COLD ROLLED HSLA SHEET AND STRIP PRODUCTS

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Abstract

Higher strength microalloyed steel grades were the key fulfilling ultra-light weight design requirements. During the 80's the volume fraction of such steel grades had already reached 20 % of the total weight of the body in white. In cold rolled steels the strength is increased essentially by grain refinement and by precipitation hardening. Also microalloyed steels can exhibit a higher strength in the cold formed and painted condition. This yield strength gain derives from work-hardening plus a contribution from bake hardening. It is also found that the fatigue strength of microalloyed steels increases with the static strength even in the notched state. Successful efforts have been made to reduce the scatter in properties for microalloyed higher strength steel grades. Special emphasis was placed on the development of isotropic steel grades. The continuous annealing process results in an additional benefit of a reduced scatter in mechanical properties and shows higher strength values for the same chemical composition. An early Porsche test vehicle and the Ultra Light Steel Auto Body (ULSAB) vehicle chiefly made of microalloyed higher strength steel showed favourable behaviour. The original Porsche test results were confirmed in the later ULSAB study. Microalloying will continue to be an important aspect of materials design in the future. Any further grain refinement would promote plastic instability. However ultra fine plus multi-phase structure would be an ideal approach to overcome this problem. Microalloying, especially with niobium, will retain a dominant role in the achievement of the desired structures and the resulting properties of future materials.

Introduction

In the course of time the steel industry has developed a number of steel grades in order to meet increasingly demanding customer requirements (Figure 1).

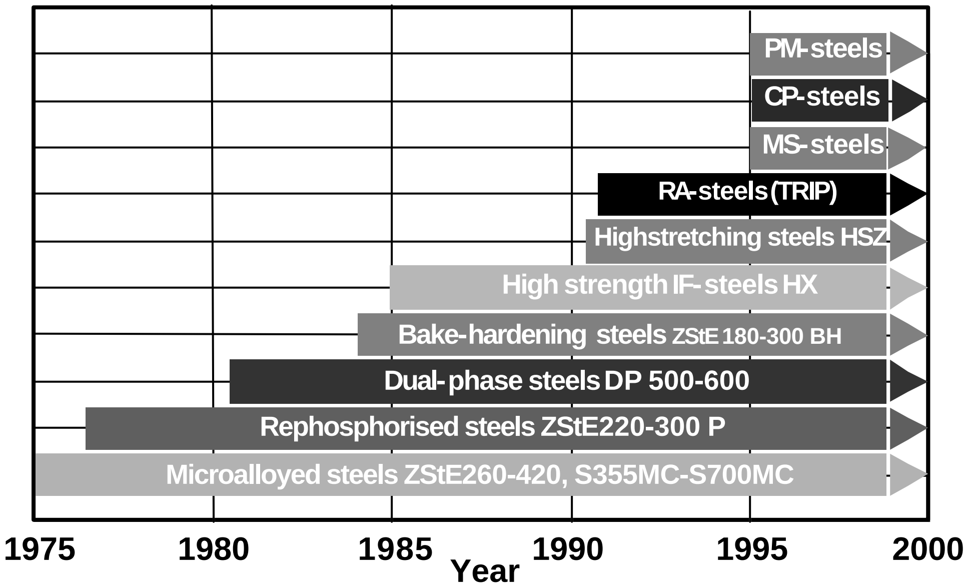


Figure 1: History of the development of high strength steels. PM – partially martensitic; CP – complex phase; MS – martensitic; RA – residual austenite TRIP – Transformation induced plasticity; IF – interstitial-free.

The development of higher strength steel grades has acquired great significance for fulfilling ultra-light design requirements. Higher strength microalloyed steel grades were the beginning of this development. At first hot rolled steel grades were developed reaching their optimum potential in the mid-seventies. A few years later cold rolled conventional microalloyed higher strength steel grades were conceived in a logical further development of the materials. Following this new steel groups emerged, such as hot rolled dual-phase steels as well as the bake-hardening and higher strength IF steels. The nineties were marked by the development and introduction of higher strength stretch-forming grades with isotropic properties and the further development of multi-phase steels with residual-austenite or TRIP grades, cold rolled dual-phase steels and hot rolled higher strength complex-phase and martensite-phase steels. The application of microalloying played a more or less important role in all these further developments.

Soon after their market introduction in Germany the cold rolled steels were defined by a set of standards, and in the meantime European standards were also established (Figure 2).

Especially for car body structural parts microalloyed HSLA sheet has been established in Europe for many years and the volume fraction has reached 20 % of the total weight of the body in white. Figure 3 shows the application of the most prominent HSLA steel ZStE 340, which is characterised by a minimum yield strength of 340 MPa, in a 1985 model. As a result of the Ultra Light Steel Auto Body (ULSAB) project a further growth in the usage of HSLA steels in the automotive industry has been observed, especially in newly designed models, and a continuation of this trend can be expected in the near future. In the ULSAB car a 25 % weight reduction over a conventional design has been achieved by using, among other high strength steel sheets, predominantly niobium-microalloyed steel with a minimum yield strength of 350 MPa strip steels of this strength amounted to more than 50 % of the total car body weight.

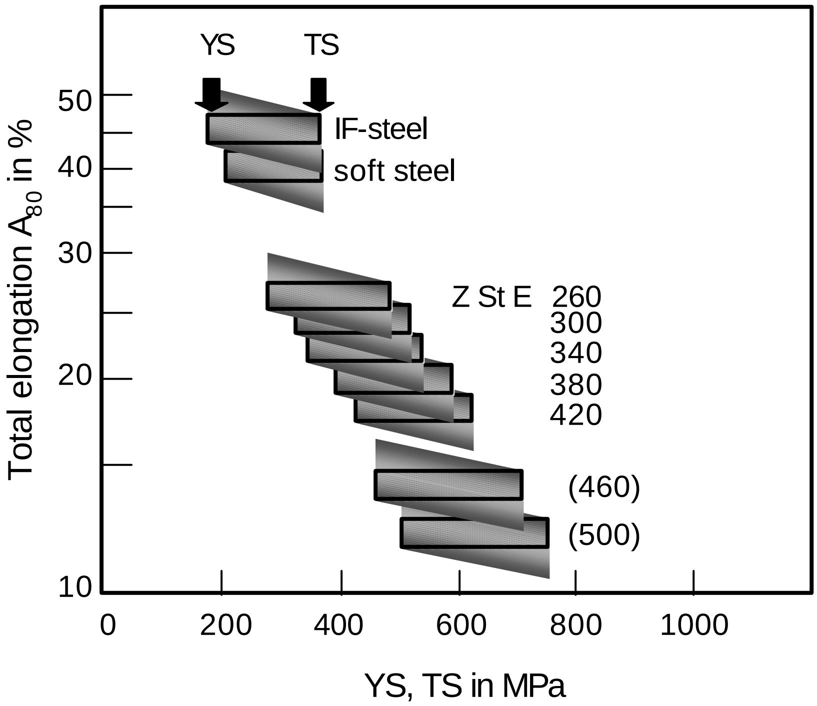


Figure 2: Mechanical properties of cold rolled microalloyed sheet steels.

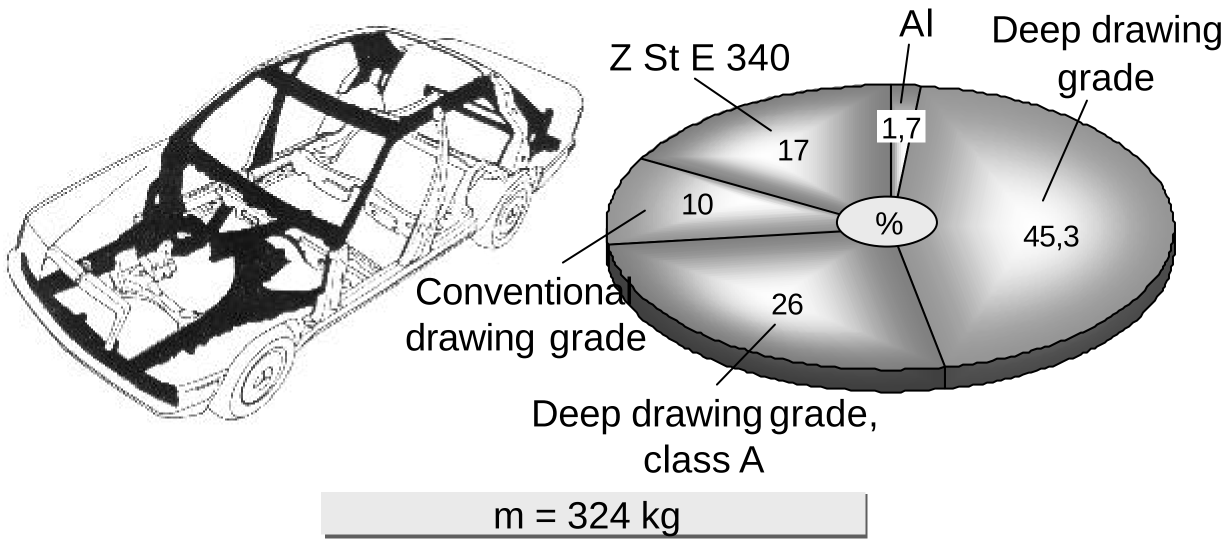


Figure 3: Materials in the body in white of the Mercedes model W 124 (1).

Principles

Several possibilities are available to the metallurgist for increasing the strength of steel. Figure 4 shows how the various strengthening mechanisms affect the tensile test values, in particular the yield strength. For hardening cold rolled sheet steel, precipitation is exploited which also produces strengthening by grain refinement. A dual-phase microstructure with a certain fraction of martensite in the ferrite gives a particularly advantageous strengthening behaviour particularly with slight cold deformation.

