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FUNDAMENTALS OF COLD FORMABLE HSLA STEELS

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Abstract

High **S**trength **L**ow **A**lloy (HSLA) steels, or more precisely microalloyed low carbon steels, are the classic solution for the automotive industry when high strength and good cold formability is required. By adding small amounts of niobium, titanium, vanadium strength is increased by grain refinement, precipitation, and solid solution hardening without significantly impairing formability. These steels are supplied in different strength levels as hot or cold rolled grades; the annealing after cold rolling might be of the batch annealing or the continuous annealing type.

The mechanical properties of HSLA steels are not only determined by their chemical composition but also by the processing parameters during hot rolling, cold rolling, and annealing. While the different yield strength levels can be easily reached by adding microalloying or solid solution strengthening elements, formability is strongly affected by the large number of fine precipitates, which retard recrystallization and texture formation and result in poor r-values. Thus the deep drawing properties are limited, while the stretch formability is attractive due to the pronounced strain hardening when the precipitates are distributed finely and homogeneously.

The corrosion protection of HSLA sheet steels can be obtained by electro or by hot dip galvanizing; the later need a proper control of the recrystallization behavior in a hot dip galvanizing line. Recent developments are steels with isotropic plastic behavior and the processing of HSLA steels on compact strip mills to very thin gauges.

The major benefit of HSLA steels are their processabilty in world wide available classical hot and cold rolling facilities and their applicability for many different car body and under body parts. These steels represent the vast majority of currently used high strength steels in the automotive industry.

Introduction

The history of high strength steels for car body applications is given in Figure 1, which indicates the approximate first appearance of a new steel grade industrially processed on the European market. Each bar indicates a group of different grades. The development of HSS started prior to 1980 basing on post-rolled, microalloyed and P-alloyed steels. The chemical composition of microalloyed steels according to European standard EN 10292 is given in Table I [1].

Table I. Chemical composition, max. amount in mass-%.

Element	*C*	*Si*	*Mn*	*P*	*S*	*Al*	*Ti*	*Nb*
Mass-%	0.11	0.50	1.00	0.025	0.025	0.015	0.15	0.09

The microalloyed steels were first used as hot strip grades for structural purposes like longitudinal beams in trucks but soon the benefits of this steel concept were noticed for cold-rolled strips as well. It is mainly the lean chemical composition which nevertheless offers a significant strength increase and which needs only minor adjustments for forming and welding making these steels attractive for many applications.

Though a large variety of new steel concepts such as DP-, BH-, high-strength IF-, TRIP-, SULC-steels or more recently TWIP- and Al-alloyed steels have been developed during the following years the HSLA steels as hot and cold rolled grades still show an increasing market share which exceeds those of the remaining concepts by far. The automotive industry belongs to the most important customers for HSLA steels as hot and cold rolled material. Figure 2 indicates the consumption of hot rolled and cold rolled HSLA steels in the European automotive industry according to a market study of 2002 [3]. A steady increase in consumption of these grades has been predicted with a tendency to use higher strength grades.

The extensive use of the HSLA steels can be ascribed to the variety of mechanical properties, which are covered by this alloying concept, Table II [1,4]. Hot rolled grades with min. yield strength values between 340 and 700 MPa and cold rolled grades with min. yield strength values between 260 and 420 MPa are offered according to European standards. There are individual grades from different producers to serve customers with tailored mechanical properties offering strength levels in between or above. A recent development is that of isotropic steels, which are characterized by very small microalloying additions and relatively low yield strength levels. These steels gain their improved formability from the isotropic strain hardening behavior.

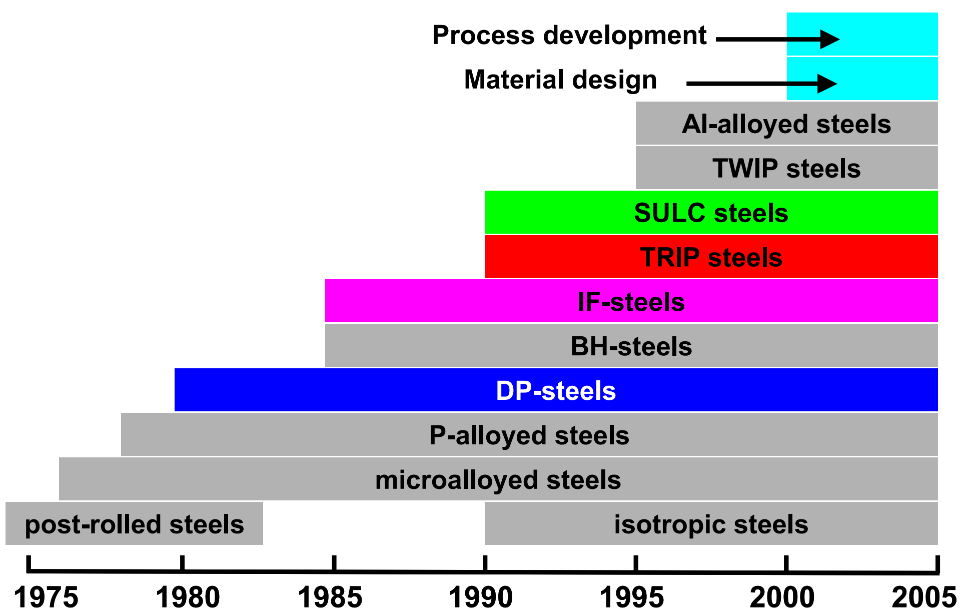

Figure 1. Chronological development of steel grades for car bodies [2].

