The Effect of Thermo-Mechanical Treatment and Adding Niobium and Titanium on Microstructure and Mechanical Properties of TWIP Steel

Davood Zamani, Abbas Najafizadeh, Hossein Monajati, and Gholmreza Razavi

***Abstract*—The effect of addition of Nb and Ti also cold rolling and annealing treatment on mechanical properties and microstructure of a twinning induced plasticity (TWIP) steel have been investigated. The results indicated that addition of Nb and Ti enhances strength. Also it is considered in the case that deformation twinning is suppressed, low stacking fault energy and Nb and Ti precipitation causes high elongation. It is because of limiteted dynamic recovery. In addition, increasing cold rolling reduction has been increased strength. The ductility increased with increasing annealing temperature; however, strength reduced. In centric limit of partial recrystallization regime, maximum increasing in work hardening capacity and also almost high yield strength has been achieved. Therefore, utilization of large cold rolling reduction and subsequently annealing treatment in the centric limit of partial recrystallization region was suggested as an effective method to obtain TWIP steel with an excellent combination of strength and ductility.**

***Index Terms*—TWIP steel, Nb, Ti, partial recrystallization, cold rolling, annealing.**

I. Introduction

Any vehicle must satisfy four primary criteria, sometimes referred to the SAFE criteria: safety, affordability, fuel efficiency, and environmental friendliness[1]. To achieve the need of vehicles, the steel industry will constantly make progress. The extensive use of light weight construction materials is the key method by which the goal of vehicle weight reduction can be achieved. The development of steels for a variety of automotive applications is focused on an increase of strength combined with the preservation or improvement of its ductility. The increase of strength enables car manufacturers to reduce the weight of the car, whereas the increase of ductility allows for more complex car design [2].

Recently, Twinning Induced Plasticity (TWIP) steels containing 25-35 wt % Mn with small additions of Al, and Si have been developed as a promising material for automotive applications [3], [4]. The high Mn content stabilises austenite at room temperature and produces a single phase face centred cubic (FCC) steel with low stacking fault energy (SFE) between 15-40 mJ/m^2.

TWIP steels are characterised by high strain hardening rates leading to ultimate tensile strengths of 600-1000 MPa and total elongations exceeding 50% [5]. Extensive studies have been carried out to understand the work hardening behavior of low SFE metals and alloys as well as TWIP steels. It is believed that formation of mechanical twins during deformation leads to an increase in the instantaneous work hardening rate. In other words, twin boundaries act as strong obstacles for subsequence movement of dislocations. As a result, the ductility is improved by the retardation of local necking [5], [6].

The achievement of this combination of mechanical properties challenges the conventional perception of an inverse relationship between strength and ductility and occurs mainly via the lowered SFE producing substantial twinning during plastic deformation. However, the yield strength of TWIP steels is relatively low [7].

On the other hand, there are some way to improve it which are mentioned below:

One way has been suggested by Bouaziz *et al.* [8]. They found that mechanical twins have a thermal stability during recovery treatment (e.g. holding at 500 °C for 3.6 ks) and so mechanical twin boundaries contribute to the strengthening of metal (just like grain boundaries) during further deformation while ductility is improved by decreasing dislocation density as a result of recovery treatment.

Another way that has been suggested by Wang *et al.* [9] have been confirmed that a bimodal grain size distribution consisting of a mixture of both ultrafine and fine grains may be also effective in achieving the best combination of strength-ductility in ultrafine grained materials.

Moreover, it has been mentioned that addition of Nb and Ti microadditions to steels could form dispersive nitrides, carbonitrides and carbides which are the cause of additional precipitation strengthening what has a particular meaning for steels with austenitic matrix and relatively low yield stress [10].

Therefore, the aim of this study is to clarify the mechanical properties of TWIP steel with utilization of three methods that mentioned above. For this propose, after evaluate of effect of adding Nb and Ti, the effect of cold rolling reduction and annealing temperature on the mechanical properties and microstructural evolutions of Fe–31Mn–4Si-2Al-Nb-Ti TWIP steel were investigated.

