review paper

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Niobium Alloyed High Strength Steels for Automotive Applications

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Abstract

Modern vehicle bodies make intensive use of high strength steel grades to meet the contradicting demand of lighter weight and simultaneously better mechanical performance. For many steel grades microalloying by niobium is the key to achieve their characteristic property profile. In HSLA steels niobium enhances the strength primarily by grain refinement. In interstitial free high strength steels niobium serves as a stabilizing element. Some modern multiphase steels rely on niobium to achieve additional strength via grain refinement and precipitation hardening. Microstructural control constitutes a powerful means to further optimize properties relevant to automotive processing such as cutting and forming. The role of niobium microalloying in that respect will be outlined.

Keywords: Niobium microalloying, Microstructure, Formability, Weldability

Introduction

In recent passenger vehicles a broad variety of high strength steel grades has been introduced as an alternative for mild steel grades. The share of mild steel is now below 50% of the total body weight in many vehicles and in particular cases even below 30%. Accordingly, the share of high strength steel has significantly increased.The focus has been much on multiphase steels for e.g. Dual Phase (DP), Complex Phase (CP),Transformation Induced Plasticity (TRIP) Steel during recent years, which typically account for around 20% of the body weight in current vehicles.The remaining part spectrum is mainly made from microalloyed (HSLA), high strength interstitial free (IF-HSS), bake hardening (BH) and rephosphorized (P) steel grades. Figure 1 ranks these steel grades according to yield strength and elongation. It is the aim of developing steels with good formability at high strength. Taking elongation as a criterion, DP and particularly TRIP steel appear to have the highest potential to reach this aim.

Automotive forming methods usually consist of a sequence of individual forming operations. Figure 2 defines the basic forming operations such as deep-drawing, stretching, stretch-flanging, and bending. With regard to these specific forming conditions the mere contemplation of the strength – elongation diagram is not sufficient to select the optimum material. Each forming mode has additional demands with regard to specific mechanical parameters like the Lankford parameter (r-value), work hardening coefficient (n-value) and hole expansion ratio (λ-value).

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These parameters are strongly related to microstructural features of the material and can be influenced by a suitable processing and alloying strategy. Niobium microalloying typically induces refinement and homogenization of the microstructure and thus has in many cases a beneficial influence on the resulting properties.

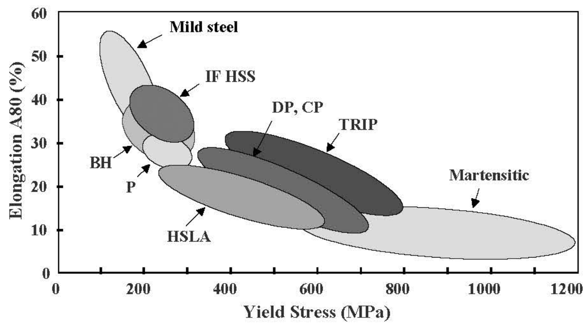


Fig. 1. Strength and elongation diagram of cold rolled steel types.

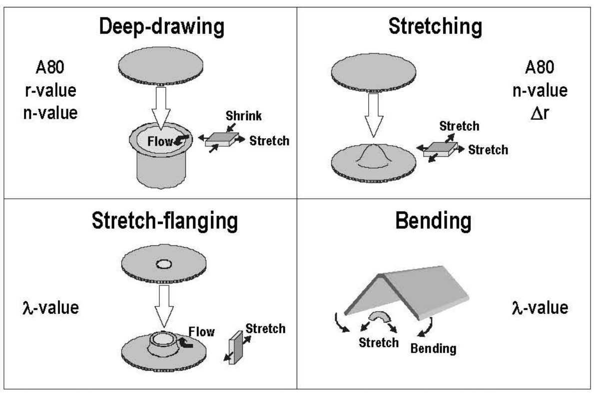


Fig. 2. Basic operations in automotive press forming.

