HIGH STRENGTH AND ULTRA HIGH STRENGTH HOT ROLLED STEEL GRADES – PRODUCTS FOR ADVANCED APPLICATIONS

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ABSTRACT

In all application fields for hot rolled strip products for direct processing, e.g. automotive and truck but also construction and engineering industries, there is a strong demand for grades with increased strength levels and well balanced formability. To meet these requirements at voestalpine Stahl GmbH the development of hot rolled high strength and ultra high strength steel grades is in principle focused on two different material concepts: on the one hand the high strength microalloyed and thermomechanically rolled steel grades (ALFORM® grades) on the other hand the transformation hardened (ferritic bainitic, dualphase, multiphase, martensitic) steel grades. Therefore, in the present paper investigations on the commercially available high strength microalloyed steel grade ALFORM700M® and the ultra high strength steel grade ALFORM900M® with a minimum yield strength of 700MPa and 900MPa, respectively, are introduced. Furthermore, the dualphase steel grade DP600 and the ferritic bainitic HR60/HR45 are presented. The second focus is put on the newly developed steel grades multiphase MP800 and martensitic MS1200. Some aspects of the alloy design and the industrial production process for these steel grades are highlighted on the base of dilatometric experiments and microstructural investigations. The specific mechanical and mechanic-technological properties of these high strength steel grades are derived from the complex microstructures consisting of ferrite, irregular ferrite, bainite, martensite and M/A constituents. Furthermore, some applications engineering aspects as weldability and bending behaviour are discussed. Finally, some typical applications for these high and ultra high strength steel grades are presented.

KEYWORDS

HSLA, microalloyed, transformation hardening, dualphase, ferritic bainitic, multiphase, martensitic, ALFORM®, voestalpine Stahl GmbH

INTRODUCTION

The demand for steel grades with increased strength levels and well balanced formability has strongly been increasing over the last years in a wide range of application fields such as automotive and truck but also construction engineering and crane industry. The main goal is the reduction of weight of vehicles, crane arms or any constructional element. As a consequence fuel consumption of cars and trucks can be reduced at the same time keeping or even improving safety standards. The maximum loads of cranes can be increased as well as carrying capacities of lorries. In this sense apart from cold rolled high strength steel products also hot rolled steel grades for direct processing with high and ultra high strength levels have gained more and more a value added product. The steel industry can offer their customers a large variety of high strength and ultra high strength steel grades which fit best to the respective appropriate application [e.g. 1, 2]. Figure 1 gives an overview of the high and ultra high strength hot rolled steel grades for direct processing produced at

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voestalpine Stahl GmbH and puts these steel grades in the context of the standard hot rolled material such as mild steels, structural steels or normalised hot rolled ALFORM® grades. Further available steel grades such as case hardening or heat treatable steel grades as well as steels for gas cylinders are not shown in the graph. As can be seen the high and ultra high strength hot rolled steel grades cover a wide range of tensile strength values from 400 MPa for the thermomechanically rolled microalloyed ALFORM® grades up to 1400 MPa for the martensitic steel grades.

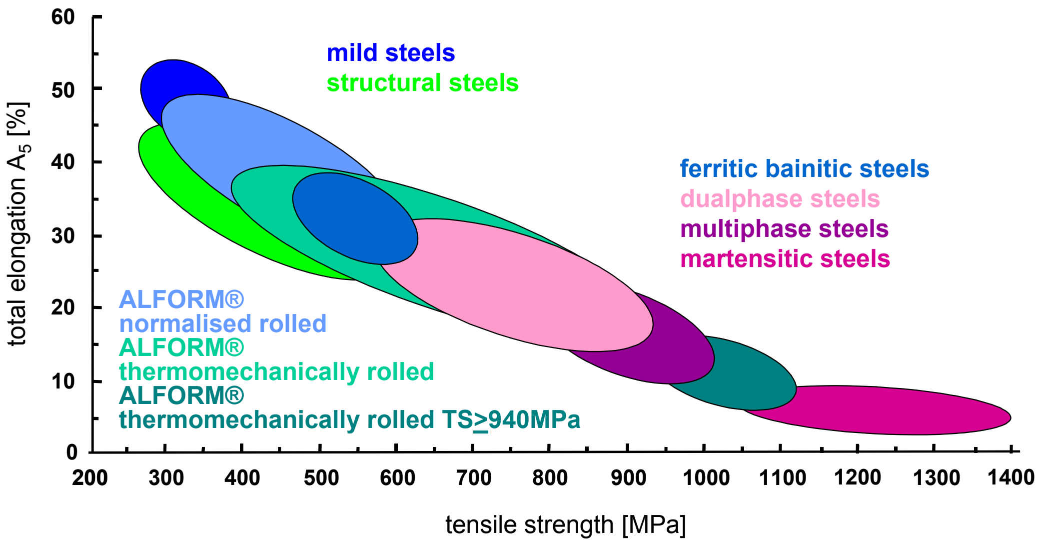

Fig. 1: Overview of hot rolled steel grades at voestalpine (full scale production and trial production)

To reach such high strength levels it is necessary to optimize the contributions of each hardening mechanism which can be briefly described with the following keywords:

(a) solid solution hardening by interstitial and substitutional elements (C, Mn, Si)
(b) precipitation hardening (Ti, Nb, V)
(c) grain refinement
(d) dislocation hardening

Making use of these hardening mechanisms when developing a high strength steel grade means firstly to adjust the chemical composition in a proper way. Secondly, to apply the appropriate production practices such as thermomechanical rolling, multi stage cooling and/or accelerated cooling. Thus, the specific microstructures typical for each steel group are obtained. As can be seen in the schematic temperature-time-transformation diagram in Figure 2 these particular microstructures are connected with a respective production route – here the temperature-time schedule on the run out table of the hot rolling mill. But not only the cooling section (cooling rates, intermediate temperatures, coiling temperature) of a hot strip mill plays an important role for the production of hot rolled high strength steel grades. Especially for microalloyed thermomechanically rolled steels grades dissolution during soaking (slab reheating temperature) and conditioning of austenite (strain, strain rates, deformation temperatures) prior to transformation are additionally necessary issues for adjusting materials properties. A survey of relevant hot rolling parameters is given in Figure 3.

