THE ROLE OF NIOBIUM IN MULTI-PHASE STEEL

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Abstract
Compared to microalloyed high strength low alloy steel sheet, multi-phase steels offer a favourable combination of strength and cold formability. However, their production is possible only via continuous annealing lines. With a finer grain size, also the dual phase and TRIP steels offer a better combination of properties, and thus microalloying with niobium is a very effective means to optimize multi-phase steel.

1. INTRODUCTION
Fuel economy together with safety considerations are the driving forces for the steadily increasing usage of higher strength steels in the automotive industry. Compared to other materials, such as the light metals aluminium and magnesium or plastics and composites, the higher strength steels have, besides weight reduction, the additional advantages, that the processing is similar to that of conventional mild steel. Therefore the overall fabrication costs will not be increased in addition to the benefit of weight saving, which is exactly the opposite for all other competing materials. Depending on the required strength and the necessary cold forming operation a big variety of steels are actually available and figure 1 (1) gives an overview.

Figure 1: Strength and cold forming properties of various automotive sheet materials

Concurrently with the use of microalloyed sheet, steels with a microstructure consisting of at least two different components led to higher strength without deterioration of ductility. These so called multi-phase steels offer attractive combinations of strength and ductility as a result of the different mechanical properties of the microstructural components and their interaction. The most prominent ones are the dual phase (DP) and the TRIP steels.
2. CHARACTERISTICS OF MULTI-PHASE STEEL

Dual phase steels consist of a relatively soft ferrite matrix responsible for low yield strength and a second hard phase (typically 5 to 30 % martensite) improving good formability along with a high tensile strength. It is possible to vary the mechanical properties tailored to the respective application by adjusting volume fraction, size and distribution of the different phases.

Additional potential for the improvement of mechanical properties can arise from the presence of the austenite phase, which transforms during the cold forming of sheet, when the necessary activation energy is supplied. The transformation of face centred cubic austenite into body centred cubic martensite induces additional plasticity and this transformation induced plasticity is called the TRIP effect.

Apart from the different levels of strength and ductility the flow behaviour of dual phase steels and TRIP steels shows characteristic differences to the microalloyed cold formable high strength low alloy (HSLA) steels, namely continuous yielding in the first case and high uniform elongation and relatively low necking elongation in the second, figure 2 (2).

The different character of these steels becomes even more obvious with their work hardening behaviour, Figure 3. It is obvious that all multi-phase steel types exhibit a higher work hardening exponent n than the conventional microalloyed HSLA steel. But also the two steel types DP and TRIP are different: While the dual phase steel shows a very high work hardening respond only at low deformation, which gets continuously reduced with higher strain, the high differential n value of the TRIP steel is almost constant over a wide range of cold deformation, as result of the progressing transformation of retained austenite into martensite.

![Figure 2: Stress-strain curves of high strength steels with similar yield strength level](image)

![Figure 3: Differential strain hardening value n for various high strength steels](image)
3. PROCESSING ROUTE

In order to guarantee good formability, all cold rolled steel have to be recrystallize annealed. For HSLA steel such heat treatment is carried in the upper range of the ferrite region and both, batch or by continuous annealing, are standard production routes. In order to obtain a multi-phase microstructure, a temperature above the recrystallization temperature is needed and the annealing process has to be in the two-phase region $\alpha + \gamma$. The volume fraction of austenite formed within this annealing process is higher with higher annealing temperature.

For DP steel typically around 20% austenite is needed. According to the equilibrium condition, this austenite is rich in carbon, while the ferrite fraction contains relatively little carbon. When quenching this microstructure below the martensite-start temperature $M_s$, the austenite volume fraction transforms into martensite and thus the final sheet exhibits a microstructure of soft ferrite plus about 20% hard (carbon rich) martensite. In order to implement such annealing cycle, see Figure 4a, the fast cooling rate asks for a continuous annealing line.