Microalloyed HSLA Steel

Microalloyed HSLA steels were among the first high strength steel grades used in vehicle construction[1]. In some recent passenger cars they account for up to 40% of the body mass. A high yield ratio and thus a low work hardening potential is characteristic of these steel grades. This can be advantageous in achieving the specified minimum yield strength in the component, as the local yield strength is rather insensitive to the level of deformation induced during forming. Other characteristics of HSLA steel are the quasi-isotropy (Δr-value ~ 0) and the good fatigue resistance. HSLA steel is typically used for the manufacturing of parts with low and medium geometric complexity such as members, reinforcement and chassis components. The low alloying content and the limited carbon content in particular reduces the hardness in the heat affected zone after welding processes comprising a fast cooling speed.

HSLA steel is available as hot-rolled and cold-rolled material. Cold rolled sheet can be produced by batch and continuous annealing in most of the existing cold rolling mills[2]. Accordingly, there is a broad availability of this material also concerning the dimensions and surface treatments.

The production of HSLA steel is relying on niobium microalloying in combination with thermo-mechanical rolling in the hot rolling mill. This treatment provides grain refinement and a homogeneous microstructure. Particularly the refinement of cementite particles is beneficial to improve the forming behavior. The desired strength level is adjusted by the Nb content (0.02 - 0.05%) and the content of solid solution strengtheners like Mn and Si. Niobium is by far the most effective element for increasing the recrystallization stop temperature. A typical finishing temperature is about 875 °C and the coiling temperature is around 600 °C for all Nb-alloyed grades in order to optimize precipitation hardening. The microalloyed cold-rolled grades utilize maximum precipitation hardening in the hot-rolling mill. To achieve a yield stress of more than 400 MPa usually additional microalloying of Ti is applied (Figure 3). The target for the heat treatment is to recrystallize the brittle cold-rolled microstructure without enlarging the precipitations. For a given chemical composition, hot-rolled material always has higher strength values as compared to cold-rolled material (Figure 3).

A recent approach to produce microalloyed hot-rolled strip of 500 MPa minimum yield strength was successfully put into practice by reducing the carbon content (0.04 wt.%) and increasing niobium content (0.09 wt.%)[3]. Besides an extremely fine-grained ferritic-bainitic microstructure, very low scattering in the mechanical properties within the coil and across batches was obtained (Figure 4). Particularly the narrow scattering of the yield strength is helpful to avoid spring-back. The sheet edges are particularly smooth after mechanical cutting operations due to the ferritic-bainitic structure. Furthermore, the rather low carbon content also results in a reduced edge hardening when laser cutting is employed. Accordingly, this steel is well suited for forming methods where high peripheral stress is induced to the sheet edge.

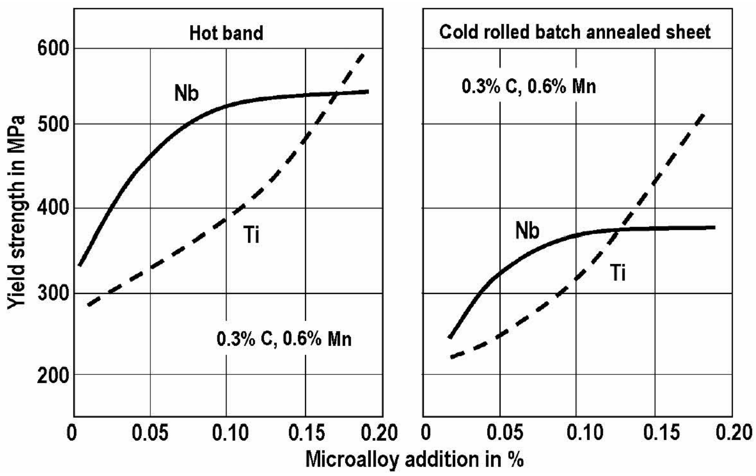


Fig. 3. Strength increase of mild steel by Nb or Ti microalloying[1].