Taking the hardening mechanisms as a basis the hot rolled strip with high strength of voestalpine Stahl GmbH could in principle be divided in two different material concepts: on the one hand the microalloyed and thermomechanically rolled ALFORM® steel grades on the other hand the

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transformation hardened (ferritic bainitic, dualphase, multiphase, martensitic) steel grades. Both concepts have their main hardening mechanisms. Thermomechanically rolled steel grades for example utilize grain refinement and precipitation hardening. Transformation hardening is based on dislocation hardening, grain refinement and solid solution hardening (e.g. carbon). Nevertheless, especially when reaching higher strength levels above mentioned hardening mechanisms must be used in combination to realise the high and ultra high strength levels. Therefore, in this paper an overview of the high and ultra high strength hot rolled steel grades for direct processing produced at voestalpine Stahl GmbH will be given with respect to a more detailed classification of these steel grades. Thus, emphasize will be put on both the portion of transformation hardening and the homogeneity of the microstructure. The latter being not only an important criterion regarding mechanical properties but also when looking at the interrelation of formability and the type of forming operation.

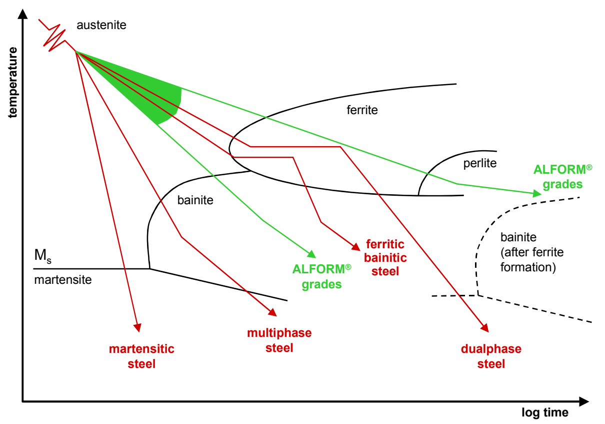

Fig. 2: Schematic temperature-time-transformation diagram representing the different temperature-time schedules on the runout table of the hot rolling mill and the corresponding microstructures of the different high strength and ultra high strength steel grades.

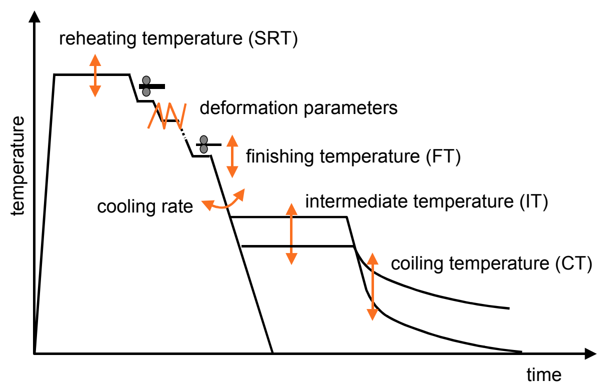

Fig. 3: Schematic illustration of important hot rolling parameters

1. THERMOMECHANICALLY ROLLED MICROALLOYED STEEL GRADES (ALFORM®)

Thermomechanically rolled steel grades are low carbon steels microalloyed with titanium, niobium and vanadium. They are also named HSLA steels (high strength low alloy). In comparison to structural steel grades which are strengthened by solid solution hardening elements such as manganese (Mn) or silicon (Si) and different amounts of pearlite (dependent on the carbon content) microalloyed steel grades derive a significant amount of their strength from precipitation hardening by titanium-niobium carbonitrides (Ti,Nb)(C,N) and vanadium carbides (VC) and from the grain refinement caused by the thermomechanical treatment. That means that during the hot rolling deformation induced precipitation of (Ti,Nb)(C,N) occurs. These fine precipitates as well as the microalloying elements in solution delay the recrystallization of the deformed austenite which then after the last stand of the finishing mill transforms in a dislocation enriched fine grained ferrite [3]. The strength level of the HSLA steels can be enhanced by both increasing the amount of precipitates (e.g. higher Ti, Nb and V contents) and by using solid solution hardening by elements such as Mn or Si. To reach ultra high strength levels additionally transformation hardening must be applied. Therefore, the temperature time schedule on the cooling section of the hot strip mill has to

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be adapted for each steel grade to control the transformation of the conditioned austenite. Different multi stage cooling patterns with variation of cooling rates, intermediate temperatures and coiling temperatures help to get the desired hardening microstructures such as irregular ferrite, bainite or martensite.

Microalloyed and thermomechanically rolled steels are standardized according to EN10149-2 with minimum yield strength levels of 315-700MPa. voestalpine Stahl GmbH sells these steel grades under the brand name ALFORM® with narrower tolerances for the mechanical properties and inner edging radii as well as with stronger restrictions for the chemical composition compared to the EN standard. Additionally, voestalpine Stahl GmbH provides with the ALFORM900M® a commercially available ultra high strength steel on the basis of thermomechanically hot rolling not included in EN10149-2. This steel grade is comparable with the quenched and tempered steel S890Q according to EN10137-2 but exhibits a better surface quality due to the different production process.

In the following chapter some investigations on the two grades with the highest strength levels ALFORM700M® and ALFORM900M® with minimum yield strength values of 700MPa and 900 MPa, respectively, are outlined (see also [4]). The former one is a classical HSLA steel microalloyed with Ti, Nb and V, which can be used in the as hot rolled condition. The latter one needs a thermal treatment after hot rolling to reach its ultra high strength level. As can be seen in Table 1 the main difference between the two materials lies in the different amount of transformation retarding elements (Ni, Mo, B) which causes in the case of ALFORM900M® a finer and more transformation hardened microstructure. The contribution of precipitation strengthening is also enhanced for this grade.