The temperature-time schedule for TRIP steel is even more complex (Figure 4b) and is also feasible only in continuous annealing line, which have to comprise also an ‘overaging’ part. Typically, the first heat treatment is carried out at slightly higher temperature in the two-phase region than discussed above, leading to a microstructure of about 50% ferrite and 50% austenite. A fast cooling rate after annealing helps to avoid any major ferrite formation and the final transformation is carried out isothermally in the bainite region (second heat treatment). During the bainite formation, the carbon diffuses into the remaining austenite islands, which get finally enriched to a level of more than 1% C. Austenite with such high carbon is stable also at room temperature.

While the chemical composition of dual phase steel is very similar to that of conventional HSLA steel, the TRIP steel exhibits much higher carbon (about 0.20%) and applies additions of manganese and silicon, which support the formation of stable retained austenite. Figure 5 (4) describes the role of manganese (lowering the $\gamma$ to $\alpha$ transformation and thus increasing the amount of retained austenite) and silicon (retarding the cementite formation and thus increasing the stability of austenite by enhanced carbon enrichment) on the mechanical properties. The diagram also shows the importance of the temperature and time for the transformation in the bainite region.
4. THE ROLE OF NIOBIUM

Niobium has become the first choice as microalloy in HSLA sheet, since it increases the strength predominately via grain refinement, figure 6 (5), while the other microalloys apply the strengthening mechanism precipitation hardening to a major extent (titanium) or totally (vanadium). In order to obtain the same strength increase, also higher amounts of microalloy addition titanium or vanadium are needed compared to niobium(6).

Recalling, that grain refinement is the only strengthening mechanism, which has a positive effect on toughness and no deteriorating effect on ductility (7), one also achieves a better combination of strength and cold forming behaviour by using niobium as a microalloy besides its economical merits. A finer grain size of the ferrite phase and also a finer grain size of the second phase martensite in the dual phase steel have a positive effect on both, strength and ductility, as demonstrated in figure 7 (7). As a consequence, the product of tensile strength times elongation increases exponentially with a finer grained microstructure. Therefore dual phase steel, especially in case of tensile strength levels above 550 MPa apply niobium microalloying in order to refine the grain size. In this context niobium is double effective:
-First, it retards the recrystallization of austenite during hot strip rolling in the final passes of the finishing train and thus prepares more nuclei for the γ to α transformation, resulting in a finer grain size of the hot band. Such finer hot strip microstructure is passed on to the cold rolled material and is still obvious in the recrystallize-annealed sheet.

-Already in the coiled hot band and certainly during the annealing process for recrystallization of cold rolled sheet the equilibrium condition for NbC in steel is reached, which means, that practically all the niobium exists in form of carbide precipitates. Also with annealing in the lower austenite region the solubility product tells, that just a marginal amount of NbC can get dissolved. The major part remains as NbC and adds remarkably to grain size control, since precipitates hamper grain growth, especially when they are relatively fine and equally distributed.

One of the first applications of high strength dual phase steel was the impact side beam of a passenger car (8). Figure 8 shows the chemical composition, the production route and the resulting mechanical properties of that component. After cold rolling, continuous annealing and water quenching the typical dual phase microstructure of ferrite plus martensite is obtained and the steel exhibits yield strength of about 550 MPa. As described earlier, this DP-microstructure responds remarkably to work hardening and by forming a tubular bar, a yield strength increase of 200 MPa is observed. Similar as all the other high strength steels, also the DP steel shows a bake hardening (BH) effect, which brings the yield strength of the bar in the final automobile after paint baking to >800 MPa.

Understanding the effect of NbC, it is not surprising, that also TRIP steel with niobium exhibits a finer grain size than niobium free steel. As result of the finer grain size, TRIP steel with about 0.03 to 0.04 %Nb exhibits higher strength than niobium free steel. The increase in both, yield strength and tensile strength is typically around 15 MPa per 0.01 %Nb (10,11). Since almost all the niobium exists in form of precipitates, confirmed by chemical dissolution
of the matrix, it is obvious, that the strength increase via precipitation hardening is marginal, since this mechanism needs very small particles of about 2 nm, which would not be found in the residue.