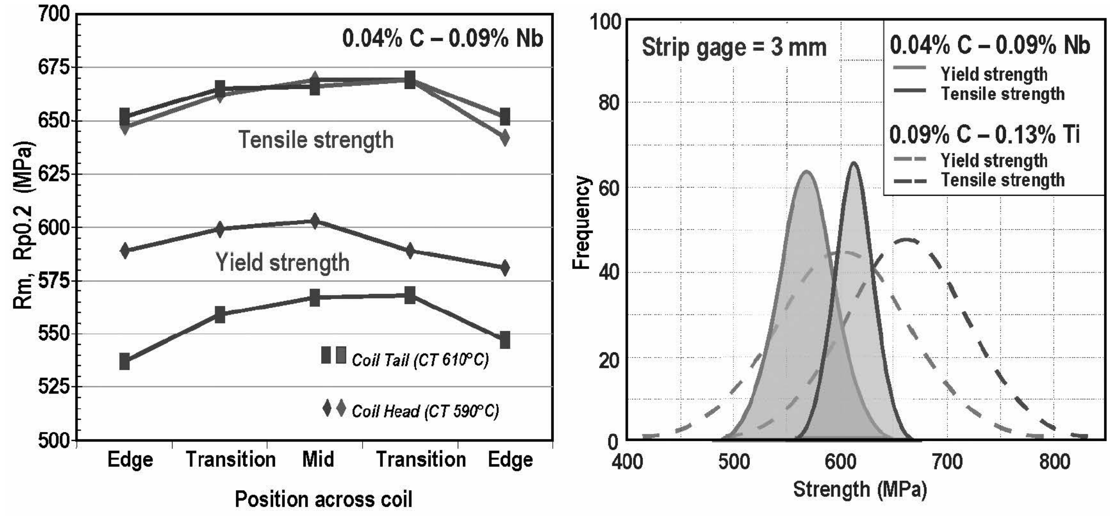


Fig. 4. Property scattering of a 500 MPa min. yield strength hot-rolled steel with low C – high Nb concept[3].

Dual Phase Steel

Dual phase steels achieve their favorable combination of strength and ductility by developing hard martensitic particles embedded in a ductile ferritic matrix. The strength increase is mainly controlled by the volume fraction of the hard martensite phase ranging typically from 5 to 30 percent. A combination of low yield and high tensile strength, and consequently high work hardening is characteristic of this steel type. Currently commercialized cold-rolled DP steels with a strength level up to 600 MPa rarely use niobium alloying whereas in DP800 and DP1000 niobium helps to gain extra strength by grain refinement and precipitation hardening. It has been theoretically and experimentally shown that refinement of the microstructure in DP steel also leads to a better work hardening rate[4-6]. Accordingly, the optimum combination of strength and formability can be achieved by homogeneously dispersing fine martensite islands in a fine-grained ferrite matrix. Conglomerates of interconnected martensite should be avoided as much as possible. The basis of obtaining a fine grained and homogeneous microstructure in cold rolled DP steel is the preparation of a suitable microstructure already in the hot band. This can be achieved by niobium microalloying and a low finishing temperature in the austenite region. A coiling temperature of 600°C appeared to be most effective for precipitation of niobium carbide[7]. However, when exceeding 630°C an increased degree of banded microstructure was found causing a deterioration of the n-value and the yield ratio [8].

In hot-rolled DP steel, niobium microalloying yields a significant grain refinement causing a clear increase in strength[9]. Experiments have been carried out with microalloying of 300 ppm Nb. The basis was a CMnCr-steel. Phosphorus was alloyed additionally in the Nb-free variant, whereas the Nb-alloyed variant contained only the usual phosphorus contents. This leads to a different transformation behavior of the two steels. The Nb-alloyed variant shows a significantly accelerated rate of pearlite formation. The desired gap between the end of bainite formation and the beginning of pearlite formation does not exist. Nevertheless, using a suitable cooling strategy with a cooling interruption in the region of ferrite formation, the desired microstructure consisting of ferrite with embedded martensite islands can be produced.

