# The 1st International Conference on Automobile Steel

# The 3rd International Conference on High Manganese Steels

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# Direct and Indirect Benefits of Niobium Microalloying to Automotive Sheet Steel

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**Abstract:** Automotive sheetsteel grade cover today a wide range of properties from very soft grades with highest formability to extremely strong grades being very difficult to form. In the same respect the carbon content ranges from nearly zero in interstitial-free steel up to 0.35% in the strongest press hardening steel. In the widely used HSLA steel grades the addition of carbon is mediated against microstructural optimization with the aim of obtaining high strength steel having acceptable formability and weldability. Niobium microalloying has been established in these steels as the most efficient element for obtaining grain refinement and precipitation strengthening. Furthermore, niobium acts as a carbon stabilizer to provide steel with an interstitial-free matrix. These well-known direct metallurgical benefits of niobium are complemented by several less-known indirect effects bringing substantial benefits for either processing the steel in the mill or improving particular properties of the steel. Examples of such indirect benefits are texture control, phase transformation kinetics, stabilization of properties or hydrogen trapping. Accordingly, this paper will comprehensively explain the currently understood effects of niobium relevant to the production and properties of automotive sheet steel.

From the mid-1980s increasing attention has been paid to developing automotive sheet answering thedemands of carmakers to produce complex shapes, to use thinner gages for weight reduction as well as to apply higher strength for better crash resistance. The challenge lies in designing microstructures allowing combiningthe desired strength with suitable press formability. The microstructure generally is the result of an alloy concept being subjected to a particular processing route. Hot-rolled strip is used for heavier gaged parts especially in chassis applications. Body components are mostly made from cold-rolled sheet,which is nowadays typically hot-dip galvanized. Both, hot-rolled and cold-rolled strip generally employ lean alloy concepts with carbon being below 0.1% in the majority of steel grades. Standard alloying elements are silicon and manganese.Selected grades foresee the addition of molybdenum, chromium, aluminum, phosphorous, titanium and boron. On the contrary, niobium microalloying is being applied to a wide range of automotive flat steelstoday. This is due to the multitude of beneficial metallurgical effects caused by niobium making it one of the most versatile and efficient alloying elements. With regard to specified properties of automotive steel grades, niobium provides microstructural characteristics relevant for strength and formability. Besides those, niobium microalloyingbrings along many fringe benefits that are not explicitly specified but have been perceived particularly useful during processing and in service. In the following, these direct and indirect effects of niobium will be discussed for major automotive sheet steel classes.

## 1 Ultra-low Carbon Steels

Ultra-low carbon steels provide the best formability and are excellently suited for deep- drawing and stretch forming. They are produced by vacuum degassing bringing the amount of interstitial carbon and nitrogen to a level below approximately 30 ppm. The low level or complete absence of interstitials provides low yield strength and high elongation.

### 1.1 Nb in interstitial-free (IF) steel

Strong carbide and nitride formers such as niobium or titanium bind any remaining carbon and nitrogen after degassing. Although both elements are equally suited for this purpose, titanium stabilizationdelivers a softer material, which is due to the coarser grain size in such steel. Niobium added to IF steel remains in solid solution at the end of the hot rolling stage. This solute Nb causes a marked retardation of the austenite-to ferrite transformation resulting in a refined ferrite grain size in the hot strip, which is carried on into the cold strip raising the yield strength typically by around 20 MPa as compared to Ti-stabilized IF steel. Yet, the refined and more homogenous grain size distribution in Nb-stabilized steel leads to very low planar anisotropy avoiding the phenomenon of “earing” after deep drawing. Furthermore the absence of individual large ferrite grains results in a clearly reduced tendency for “orange peel” appearance at the painted surface of heavily drawn parts.Nb-stabilized IF steel and especially those with over-stoichiometric Nb addition remaining partially in solution can promote particularly high r-valueby favourable texture development.

With regard to IF steel with increased strength, the grain refining effect of solute Nb after hot rolling offers an intrinsic advantage. Accelerated cooling further enhances this effect. Additional strength increase is achieved by solid solution strengthening using phosphorous alloying. Titanium as stabilizing element can lead to the formation of Fe-Ti-P diminishing the strengthening effect of phosphorous. Niobium does not react with phosphorous so that the combination of grain refinement and solid solution hardening leads to the highest possible strength in this type of steel. However, the so-called “secondary cold work embrittlement” became apparent as a problem in higher strength IF steels and especially those using Ti-stabilization. This phenomenon is related to phosphorous reducing grain boundary cohesion. Alloying of a few ppm boron to these steels can alleviate the problem as boron competes with phosphorous for grain boundary sites. The addition of boron is however detrimental to properties relevant for forming. It was shown that over-stoichiometric addition of Nbcouldalso reduce the embrittlement tendency. Solute excess niobium segregates to the grain boundary and deploys there an increase of cohesion counteracting the deleterious effect of phosphorous.