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II. Experimental

A 30 kg and a 10 kg ingot, whose chemical composition can be found in TABLE I, was prepared by vacuum induction melting, then homogenized at 1100 °C for 3.6 ks in an argon atmosphere, after that plates were hot-rolled to reduction of 50% at the temperatures between 1100 and 900 ◦C. To isolate the influence of Nb and Ti were prepared samples with coled rolled reduction of 50% and subsequently annealed at 750 °C from both steels. In order to obtain samples with different cold rolling reductions and recovered-to-fully recrystallized structures, the hot-rolled plate of Fe-31Mn-4Si-2Al-Nb-Ti steel was cold-rolled at room temperature to reductions of 50%, 65% and 80%, and subsequently annealed at 550°C, 600°C, 650°C, 700°C and 750 °C for 1.8 ks and then air-cooled

TABLE I: Chemical Compositions of Investigated Steel (wt %)

Fe	C	Mn	Al	Si	S	Nb	Ti
Bal.	0.13	31.5±0.5	1.9±0.1	3.7±0.1	<0.009	0.06	0.09
Bal.	0.13	32.5±0.5	2±0.1	3.7±.0.1	<0.009	-	-

Tensile tests were carried out with a strain rate of 10^{-3} s^{-1} using test pieces which were prepared according to ASTM E8M at room temperature. All tensile test samples were cut along the rolling direction (RD). Microstructural evaluations were conducted by the optical microscopy (OM) and scanning electron microscopy (SEM).

III. Result and Discussion

Fig. 1 shows the Engineering stress-Engineering strain curves of Fe-31Mn-4Si-2Al and Fe-31Mn-4Si-2Al-Nb-Ti steel after 50% cold rolling and annealing at 750°C for 1800 seconds.

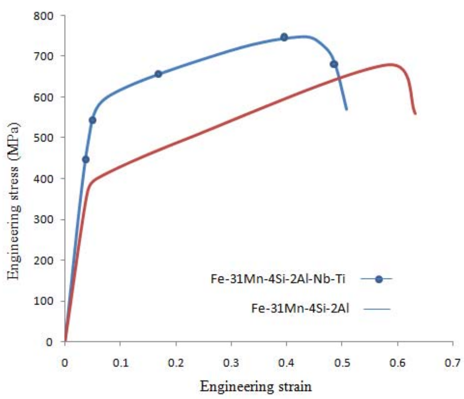
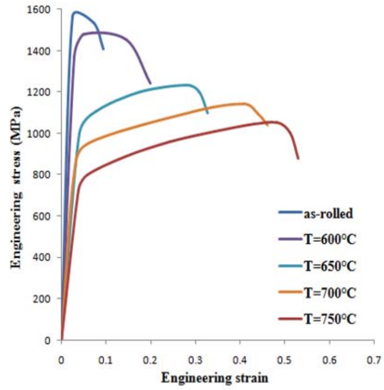


Fig. 1. Engineering stress-Engineering strain curves of Fe-31Mn-4Si-2Al and Fe-31Mn-4Si-2Al-Nb-Ti TWIP steel with 50% cold reduction and annealed at 750°C for 1.8 ks.

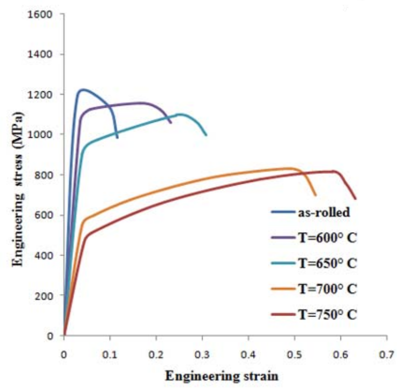
It is observed that the steel containing Nb and Ti has greater tensile strength and yield strength than the steel without Nb and Ti. Optical observation showed that the steel containing Nb and Ti have smaller grain size. It has been reported [6] that grain size reduction and also precipitation hardening of Nb and Ti precipitations, cause the strengthening of steels.

On the other hand, steel containing Nb and Ti has shown lower work hardening rate than steel without Nb and Ti. Mechanical twin boundaries act as obstacles to the dislocation movement (like grain boundaries) [11]. Reduction of work hardening rate as a result of adding Nb and Ti, despite of their cumulative effect on work hardening rate, has shown that the mechanical twinning was significantly suppressed by the precipitations of these elements.