Nb microalloying with a suitable cooling strategy on the run-out table allows achieving a specified strength level at a lower martensite content, which is beneficial in maintaining a low yield ratio and high elongation (Figure 5). High cooling rates of 200 K/s and single-step cooling down to coiling temperatures below 200°C yield extremely fine-grained microstructures with a mean ferrite grain size below 2 μm in the niobium-alloyed variants. In 0.07% CMnSiCrNb steel the grain size is mainly influenced by the niobium and the carbon contents as well as the cooling strategy. In most cases the finish rolling temperature has only little influence on the grain size[10].

In forming operations, the low yield strength facilitates the onset of plastic flow during stamping and the high strain hardening capacity of dual phase steel enhances the strain redistribution thus preventing local thinning. Quasi-isotropy, which is typical for all DP steels is beneficial for stretch forming. Depending on the forming method, the actual yield strength in the finished component varies locally according to the actual degree of forming and thus influencing the crash resistance of the component[11]. The large difference in hardness between ferrite and martensite impairs the performance of DP steel under forming methods with highly localized strain such as bending or stretch-flanging (Figure 2). Microstructural refinement as induced by niobium microalloying (Figure 6) as well as the presence of a small amount of bainite help to improve the λ-value controlling this performance.

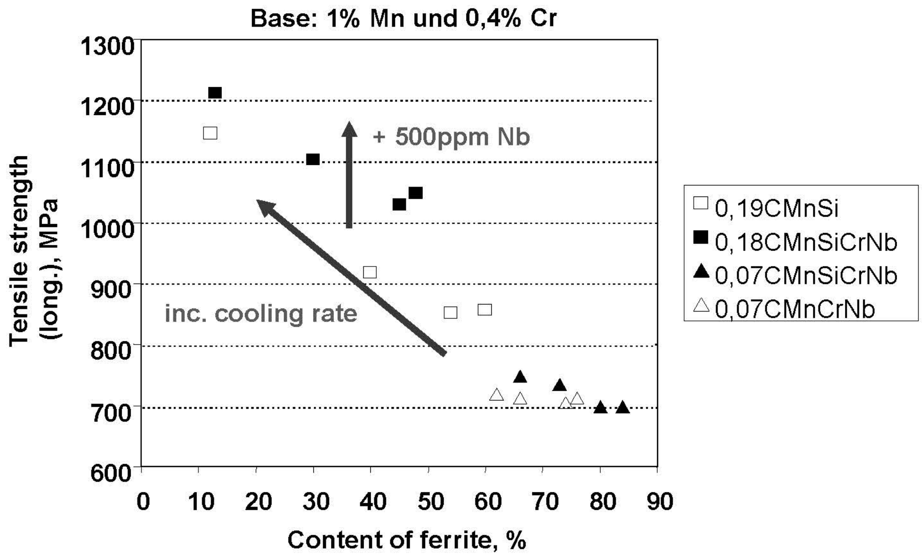
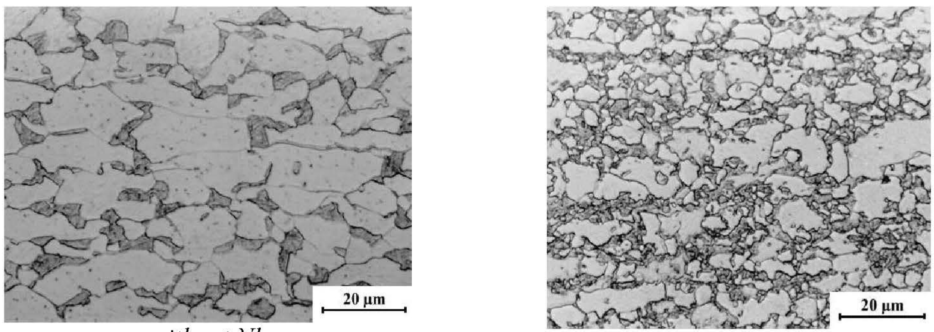


Fig. 5. The effect of chemical composition and ferrite content on the mechanical properties of hot-rolled dual phase-steels[10].



without Nb *with Nb*

Fig. 6. Effect of Nb addition on the microstructure in an industrially produced DP 800 material.