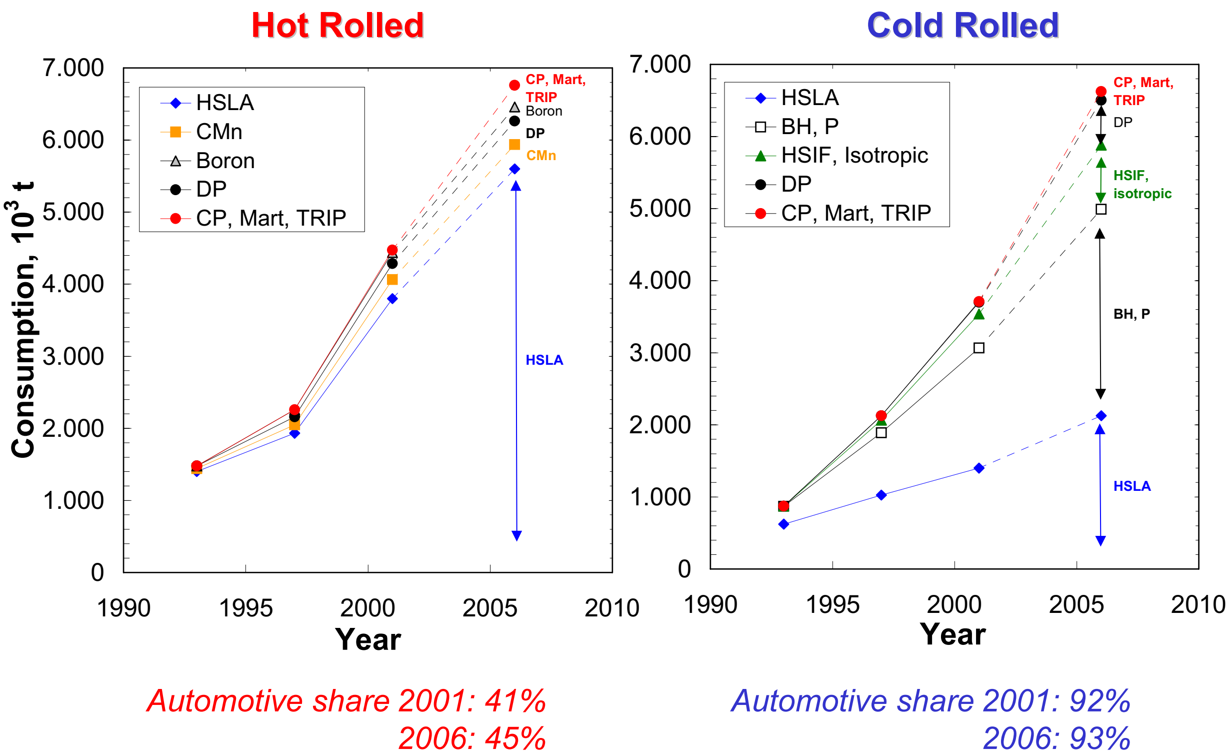

Figure 2. Consumption of HSLA steels in the European automotive industry.

Table II. Mechanical properties of several microalloyed steels [1,4].

Grade	Number	YS	TS	TE
-	-	MPa	MPa	min, %
Hot rolled high yield strength steel for cold forming				
S340MC	1.0974	> 340	420-540	25
S500MC	1.0984	> 500	550-700	14
S600MC	1.8969	> 600	650-820	13
S700MC	1.8974	> 700	750-950	12
Cold rolled higher yield strength for cold forming				
H260LAD	1.0929	260-330	350-430	26
H300LAD	1.0932	300-380	380-480	23
H340LAD	1.0933	340-420	410-510	21
H380LAD	1.0934	380-480	440-560	19
H420LAD	1.0935	420-520	470-590	17

Strengthening Mechanisms

The transition elements of the groups IV, V and VI are often utilized in small additions in order to obtain the desired processing behavior and the desired properties. Among these the elements titanium, vanadium and niobium have proven to be very effective in spite of the usual lean alloying in the order of just 0.01 to approximately 0.1 mass-%. This is mainly a consequence of their ability to form a series of compounds of oxides, sulfides, carbides, and nitrides, which affect many physical phenomena in steels. To a smaller amount also a solute drag effect on grain or phase boundary mobility is observed, The requirements of formability and weldability demand a low level of non-metallic inclusions, thus the relative coarse oxides and sulfides have to be avoided. Consequently low oxygen and sulfur levels are a prerequisite for HSLA steels like for most of all modern steels. Desoxidation with Al is the standard practice for the removal of oxides from molten steel while low sulfur levels are obtained by desulphurization treatments in

secondary steel making operations. Thus it is the carbide, nitride or due to their miscibility the carbonitride formation which governs the specific effects of microalloying elements on the mechanical properties.
Their strong interaction with the microstructure depends on their dissolution and precipitation behavior. For most processing routes it is desirable to completely dissolve the microalloying elements prior to the hot rolling stage in order to enable a controlled precipitation in the recrystallized or non recrystallized austenite, during γ/α phase transformation or in the ferrite. The precipitation temperature has a pronounced influence on the precipitates size and thus on their effects with regard to the final mechanical properties. Figure 3 gives a first indication on the relationship between precipitation temperature and precipitate size as well as on the specific effects on some physical phenomena and subsequently on mechanical properties. The precipitate size is roughly divided into the three categories very coarse with sizes of 100 nm or above, fine with sizes of 10 nm or below and coarse in-between. While fine precipitates increase strength as a consequence of the direct interaction with dislocations resulting in the from many metals well known effects of precipitation strengthening there is an indirect contribution to strength by coarser precipitates due to their grain refinement and the control of transformation processes.