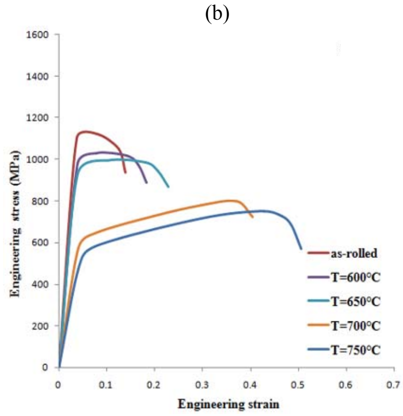
Moreover, Fig. 1 has illustrated total elongation of the steel containing Nb and Ti that the mean grain size is 2μm is about 50%. In contrast, investigations [12], [13] have indicated submicron FCC steels with high SFE and BCC steels exhibit about a few percent total elongation. Additionally, Dini *et al.* have confirmed deformation twinning was strongly inhibited by grain refinement, and it has considered that Nb and Ti precipitation act as obstacles to form mechanical twinning. Consequently, mechanical twinning is not the reason of the high obtained elongation.



(a)



(b)



(c)

Fig. 2. Engineering stress-Engineering strain curves of Fe-31Mn-4Si-2Al-Nb-Ti TWIP steel with different cold rolling reductions (R) and annealed at various temperatures for 1.8 ks a) R=80% b) R=65% c) R=50%.

The uniform elongation can be explained by the necking instability condition [14]. The condition of necking propagation in a tensile test is expressed by the instability criterion (i.e., $d\sigma/d\varepsilon<\sigma$). When the work hardening rate is equal to the σ, uniform elongation stops and necking is initiated. Therefore, the high uniform elongation requires the high work hardening during tensile deformation. The strengthening due to Nb and Ti precipitate and restricted dynamic recovery due to the low SFE, leads to a higher instantaneous work hardening (a slow decrease in work hardening rate) and enhances the uniform elongation via retardation of local necking.

Fig. 2 shows the Engineering stress-Engineering strain curves of Fe-31Mn-4Si-2Al-Nb-Ti TWIP steel after 50, 65 and 80% cold rolling reduction and annealing at Temperature range of 550°C to 750°C.

In as-rolled samples, strength increases with increasing the cold rolling reduction. Increasing annealing temperature reduces the strength and increase the total elongation. Fig. 3 shows the microstructure of samples, which is 50% cold rolled and annealed at 600°C, 700°C and 750°C for 1.8 ks.

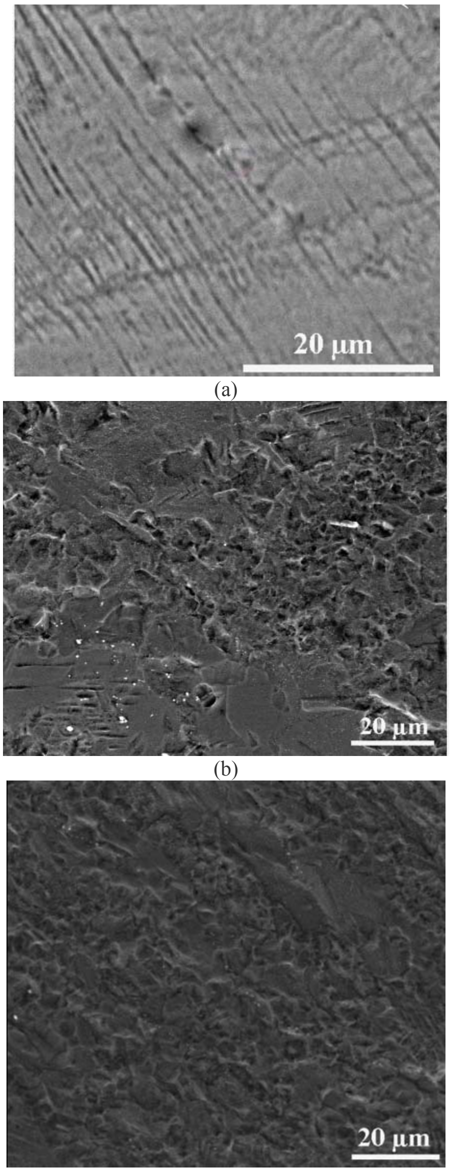


Fig. 3. SEM images of 50% cold rolled and annealed samples for 1.8 ks at a) 600 b) 700 c) 750 temperatures.