TRIP Steel

The highest elongation at very high strength level is currently offered by TRIP steel. Two factors determine the TRIP effect, causing enhancement of mechanical properties of TRIP steels: the volume fraction and the stability of the retained austenite[12]. The optimal volume fraction of retained austenite to achieve a TRIP effect to occur is reported to be in the range of 10-20 vol. %. Moreover, the volume fraction of retained austenite directly determines the C content and grain size of the retained austenite, its two main stabilization factors. The stability of the retained austenite dictates when the Strain-Induced Martensite Transformation (SIMT) occurs during straining of TRIP steel. Unstable retained austenite transforms almost immediately upon deformation, increasing work hardening rate and formability during the stamping process. At the appropriate stability of the retained austenite, the SIMT begins only at strain levels beyond those produced during stamping and forming, and the retained austenite is still present in the final part; it can transform into martensite in the event of a crash, providing greater crash energy absorption. If the retained austenite is too stable, the SIMT may start beyond the uniform elongation. In this case, no additional work hardening is expected and this delayed TRIP effect will not contribute to the enhancement of mechanical properties. The stability of the retained austenite depends on a number of stabilization factors:

The C content lowers the Ms temperature and therefore stabilizes retained austenite. The optimal C content in the retained austenite has to be in the range of 0.5-1.8 wt. % in order to provide the desirable TRIP effect.

The Ms temperature of the retained austenite is above room temperature. Smaller austenite particles contain less potential nucleation sites for transformation to martensite and consequently require a greater total driving force for the nucleation of martensite. This will lower the Ms temperature to below room temperature. It has been suggested that the grain size of the retained austenite must be in the range of 0.01 mm to 1 mm to ensure the TRIP effect in low- alloyed multiphase TRIP steels. Larger retained austenite particles may already be partially transformed into martensite or transform into the martensite at the early stages of straining. Particles smaller than 0.01 mm do not undergo the strain-induced transformation. The stabilization of retained austenite due to the smaller grain size can also be explained by the size of the strain induced martensite formed. If the same volume fraction of retained austenite is considered for large and small retained austenite grains with the same volume density of the potential nuclei available for the strain-induced martensite transformation. The activation of the martensitic nuclei in the case of the smaller retained austenite grain will lead to a formation of the less martensite than in the case of the larger retained austenite grains, i.e. the transformation kinetics are reduced for smaller austenite particles.

As mentioned in the previous paragraph, the optimal volume fraction of retained austenite for a pronounced TRIP effect is reported to be in the range of 10 - 20 vol. %. Smaller amounts of retained austenite cannot ensure a significant TRIP effect, since the C content may then be too high to result in strain-induced formation of martensite. Large amounts of retained austenite have a low C content, leading to a low stability of the retained austenite.

As a result of the volume change associated with the transformation, the stability of retained austenite is stress state dependent; it is highest for uniaxial compression and lowest for plane strain conditions.

The retained austenite can be classified in two groups: (1) isolated retained austenite islands in a soft ferrite matrix adjacent to bainite and possibly martensite and (2) thin films of retained austenite along the martensite or bainite lath boundaries, or blocky retained austenite in these hard second phases. In group (2), a higher hydrostatic pressure, resulting from the surrounding hard phase, constrains a higher volume expansion and shear deformation provoked by the strain-induced martensite transformation more than in the retained austenite of group (1).

Niobium microalloying to hot-rolled TRIP steel has been shown to stabilize retained austenite. Already the addition of a small quantity of niobium results in a significant increase in the retained austenite fraction[9]. Moreover, grain refinement of the ferritic matrix is achieved contributing to a generally higher strength level. Both niobium induced effects work in a synergetic way towards a significantly increased energy absorption capability (Figure 7).