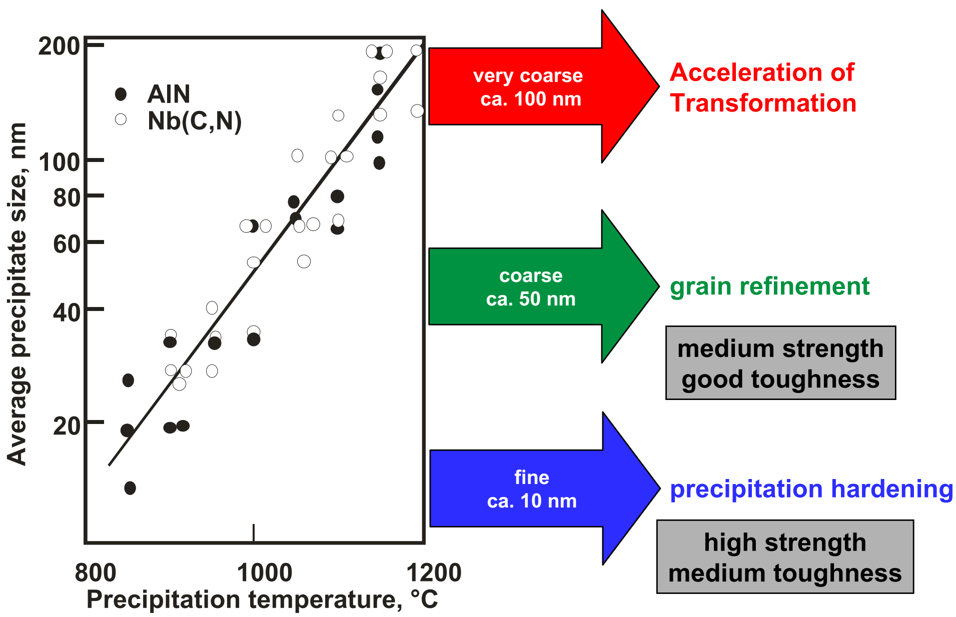

Figure 3. Influence of precipitation temperature on the precipitation size and some resulting effects.

Microalloying elements can be present either in solution or as precipitates. Both forms influence the microstructure formation during hot forming. The influence of precipitation is in this respect more pronounced as for the dissolute microalloying elements. An increase in strength and toughness is attained by grain refinement and precipitation hardening. Of those only grain refinement increases strength and toughness by the same time. The underlying mechanisms are the obstruction of grain growth in the austenite, the delaying of recrystallization during hot forming, the change of the recrystallization kinetics and the formation of precipitates. These different contributions to strength have been investigated by hot rolling experiments of Nb microalloyed steel by changing the cooling rate after hot deformation between 3 and 100 K/s and by applying coiling temperatures between room temperature and 700 °C. Figure 4 gives the strength increase as a function of cooling rate and coiling temperature; the individual strength distribution by dislocation and precipitation hardening are indicated. There is also a microstructural contribution as with increasing cooling rate the ferrite and pearlite microstructure changes to bainite [5].

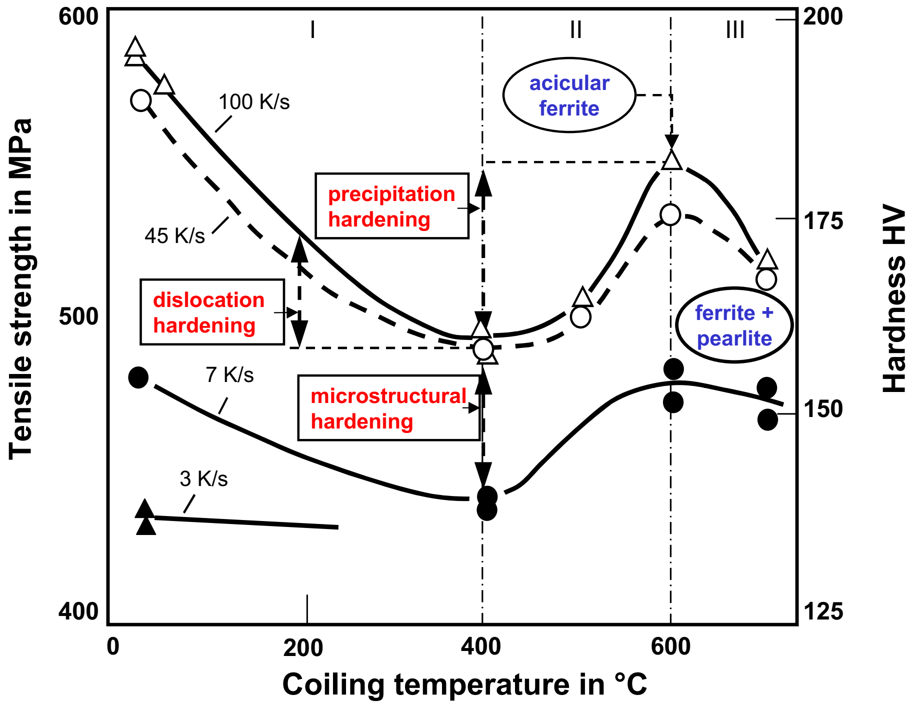

Figure 4. Strength increase as a function of cooling rate and coiling temperature of hot rolled strip.

Precipitation hardening is most effective if small precipitates are obtained. At a high cooling rate a large amount of niobium is in solid solution and is available for precipitation in the ferrite. Thus a maximum strength at a coiling temperature of 600 °C is achieved. The observed precipitates are considered to be coherent or semi-coherent which can be subsumed in terms of the predominant mechanism of precipitation hardening. Accelerated cooling to coiling temperatures of 650 to 680 °C suppresses the interphase and ferrite precipitation and a lower percentage of niobium is found as being precipitated. A cooling to lower coiling temperatures leads to a not completely recrystallized structure with a high dislocation density and increased strength.

A more reduced cooling rate of 7 K/s shows a precipitation on the deformation induced austenitic dislocation substructure. Carbonitride precipitation in austenite can be identified. The interphase precipitation is reduced and the ferrite precipitation is completely suppressed. The advantages of the controlled precipitation, which is observed at accelerated cooling rates, cannot be realized any longer. The microstructural hardening is reduced and a significantly lower strength level is obtained [6].

Accordingly, several examples of the effect of microalloying elements and their application to attain optimized mechanical properties are described both in hot and in cold strip processing.

Hot Strip Processing

The multitude of effects during hot strip processing, which is dependent on the form of the microalloying element either in solution or as precipitate is summarized in Figure 5. The approximate precipitate size and the final microstructure at room temperature is indicated as well. The most important mechanisms, which are addressed during hot forming, are on the one hand to retard grain growth and recrystallization and on the other hand to control transformation by the presence of the microalloying elements either in solid solution or as precipitate. The combination of these mechanisms is named austenite conditioning with controlled rolling, normalizing rolling or thermomechanical rolling being specific forms of it.