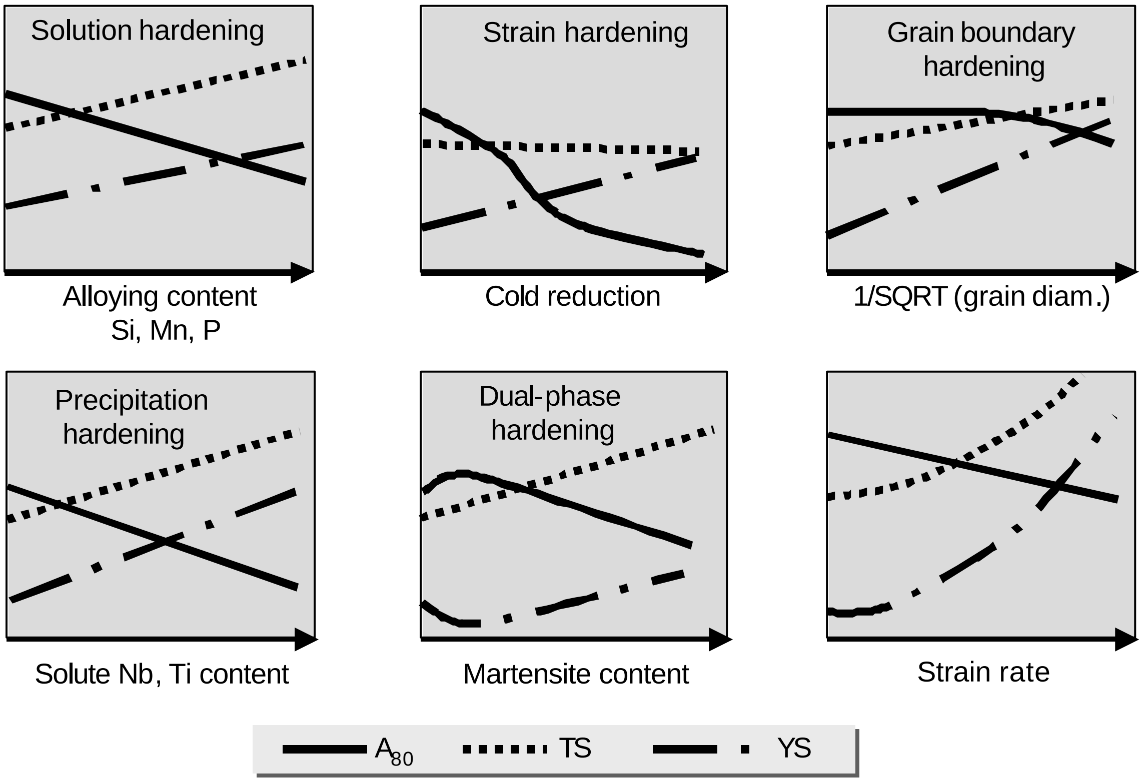


Figure 4: Comparison of the different hardening mechanisms with respect to yield strength, tensile strength and elongation (2).

The physical and chemical properties of the elements manifest strict periodicity. The atomic volumes and atomic radii closely related thereto have a profound effect on the properties of the elements (Figure 5).

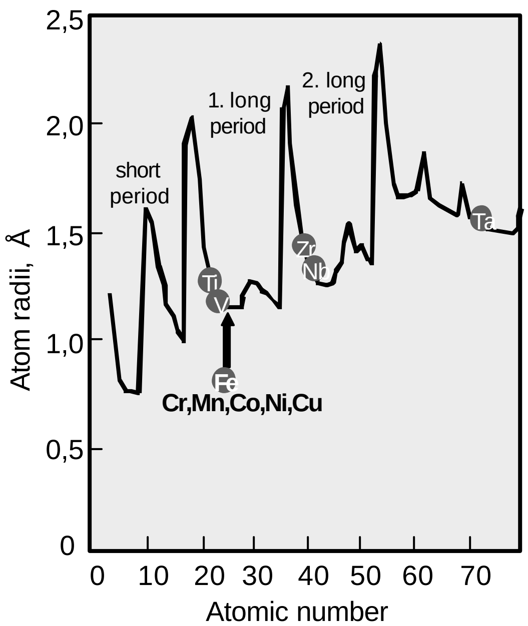


Figure 5: Periodicity of the element properties, Atom radii depending on atomic number.

For example, if the radii are plotted against the atomic number (3), similar positions in the respective periods result in similar properties. The elements chromium, manganese, cobalt, nickel, copper lie in the minimum group close to iron. They have relatively large solubilities in iron and are important alloying elements in steels.

For the transition elements titanium, vanadium, zirconium, niobium and tantalum the positions are found to lie close to the left of the minima; consequently their effects are similar.

In steel making the transition elements are often utilised as microalloying elements in order to obtain the specifically desired steel properties. Transition metals are known to form a series of simple and solid solution compounds of oxides, sulphides, carbides and nitrides. The compound-forming tendencies of several of the transition metals in steel have been summarised (Figure 6).

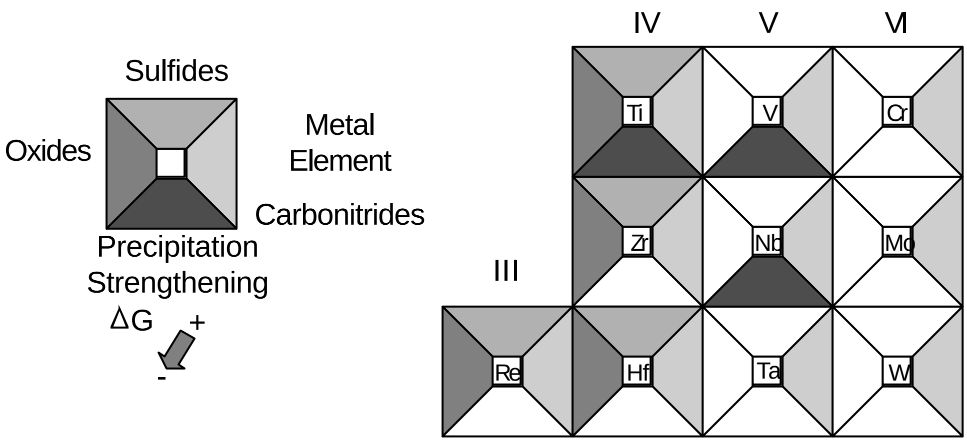
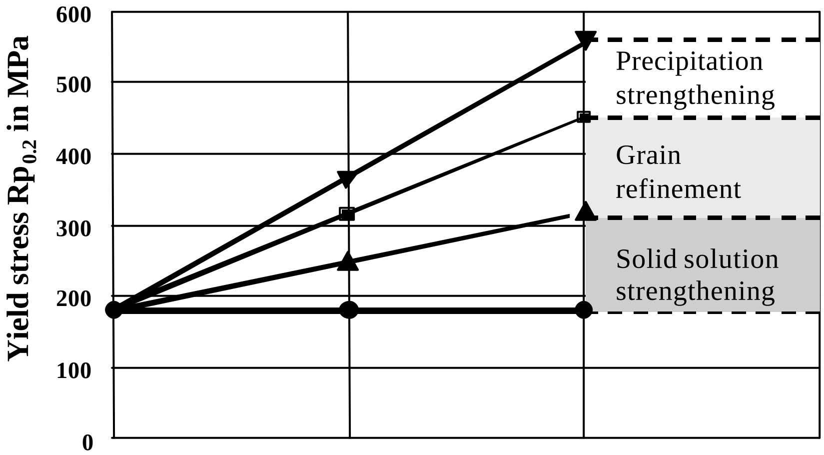


Figure 6: The tendency of certain metals to form oxides, sulphides, carbides, and nitrides and their precipitation-strengthening potential (4).

Niobium shows a strong tendency to form carbonitrides, but relatively little tendency to form oxides, sulphides or solid solutions of these compounds. In this respect it behaves similarly to vanadium. This characteristic distinguishes it from titanium which does not act as a carbide former until all oxygen, nitrogen and sulphur have been consumed by prior additions of titanium.

In cold rolled steels the strength is increased essentially by of grain refinement and, to a smaller extent, of precipitation hardening (5). This is supplemented in most cases by solid-solution strengthening by means of manganese or silicon additions (Figure 7).

The assessment of the contributions of the individual strength-increasing mechanisms for two groups of steels was made using the Hall-Petch relationship for grain size and yield strength commonly assumed values for the solid solution strengthening effects of manganese and silicon. The precipitation-hardening effect of titanium and niobium can be determined for hot rolled strip on the basis of the acid-soluble content of these microalloying elements. In the case of a ferritic-pearlitic structure the yield strength is increased by around 50MPa for every 0,01% of soluble Ti. No comparable assessment is available for cold-rolled strip, but a much smaller increase in the yield strength can be assumed at least for batch annealed steels. This is explainable mainly by the Ostwald ripening of the coherent precipitates.



Alloy concept			
C:	0.040 %	0.060 %	0.060 %
Mn:	0.250 %	0.300 %	0.800 %
Al:	0.045 %	0.045 %	0.045 %
Nb:	-	0.040 %	0.020 %
Ti:	-	-	0.080 %

Figure 7: Alloy concept and strengthening mechanisms in batch annealed high strength cold rolled strip.