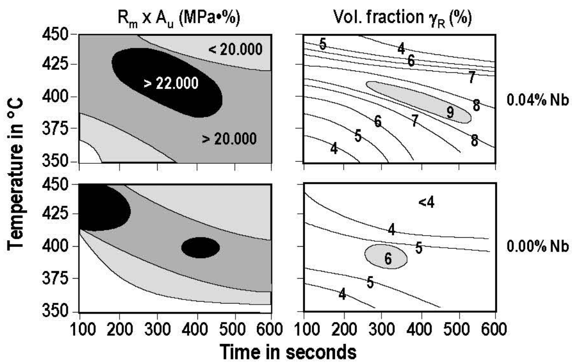
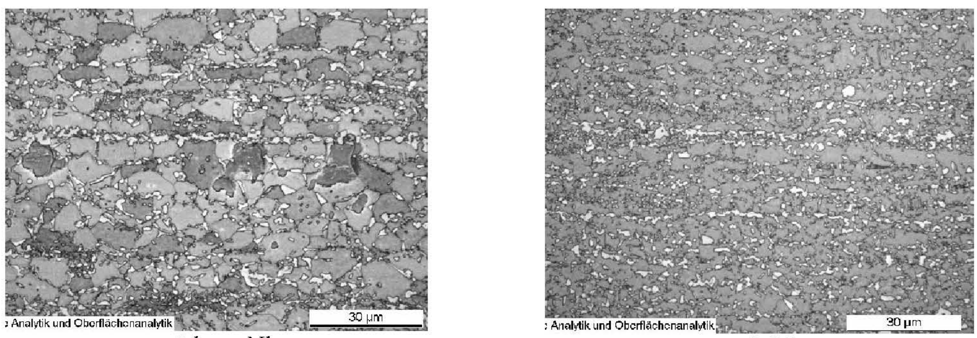


Fig. 7. Effect of niobium on energy absorption capability and volume fraction of retained austenite in TRIP steel as a function of bainitic holding time and temperature (composition in wt. % C: 0.17, Mn: 1.4, Si: 1.5)[13].

When producing cold-rolled TRIP steels the combination of a low coiling temperature (~500°C) and Nb microalloying was found to cause a remarkable decrease of the martensite start temperature[13]. Solute Nb precipitates as very small particles during intercritical annealing after cold rolling controlling the grain size and ensuring a homogeneous microstructure. It has also been speculated that the fine-grained microstructure might be responsible for a delayed bainite formation and could thus explain the reduced amount of bainite found experimentally (Figure 8).



without Nb *with Nb*

Fig. 8. Effect of Nb addition on the microstructure in an industrially produced HDG TRIP 700 material[16].

Similar to DP steel, TRIP steel shows excellent performance under stretching conditions due to its significant work hardening behavior, high homogeneous elongation and quasi-isotropy. Although TRIP steel has an r-value of around unity[14)], it is noteworthy that TRIP steel also exhibits a good deep-drawability. This is due to the observation that less austenite is converted to martensite under shrink flanging conditions (uniaxial compression in the flange) and more during plane strain deformation in the wall[15)]. Accordingly, the stronger wall area is pulling the softer flange area into the die without breakage. The potential of this mechanism should be enhanced by Nb microalloying as it increases the retained austenite content in the steel.

The refinement of the microstructure of cold-rolled hot dip galvanized steel sheet by adding Nb has resulted in a remarkable improvement of the bending and stretch-flanging behavior. Simultaneously the yield and tensile strength were both increased by up to 50 MPa depending on the Nb content whereas other mechanical properties such as elongation and n-value remained nearly unaffected[16)].

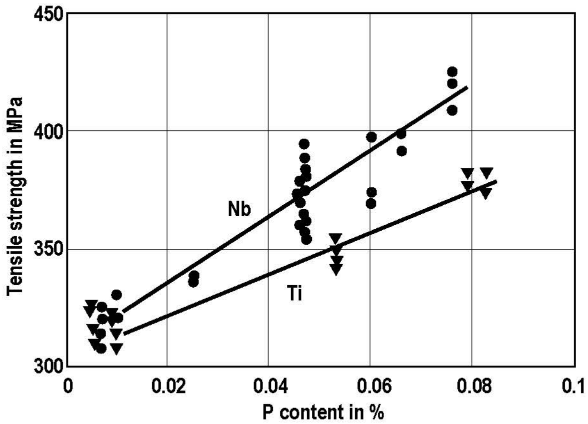


Fig. 9. Strengthening by phosphorous of Nb or Ti stabilized interstitial free steels[18)].