Table 1: Chemical composition of microalloyed steel grades ALFORM700M® and ALFORM900M® (mass %)

steel grade	**C** max.	**Mn** max.	**Si** max.	**Nb** max.	**Ti** max.	**V** max.	**Ni+Mo+B** max.	**N**
ALFORM700M®	0.12	2.0	0.30	0.07	0.15	0.07	0.3	~0.0050
ALFORM900M®	0.18	2.1	0.50	0.07	0.24	0.07	1.5	~0.0050

Production process of hot rolling starts with soaking in a reheating furnace at a temperature of about 1220°C. Reheating temperature controls the required dissolution of Ti, Nb and V precipitates which have formed while cooling the slab after the casting process. At soaking temperature most of the carbides and nitrides should be dissolved. The uninhibited growth of the austenite grains is prevented by the undissolved carbonitrides. During roughing precipitation of carbonitrides is stimulated by the temperature loss. Recrystallization during and between the deformation passes should lead to a uniform equiaxed austenite which is the desired starting point for the thermomechanically rolling in the finishing mill. One important question for the production is therefore the recrystallization stop temperature of the materials. As was proved for a ALFORM900M® by investigation of the microstructure of a water quenched crop this steel grade is almost fully recrystallized after roughing. Only at the surface of the coldest spot of the transfer bar a thin layer of an elongated unrecrystallized structure was found. Investigations using hot compression tests in a deformation dilatometer supported this finding. For the ALFORM700M® with a lower content of microalloying elements also full recrystallization during and after roughing can be assumed. In contrary to the roughing during finishing rolling incomplete recrystallization is desired to utilize the strengthening mechanisms by thermomechanically rolling. Microstructural investigations while finishing rolling are difficult. Direct sampling from the finishing mill is impossible, deformation experiments do not allow to simulate real strain rates and interpass periods. Nevertheless, the elongated microstructure in the as hot rolled material of ALFORM900M® (Figure 4) indicates that recrystallization is not completed during or between the final deformation passes. Also the aspect ratio of the shown grains correlates with the elongation of the hot strip while finishing. The same results were obtained for ALFORM700M®.

As was already stated, ALFORM700M® and especially ALFORM900M® derive their high strength levels to a certain amount from transformation hardening. To adjust the microstructure on the cooling section of the hot strip mill the transformation behaviour of the materials must be known. Deformation dilatometry is one way to gain knowledge about how different phases form in dependence on cooling rate, intermediate temperatures or coiling temperatures. Figure 5 shows the relative dilatation out of dilatometric experiments on samples of ALFORM700M® and ALFORM900M®. Both specimens were heated to 900°C, cooled to 850°C with a cooling rate of $10Ks^{-1}$ and afterwards deformed to $\varphi \sim 0.5$ at 850°C. After holding at this temperature for 5s cooling was carried out with 20°C/s to an intermediate temperature of 550°C. Afterwards samples were cooled to room temperatures as fast as possible (about 100°C/s).

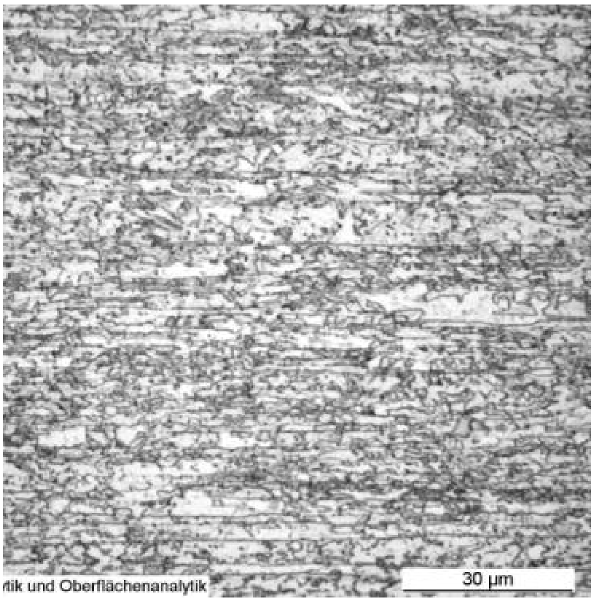

Fig. 4: Microstructure ALFORM900® in the as hot rolled condition (etching: nital)

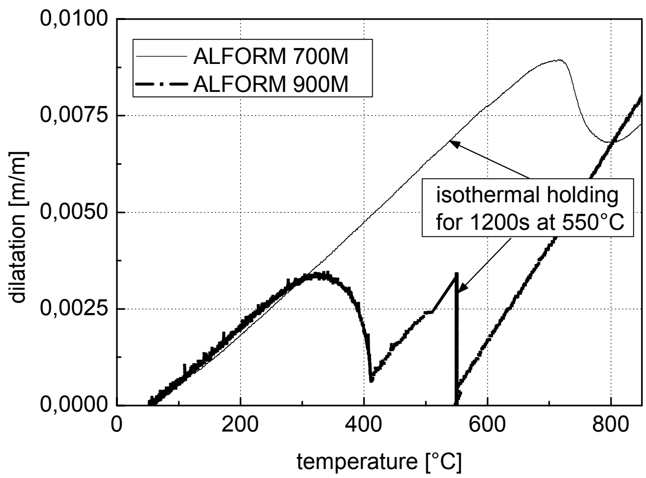

Fig. 5: Relative dilatation of ALFORM700M®and ALFORM900M® during cooling from 850°C to 550° with 20°C/s , subsequent cooling to room temperature with maximum cooling rate (about 100°C/s)

In the case of ALFORM700M® transformation starts immediately after the onset of cooling. The major fraction of austenite transforms here between 850°C and 700°C. ALFORM900M® shows a quite different behaviour. Due to a significant higher amount of elements delaying the transformation cooling to 550°C does not trigger any transformation until the isothermal period. At 550°C transformation starts after an incubation period of a few seconds and comes to rest after about one minute. From Figure 5 it can be estimated that the bcc phase amounts to the half of the sample. Subsequent fast cooling in the experiment with about 100°C/s leads to super cooling of the fcc-bcc mixture until 400°C and a martensitic reaction at lower temperatures. During full scale production cooling rates in the final cooling zone and after coiling are significantly lower than 100

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°C/s. Hence, the microstructure of the ALFORM900M® only shows few small martensitic islands. The main component of the matrix, however, is substructured lath-like bainite with high dislocation density. The microstructure of full scale produced ALFORM700M® is less transformation hardened and consists mainly of irregular ferrite.