Similar to other steels, a finer grain size in HSLA sheet is the only strengthening mechanism, which has no detrimental effect on cold formability (6). Consequently, as in hot strip, HSLA cold rolled strip steels preferably make use of the microalloying element niobium, which acts mainly by grain refinement. Since the strengthening effect of niobium alone is not sufficient to economically guarantee a yield strength higher than 350MPa. (Figure 8), for higher strength steel a combination of niobium plus titanium is often used together with higher additions of solid solution hardening elements.

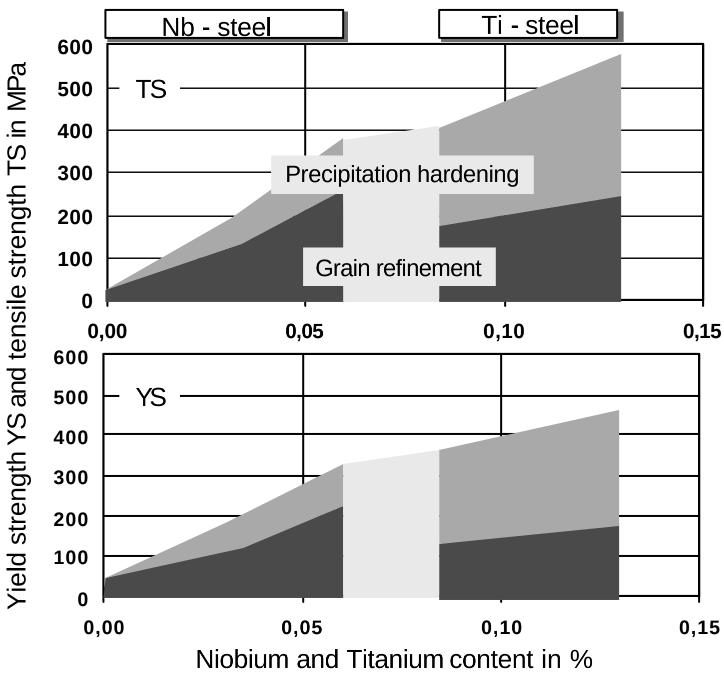


Figure 8: Strengthening mechanisms of niobium and titanium in HSLA.

Processing

Figure 9 schematically depicts the production route from the slab stage to the higher strength cold-rolled strip as well as the chief process parameters of the individual production stages (7).

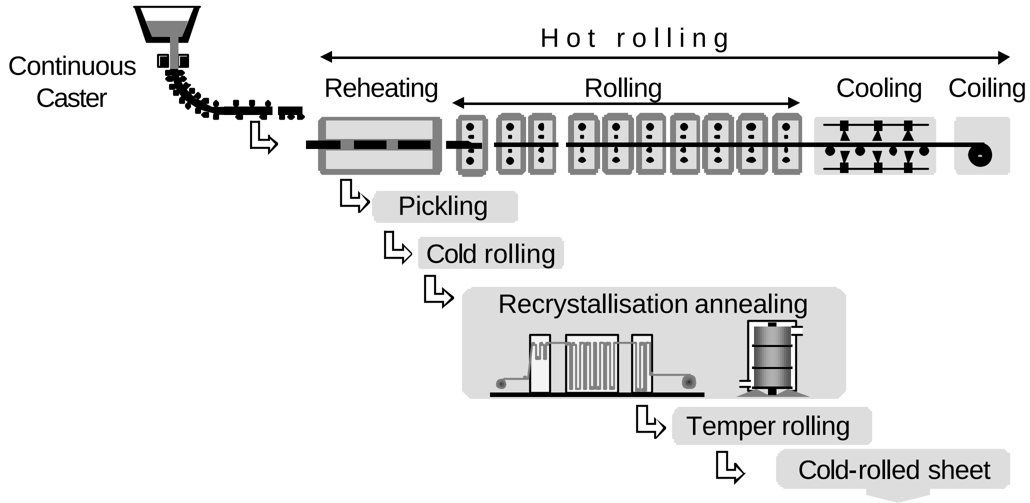


Figure 9: Production route for the manufacture of cold strip.

Batch annealing serves to eliminate work hardening after large cold deformation, thus improving formability of the sheet steel. Depending on the batch allocation and the coil weight, different annealing times are required for batch annealing in order to achieve uniform heating. With the help of a correlation and regression analysis for the effect of the process parameters on the mechanical properties of microalloyed higher strength steel grades, it was found that, in particular, the parameter annealing time in batch annealing has a strong effect on the properties. Therefore differences in annealing time are the chief cause of scatter in the properties of the batches of strip. Consequently three fundamental approaches come into consideration to reduce the scatter in the batch annealed microalloyed higher strength steel grades:

- Control of the annealing time within tight limits,
- shift of the annealing conditions to regions in which variations have little effect, and
- general reduction in the effect of the annealing time.

How does the steel industry support the realisation of the new steel concepts and accompany them by special investments? Firstly, a new thin slab casting process allows the production of hot strip which is, in terms of dimensions, close to the cold rolled product: Strip thicknesses of 1.0 mm and less can be produced with reduced deviations (Figure 10). Secondly, this new technology is best suited to produce the newest steel grades with very high strengths.

Greatly improved cold rolling mills like the new cold rolling mill TAKO of ThyssenKrupp Stahl AG are able to roll down hot strip with very high strength to relatively low gauges, if required (Figure 11).

width: 900 - 1.600 mm
thickness: 0,8 - 6,35 mm
length: 450 m
rolling power: 70 MW

Figure 10: Thin slab caster.

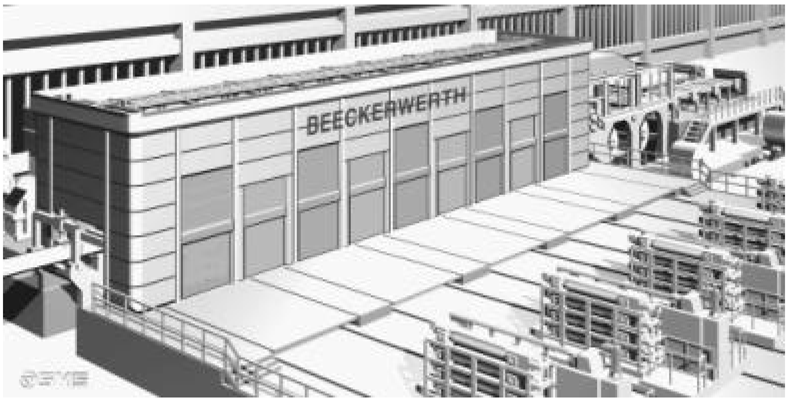


Figure 11: New cold rolling mill TAKO, general view.

A new hot dip galvanising line is capable of processing strips with the first class surfaces which are primarily needed in the automotive industry, and to process improved and newly developed steels with comparatively high strength including niobium-microalloyed steels, which may be galvanized or galvannealed. An increased substitution of cold rolled material by thin hot rolled material can already be recognized at present. With these new facilities the ambitious demands of the market for significantly improved products can readily be fulfilled.

Connection Hot and Cold Rolling

Achieving high strength in cold rolled and annealed steels is more difficult than in hot rolled steels (6). Traditionally, the final annealing treatment has been performed by the box or batch annealing process involving slow heating, long soaking times at the annealing temperature and slow cooling. Such processing reduces strengthening by precipitation hardening, hence the maximum strengths achievable are lower than for hot rolled products (Figure 12).

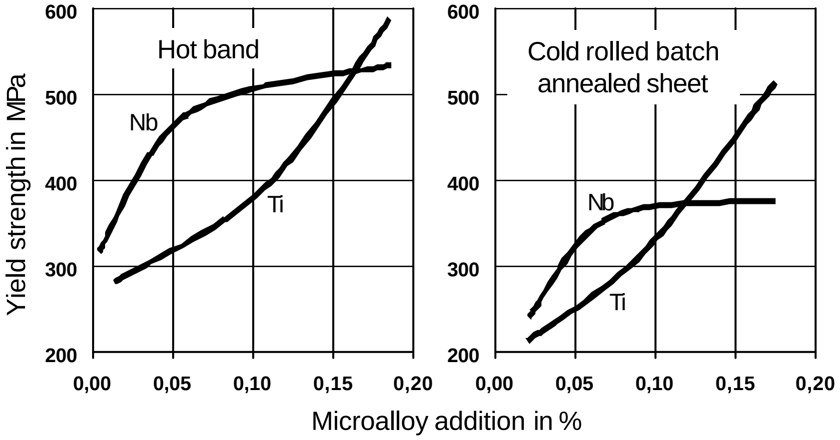


Figure 12: Yield strength increase by microalloying hot and cold rolled mild steel with niobium and titanium.

The role of microalloys in cold rolled sheet is similar to that in hot strip material, by acting via grain refinement and precipitation hardening. However, due to the recrystallisation annealing process, which is necessary after cold rolling, the absolute strength value of the resultant strip is significantly lower than in thermomechanically processed hot strip of the same chemical composition.

The direct relationship between the cold strip and hot strip yield strength is shown in Figure 13.