When austenite is deformed at a temperature where it is supersaturated with respect to the microalloying element a temperature will be reached where strain-induced precipitation will form thereby preventing the nucleation of recrystallization. The influence of the microalloying elements on the recrystallization can be clarified by analyzing the temperature, which must be exceeded to allow recrystallization after a certain hot processing step. Figure 6 shows the influence of niobium, titanium, and vanadium. In the area above the different curves recrystallization takes place whereas underneath the curve the recrystallization is suppressed. Obviously, niobium leads to a pronounced rise of the threshold temperature necessary for recrystallization, while titanium shows a comparable effect when added in larger amounts. Vanadium only causes a little increase of the threshold temperature of the deformed austenite.

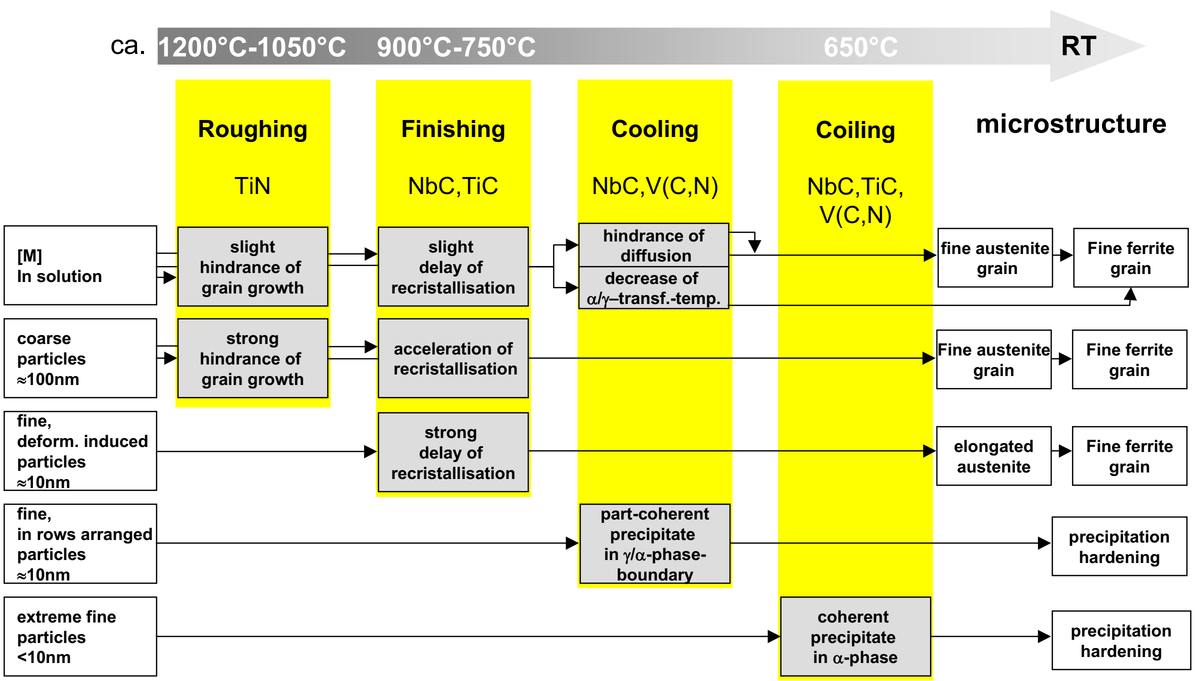

Figure 5. Effects of microalloying elements during hot strip processing.

The benefit of microalloying for austenite conditioning comes from the fact that processing in the finishing train of a hot strip mill can be controlled by accumulating strain without recovery or recrystallization. Thus a high density of lattice defects is developed during austenite rolling which can result in a small recrystallized austenite grain size prior to γ/α – transformation or in the transformation start from a deformed austenite structure. The effect on recrystallization is dependent on the form the microalloying element is present in the microstructure. In Figure 7 the influence of dissolved niobium is compared to the effect of niobium carbide precipitates with regard to the interpass time between the stand of the finishing train. The recrystallized fraction is given as a function of this interpass time indicating the strong effect of niobium in solid solution and the somewhat smaller effect of niobium precipitated. While steel without niobium additions is fully recrystallized after 10 seconds, dissolved niobium delays the recrystallization markedly. A further delay is obtained if niobium is precipitated as carbide [7].

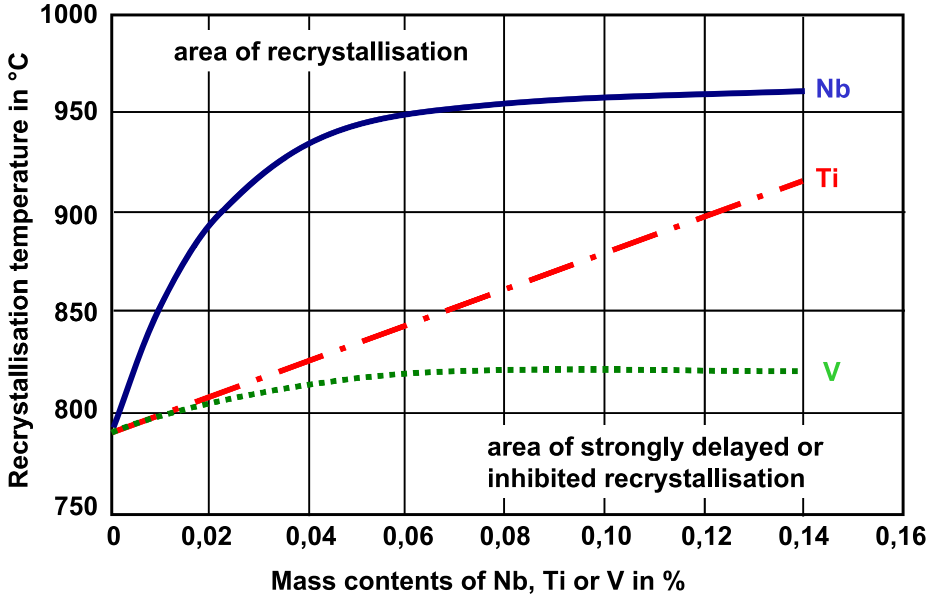

Figure 6. Influence of Nb, Ti and V on the threshold temperature of austenite recrystallization.