The key properties for the application in construction are of course yield strength (YS), tensile strength (UTS) and total elongation as well as low temperature toughness and formability. These properties should be convenient not only on the flat strip before but also after processing. Critical demands on high and ultra high steel grades are suitability for bending operations, resistance against thermal treatments and weldability. Table 2 shows the properties of ALFORM700M® und ALFORM900M® achieved in the as delivered condition. Concerning bending, inner radii of 1 times thickness (1s), are reached for both materials at bending angels of 180° if cut edges of the bending specimens are ground. From the practical point of view the cant test with unground but deburred cut edges is more significant. Specimens of a length of 500mm are canted into a die of 90°. For strips with a thickness over 6mm inner radii of 2s at ALFORM700M®and 3s at ALFORM900M®are achieved (below 6mm thickness 1.5s and 2.5s, respectively). Stress relief heat treatment after processing at the customer can be done without problems up to 600°C. Both grades withstand these temperatures over hours without degradation of the mentioned properties.

Table 2: Properties of ALFORM700M® and ALFORM900M® in the as supplied condition (A_5: total elongation, $A_{v(-20°C)}$: charpy notch impact toughness at –20°C)

steel grade	**YS** [MPa]	**UTS** [MPa]	**A_5** [%]	**$A_{v(-20°C)}$** [J]
ALFORM700M®	≥ 700	750-930	≥ 15	≥ 40
ALFORM900M®	≥ 900	940-1100	≥ 11	≥ 40

For ALFORM700M®and ALFORM900M® fusion welding, flash butt welding, high frequency welding and resistance welding can be employed. Hardening in the heat affected zone (HAZ) of welded joints is very low because of their low carbon equivalent. To avoid the occurrence of a so called soft zone in the area around the joint heat input has to be limited. From this the cooling time $t_{8/5}$ has to be restricted to 20 s in the case of ALFORM700M®and 10 s in the case of ALFORM900M®.

The presented spectrum of intrinsic as well as processing properties permits the application of ALFORM700M®and ALFORM900M® in a wide field of construction. Both grades have been using with success for more than ten years in the construction of cantilever beams for vehicle cranes (see Figure 6) and concrete pumps, in the domain of structural engineering, production of vehicles and agricultural equipment. ALFORM700M® is also applied in the roll forming industry for the production of tubes and profiles.

Fig. 6: Application of ALFORM® grades: Mobile bridge inspection

2. MULTIPHASE STEELS

Multiphase steel grades derive in comparison to the microalloyed thermomechanically rolled steels of the same strength level a larger part of their strength from transformation hardening. Thus, chemical composition and production parameters (especially cooling and coiling conditions) must be adjusted in a proper way to delay the formation of polygonal ferrite and pearlite. The goal is to transform as much austenite as possible into a fine grained bainitic matrix with a dispersion of fine islands of martensite and/or retained austenite. The strength level of multiphase steels is adjusted by solid solution hardening and the type and fraction of the different hardening phases. Additionally, also precipitation hardening can be utilized. Due to the higher amount of transformation hardening (resulting in microstructural constituents of different hardness) the yield ratio of multiphase steels is in general lower than that of microalloyed thermomechanically rolled steel grades of the same strength level. Nevertheless, in comparison to dualphase steel grades of the same strength level multiphase steels exhibit higher yield strength values and a less pronounced work hardening behaviour (that means lower n-values and lower uniform elongation values). This is caused by a more uniform hardness distribution within the microstructural constituents compared to dualphase steels. Multiphase steel grades are therefore not as good as dualphase steels in stretch forming applications. Nevertheless, exactly this more homogeneous microstructure with respect to hardness differences predestines multiphase steels for bending and stretch flanging operations. In comparison to dualphase steels here fewer geometric dislocations are necessary to achieve compatibility.
Due to the smaller hardness difference of the microconstituents the strain localization in multiphase steels is less pronounced than for ferritic-martensitic DP grades. This is the reason for an increased resistance against void formation.

At voestalpine the multiphase steel MP800 with a minimum UTS of 800 MPa is based on the alloying concept shown in Table 3. C and Mn give the base for a solid solution strengthened matrix. The austenite grain size during hot rolling is kept small due to some amount of microalloying elements. The transformation of this fine grained austenite is controlled by high cooling rates on the run out table and coiling temperatures in the bainitic region. The transformation retarding alloying elements given in Table 3 support the formation of hardening phases by retardation of the ferrite and pearlite transformation. As can be seen in Figure 7 the microstructure of the multiphase steel MP800 consists of a bainitic matrix (mainly granular bainite and some lower lath bainite (according to [5]) in which fine martensite and retained austenite islands are dispersed. The retained austenite is unstable and is transformed after a strain of 3-4% fully into martensite.

Table 3: Chemical composition of the multiphase steel grade MP800 (mass %)

steel grade	**C** max.	**Mn** max.	**Si** max.	**Ni+Mo+Cr** max.	**B** max.	**Nb+Ti** max.	**N**
MP800	0.15	2.5	0.8	1.5	0.0030	0.20	~0.0050

The mechanical properties of the multiphase MP800 are compared for the longitudinal and transversal direction in Figure 8. The tensile strength values are at about 870MPa and are rather isotropic. The yield strength in contrast shows slightly higher values for the transversal direction than for the longitudinal direction. Longitudinal yield strength values of about 730MPa were measured. Total elongation values (A_{80}) are higher than 12% (T) and 14% (L), respectively. BH_2 values in longitudinal direction are higher than 40MPa. Concerning bending behaviour inner bending radii of 1 times thickness ($r_i = 1s$) and even less were measured without fracture (bending angle: 180°). Furthermore, multiphase steels can also be delivered in a hot rolled and hot dip galvanized condition. As the laboratory annealing simulation in Figure 9 shows the thermal treatment during the hot dip galvanizing process causes to a small increase in tensile strength and a stronger in the yield strength values. Nevertheless, in the typical temperature range for hot dip galvanizing of hot rolled products (650-750°C) the mechanical properties are nearly independent of the annealing temperature.