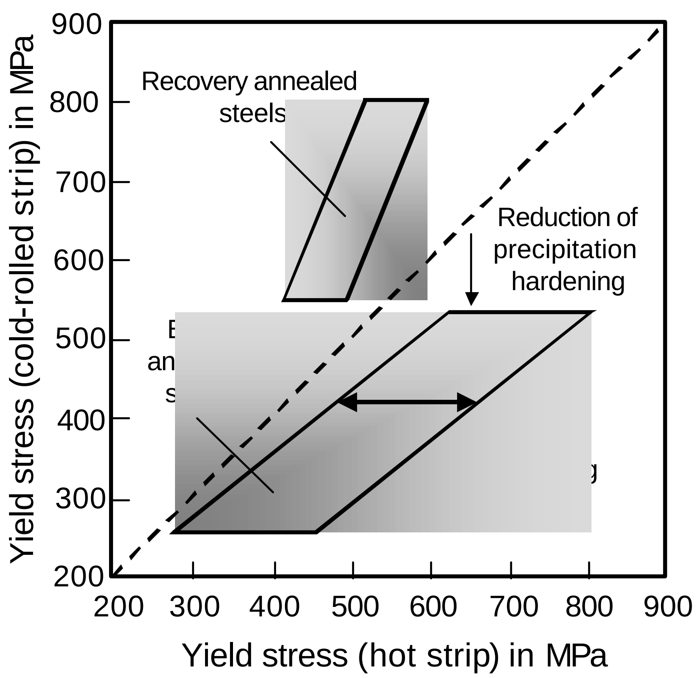


Figure 13: Correlation between the yield stress of hot and cold rolled microalloyed steel (8).

For small hot strip thicknesses with specific temperature control in the hot strip line, yield strengths of up to 800 MPa can be obtained, whereby under certain circumstances it may be possible using a suitable analytical approach to produce several hot strip steel grades. The yield strength is significantly lower after batch annealing. The highest strength grade of batch annealed steels usually has a minimum yield strength of 500 MPa. Higher strengths are achievable in principle, but only in the recovery annealed state. Characteristic features of recovery annealed steels are low cold formability and large scatter of the properties along the strip.

Batch Annealed Steels

In niobium-alloyed steels a significant delay in recrystallisation (Figure 14) is observed especially when atoms are dissolved both in the austenite and in the ferrite (5). A theoretical interpretation of the influence of dissolved atoms on recrystallisation takes account of differences in the electronic structure of the various alloying elements in iron. According to this, an addition of 0.01 % dissolved niobium increases the recrystallisation temperature by around 20 K. This numerical value approximately corresponds to the experimental results up to $Nb_{dissolved}$ contents of around 0.05 %. Contents above this hardly exert any further influence on the recrystallisation temperature. When alloying is over-stoichiometric, the carbon-content is a measure of the amount of precipitation. NbC-precipitation also exerts a strong influence on the recrystallisation temperature. Compared with non-microalloyed steels, the recrystallisation temperature of niobium-microalloyed steels is about 100 K higher.

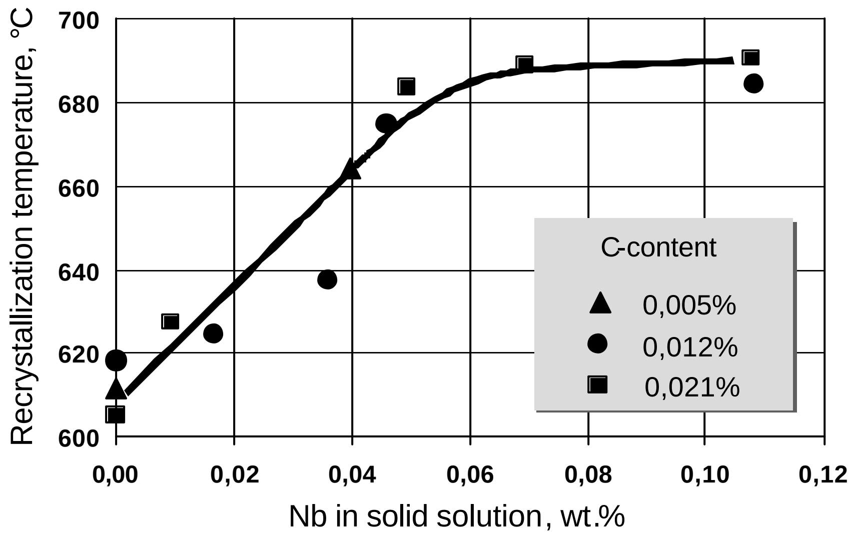


Figure 14: Increase of recrystallization temperature by niobium in solid solution, determined with isochronal anneals, recrystallized = 5%.

Of importance for the cold strip grain size in the case of microalloyed steels is the hot strip grain size (5). This applies in particular to steels with relatively high contents of alloying elements in which the precipitate distribution can be greatly influenced by temperature control in the hot strip mill. Two hot rolled strip coils originating from the same heat and coiled at different coiling temperatures were cold rolled and recrystallisation-annealed at 700°C in a batch-type furnace. In the frequency distribution of individual grain sizes in two cold rolled steels, the influence of the coiling temperature is still evident even after recrystallisation (Figure 15). High coiling temperatures, and the coarse particle dispersion that they cause, result in a coarser mean grain size and an altogether broader grain size distribution.

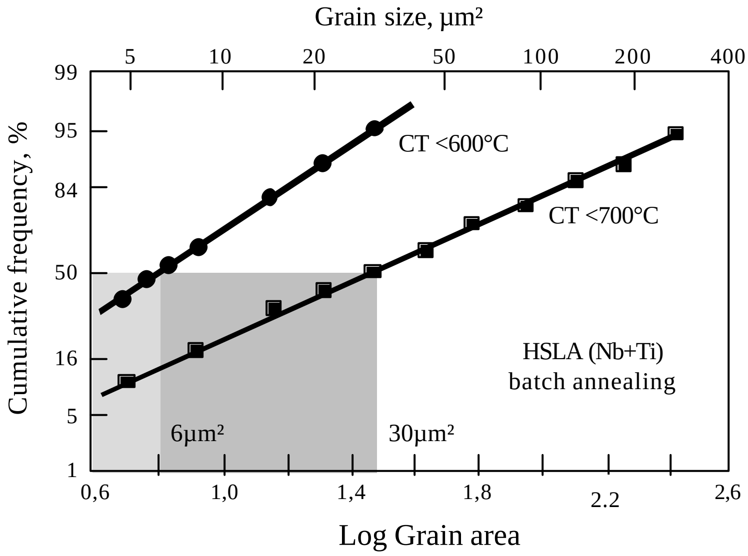


Figure 15: Distribution of individual grain sizes in two cold rolled steels after batch annealing; effect of coiling temperature.

In the course of many years, great efforts were made, through knowledge of the effects of operational production parameters on the mechanical properties, to reduce the scatter of the latter. It is important to know how the scatter in mechanical properties is influenced by the coiling temperature dependent values of the size of the precipitates and of the grains on the one hand and of the grain size distribution on the other hand.

The knowledge of the effect of the annealing time on the microstructure after batch annealing obtained from investigations and accompanying calculations is summarised schematically as shown in Figure 16. The grain size of the strip is largely unaffected by the annealing conditions.

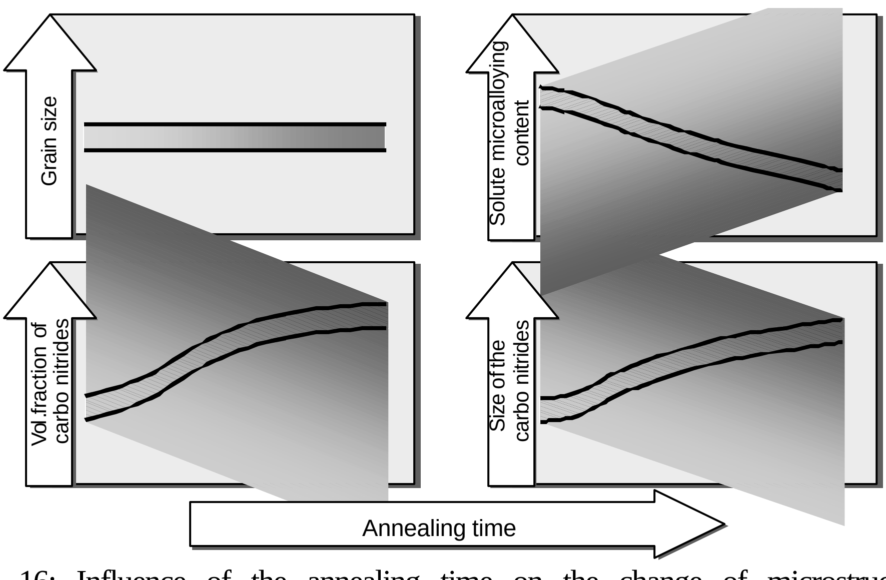


Figure 16: Influence of the annealing time on the change of microstructure in batch annealed microalloyed strip steel (7).

Depending on the annealing time, pronounced precipitation takes place followed by coarsening of the precipitates. The microstructure is completely recrystallised irrespective of the investigated annealing time.

The effect of the annealing time on the mechanical properties and the resulting scatter (Figure 17) become smaller through reduction of the hardening contribution with increasing coiling temperature (7).

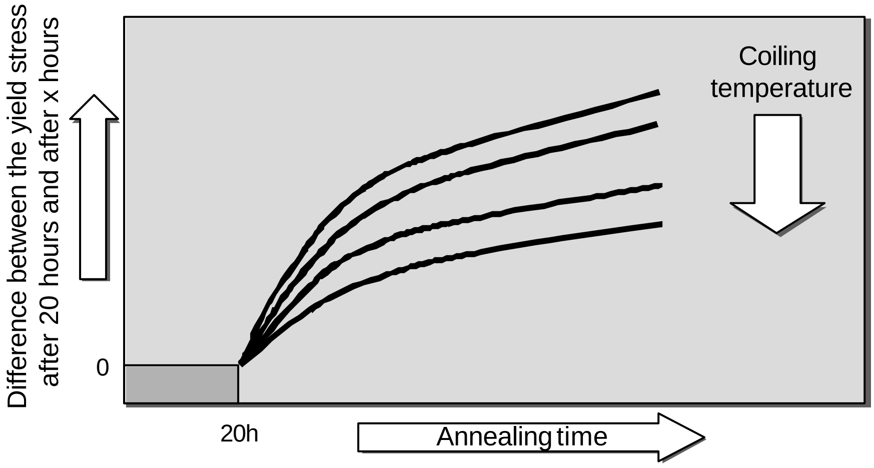


Figure 17: Influence of the coiling temperature and the batch annealing time on the decrease of the yield strength.