### 1.2 Nb in bake-hardening (BH) steel

Bake-hardening steel is a particular variant of higher strength IF steel where carbon is not completely stabilized but a small amount is left in interstitial solution. This free carbon is diffusing to dislocations generated during forming and locking them by the so-called Cottrell effect. The effect delivers a yield strength increase of 30~40 MPa, yet too much free carbon leads to premature ageing already at ambient temperature. The difficulty for the steelmaker is to accurately adjust the amount of free carbon in the range of 5~10 ppm. This adjustment is most efficiently done in Nb-Ti dual stabilized steel. In this concept Ti is added only for fixing nitrogen. Carbon is partially fixed by under-stoichiometric addition of niobium. Since niobium does not react with other elements present in these steels and its addition can be done very accurately due to high recovery, it is comparably much easier for the steelmaker to hit the targeted free carbon range.

## 2 High Strength Low Alloy (HSLA) Steels

### 2.1 Nb in hot-rolled HSLA steel

HSLA steel has a ferritic-pearlitic microstructure covering the medium strength range and offering moderate formability. Strength is generated by grain refinement for the lower grades and a combination of grain refinement and precipitation hardening for the higher grades. Niobium provides both strengthening mechanisms to the highest extent amongst all microalloying elements.In hot-rolled HSLA steel both, grain refinement and precipitation hardening, can enablearound 200 MPa yield strength increase each. Thus, the soleaddition of 0.05~0.06% Nb to low-carbon manganese steel basically allows producing hot strip with 600 MPa yield strength. Lowering the carbon content in medium and higher Nb alloyed HSLA steel permits the production of pearlite-reduced or ferritic-bainitic microstructures. The increased amount of solute Nb after finish rolling reducing the diffusivity of carbon in austenite is responsible for this suppression of pearlite forming. Pearlite reduced steels have very good bendability and flangeability. Moreover, the absence of hard pearlite islands from the microstructure prolongs the lifetime of cutting and punching tools.

### 2.2 Nb in cold-rolled HSLA steel

Cold-rolled HSLA steel practically applies the same alloy concepts as hot-rolled grades. However, due to annealing after cold rolling the grain size increases somewhat and over-ageing of particles reduces precipitation hardening. Thus, cold-rolled HSLA steel is always softer than the hot-rolled sibling. Nowadays, steelmakers often apply aNb-only microalloying alloy strategy for producing these steels.

## 3 Multi-phase Steels

Multi-phase steels a characterized by a ferritic microstructure embedding additional phases other than pearlite. Most prominent and widely used in car making is dual phase (DP) steel. DP steel offers higher strength than HSLA steel and simultaneously provides comparably good elongation. The tensile strength of DP steel is directly controlled by the amount of martensite present in the microstructure. The rather good elongation is the result of instantaneous and pronounced work hardening in this microstructure reflecting also in a high n-value. DP steel is thus excellently suited for stretch forming but also provides reasonably good drawability considering the high strength level. Due to these microstructural mechanisms, niobium microalloying was initially not foreseen in DP steel.

### 3.1 Nb in DP steel

In practice, however, DP steels showed some specific forming issues despite their generally good formability. This became apparent in bending operations (roll forming and die bending) by cracks forming in the bend especially for tighter radii. Furthermore, DP steel showed to be sensitive to edge cracking during flanging operations. These problems are becoming more severe with increasing martensite share. The origin of cracking is caused by the hard-soft contrast between the phase constituents within the DP microstructure. Plastic deformation is localized in the soft ferrite grain leading to delamination from the hard martensite phase or inducing cracking in the martensite. This can result in macroscopic cracking when martensite islands are large in size or clustered.Niobium microalloying was shown to alleviate this problem. The simple addition of niobium to an existing DP steel results in a much-refined microstructure in the ferritic-pearlitic hot-rolled strip that is subsequently inherited to the cold-rolled annealed (galvanized) strip. This refinement naturally results in smaller martensite island size and a more homogeneous dispersion of martensite in the ferrite matrix. Consequently crack starters are smaller in size and crack propagation is obstructed. By such approach, the bending behaviour (critical bending angle / radius) could be improved by around 30%.

New demands from the automotive industry have triggered metallurgical re-design of the initial generation DP steels. The need for improved weldability and better hole expansion ratio (HER) can be fulfilled by reducing the carbon content from traditionally over-peritectic (0.14~0.16%) to under-peritectic (<0.10%). In such new alloy design niobium plays a manifold role. The presence of niobium generally results in a strength increase of 70~100 MPa via grain refinement and precipitation hardening. This means the specified minimum strength can be achieved with a lower share of martensite phase. Consequently elongation becomes better due to an equivalent larger share of ductile ferrite. Industrial experience has shown that for under-peritectic alloys elongation is typically 2 points higher than in the over-peritecticvariant, whereas the HER increases by 70~100%.