Fig. 3(a) (recovery region) shows the recovered microstructure sample containing mechanical twin. Fig. 3(b) (partial recrystallization region) shows the recrystallized grains in matrix containing mechanical twin, which is in agreement with the observations of Bouaziz *et al.* [8] on an Fe–22%Mn–0.6%C TWIP steel. Fig. 3(c) has only the small amount of the unrecrystallized area. The results of hardness tests and also optical observations showed that the starting temperatures of recrystallization of 50%, 65% and 80% cold rolled samples are 620°C, 640°C and 650°C respectively and ending temperatures of recrystallization are 720 °C, 750 °C and 775 °C respectively.

As-rolled samples and recovered samples provide the higher yield strength. But the ductility in this condition is very low. The maximum value of total elongation is approximately 20%, which is occurred in 80% cold rolled and annealed sample at 600°C. The increase in ductility, attributed to the microstructural changes due to the annihilation of dislocations and formation of sub-boundries.

On the other hand, the yield strength decreases significantly with annealing samples in grain growth region. With the formation of new grains during recrystallization heat treatment, formed mechanical twin during the cold rolling are lost and severely reduce the yield strength.

It is observed that annealed samples in partial recrystallization region, provide acceptable yield strengths. Obtained microstructure with annealling in this temperature range consists of mechanical twin and also recrystallized grains (Figure 3b). Therefore, mechanical twins contribute in strengthening and on the contrary, recrystallized grains lead to increasing ductility. With increasing annealing temperature the recrystallized fraction increases and as results ductility increases, but strength decreases.

On the other hand, work hardening capacity is one of the important parameters in Industrial applications [6]. Work hardening capacity (UTS*TEL) provides a good agreement between tensile strength and ductility. In order to have a better comparison, the work hardening capacity's values has been present in Fig. 4.

It is observed that, by annealing in the centric partial recrystallization region (650°C to 700°C) significant increase in the work hardening capacity occurs.

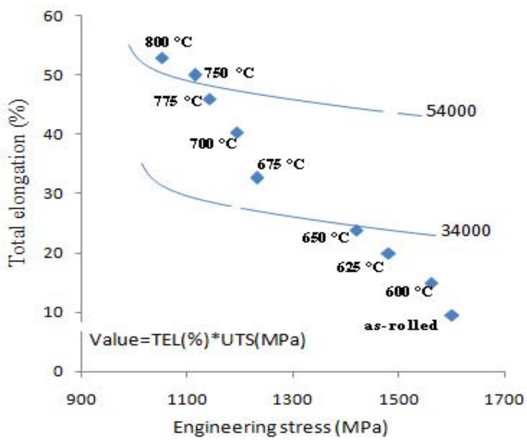


Fig. 4. The comparison between ductility and strength (i.e., TEL vs. UTS) of TWIPsteel samples with 80% colled rolled reduction and annealed for 1.8 ks at various temperature.

IV. Conclusion

Despite the suppression of forming the mechanical twin, adding Micro-alloy elements Nb and Ti to Fe-31Mn-4Si-2Al TWIP steel increase the tensile strength and the yield strength of cold rolled and annealed sample. Moreover, Nb and Ti precipitation and low SFE is identified as reasons for high obtained elongation. In addition, by increasing cold rolling reduction, the strengthening effect of the areas that are not recrystallized during annealing in partial recrystallization region increase. On the other hand, by increasing annealing temperature ductility increases. In contrast, by increasing the annealing temperature to grain growth region, significant drop in yield strength occurs.

In addition, annealing in centric partial recrystallization region has the greatest increase in work hardening capacity.

Consequently, utilization of large cold rolling reduction on Micro-alloyed TWIP steel (Fe-31Mn-4Si-2Al-Nb-Ti) and subsequently annealing treatment in the centric limit of partial recrystallization region was suggested as an effective method to obtain TWIP steel with an excellent combination of tensile strength, yield strength and ductility.

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