In order to verify the ability to reduce the scatter band from coil to coil on the basis of the available knowledge, production trials were carried out with coils of the niobium/titanium alloyed higher strength cold rolled strip grade MHZ 460 (7) which is utilised, for example, to make dashboard cross members. Altogether 82 coils were produced with high and low coiling temperature and with annealing times of 25 to about 50 hours after the cold rolling. Figure 18 shows a plot of the yield strength against the annealing time. Whereas with the low coiling temperature of 640°C increasing the annealing time leads to great decrease of the yield strength, the yield strengths after the application of high coiling temperatures of 700°C have a constant value which is largely independent of the annealing time. Evidently the tests confirm the results of the laboratory investigations and model calculations, that increasing the coiling temperature and thus promoting precipitation coarsening already initiated in the hot strip, reduces the influence of the annealing time. This makes possible a significant reduction in the scatter band from coil to coil.

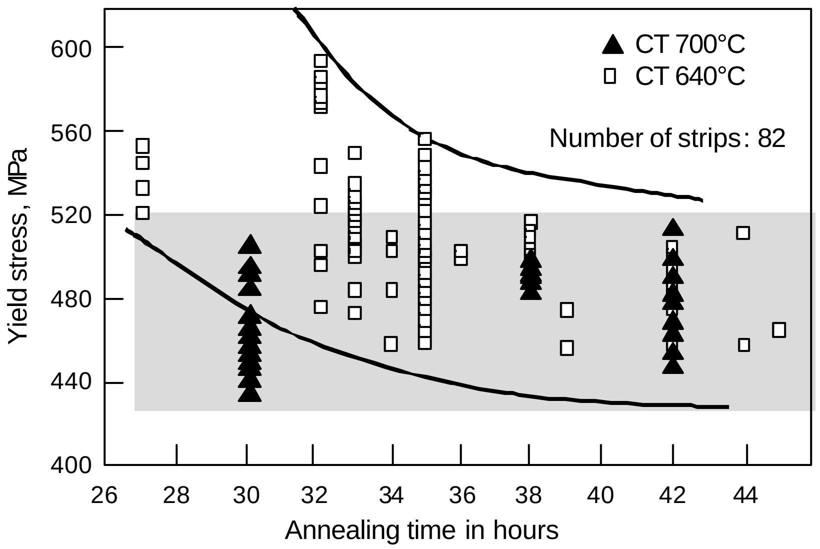


Figure 18: Influence of the coiling temperature on the scatter in the yield stress of a batch-annealed niobium/titanium microalloyed steel with a min. YS of 460 MPa.

Furthermore, by applying lower finish rolling and higher coiling temperatures during hot strip rolling (Figure 19) the precipitation hardening potential is reduced, resulting in a more homogeneous distribution of properties (9). Not the highest possible strength but the lowest scatter in mechanical properties is the customer's preference and this determines the processing conditions.

Further efforts have also been made to reduce the scatter in mechanical properties regarding the type of annealing process and the more effective high convection batch annealing process also shows better results in this context. A helpful consideration is to adjust the positioning of coils in the bell, where typically the top piling position results in the highest strength.

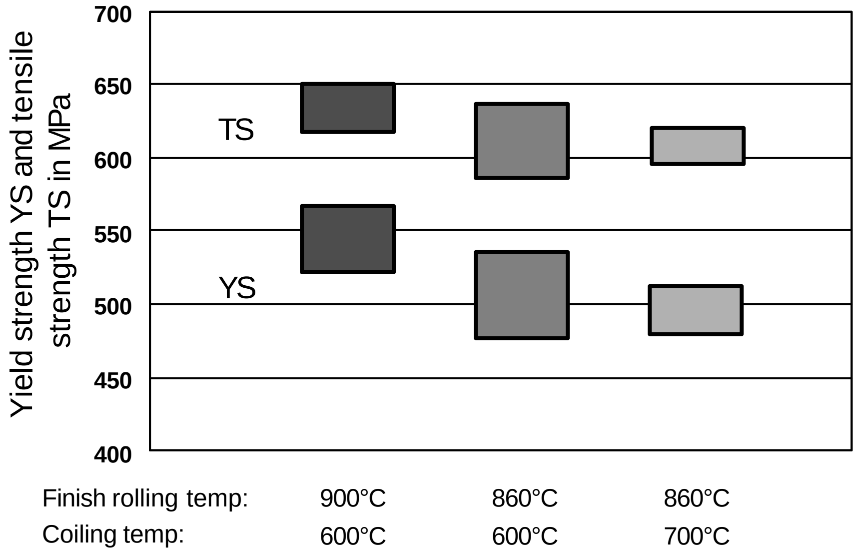


Figure 19: Scatter in tensile properties of a batch annealed HSLA sheet steel (0.06% C, 0.80% Mn, 0.02% Nb and 0.08% Ti) after different hot strip rolling conditions.

Because the microalloyed steels show an inherent tendency to display isotropic behaviour, special emphasis was put on the development of particularly isotropic steel grades. These steels have unidirectional flow properties in the plane of the strip and thus little tendency to produce earing, and they also have high strength.

Figure 20 shows the chief features of these isotropic steels (10). Starting from the conventional concept of a batch annealed isotropic steel which may be alloyed with titanium, niobium and/or boron, further developments led to the continuously annealed or galvanised isotropic steel including a galvannealed coating (ZF). In addition to the assurance of bake-hardenability after deformation, these steels are characterised by further enhanced formability with significantly increased r-value. A further development initiative led to significantly increased strength with bake-hardenability by the application of a dual-phase (DP) steel concept featuring good formability in relation to its high strength.

When deep drawing with a flat bottom or round bottom punch, a comparatively small limit drawing ratio with additional large reduction of sheet thickness is achieved with microalloyed isotropic steel (11). In the case of pure stretch-forming, material flow takes place from the sheet thickness. Isotropic steel thereby achieves a large limit drawing depth, together with a large thickness reduction (Figure 21).

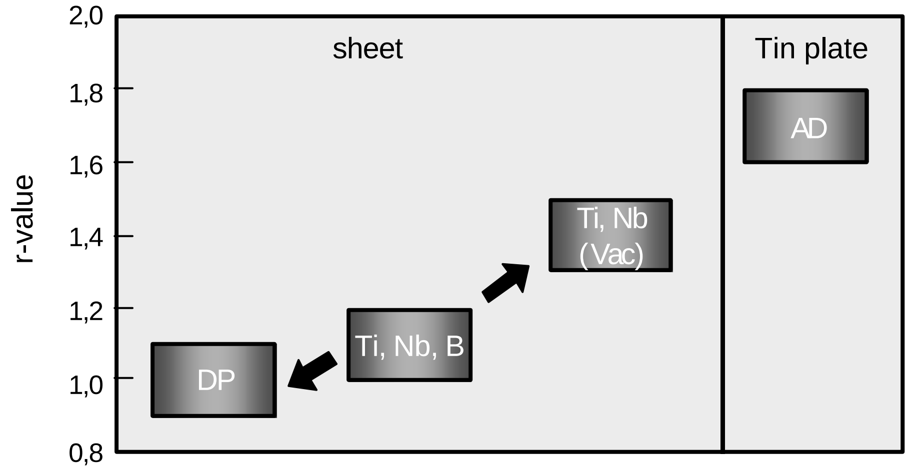


Figure 20: Different steel concepts to achieve isotropic behaviour and low earring.

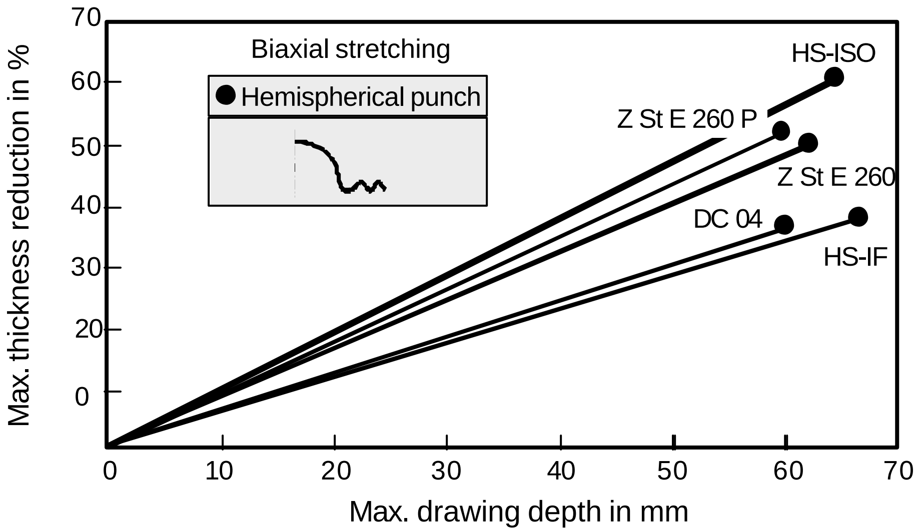


Figure 21: Thickness reduction depending on the maximum drawing depth of biaxial stretching for different steels.

