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Mechanical properties, formability and corrosion resistance of thermomechanically controlled processed Ti-Nb stabilized IF steel

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ABSTRACT

Aim of the present study is to examine the possibilities of achieving a better combination of yield strength (YS), ductility and formability with a better corrosion resistance of a Ti-Nb stabilize IF steel through microstructural refinement by simple phase controlled thermomechanical rolling. The phase controlled thermomechanical rolling could be an industrially reliable method for the production of hot strips, which can substitute cold rolled steel sheets. Accordingly, the phase controlled multi-pass rolling was performed in 3 selected phase regimes (γ-recrystallization, γ→α transition & α-regions) on the basis of Ac_3/Ar_3, Ac_1/Ar_1 (obtained through Thermo-Calc & Gleeble-3800) and T_{nr} (from Boratto equation) followed by air cooling. The volume fraction of precipitate(s) correspond to the deformation temperature was estimated using Thermo-Calc Software and the morphology of the precipitates was analyzed by TEM. The strain induced phase transformation of unstable γ occurred during rolling at a high reduction of ~80%, ε=1.6 at γ→α transition region. Thus, dynamically recovered stable bimodal equiaxed ferrite structures (fine ferrite ~5 µm embedded with larger size ferrite grains ~32 µm) were obtained after air cooling to room temperature. In case of the rolling at α-region, improvement of the YS (> 3-fold) is attributed to the formation of ultrafine ferrite grains (1–3 µm) through subgrain structures, strain-induced precipitation of nanosize NbC and/or TiC and micro-shear bands. Very short-annealing (~100 s) at 850 °C followed by forced air cooling was employed in order to simulate continuous annealing process and was found to improve the formability without much affecting its YS. The avoidance of FeTiP phase formation (which deteriorates to form {111} recrystallization texture) and nucleation of ferrite grains within the deformation bands (studied through EBSD study) by a short-annealing treatment are accountable for regaining the formability. The role of strain hardening exponent (*n*) and plastic-strain-ratio (*r*) on the deformation characteristics of the thermomechanically treated IF steel were also investigated to correlate the YS and uniform elongation. Furthermore, the rolled (at α-region) + short-annealed samples showed an excellent corrosion resistance due to the formation of dense oxide film on the surface. This is attributed to the dissolution of Fe(Ti+Nb)P precipitates (which are the potential sites for initiation of pits), and formation of fine grains (which facilitate to form dense oxide film on the large surface area).

1. Introduction

The major requirements of materials for the automotive applications are deep drawability, high strength, weldability and surface quality [1,2]. It is well-known that the interstitial free (IF) steels are a class of high formable steels, which typically contain very low amounts of interstitial elements (Carbon ≤50 ppm and Nitrogen ≤70 ppm) resulting in excellent deep drawability [1–3]. Production of IF steels requires removal of the interstitial elements through appropriate control of melt chemistry achieved mostly with the addition of Ti and/or Nb to remove or minimize N, S and C by forming NbC/TiC, NbN/TiN and NbCS/TiCS or NbCN/TiCN [1–4]. Solid solution strengthening elements, namely, P, Mn and Si are added to the IF steel to increase their strength although Mn and Si additions may result in some loss of deep drawability [4–6]. The benefit of P addition requires tight process controls, since P can precipitate as FeTiP during batch annealing in the temperature range of 873–1123 K (600–850 °C) [7,8]. Formation of the FeTiP precipitate diminishes the P concentration in the matrix leading to a significant loss in strength [9–11]. Moreover, the precipitation of FeTiP is also detrimental for the

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Table 1
Chemical composition (wt%) of the Ti-Nb stabilized IF steel obtained by optical emission spectroscopy analysis.

Element	C	Mn	S	P	Si	Al	Nb	Ti	N	Fe
wt%	0.0026	0.14	0.008	0.031	0.007	0.052	0.012	0.042	0.0021	99.7

formation of the {111} recrystallization texture. The {111} recrystallization texture is advantageous for better deep drawability and hence, the precipitation of FeTiP should be restricted [10–12]. Misra et al. [13] have also reported that the addition of a higher amount P could lead to grain boundary segregation, which would increase the ductile-to-brittle transition temperature (DBTT) leading to cold work embrittlement [13,14]. Therefore, proper control of P, suitable annealing temperature and holding time are very important to overcome these problems. Addition of Si on the other hand is not desirable science it deteriorates surface quality, coating adhesion and causes surface oxidation of the IF steel [11]. Yasushi et al. [12] have demonstrated that the high strength can be achieved without Si addition, instead by forming fine Nb(C,N) precipitates, which increase the strength by dispersion hardening in combination with ferrite grain size refinement.

Recently, attention has been focused on the improvement of strength of IF steels by microstructural modification through proper control of the hot rolling parameters. Usually, the processing of an IF steel sheet consists of slab reheating, hot rolling, pickling, cold rolling and final annealing. The mechanical properties can be tailored in a wide range by controlling the complex interaction of several metallurgical changes during processing [1–4]. Several investigations have been carried out on microstructure and texture evolution during cold rolling followed by annealing of the IF steels [4,5,10].