The important role of the cooling rate after finish rolling and the coiling temperature has already been described in the previous chapter. Recently, cooling in hot strip mills have adopted ultra fast cooling devices, which offer cooling rates 5 to 10-times more than in conventional laminar cooling lines. This new technology can be utilized for improving microstructure refinement and for most efficient usage of microalloying additions. Furthermore, it needs to be mentioned that the principles of austenite conditioning by microalloying are also applicable for the hot strip processing on compact strip mills with inline casting and rolling. The rolling temperatures, the entry bar thickness, and the microalloying addition have to be adopted to the plant layout.

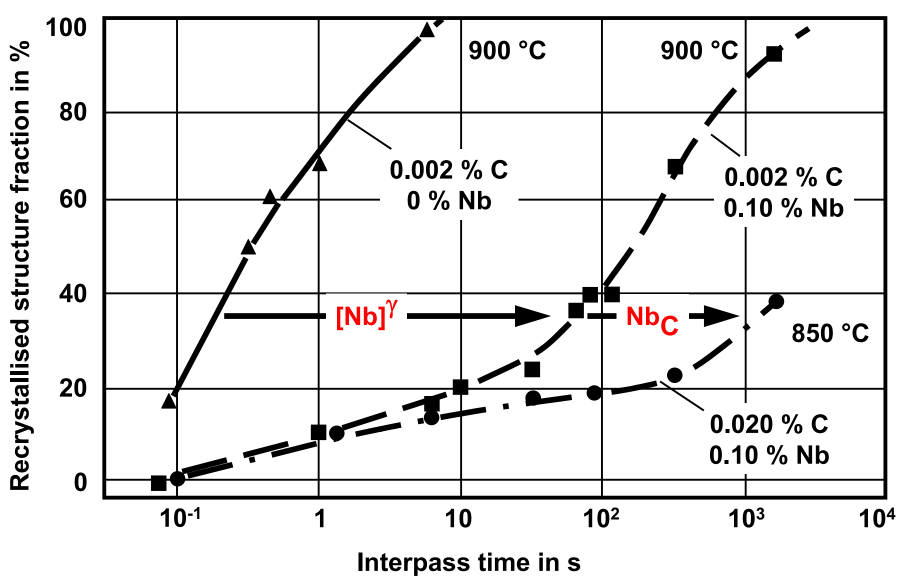

Figure 7. Effects of soluble and precipitated niobium on austenite recrystallization (rolling temperatures are indicated).

When thin gauges and excellent surface quality are required – e.g. for exposed panel application in the automotive industry - cold rolled strip is needed. The further process steps after hot rolling include continuous descaling, cold rolling, recrystallization annealing, sometimes coating, and skin passing. Beside the somewhat higher rolling forces the recrystallization behavior of HSLA steels differs significantly from conventional mild steels. With respect to the mechanical properties and the formability annealing is the crucial production step. The annealing can be carried out either by batch annealing which comprises long annealing times of several hours at moderate temperatures up to 700°C or by continuous annealing in continuous annealing lines with inline overaging treatment or in hot dip galvanizing lines.

Figure 8 compares the recrystallization response during batch annealing of a mild steel DDQ and two microalloyed steels with a low level of alloy addition in grade HSLA(Nb) and a higher degree of alloying in HSLA(Ti+Nb) [7]. The resulting yield strengths between 200 and 800 MPa are given as a function of steel chemistry and annealing temperature. The HSLA steels require significant longer annealing times and/or higher annealing temperatures to be fully recrystallized. An alloying with Nb leads to a delay of factor 10 and even of more than 100 when adding titanium and niobium.

When applying relative low temperatures the as rolled microstructure will only recover; by this high strength values with a moderate formability can be obtained. But, these properties in the as recovery annealed condition seem to be difficult to control during batch annealing, which limits this type of annealing process to less demanding applications. For automotive applications a fully recrystallized microstructure is necessary in order to develop mechanical properties for cold forming with a low scatter and high reproducibility. It needs to be mentioned that the higher manganese contents in most HSLA steels also require a close control of the protective gas atmosphere and especially the dew point in order to prevent surface defects by scale formation.

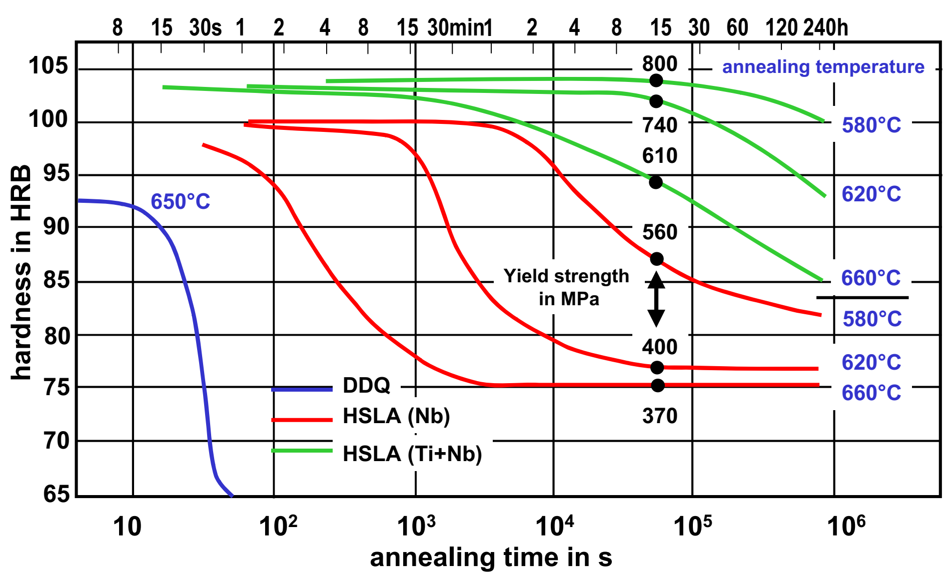

Figure 8. Effects of microalloying elements on hardness development during batch-type recrystallization annealing.