Continuously Annealed Steels

The role of microalloys in cold rolled steels is similar to that in hot strip material, by acting via grain refinement and precipitation hardening. Due to the greater coarsening of the grain size and of the precipitates during the batch annealing process, the yield strength is considerably lower than in continously annealed strip steel of the same chemical composition (Figure 22).

As in typical hot strip alloy design, HSLA steels prefer the microalloying element niobium, which acts mainly via grain refinement. Since the strength increasing effect of niobium alone is not sufficient to economically guarantee a yield strength higher than 350 MPa, for higher strength strip the combination of niobium plus titanium is often used together with higher additions of solid solution hardening elements.

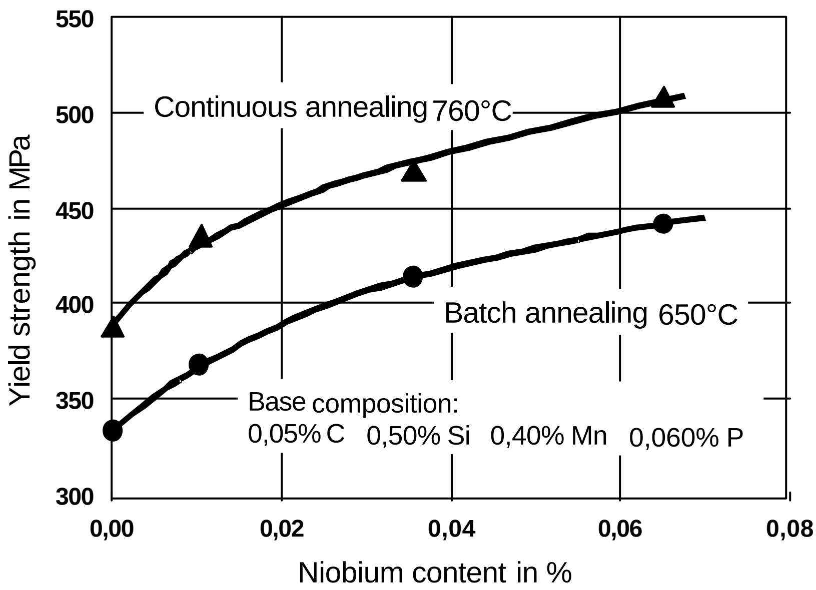


Figure 22: Comparison of the effects of batch and continuous annealing on the yield strength of cold-rolled niobium steels.

Contrary to the economics of mild deep drawing quality steel, continuous annealing is considered to be cheaper than the batch annealing process for all strip steel with a minimum yield strength of 230 MPa and greater (1). In addition to these economical considerations, the continuous annealing process results in an additional benefit of a reduced scatter in mechanical properties and shows even higher mean values for the same chemical composition (Figure 23). Therefore, for the same strength, the continuously annealed HSLA steel can utilise a somewhat leaner alloy design than that used for batch annealed steel.

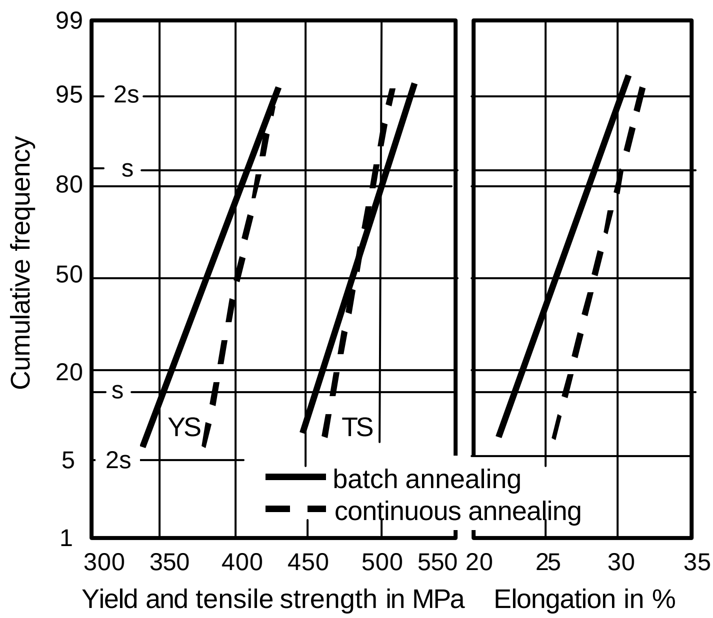


Figure 23: Properties of a niobium microalloyed strip steel after two different annealing processes.

In view of the complex combination of the different factors that exert an influence during a continuous annealing process, any quantification with the aid of the different strength-increasing mechanisms is impossible without a detailed metallographic examination (5). The recrystallisation annealing of high-strength microalloyed cold rolled strip in a hot-dip galvanising line is therefore a process aspect requiring optimisation by the engineer. Good formability of the material requires complete or at least very extensive recrystallisation of the structure. The annealing temperature required for complete recrystallisation depends on the alloy content and on the degree of cold rolling (Figure 24).

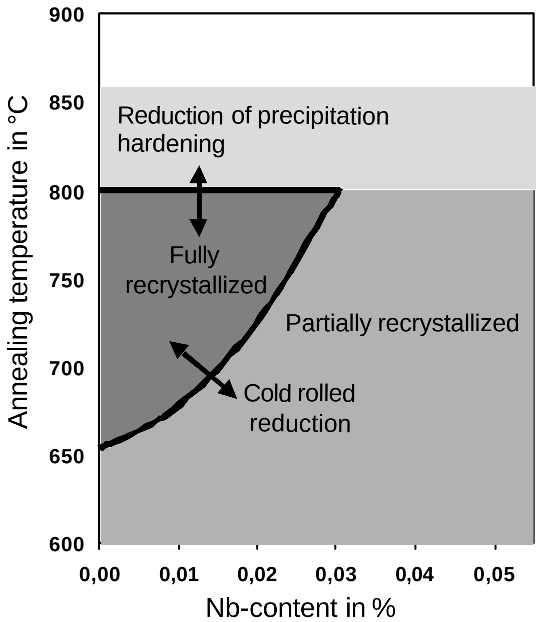


Figure 24: Limits for continuous annealing of niobium-alloyed steels.

Very high annealing temperatures are not practical, however, as then a decrease in precipitation hardening occurs as a result of particle coarsening.

The utilisation potential of a material depends critically on the extent to which its behaviour can be described in terms of material parameter values. For the traditional HSLA steels the chief properties can be demonstrated, partly in comparison with other higher strength steels. Figure 25 compares the yield strengths and tensile strengths as characteristic parameters from dynamic tensile tests which are significant for predicting crash performance. In this comparison niobium steel has the largest yield strengths.

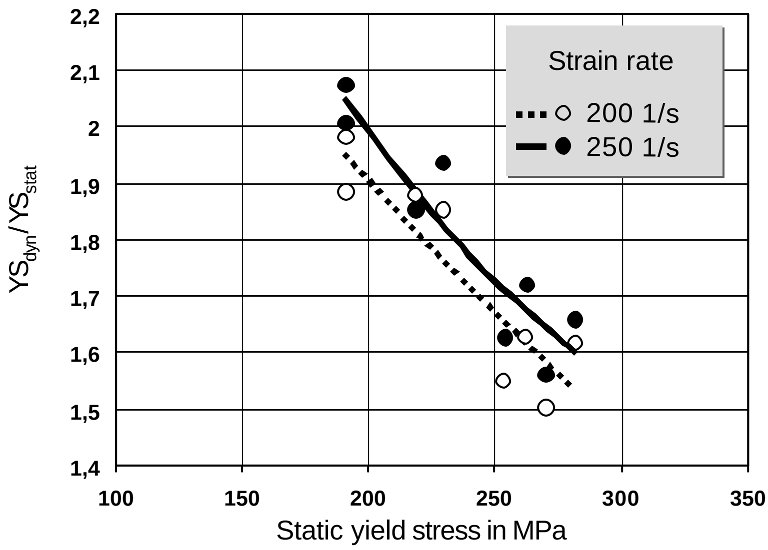


Figure 25: Influence of the strain rate on the yield stress.

The tensile strength too becomes greater with increasing strain rate, but not to the same extent as the yield strength (Figure 26).

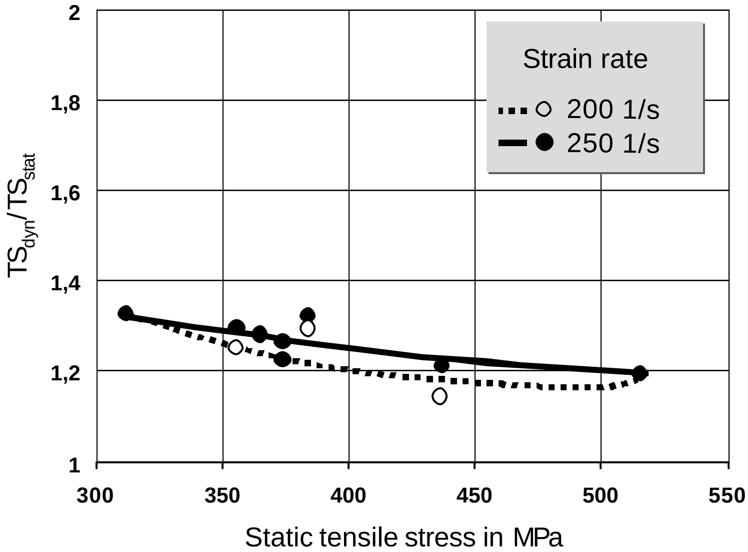


Figure 26: Influence of the strain rate on the tensile stress.