IF High Strength and IF Bake Hardening Steel

The stabilization of residual solute carbon and nitrogen (less than 30 ppm each achieved by degassing) in cold-rolled interstitial free (IF) steel is typically achieved via small additions of titanium and/or niobium. The good cold formability of IF steel is related to a high Lankford parameter and appreciable strain hardening. High strength IF steels are typically based on niobium stabilization (~0.02%). Compared to a titanium-stabilized grade, the niobium stabilized IF steel exhibits a finer grain size and thus a higher yield strength. This derives from the already finer grain size in the hot strip material as niobium retards the austenite recrystallization during the final rolling passes due to a solute drag effect of the large niobium atom[17)]. Furthermore, niobium in solid solution of the austenite also retards the transformation into ferrite, which has an additional grain refining effect. It should be noted however, that niobium stabilized IF steel requires a somewhat higher annealing temperature to achieve complete recrystallization after cold rolling as compared to titanium stabilization.

The increased strength compared to mild IF steel is achieved by adding solid solution hardening elements, and besides manganese of around 0.35 % the very effective element phosphorus is widely used. The strength increase by phosphorus addition is significantly higher in a niobium stabilized IF steel as compared to titanium stabilized one (Figure 8), which can be explained by the fact that titanium forms finally also titanium phosphides besides oxides, nitrides, sulphides and carbides[18)]. Consequently, the amount of phosphorus in solid solution, the responsible fraction for the strength increase, is reduced at higher titanium level.

It is also possible to produce a bake hardening steel based on a Nb stabilized ULC metallurgy[19)]. A solute carbon content of 6 ppm is necessary to obtain a BH-effect of at least 30 MPa. This can be achieved by redissolving a fraction of the precipitated NbC in the annealing cycle requiring, however, annealing temperatures of up to 870°C. It has been shown that a low Ti content facilitates the NbC dissolution during annealing and also lowers the recrystallization start temperature resulting in an improved r-value. Other BH steel concepts rely on retaining a defined small amount of C in solution being typically 5 to 10 ppm of C. To achieve this narrow range of solute carbon, partial stabilization has to be done by either Ti or Nb. It is known however that Ti forms a variety of compounds with S, N, and C making it difficult to target the mentioned narrow range. Nb on the contrary only forms NbC in such steels and therefore the target range of solute C can be hit much more precisely [20].

In contrast to the conventional ULC alloy design, a novel metallurgical approach has been reported where the niobium content is increased to around 0.07% and carbon remains at around 60 ppm as compared to the typical 20 ppm[21)]. Hot rolling of this steel results in a very fine grain size and the formation of Nb(C, N) precipitates. After subsequent cold rolling and recrystallization annealing a strong {111} orientation is developed leading to a high mean r-value. A particular feature of this steel is the formation of precipitate free zones in the vicinity of the grain boundaries after recrystallization annealing. These soft domains are responsible for a low yield point whereas the tensile strength is not affected by their presence, thus achieving a low yield ratio and a high n-value.

Conclusions

The different classes of high strength steel for automotive applications are primarily defined by the constitution of phases being ferrite, pearlite, martensite, bainite and retained austenite. The deliberate mixture of two or more phases is used to achieve a particular property profile of the steel. Microstructural control by niobium microalloying was demonstrated to be a powerful tool for optimization of the property profile of such steels.

The fundamental effect of niobium is that of grain refinement increasing the strength without deteriorating the ductility. It thus allows working with a leaner alloying concept to reach a specified strength level.

A leaner alloy concept is beneficial with regard to welding operations.

Grain refinement also brings about a more homogeneous microstructure improving the forming behavior particularly when high, localized strains are being induced.

Niobium can exert a significant influence on the transformation behavior allowing to promote or retard the formation of individual phases. This can be exploited to exert better process control and optimize properties when producing multiphase steels.

The formation of NbC precipitates is used to scavenge carbon from the ferrite matrix in IF steel. Partial stabilization of carbon by Nb generates the bake hardening effect.

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