The retarded recrystallization in microalloyed steels also requires high annealing temperatures during continuous annealing. As typically higher annealing temperatures are applicable in this process compared to batch annealing a complete recrystallization can be obtained in a process window which in limited by the recrystallization temperature and the precipitation coarsening temperature. Both temperatures are strongly affected by many process variables and by the balance of alloying elements. Thus Figure 9 only provides a specific view of the process window for a microalloyed grade in a hot dip galvanizing line, indicating that with raising niobium content increasing annealing temperatures are required but when surpassing approximately 800°C the precipitation hardening effect can no longer be utilized. In view of the industrial processing too high annealing temperatures are not aspired [9]. Thus, the recrystallization behavior needs to be controlled by the amount of microalloying addition but also by the hot strip processing and the precipitation state, which is available prior to cold processing.

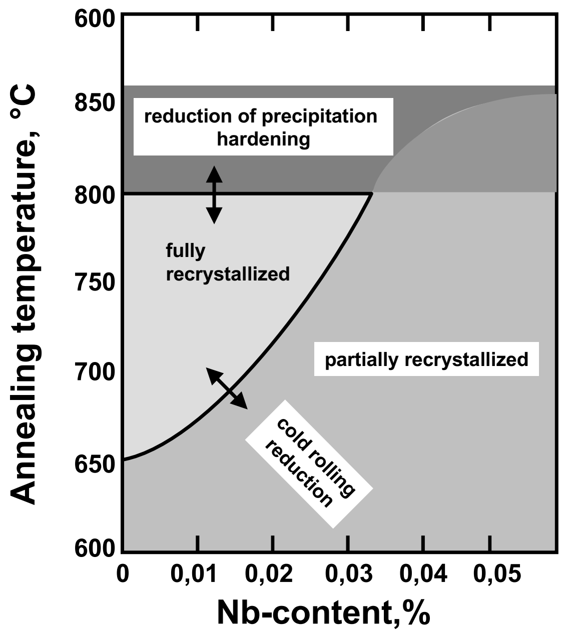

Figure 9. Annealing limits for HSLA steels in a hot-dip galvanizing line.

Figure 10 gives an overview about the possibilities to adjust the cold strip strength by means of hot strip processing followed by cold rolling and annealing. The possible cold strip yield strength is plotted against the yield strength of the previous hot strip.

Depending on the strengthening mechanisms a variety of cold rolled strips can be produced by an adjusted hot strip processing. The cold rolled batch annealed steels are usually restricted to a maximum strength level of about 500 MPa yield strength. A much higher yield strength level can be reached by recovery annealing. Nevertheless this process bears the disadvantage of relatively inhomogeneous properties over the strip length and a poor reproducibility.

Beside these effects on the recrystallization kinetics the grain size of the cold rolled strip after recrystallization annealing is strongly affected by microalloying. As shown in Figure 11 the addition of microalloying elements leads to a cumulative grain size distribution which is characterized by a small average grain size and by a very small standard deviations of the log normal statistical distribution. While the conventional Al-killed steel (Ak) shows a large scatter in grain size combined with a large medium grain size, small additions of titanium of approximately 0.01 mass-% shift the distribution to smaller mean grain sizes. With higher microalloying addition in the interstitial free steel (IF) or even more pronounced in the HSLA steel a more homogeneous grain distribution is obtained. For the niobium alloyed HSLA steel a very small grain size of ASTM 10 or even finer can be obtained after batch or continuous annealing [9]. Recent results on ultra fast annealing cycles in combination with a partly of full γ/α – transformation indicated that even grain sizes of ASTM 14 are achievable. This new process of rapid transformation annealing is described elsewhere in detail.

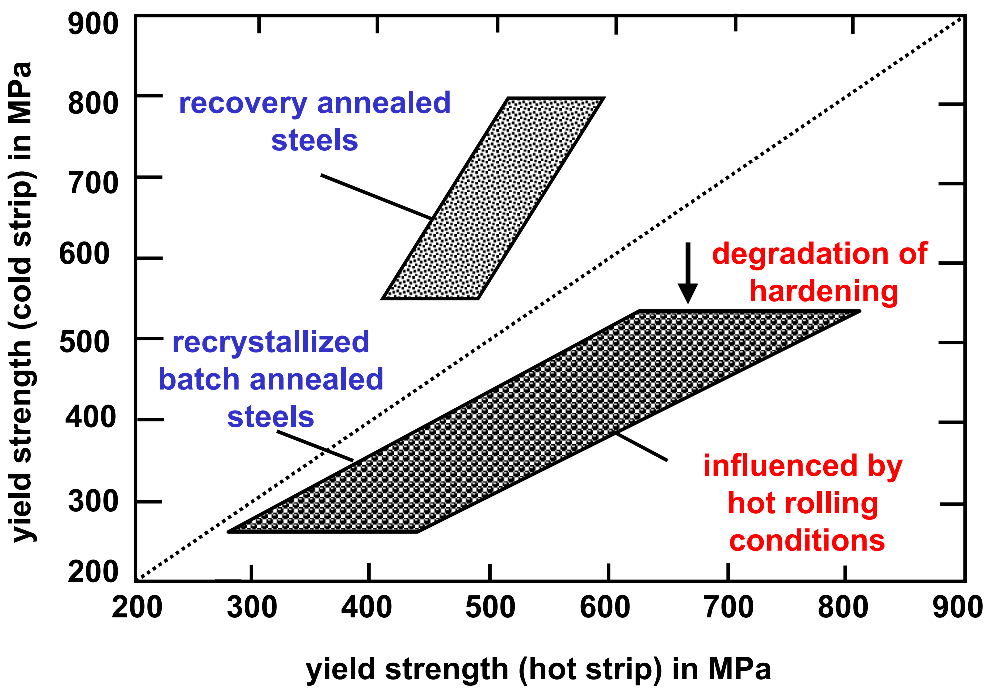

Figure 10. Relationship of hot strip and cold strip yield strength.