Not only conventional bake-hardening steels and multi-phase steels, but also microalloyed steels can exhibit a higher strength in the cold formed and painted material than in the as-delivered condition (14). This yield strength gain derives from work-hardening plus a certain BH-effect (Figure 27). The figure shows this behaviour for continuously annealed sheet, underlining once more the very high work hardening effect of the dual-phase steel. Both steel types show almost no strength increase by bake-hardening in the non-deformed condition. But in the deformed condition there is a significant BH effect.

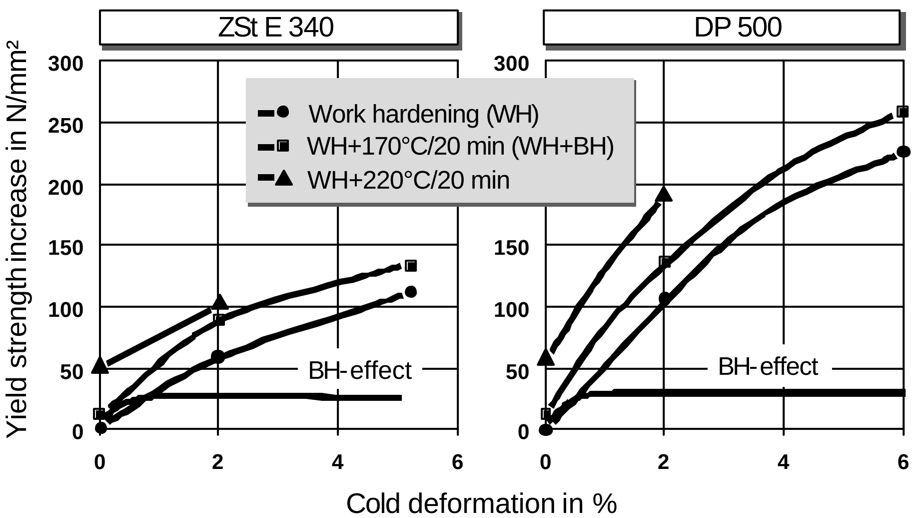


Figure 27: Yield strength increase of continuously annealed high strength sheet by cold deformation and bake-hardening.

Knowledge of the behaviour under cyclic stress is also important for assessing the performance.
In the fatigue strength limit range it is found that the tolerated stresses of all steels here investigated increase with the static strength even in the notched state (Figure 28).

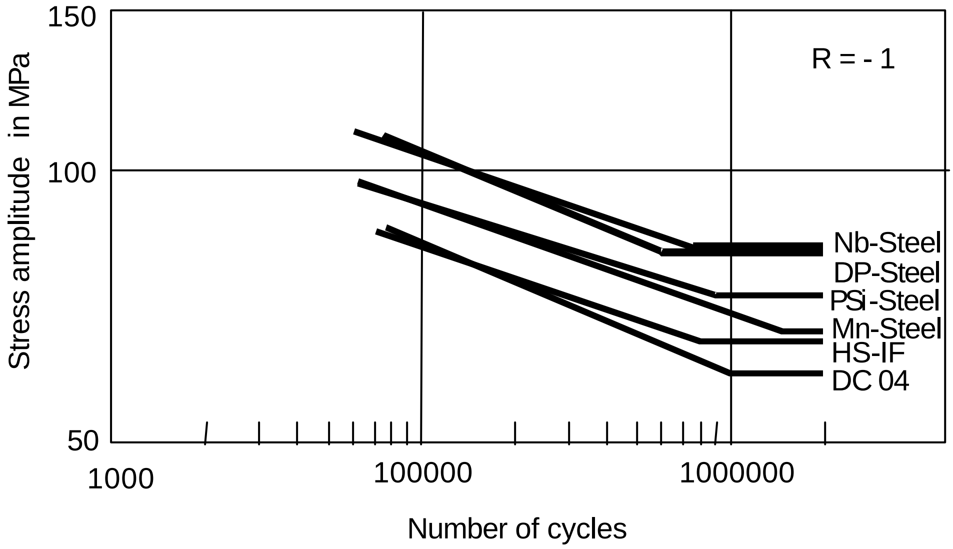


Figure 28: Wöhler-lines of notched specimens (K_t=6).

Further assessment of the fatigue behaviour is possible by evaluating the stress-strain diagrams. For this purpose the stresses for specified numbers of cycles are plotted as a function of the strain values. Figure 29 shows a comparison of these cyclic curves with the monotonic curves. The solid solution hardened, the niobium-microalloyed and the soft reference steel manifest cyclic softening, which does not arise with the dual-phase steel, which was also tested.

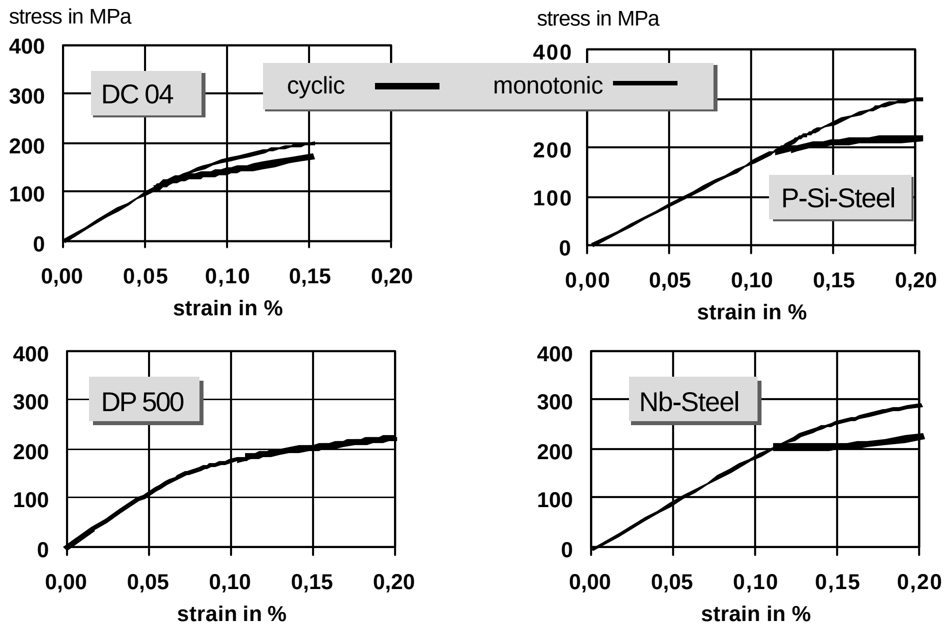


Figure 29: Comparison of the monotonic and the cyclic stress strain curve, R=-1.

Figure 30 provides information regarding the effect of notching for various higher strength steels. In general, higher strength steels are more sensitive to notching than the soft reference steel. However, there are ways to overcome this disadvantage in the design and production of components (13).

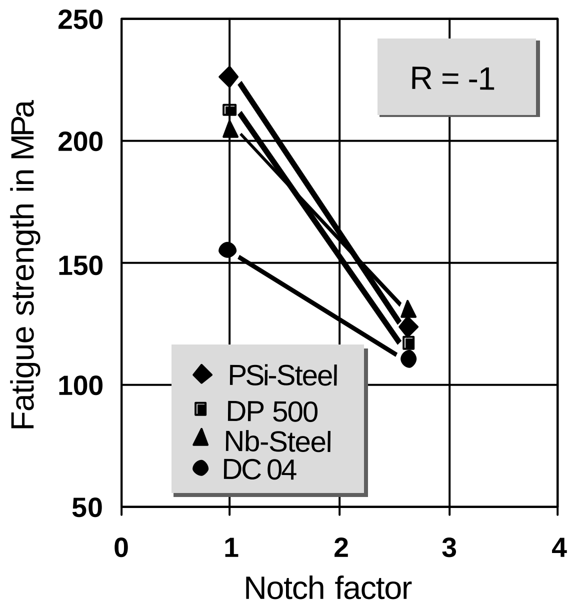


Figure 30: Influence of the notch factor on the fatigue strength.

Crash Performance

Figure 31 shows the energy dissipation of a higher strength steel and a soft steel as a function of the impact speed (12). For the same sheet thickness and the same weight, the component made of high strength steel is considerably stronger at low impact speeds. Accordingly, the deformation is decisively smaller at low speeds compared with components made of non-alloyed soft steel which require a longer deformation path for energy dissipation. At high impact speeds the two types of steel become more equal in their energy absorption behaviour, finally reaching the same values at a speed of about 70 km/h. These results were confirmed by crash tests with complete vehicles whose bodies were chiefly made of HSLA steels (12). A test vehicle chiefly made of higher strength steel showed favourable behaviour (Figure 32).

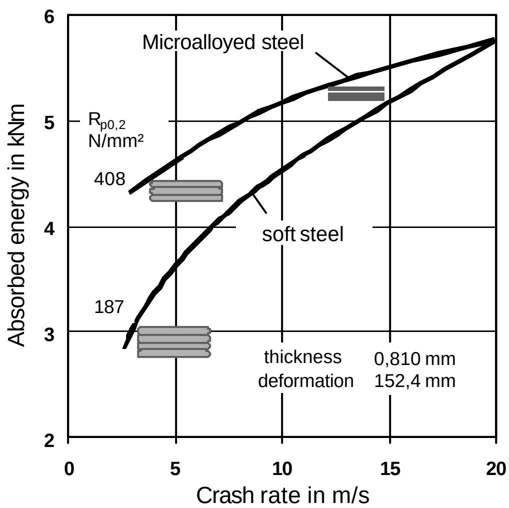


Figure 31: Energy absorption of high strength microalloyed and of soft steel.

Figure 32: Porsche test car mainly made of microalloyed HSLA steels.

