balance [12].

These routes should be applied to different steel compositions, especially the low-cost commercial grades, for augmenting their potential applications. Accordingly, the present work is dedicated to the evaluation of the effect of simple thermal and thermo-mechanical routes on the enhancement of the mechanical properties of a widely accessible st37 grade.

2. Material and experimental details

A 0.12C-1.11Mn-0.16Si (wt%) steel sheet was subjected to the processing routes shown in Figure 1, where austenitization, quenching, rolling, and tempering were used to process DP, Bimodal, and ultrafine-grained (UFG) steels. The selected tempering conditions are based on the previous works on the UFG steel [6-8] and preliminary experiments. Optical and scanning electron microscopies (CamScan SEM) were used for microstructural investigations after etching by the Nital solution. Room-temperature tensile tests were also performed at the initial strain rate of 0.001 s^{-1}. These tests were repeated once to ensure the reproducibility of results.

3. Result and discussion

As represented in Figure 2a, ferrite grains of 15 ± 1.1 μm on average and pearlite colonies constitute the as-received microstructure. A coarser microstructure (ferrite grains of 35 ± 1.3 μm on average) can be seen for the full annealed sample (Figure 2b). The lath morphology of martensite is evident from the SEM image of the quenched sheet (Figure 2c). As can be seen in Figure 2d, for the DP sheet with 60 vol% martensite, austenite (or martensite after quenching) appears in place of both pearlite and the surrounding ferrite. Engineering stress-strain curves are shown in Figure 3. The full annealed sheet shows low yield stress (YS) and tensile strength (UTS) but it is highly ductile. In contrast, the DP steel shows much higher UTS, and as it is apparent, its work-hardening ability is much better. This aspect will be revisited later.

The cold-rolled sheet (Figure 2e) shows poor ductility but much higher strength level compared with the other sheets (Figure 3). Tempering of this structure has resulted in the formation of UFG grains (~ 0.7 ± 0.09 μm) and nano carbides (based on the image analysis of Figure 2f); whereas tempering of the cold-rolled DP sheet has resulted in the formation of a bimodal-sized ferrite (Figure 2g) with grains of ~ 0.9 ± 0.1 μm originated from martensite and ~ 9.2 ± 0.8 μm originated from ferrite (Bimodal steel).

As can be seen in Figure 3, the yield ratio (YS/UTS) for the UFG and Bimodal steels is very high but the latter shows higher total elongation, which is related to the co-presence of large and fine ferrite grains. These findings can be rationalized based on the work-hardening rate - true strain (θ-ε) plots (Figure 4), where the Bimodal steel maintains relatively high θ values up to high ε. However, in the case of UFG steel with ultrafine microstructure, θ falls rapidly. Figure 3 also reveals that the total elongations of DP and Bimodal steels are near each other. However, the former shows high tensile strength while the latter has high yield strength. The DP steel shows much higher