Another major benefit of niobium microalloying in DP steels is processing robustness. These steels are in the majority of cases produced via hot dip galvanizing lines. The challenge is to adjust the required phase distribution of ferrite and austenite during intercritical annealing. The austenite phase fraction should transform into martensite during quenching, but not partially decay into bainite. Grain refinement in the original ferritic-pearlitic cold-rolled microstructure accelerates the transformation kinetics and leads to quicker achievementof the desired amount of austenite. The smaller grain sizes also result in shorter diffusion distances and thus more efficient partitioning of carbon. This leads to more stable austenite islands and less decay into bainite. Via these mechanisms Nb-microalloyed DP steel is more robust against variations in line speed and can be processed on galvanizing lines with vertical as well as horizontal furnace.

### 3.2 Nb in TRIP steel

The metallurgical mechanisms of Nb in DP steelfunction identically in the production of TRIP steel. The smaller austenite grains in this case can accumulate more easily sufficiently much carbon to stabilize the phase down to ambient temperature. Furthermore, solute niobium contributes to preventing cementite precipitation during bainitic holding, thus preserving more carbon for austenite stabilization. As a consequence, niobium alloyed TRIP steel is showing increased amounts of retained austenite in the final product. The fact that austenite grains are smaller in size causes them to transform into martensite only at higher applied strain. In this way two-fold work hardening behaviour is achieved, firstly by a DP-like effect at low strain and secondly by the TRIP effect at higher strain.

## 4 Martensitic and Press-hardening Steels

### 4.1 Enhancing the ductile range

In martensitic steel strength is achieved directly by the carbon content. The strength contributions by grain refinement and precipitation hardening being the classic functions of niobium are rather marginal. Unlike other automotive sheet steel, martensitic steel can show brittle fracture behaviour, characterized by low energy absorption. This feature is prohibitive for body parts exposed to crash impact.Therefore it is important to extend the range of ductile fracture behaviour over the entire temperature range of vehicle operation as well as to increase the ductile fracture toughness. This can be achieved by a refinement of the austenite grain structure before quenching into martensite as the martensite sub-structure develops within the prior austenite grains. With enhancing the amount of large-angle grain boundaries, i.e. prior austenite grain boundaries as well as substructure, the resistance against crack propagation is increased. Hence the material becomes tougher. Secondly the transition temperature from ductile to brittle behaviour is lowered.

In a reheat-quenching process, as it is used in press hardening, austenite grain growth is efficiently obstructed by NbC precipitates. These precipitates a formed after hot rolling or by in-situ precipitation during reheating.In steels directly quenched from the rolling heat niobium microalloying provides a non-recrystallized (pancaked) microstructure prior to quenching. For both processing conditions ductile toughness increased and ductile-to-brittle transition temperature decreased significantly.

### 4.2 Resistance against hydrogenembrittlement

A severe problem appearing in steels with more than 1000 MPa yield strength is hydrogen embrittlement and the related phenomenon of delayed cracking. This problem inherently applies to all as-quenched martensitic steels. Current and on-going research has clearly indicated a beneficial role of niobium by reducing the hydrogen embrittlement sensitivity of martensitic steels. Two principal effects have been identified:

(1) Enhancement of the total large-angle grain boundary area results in lower specific hydrogen concentration per grain boundary unit area reducing the sensitivity for intergranular fracture.

(2) Hydrogen trapping by dispersion of ultrafine (<10 nm) sized NbC precipitates. Trapped hydrogen cannot easily diffuse to active damage sites reducing delayed cracking sensitvity.

Activating both effects together results in considerably increased threshold stress and time to fracture at a given stress level under hydrogen charged conditions. Recently developed press hardening steels in the strength range of 1800~2000 MPa integrally implemented these metallurgical mechanisms induced by niobium to comply with OEM demands.

## 5 Conclusions

Niobium microalloying provides a multitude of beneficial effects in automotive sheet steel as it cannot be provided in this combination by any other alloying element. These effects can originate form both, solute or precipitate niobium. Niobium has direct effects with regard to strength and formability enabling or enhancing properties that are specified in automotive steel standards. Yet, niobium also has beneficial effects on fringe properties that are not specified as such but decisively influence the manufacturing of components.Last but not least, niobium improves the robustness of processing for many automotive steel grades. Currently, about 80% of all automotive sheet steels grades are regularly microalloyed with niobium. Comparing these advantages to the moderate alloy cost explains why niobium has taken such a prominent role in alloy design for automotive sheet steel.

**References:**

Detailed information and references can be obtained via hm(at)niobelcon.net or www.niobelcon.com