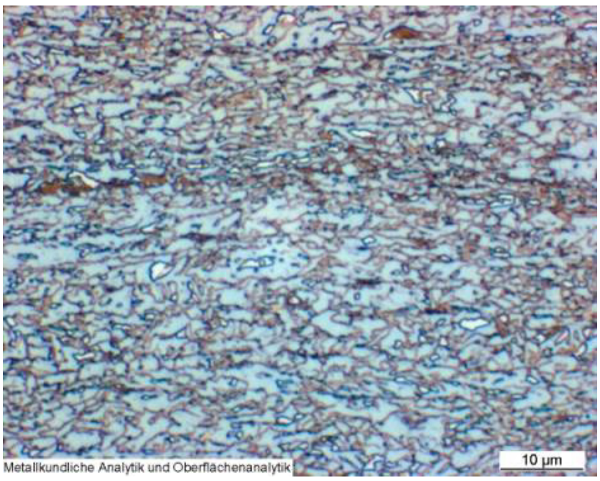

Fig. 7: Microstructure MP800 (etching LePera)

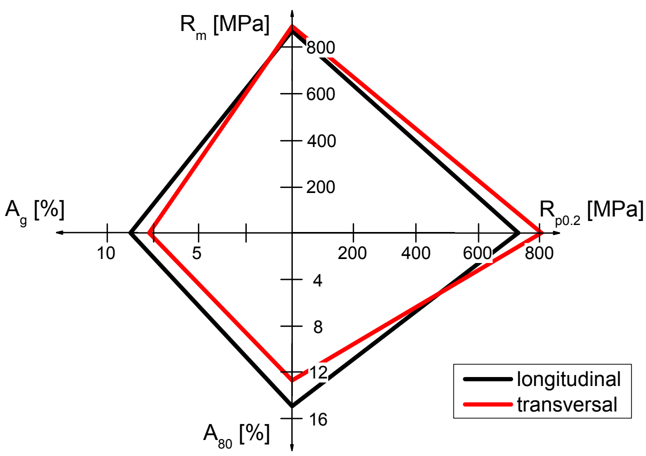

Fig. 8: typical mechanical properties of multiphase steel MP800 in longitudinal and transversal direction

The weldability of steel grade MP 800 was examined on a gas metal arc (GMAW) butt weld (welding wire: Boehler X70 / ER110S-G according to AWS A5.28-96; gas: Linde CORGON18 / M21 according to EN 439). As can be seen in Figure 10 increasing the cooling time $t_{8/5}$ leads to a slight decrease of strength and elongation values of GMAW butt welded tensile specimens. Nevertheless, the mechanical properties fulfill the requirements of a MP800 up to a $t_{8/5}$ time of 20s. Furthermore, it must be noted that for the higher $t_{8/5}$ times (15s and 20s) the location of fracture lies in the weld metal. Hardness tests showed an increased softening not only in the heat affected zone (HAZ) but also in the weld metal. Using an adapted weld metal could therefore hinder softening and such increase the possible $t_{8/5}$ times. The hardness increase in the HAZ never exceeded 350 HV10.

Typical applications for multiphase steel grades are e.g. in the automotive industry parts with a demand for high yield strength values especially in crash relevant parts such as side impact protection and bumpers but also structural parts (reinforcements or cross members). Especially, if parts can be produced via roll-forming multiphase steel grades can show their full potential of balanced strength and formability properties.

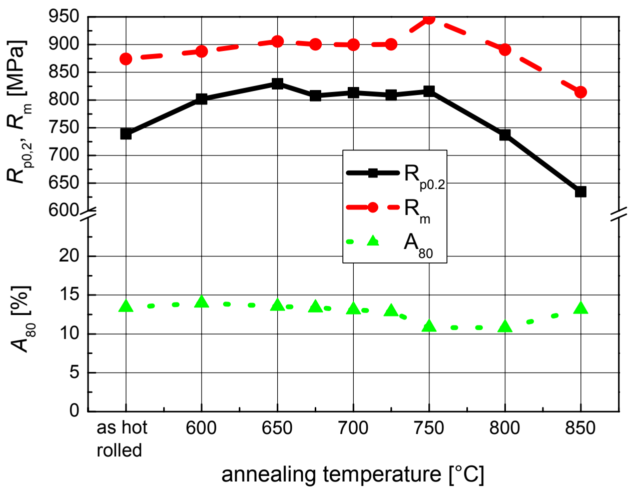

Fig. 9: Laboratory annealing simulation of the thermal cycle of a hot dip galvanizing treatment for the multiphase steel MP800 (longitudinal values)

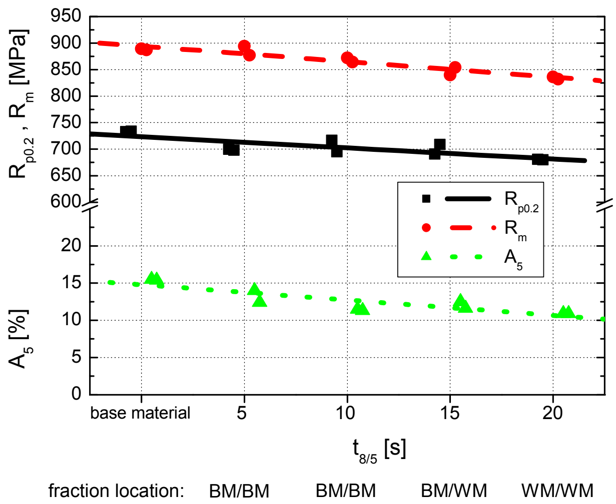

Fig. 10: Influence of $t_{8/5}$ times on the mechanical properties of a multiphase steel MP800 (transversal values; gas metal arc welding; BM=base material, WM=weld metal)

3. MARTENSITIC STEELS

As expressed by the name the microstructure of martensitic steels consists to a large extent of martensite. Nevertheless, further microstructural constituents like autotempered martensite, bainite irregular ferrite and/or retained austenite can additionally occur. The morphology of the martensite is lathlike according to the low carbon content of the martensitic steel grades which normally is below 0.2%. To adjust a martensitic microstructure during hot rolling high cooling rates and coiling temperatures below martensite start temperature must be applied. The major strengthening factor for martensite is the interstitial solid solution of carbon. Therefore, the strength level of martensitic steels can be adjusted by variation of the carbon content [6]. Furthermore, also the amount of second phase determines the mechanical properties. Increasing the amount of e.g. autotempered martensite decreases strength values but at the same time enhances formability. Some dependency of the strength may also arise from the austenite grain size which transforms into martensite. Small amounts of microalloying elements might help to utilize this strengthening potential. As multiphase steel grades martensitic steels exhibit microstructural constituents with much smaller hardness differences than dualphase steels. Hence, the aforesaid concerning strain localisation during forming is also valid for martensitic steels, of course at a higher level of strength and lower degree of elongation values.