After a frontal collision with a rigid barrier at 50 km/h speed. The passenger cabin was not damaged, and it was possible to open the door. With the help of acceleration sensors it was verified that no physiologically critical values appeared during the crash. These early test results obtained on Porsche vehicles made of HSLA steels were impressively confirmed in the later ULSAB study with regard to the significance of the utilisation of higher strength steels. However the goals and success of the ULSAB study went considerably further.

New Developments and Prospects

Since a higher tensile strength normally means a reduced processability, especially formability, the more recent developments aim, primarily, at improving the formability/tensile strength ratio.

In the search for better material concepts with more favourable hardening mechanisms in respect of the formability/tensile strength ratio, material science developed the family of multi-phase steels (Figure 33).

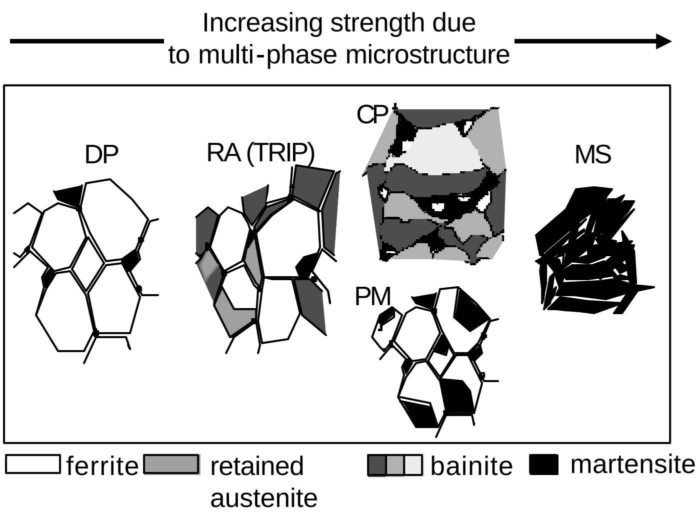


Figure 33: Structural hardening of multi-phase steels. DP – dual phase; RA – retained austenite; TRIP – transformation induced plasticity, CP – complex phase; PM – partially martensitic; MS – Martensitic.

The increase in tensile strength is obtained by incorporating hard phases next to the soft phases in the microstructure. The microstructure of dual-phase steels consists basically of ferrite with a martensite constituent of up to about 20 %. A stage of further development is represented by RA (TRIP) -steels which contain in their ferritic/bainitic matrix residual austenite constituent which is converted into martensite in the forming process. The transition to steels with very high tensile strengths of over 800 MPa is marked by the complex-phase steels. In their microstructure, a greater volume fraction of hard phases, together with fine precipitates, can be found next to softer constituents in a very fine structure. A further development stage in the same tensile strength range is represented by the concept of partially martensitic steels. When the martensite content is markedly above 20 %, such steels tend to feature relatively low yield strength and high tensile strength. The absolutely highest tensile strength of up to 1400 MPa can be attained with martensite-phase steels.

But what are the most realistic future aspects in materials design? Two essential features can already be realised rather easily : fine grained structures and multi-phase structures. As already pointed out for the conventional microalloyed steels, fine grain size is an ideal strengthening mechanism in terms of strength and toughness. But as grain size decreases, the yield strength is more affected than the ultimate tensile strength, so that in an extreme case the ratio of yield stress to TS approaches 1 (Figure 34).

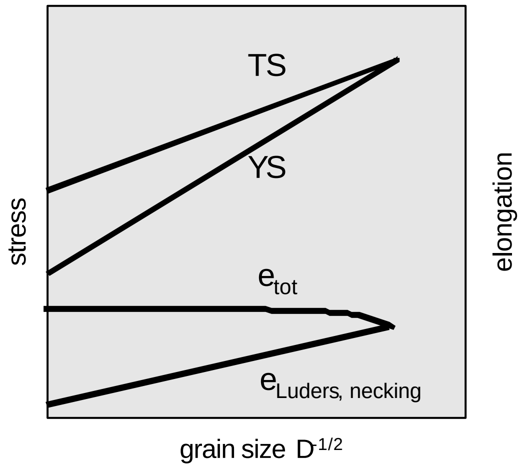


Figure 34: Influence of the grain size on the mechanical properties.

There is a question mark regarding the ductility of such material. In bcc-alloys which show yield drops followed by Lüders-strain, continued grain refinement eventually promotes plastic instability.

The amount of work hardening following Lüders-strain decreases with decreasing grain size until at the finest grain size studied (~ 1 µm) necking of the tensile specimen started simultaneously with yielding, implying that the Lüders strain exceeds the strain at maximum load. Such inhomogeneous deformation and plastic instability would obviously present difficulty in any practical application of ultra-fine grained material.

A future development to overcome this problem could be a fine structured multi-phase steel, aiming for an ultimate superfine multi-phase structure resulting in excellent mechanical properties in terms of a very good formability-strength relationship. Ultra-fine errite/martensite and ferrite/carbide structures exhibit much more attractive room temperature ductility than does ultra-fine ferrite. Accordingly, ultra fine plus multi-phase structure would be an ideal approach to overcome the problems of mechanical instability of single phase ultra fine grained steel.

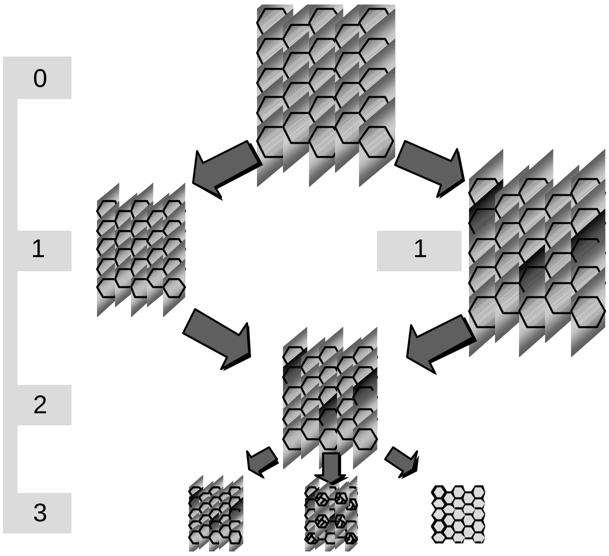


Figure 35: Steps for the development of super fine grain multi-phase structure.

The physical metallurgist knows a variety of measures to achieve superfine microstructural features like the formation of finely structured hard phases e.g. in TRIP-steels or the grain refinement of dual-phase steels by microalloying (Figure 36).

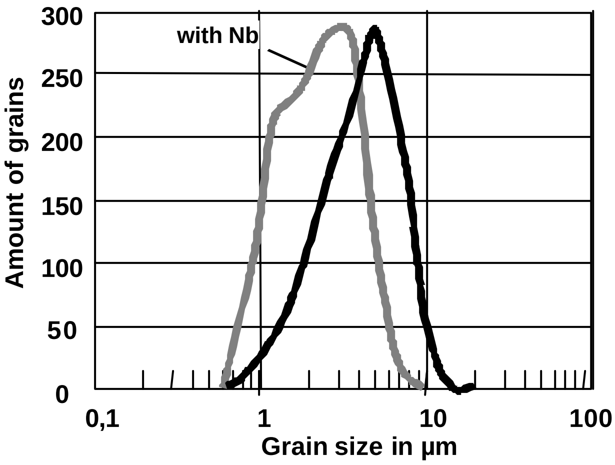


Figure 36: Influence of Niobium on the grain size of hot rolled dual-phase steel.

Accordingly, a variety of microstructures with nanometer dimensions, also called nano steels, are being developed, some of these having already been introduced into the market, such as microalloyed PAS 700 with a minimum yield stress of 700 MPa (Figure 37).

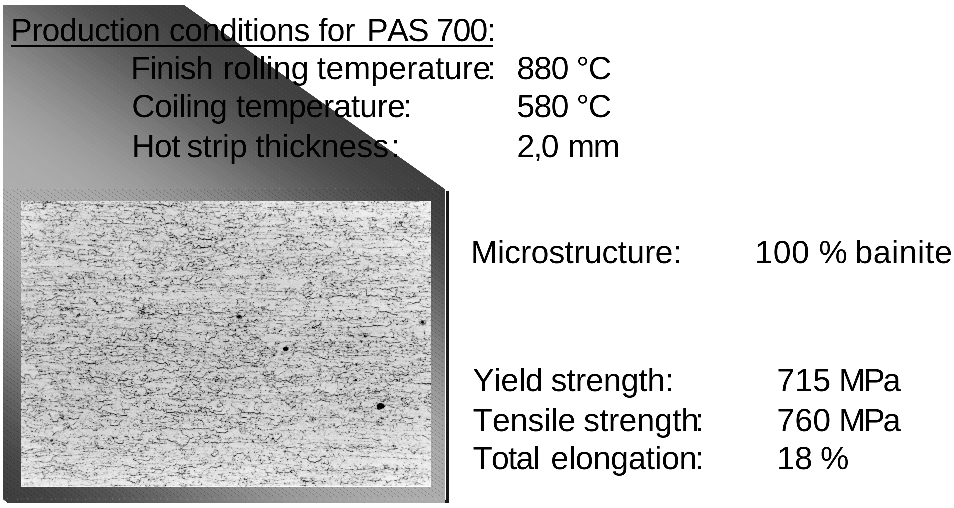


Figure 37: Mechanical properties of a high-tensile steel.

The microstructural features, which control the mechanical properties, are of the order of magnitude of less than a micron and most importantly, microalloying, especially with niobium, will retain a dominant role in the achievement of the desired structures and the resulting properties of the future materials.

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