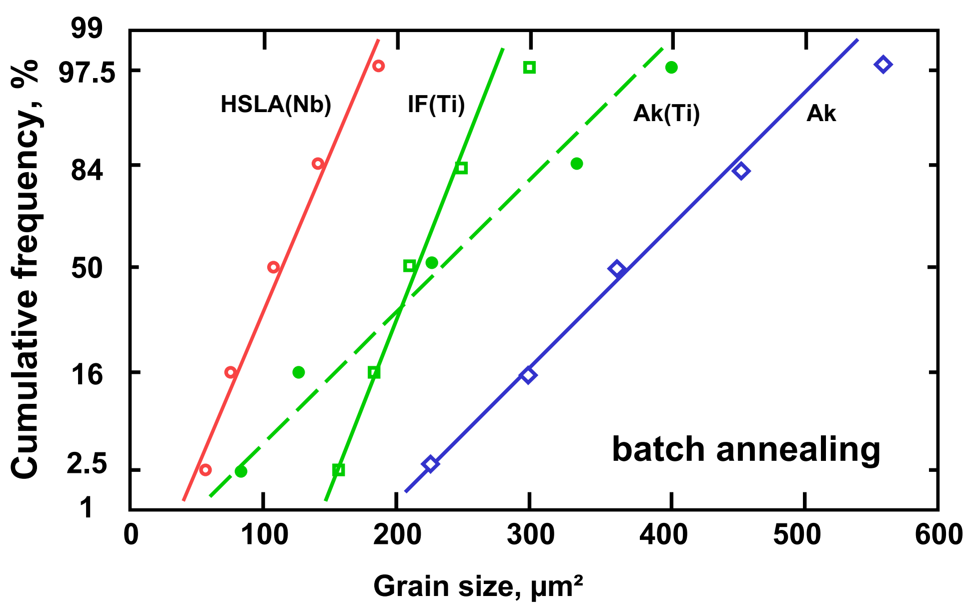

Figure 11. Grain size distributions of different cold-rolled steels after batch annealing.

The grain size of the final cold rolled strip depends on the grain size of the hot rolled strip as demonstrated by Figure 12. In general, the smaller the hot strip grain size the smaller is the cold strip grain size with the cold strip grain size being significantly larger. The mild deep drawing grade DDQ shows hot strip grain sizes of 15 to 20 µm when coiled at high coiling temperatures resulting in a globular microstructure of 15 to 30 µm after cold rolling and batch annealing.

When low coiling temperatures are applied the same steel grade develops the so-called pancake microstructure with significant grain size differences depending on the measuring direction. Compared to the DDQ-grades the HSLA steels show a smaller grain size for the hot strip, which is below 12 µm, and the cold strip, which is mostly below 15 µm corresponding to less than ASTM 9.

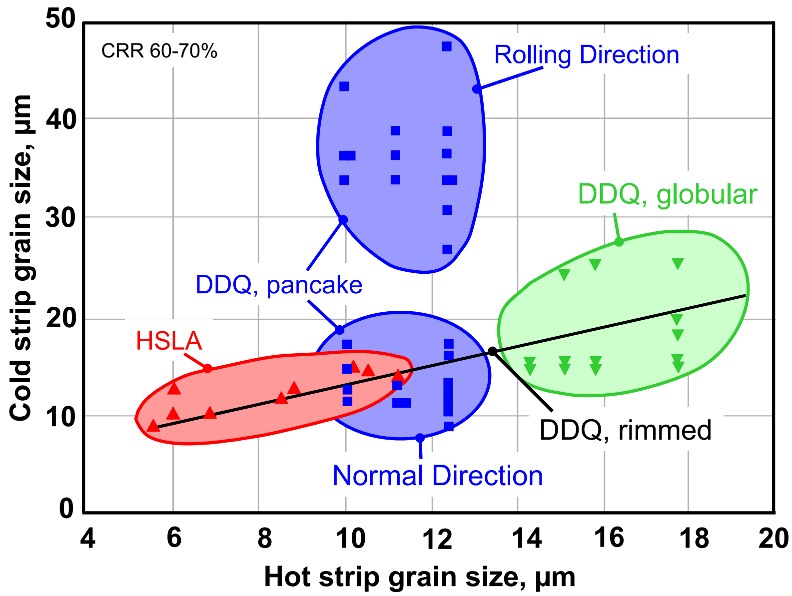

Figure 12. Relationship of hot strip and cold strip grain sizes for batch annealed steels.

Process Parameters

As described exemplarily for several stages in hot and cold strip processing the addition of microalloying elements has an influence on several metallurgical phenomena such as affecting the transformation from austenite to ferrite, recrystallization kinetics, grain size development, and precipitation behavior. To attain optimum steel properties these phenomena have to be adjusted carefully by the process parameters for the different stages in strip processing. To show the complexity of the interaction between process parameters and the resulting metallurgical processes, Figure 13 points out the most important characteristics for the different strip processing stages. The different microstructural processes such as transformation, grain growth, precipitation, and recrystallization are of significant importance throughout the entire process. As for example an undesirable grain growth cannot be inhibited by adjusted casting or hot rolling parameters only but needs to be controlled in all process steps including cold rolling and annealing.

Product Forms

In general, various process routes for HSLA steels are either already in use or are subject to discussion depending on the final product. Figure 14 summarizes the different routes and demonstrates that hot rolled, cold rolled, and galvanized products can be produced. Besides the classical slab casting followed by the rolling in a hot strip mill thin slab casting and rolling on a compact strip mill has become an important alternative route. New developments promote the production in strip casting partly with inline hot rolling; here different process types are under discussion.
In spite of these varying process routes and the customer requirements for hot or cold rolled grades, for uncoated or several coated products HSLA show the flexibility to be processed on

various routes and are offered in a large product diversity, Table III [10,11]. The high flexibility of the process route as well as the attractive mechanical properties are the reason for the success of the HSLA steel concept.