At voestalpine the martensitic steel grade MS1200 is essentially based on a C-Mn-Cr alloying concept as is summarized in Table 4. Strength level is adjusted by carbon content. As can be seen

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from the CCT diagram in Figure 11 the upper critical cooling rate for the MS1200 is about 50°C/s. Higher cooling rates than that lead to a microstructure consisting of martensite and because of the high martensite start temperature of about 400°C also to autotempered martensite. Above this cooling rate in addition to martensite and autotempered martensite some irregular ferrite and bainite (mainly lower lath bainite) is formed. A further decrease in cooling rate pronounces the ferrite and lower lath bainite formation. The resulting enrichment of the retained austenite with carbon decreases the martensite start temperature which reduces the tempering effect of the martensite. This could for example be seen after cooling with 5°C/s. There the inner part of the grains with less carbon and therefore higher martensite start temperatures showed autotempered martensite whereas the outer parts enriched with carbon consisted of martensite. Cooling with 1°C/s and 0.5°C/s leads at last to a mainly ferritic pearlitic microstructure. Additionally, some martensite was found. Based on these results cooling rates on the run out table of the hot strip mill are set higher than 40-50°C/s for MS1200 production coiling temperatures below 300°C. Thus, a microstructure consisting of mainly martensite and autotempered martensite with its characteristic orientation of cementite precipitates [7] is obtained as can be seen in Figure 12.

Table 4: Chemical composition of the martensitic steel grade MS1200 (mass %)

steel grade	**C** max.	**Mn** max.	**Si** max.	**Cr+Mo+B** max.	**Nb+Ti** max.	**N**
MS1200	0.18	2.5	0.2	1.5	0.08	~0.0050

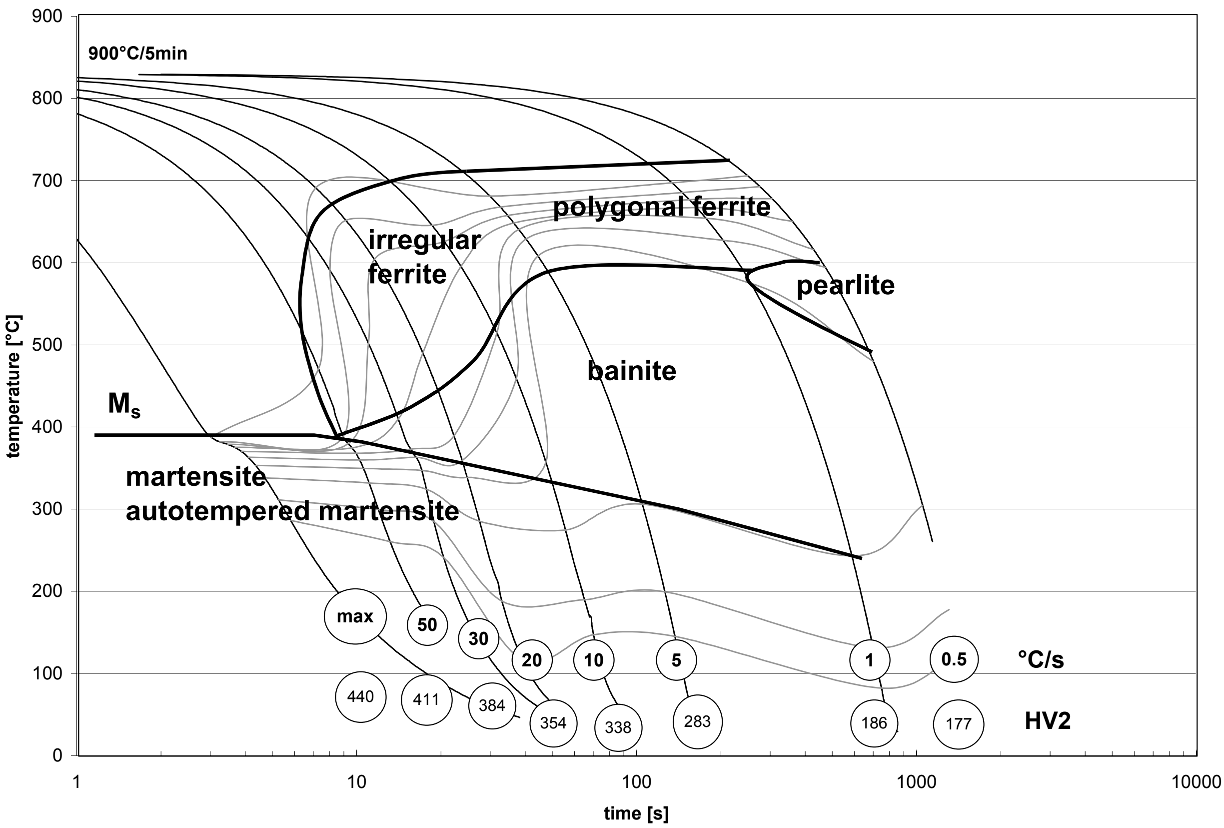

Fig. 11: CCT diagram of the martensitic steel grade MS1200 (deformation dilatometer, austenitization temperature: 900°C)