Besides the strength, a high uniform elongation is the most characteristic feature of TRIP steel. It depends on the amount and the stability of retained austenite. Figure 9 shows the volume fraction of retained austenite as a function of the holding time and temperature of the isothermal transformation in the bainite region, indicating, that the austenite content increases
first with holding time up to a maximum level for each temperature before it gets reduced with longer holding time owing to cementite precipitation. With niobium microalloying a much higher volume fraction of retained austenite is observed and relative high values occur already at short annealing time, which is of practical importance.

The higher amount of retained austenite is caused by at least two reasons, both also related to the grain refining effect by niobium:

- The finer grain size of the austenite formed in the two-phase region \( \alpha + \gamma \) promotes some ferrite to nucleate at the austenite/ferrite interphase during cooling to the temperature of bainitic transformation. Consequently, the enrichment in carbon in the remaining austenite will be further enhanced. Such proeutectoid ferrite formation has been demonstrated by dilatometer studies of the bainitic transformation, **figure 10**.

![Figure 10: Kinetics of bainite transformation in TRIP steel and volume transformed](image)

- Furthermore, a finer grain size itself reduces also the martensite-start temperature, a fact, which is especially important, since it represents the stability of the retained austenite. Results of other dilatometer studies, where the martensite-start temperature \( M_s \) was determined by quenching from the temperature of intercritical annealing, are given in **Figure 11**. When a finer microstructure exists (either in the niobium containing steel or in hot band applying a lower coiling temperature) the \( M_s \) temperature gets significantly lowered, which can be explained by the higher resistance of the surrounding matrix (higher strength) against the volume extension needed for the transformation. It has been measured, that in case of niobium microalloyed TRIP steel the hardness is about 20% higher than in niobium free steel.

![Figure 11: Martensite-start temperature of samples directly quenched from intercritical annealing](image)
The importance of austenite stability on a high ductility is shown in Figure 12. With a relatively low austenite content of about 3% the steel exhibits the characteristic features of dual phase steel, especially a low yield to tensile strength ratio. With increasing amount of retained austenite, the uniform elongation increases remarkably and values of around 28% are obtained in all three steel grades. But it is not the highest amount of retained austenite, which leads to the best uniform elongation, it is a value below just this highest amount, which obviously is more stable. Since the niobium microalloyed grade exhibits higher strength, one needs a higher amount of retained austenite in order to guarantee the same ductility.

Figure 12: Uniform elongation and retained austenite volume fraction in TRIP steel

Figure 13: Mechanical properties of TRIP steel for various heat treatment conditions and niobium additions
Consequently steel microalloyed with niobium exhibits a better property combination of strength and ductility, as shown in figure 13. Furthermore, it is also of practical relevance, that niobium steel is not reacting so sensitively on the processing conditions during the second isothermal heat treatment, and good results are already obtained with short processing time.

5. CONCLUSION AND OUTLOOK

High strength sheet steel is continuously gaining importance in the automotive industry. For the tensile strength range of 500 to 600 MPa, the most relevant steel grade today is microalloyed HSLA steel, which is established since several decades. It is expected, that this workhorse of high strength steel will further grow in the near future.

Besides ferrite/pearlite steels, which apply niobium as prime microalloy, steel grades with a dual phase microstructure are also regularly applied, especially when high work hardening respond at small deformations is requested. In order to obtain the ferrite/martensite microstructure, continuous annealing with a subsequent quenching is common.

An annealing cycle consisting of two isothermal heat treatments is needed for the production of TRIP steel, a grade, which offers high cold formability and high strength as a result of stable austenite islands in the ferrite/bainite microstructure. However, since these steels rely on rather high carbon, their weldability is limited. Since alloy design and processing route make this steel also relatively expensive, TRIP steel has actually no widespread application.

Similar to the microalloyed HSLA steels, also the multiphase steels get refined by niobium microalloying, resulting in improved property combination.

6. BIBLIOGRAPHY

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