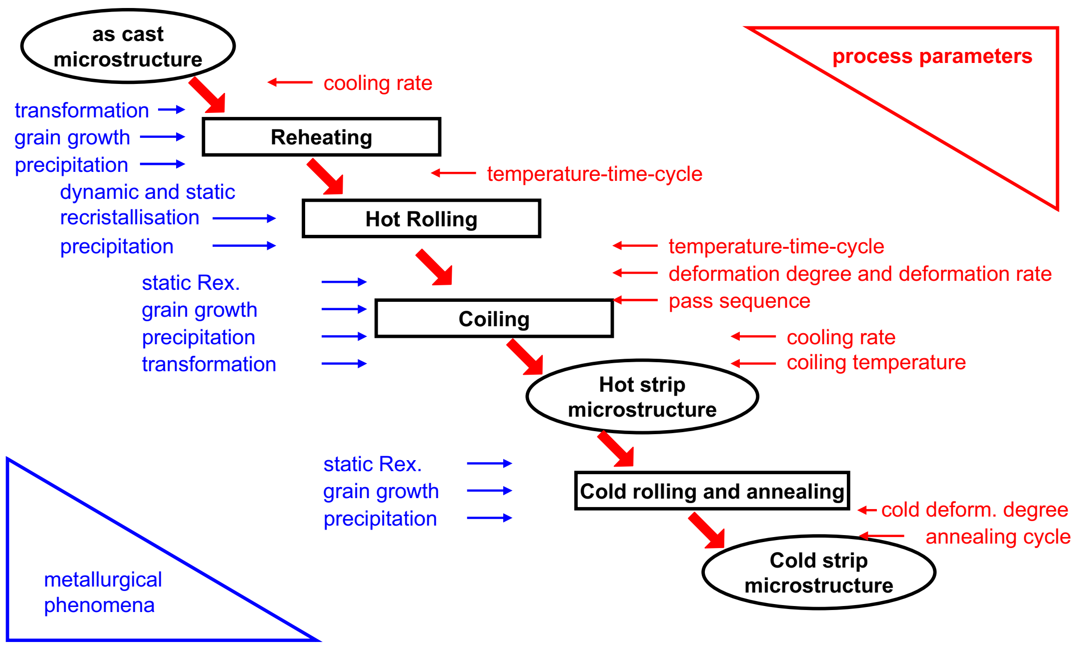

Figure 13. Metallurgical phenomena and process parameters during cold strip processing.

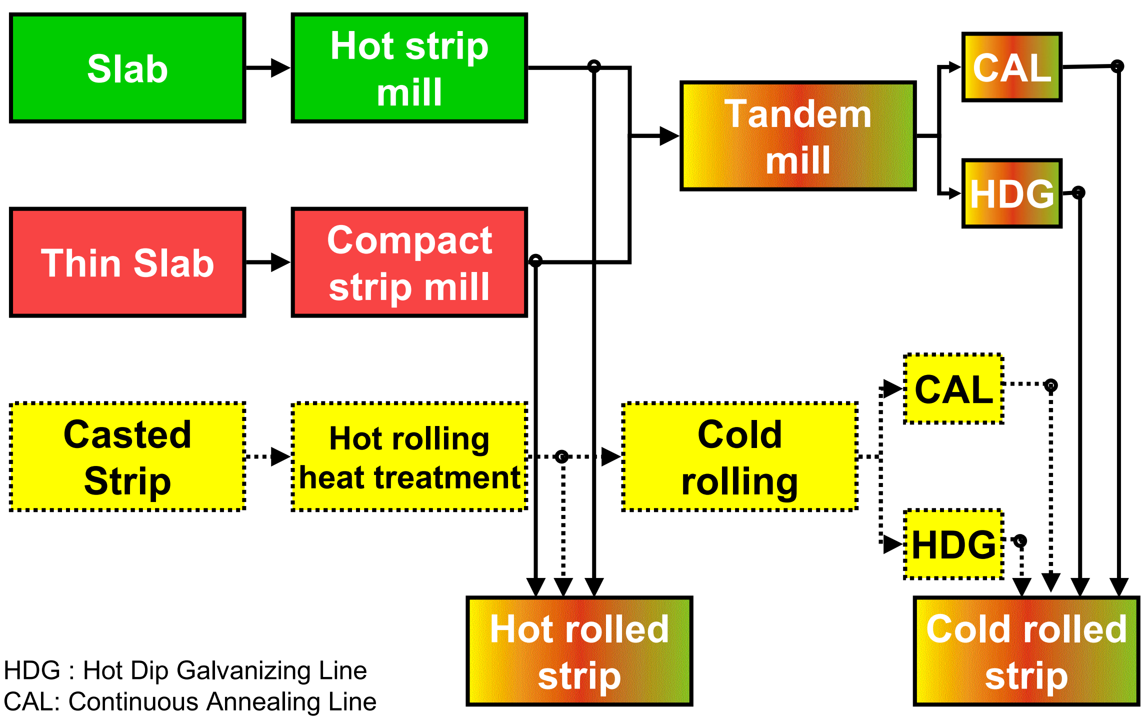

Figure 14. Process routes for hot and cold rolled steels.

Table III. Product forms of different steels in commercial production or customer trials.

	Hot rolled			Cold rolled		
	uncoated	Electro-galvanised	Hot dip galvanised	uncoated	Electro-galvanised	Hot dip galvanisied
BH				√	√	√
IF-HS				√	√	√
P				√	√	√
IS				√	√	√
HSLA	√	√	√	√	√	√
DP	√			√	√	√
TRIP	√	√		√	√	√
CP/PM	√			√		

√ : available

Conclusions

- Microalloying is a well-developed method to increase strength and simultaneously maintaining good formability.
- HSLA steels are used widely for automotive applications due to their attractive properties balance.
- HSLA steels have been developed for many different product forms and process routes.
- HSLA steels are „easy-to-handle“ materials both from the processing and from the application point of view.

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