The use of hot-rolled steel sheet as a substitute for its cold-rolled counterpart has been considered a cost saving method for the IF steels [15–17], although hot-rolled steel sheet does not have good formability. Some investigations have been carried out on texture control of hot-rolled sheets that propose the finish hot-rolling to occur in the ferrite region. This is beneficial as the subsequent recrystallization annealing is not essential after the finish rolling [18–20]. The physical metallurgy of ferritic hot rolling is significantly different than that of conventional austenitic hot rolling [21–23], and has many advantages such as energy saving, uniformity of temperature control through the thickness etc [17]. Moreover, high intense rolling texture, including normal direction (ND) fibers and rolling direction fibers, that are developed during ferritic rolling of the IF steels, can transform to ⟨111⟩//ND recrystallization, which is highly beneficial for deep drawability. During high temperature coiling, deformed grains are recrystallized completely and strong ⟨111⟩//ND recrystallization textures are developed. In order to acquire good drawability, it is necessary to increase the intensity of the ⟨111⟩//ND recrystallization texture [23].

The present study investigates the effect of hot rolling temperature range (from ferritic to austenite regions) on the microstructure, mechanical properties, formability and corrosion behaviour of ultra-low carbon Ti-Nb stabilized IF steel sheets. The path controlled rolling was carried in 3 different phase regions: austenite recrystallization, non-recrystallization and dual phase region. The effect of very short-time (100 s) annealing at high temperature ~1123 K (850 °C) was also studied with an aim to recover significant amounts of formability without much interference to the yield strength. Forced air cooling was used after the short annealing to avoid formation of the FeTiP precipitates, which suppress the {111} recrystallization textures. Special attention has been given to analyze the effect of rolling temperatures on the formability in light of these two considerations (i.e., FeTiP precipitates and {111} recrystallization textures). An additional piece of this study is to understand the role of strain hardening exponent (n) and plastic strain ratio (r) on deformation characteristics of the thermomechanically treated IF steel, which has not been reported in the literature. Potentiodynamic polarization tests were conducted to investigate the corrosion resistance of the ultrafine grained IF steel.

2. Material and experimental details

The Ti-Nb stabilized IF steel used for the present investigation was supplied by TATA Steel, Jamshedpur, India. The chemical composition (wt%) obtained by optical emission spectroscopy analysis (Spectrolab, Germany) is given in Table 1.

Dilatometry tests were conducted in the Gleeble-3800 thermomechanical simulator to obtain critical temperatures such as austenite to ferrite start transformation temperature (Ar_3) and austenite to ferrite finish transformation temperature during cooling (Ar_1). A cylindrical sample (Φ10 mm×80 mm) was heated to a temperature of 1473 K (1200 °C) at a heating rate of 5 °C/s, hold for 1 min and then cooled to room temperature at a slow cooling rate of 1 °C/s. The slope of the curve changes due to the volumetric contraction/expansion of different phases as a result of phase transformation [24].

The values of Ar_3 and Ar_1 obtained from the cooling curve as shown in Fig. 1 are 974 K (701 °C) and 1133 K (860 °C), respectively; whereas, Ac_1 and Ac_3 are estimated to be 1188 K (915 °C) and 1198 K (925 °C), respectively. The experimental values Ac_1 and Ac_3 were correlated with the theoretical values (i.e. ~1183 K (910 °C) and 1203 K (930 °C)) obtained through Thermo-Calc software. Recrystallization stop temperature, T_{nr}, was calculated using the Boratto equation as follows [25]:

$$T_{nr} = 887 + 464C + (6445Nb - 644\sqrt{Nb}) + (732V - 230\sqrt{V}) + 890Ti + 363Al - 357Si \quad (1)$$

The value of T_{nr} is found to be ~1243 K (970 °C) for the experimental material. All the elementals inputs (C, Nb, Ti, etc.) to Eq. (1) are in wt%.

Based on the calculated critical temperatures (Ar_3, Ar_1 and T_{nr}), the controlled rolling was performed using a two high rolling mill at three different phase regimes: (a) pure austenitic at ~1323 K (1050 °C); (b) pure ferrite at ~923 K (650 °C); and (c) austenite -ferrite transition state zone at ~1073 K (800 °C). The rolling schedules are shown schematically in Fig. 3. The specimens used for thermo-mechanical controlled rolling with dimensions of 30 mm×24 mm×10 mm were machined from the cast steel. The samples were first homogenized at

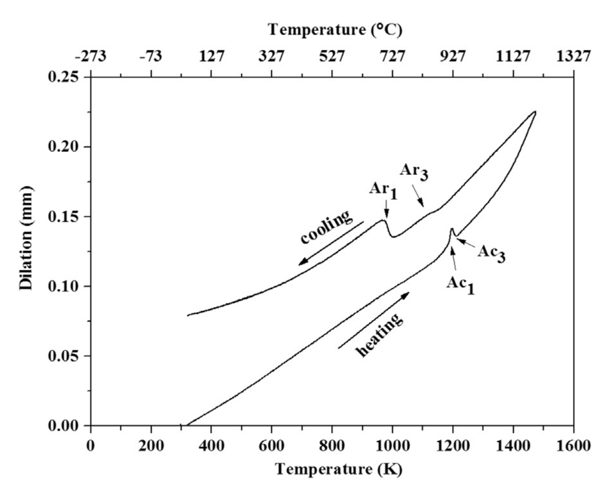

Fig. 1. Dilatometry curve for Ti-Nb stabilized IF steel obtained through Gleeble-3800.