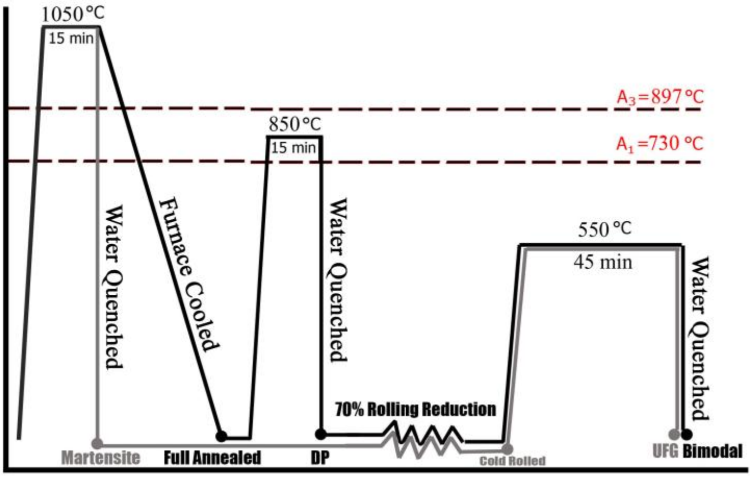
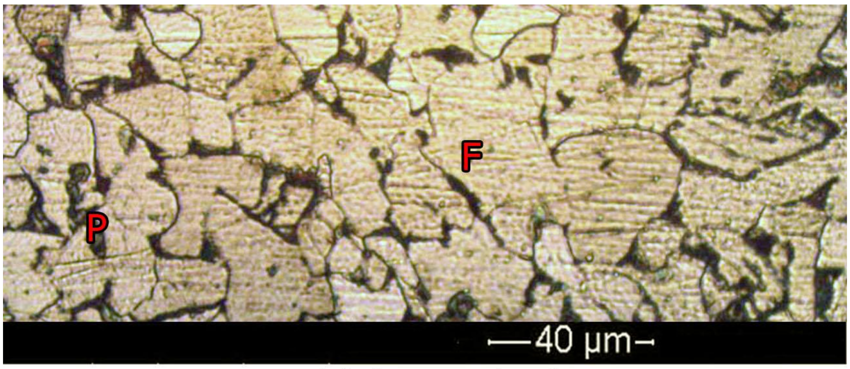


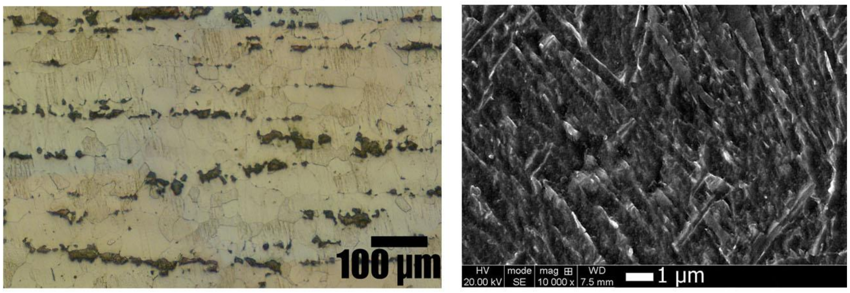
Fig. 1- Schematic representation of the processing routes used in this work.

θ at each ε with the consequent high UTS of this steel. The presence of quench-induced unpinned dislocations governs high θ for the DP steel at initial ε values.

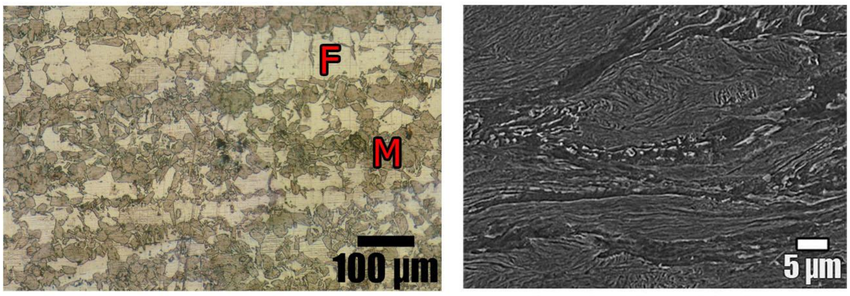
Conclusively, Figure 3 implies that controlling the properties of conventional steels is possible by applying simple thermal and thermo-mechanical routes.



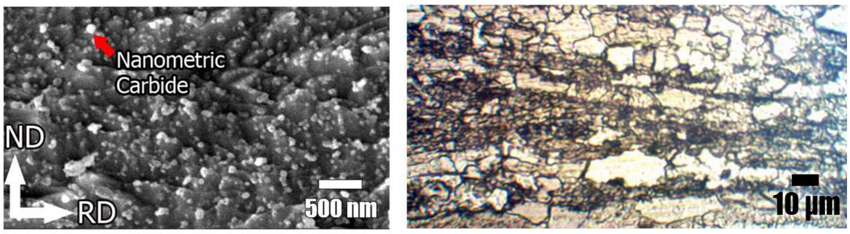
(a) As-Received



(b) Full Annealed (c) Martensite



(d) DP (e) Cold Rolled



(f) UFG (g) Bimodal

Fig. 2- Representative microstructures of different sheets. In these microstructures, F, P, and M represent ferrite, pearlite, and martensite, respectively.