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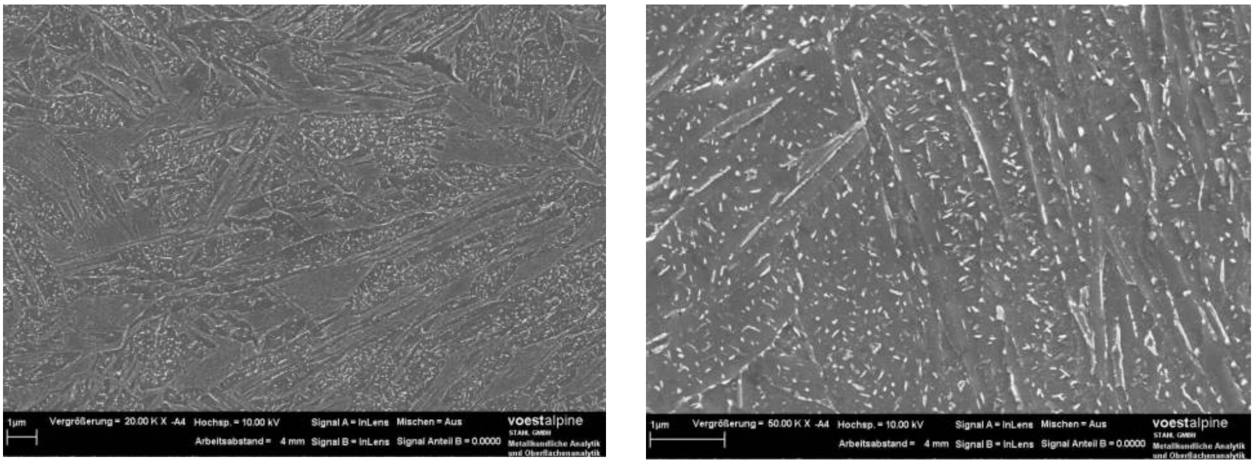

Fig. 12: Microstructure (SEM) of martensitic steel grade MS1200 from the full scale production (mainly martensite and autotempered martensite)

Table 5 summarizes the mechanical properties for the martensitic steel grade MS1200. Yield strength and tensile strength values are at about 1150MPa and 1360MPa, respectively, and show a small anisotropy. Despite the low total elongation values out of the tensile test (A_{80} ~ 5%) bending tests and especially roll forming trials show the good formability of the MS1200 which is dedicated to the uniform microstructure hardness. It is important to mention that 3 point bending test samples exhibit a strong strain localisation especially for small bending radii. Therefore, the nominal radius of the bending tool does not represent the inner bending radius of the sample. In contrast, roll forming provides the possibility to continuously bend a radius thereby hindering strain localisation. Therefore, rather small bending radii can be realized (see Table 5 and Figure 13).

Table 5: Typical mechanical properties for the martenstitic steel grade MS1200

$R_{p0.2}$ [MPa]	**R_m** [MPa]	**A_{80}** [%]	**min. bending radius** (3 point bending test)	**min. bending radius** (roll-forming)
~1150	~1360	~5	1.5-(1*) times thickness (~120°)	~1 times thickness (see also Figure 13)

* due to strain localization real inner bending radius is smaller than nominal bending radius of bending tool

Steel grade MS1200 showed on GMAW, HF, as well as on flash butt welds even at low heat input (e.g. $t_{8/5}$ of 5s) a clearly noticeable decrease in both yield and tensile strength values of about 170MPa and 230MPa, respectively, compared to the base metal. The strength drop increased continuously with longer $t_{8/5}$ times. The reason for this phenomenon is the softening in the HAZ caused by the tempering effect of the martensitic microstructure. Reducing heat input by alternative welding techniques (Laser welding, cold metal transfer process) could decrease the softened region in the HAZ. Thus, this soft zone may be supported by the surrounding not tempered microstructure leading to a lower decrease in strength values.

Parts with highest yield strength demands (e.g. side impact protection, bumper beams) are typical applications for martensitic steel grades.

So far steel grades with a rather uniform hardness distribution of the microstructural constituents such as HSLA steels, multiphase steels and martensitic steels were presented. In the following two chapters steels grades with stronger differences in the strength of microstructural constituents namely ferritic bainitic and dualphase steel grades are discussed.

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4. FERRITIC BAINITIC STEELS

The microstructure of ferritic bainitic steel grades are characterized by a matrix of quasi polygonal ferrite with a regular dispersion of bainite. They are commonly produced in two strength categories with minimum tensile strength values of 450MPa (HR45) and 600MPa (HR60), respectively. Ferritic bainitic steel grades have not yet been standardized. Therefore, there exist different specifications from different customers, which can only be fulfilled by adaptation of production parameters or even chemical composition. In general, the alloy designs for the ferritic bainitic grades are based on a C-Mn concept. Optionally microalloying with Nb and sometimes additionally with Ti is applied. Nb is reported to reduce the softening in the heat affected zone (HAZ) [8, 9] and of course helps to adjust the strength level especially for the HR60 grade. Ti combines with nitrogen to titanium nitride and hinders therefore aging caused by solute nitrogen atoms. Looking at the production process a so called multi stage cooling schedule is applied on the cooling section of the hot strip mill (schematically shown in Figure 2). The first step is to cool from finishing temperature in the austenitic region down to an intermediate temperature in the ferritic region. At the intermediate temperature air cooling for some seconds allows 80-90% of the austenite to transform into polygonal ferrite (HR45) or irregular ferrite (HR60). Afterwards in the third step fast cooling to a coiling temperature in the bainitic region is applied to fully transform the retained austenite into bainite. Ferritic bainitic steel grades show more transformation hardening than HSLA steel grades but less than dualphase steels thus exhibiting yield ratio values that lie between that of the aforesaid steel grades. Also the uniformity of the microstructure and therefore the behaviour in the context of strain localisation is between that of HSLA and dualphase steel grades. This enables ferritic bainitic steel grades to be applied for parts with a certain stretch forming portion but at the same time exhibiting a better bending and stretch flangeability than dualphase steel grades.

At voestalpine the HR45 is produced as a C-Mn steel sligthly microalloyed with either Ti or Nb depending on the customers demands for mechanical properties (see Table 6). The HR60 is alloyed with less carbon which is compensated by a higher amount of Nb and a more pronounced transformation hardening by means of higher cooling rates and lower coiling temperatures..

