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# Unexpected Effect of Nb Addition as a Microalloying Element on Mechanical Properties of δ-TRIP Steels

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**Abstract**: The concept of microalloying was applied to the δ-TRIP (transformation-induced plasticity) steel to investigate the feasibility of increasing the mechanical properties and understanding the effect of microalloying on the morphology and structure of the steel. A hot rolled δ-TRIP steel with three different contents of Nb (0, 0.03, 0.07 mass%) was subjected to the microstructural and mechanical examination. The high Al and Si concentration in these steels guaranteed the presence of the considerable δ-ferrite phase in the microstructure after the casting and the subsequent hot rolling. The obtained results showed that Nb dramatically affects the microstructure, the dynamic recovery and recrystallization behavior, as well as the grain shape and thus the stability of austenite after the thermomechanical process of hot rolling. The results also revealed an unexpected effect of Nb on the mechanical properties. The addition of Nb to the δ-TRIP steel led to a significant decrease in the ultimate strength (from 1144 to 917 MPa) and an increase in ductility (from 24% to 28%). These unconventional results could be explained by the change in the steel microstructure. The work-hardening behaviors of all samples exhibit three stages of the work-hardening rate evolution. At the stage 2, the work-hardening rate of the studied steels increased, being attributed to the TRIP effect and the transformation of austenite to martensite.

**Key words**: δ-TRIP steel; Nb microalloying; high Al steel; mechanical property; work-hardening

In recent years, transformation induced plasticity (TRIP) steel has received great attentions due to the outstanding combination of strength, ductility, as well as good crashworthiness[1,2]. These prominent advantages are the consequences of the stress- or strain-induced transformation of the retained austenite to martensite leading to delaying the onset of plastic instability, which made them one of the best potential candidates for automotive components[3].

The first TRIP steels were fully austenitic at ambient temperature, as the result of the large concentration of expensive solutes[4]. A few years later, the TRIP effect was demonstrated in the low-alloy steels made by 0.2 C, 1−2 Mn and 1−2 Si (mass%)[1,5]. The microstructures consisted of 50−60 vol.% allotriomorphic ferrite, 20−30 vol.% carbide-free bainite and only 10−30 vol.% austenite and were henceforth referred to as "TRIP-assisted" to distinguish them from the fully austenitic TRIP steels[2,6,7]. The presence of the TRIP effect in the aforementioned type of steels is a consequence of the high level of Si in the steel composition due to preventing the cementite formation[8-11].

In recent years, attempts to improve the mechanical properties and microstructure of the TRIP-assisted steels have contributed to introducing a new type of TRIP steel, which is called δ-TRIP steel[3,7,8]. This new generation of TRIP steel benefits from having a large quantity of delta (δ)-ferrite, which is retained from the solidification stage and remains as a stable phase at all temperatures in the solid state[2,7,8]. One of the significant advantages of the δ-TRIP steel is the presence of the stable δ-ferrite in the heat-affected zone, being a reason for reducing the hardness variations and considerable ductility[7,8].

Research has shown that Al is an alternative al-

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loying element optimizing the austenite stability by suppressing the cementite formation and could, therefore, be considered as a suitable substitute for Si[1,7,8]. However, it might have less potential in retarding the formation of cementite than silicon at the same mass concentration and might be less effective in providing a good combination of strength and ductility[12-14]. Yi et al.[3] showed that unlike Si, aluminium cannot be considered as a solid solution strengthener, and hence the full substitution of silicon by an equivalent amount of aluminium may result in the deterioration of the strength/ductility balance. On the other hand, Wei et al.[1] demonstrated that the flow stress of the high Al steel is higher than that of the high Si steel at the equivalent amount of Si and Al. Furthermore, Al is known as a strong ferrite stabilizer, thereby facilitating the presence of ferrite and δ-ferrite during solidification in TRIP steels and contributing to excellent tensile properties[14]. Suh et al.[10] have reported that Fe-6Mn-0.1C-3Al (mass%) steel achieved an excellent combination of high tensile strength (1000 MPa) and ductility (30%).

The microstructures and tensile properties of TRIP and δ-TRIP steels are greatly influenced by the concentrations of alloying elements. The effects of Si, Mn and C, as well as Al on the microstructure and mechanical properties of TRIP steels have been reported[1,5,14]. However, the effect of Nb on the tensile properties and work-hardening behavior of TRIP and especially δ-TRIP steels has not been reported with finality yet. Occasionally, contradictory statements have been reported in the articles. Nb in the solid solution lowers the martensite-start temperature and retards carbide precipitation during bainitic transformation, thereby enhancing the quantity of retained austenite[1,6,15]. Furthermore, Nb is known to be a ferrite stabilizer as well. The fine precipitates of niobium carbides, nitrides or carbonitrides can strengthen the ferrite and refine the grain size[6]. The improvement of manufacturability and final properties as well as elevated stretch formability and edge crack resistance of AHSS by precipitation strengthening and grain refinement has also been reported as the effect of Nb on the steel mechanical properties[1,6]. The enhancement of the tensile strength from 780 to 845 MPa has been reported by addition on Nb in C-Mn-Al-Si TRIP steel without any deterioration in the total elongation, due to the further refinement of the multiphase microstructure[6].

The effect of Nb on the phase transformation and morphology cannot be neglected either. In TRIP steels, the Nb addition was found to indirectly accelerate transformation kinetics through grain refinement, resulting in the pro-eutectoid ferrite and upper bainite formation[1,6,15]. A change in morphology of the bainitic matrix from lath-like to globular was observed as a result of grain refinement. The amount of cementite was reduced and the amount of retained austenite increased through the addition of Nb[6,15].

On the other hand, Hausmann et al.[6] clearly showed a significant decrease in strength due to the addition of Nb in the TRIP-assisted steel with three different Nb contents. They also declared that the flow curve of the Nb-free reference material is steeper and that its work-hardening rate and differential $n$-value are distinctly higher than those of the Nb containing variants, especially up to around 2% of logarithmic strain[6,15]. Feng et al.[15] investigated the microstructures and mechanical properties of the hot-rolled Nb-microalloyed TRIP steels by different thermomechanical processes, yet without using an Nb-free sample as a witness material. Thus, it cannot be regarded as evidence for the influence of the Nb element on the microstructure and mechanical properties.

Therefore, the majority of current studies concerning the stabilizing δ-ferrite in all the as-cast and as-rolled states and during the subsequent heat treatment as a subsequence of the simultaneous addition of Si and Al investigated the effect of the microalloying Nb on phase transformation and morphology of steel and the tensile properties and work-hardening behavior of the hot-rolled δ-TRIP to gain a better understanding of the Nb role and provide a basis for alloy design for the Al-Si content of the high-strength and high plasticity TRIP steels.

## 1 Experimental

The chemical compositions of the studied alloys which consist of the Nb-free reference material and two Nb containing steels are listed in Table 1. The alloys were prepared as ingots with dimensions of 60 mm×70 mm×240 mm using an induction vacuum furnace. The electro-slag refining (ESR) process was performed on the ingots to reduce the sulfur and phosphor content.

The ingots were reheated for 10 min at 1200 ℃ for the rough rolling to make 10 mm slabs, followed by air cooling. For the microstructural characterization, the specimens were cut along the longitudinal and vertical axis and the sections were observed. The optical microscopy (OM) was carried out on the sam-