4. Conclusions

In summary, thermal treatments and thermo-mechanical processing routes were applied on a conventional structural steel (st37 steel: 0.12C-1.11Mn-0.16Si) for improvement of tensile properties and enhancement of work-hardening behavior. Full annealing resulted in a sheet with coarse ferrite grains and pearlite colonies arranged alternatively in distinct bands, which showed high ductility, low strength, and the presence of the yield point elongation at the beginning of the plastic flow. The cold-rolled martensitic steel, however, with a lamellar structure along the longitudinal direction of rolling, showed poor ductility but high tensile strength. The dual phase (DP) ferritic-martensitic sheet, resulted from intercritical annealing in the austenite plus ferrite region, showed a remarkable strength-ductility balance. The latter was related to the excellent work-hardening behavior, especially at the beginning of plastic flow. Cold rolling and subcritical annealing of DP microstructure results in the development of a bimodal sized ferrite structure with high yield stress and appearance of a poor strain hardening regime. The UFG steel, processed by cold rolling and subcritical annealing of martensite, showed low ductility but high strength. These results demonstrated the ability to control the properties of conventional steels by simple thermal and thermo-mechanical treatments.

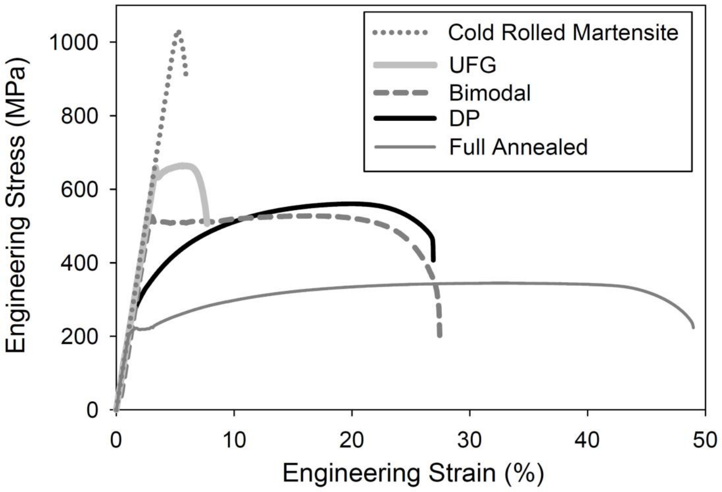


Fig. 3- Tensile stress-strain curves of different samples.

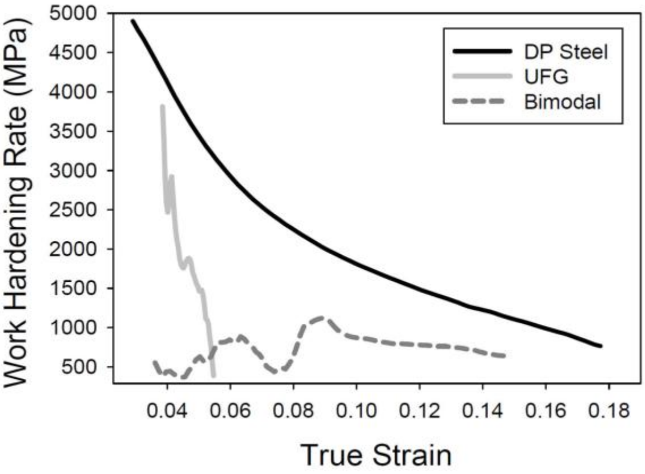


Fig. 4- Work-hardening rate plots for the UFG, bimodal, and DP steels. The true stress-strain curves up to the point of instability in tension were considered for these analyses.

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