Table 6: Chemical composition of the ferritic bainitic steel grades HR45/HR45HDG and HR60/HR60HDG (mass %)

steel grade	**C** max.	**Mn** max.	**Nb+Ti** max.	**N**
HR45/HR45 HDG	0.17	1.5 (0.9*)	0.025	~0.0050
HR60/HR60 HDG	0.10	1.8 (1.6*)	0.08	~0.0050

* due to different customer specifications

A typical microstructure of the ferritic bainitic steel grade HR60 consisting of irregular ferrite and bainite is shown in Figure 14. The mechanical properties of HR45 and HR60 grades both as hot rolled and hot dip galvanized (HDG) are compared in the diagram of Figure 15. As can be seen the hot dip galvanized grades HR45HDG and HR60HDG exhibit higher yield strength values and slightly reduced elongation values in comparison to the as hot rolled steel grades. BH_2 values are at about 45MPa for the HR60 and HR60HDG grades whereas HR45 and HR45HDG show lower BH_2 values of about 25MPa and 35MPa, respectively. Concerning bending behaviour all steel grades show minimal bending radii of 0 times thickness (bending angle: 180°).

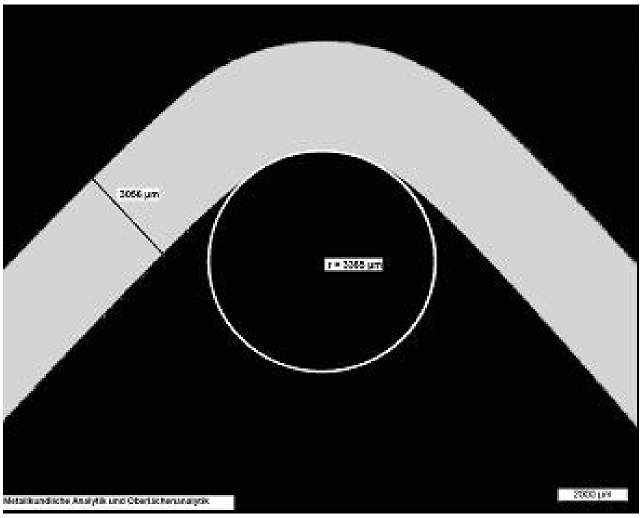

Fig. 13: Cross section of a edge of a roll formed part made of the martensitic steel grade MS1200 (thickness=3mm, inner bending radius= 3.3mm)

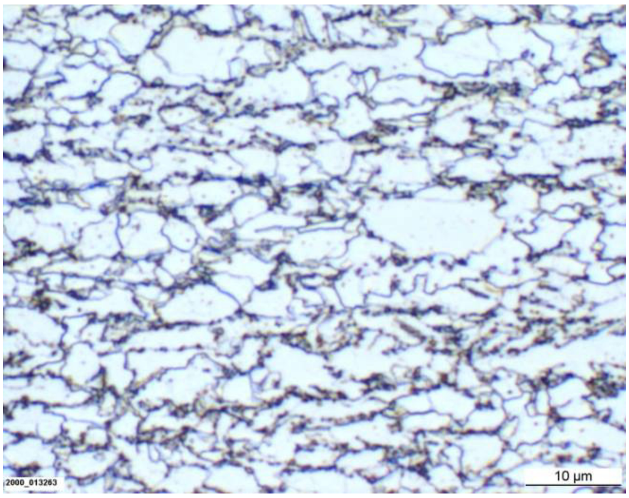

Fig. 14: Microstructure of the ferritic bainitic steel HR60 (nital etching)

Concerning weldability the steel grade HR 60 was characterized on I-butt welds made by laser, GMAW and flash butt processes ($t_{8/5}$ cooling times up to 35s). For all three welding processes strength values and formability (bending) of the welds fully met the specifications. The hardness increase in the HAZ was maximal 380 HV1 ($t_{8/5}$ ~10s). No softening zones could be detected in the HAZ (see Figure 16). For the HR45 and HR45HDG grades spot welding tests showed that the higher carbon contents of these grades do not deteriorate the weldability. It can be compared with the weldability of high strength HSLA steels grades with larger thicknesses regarding welding range and type of fracture in the chisel test and in the tensile shear test as well as hardness of the nuggets.

Typical applications for ferritic bainitic steel grades are for example structural or suspension parts in the automotive industry. Particularly, the HR60 grade is applied in the wheel production for manufacturing the wheel rims. Here the good flash butt weldability with no softening zone in the HAZ together with good forming behaviour after the welding and the high fatigue strength values in the finally mounted wheel are the most important criteria for application.

5. DUALPHASE STEELS

High strength steel grades showing the strongest differences in hardness values between microstructural constituents are dualphase steels. The microstructure consists of about 85% to 90% soft polygonal ferrite. In this ferritic matrix about 10% to 15% hard martensite island are regularly dispersed. Manufacturing of dualphase steels is therefore favoured as for ferritic bainitic steels by a multi stage cooling process: cooling into the ferritic region, formation of ferrite at an intermediate temperature, afterwards applying high cooling rates to avoid bainite formation (see Figure 2) and coiling below martensite start temperature. One premiss for getting martensite is the enrichment of carbon in the retained austenite during ferrite formation. Carbon together with further elements such as Cr, Mn, or Mo strongly retards the bainitic transformation (indicated in Figure 2 with a dashed line) but of course also lowers the martensite start temperature.

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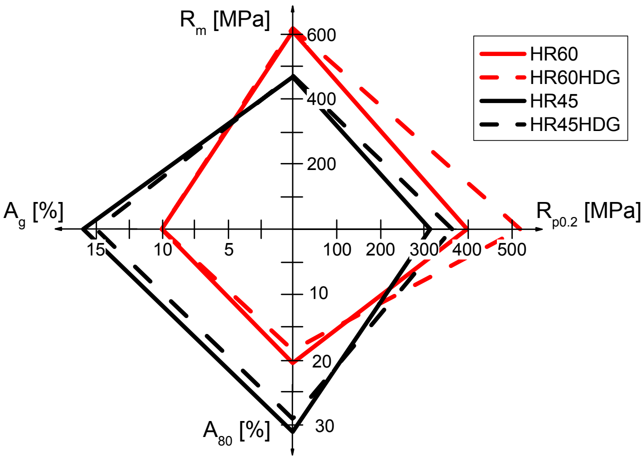

Fig. 15: Comparison of typical mechanical properties of ferritic bainitic steel grades HR60, HR60HDG, HR45 and HR45HDG

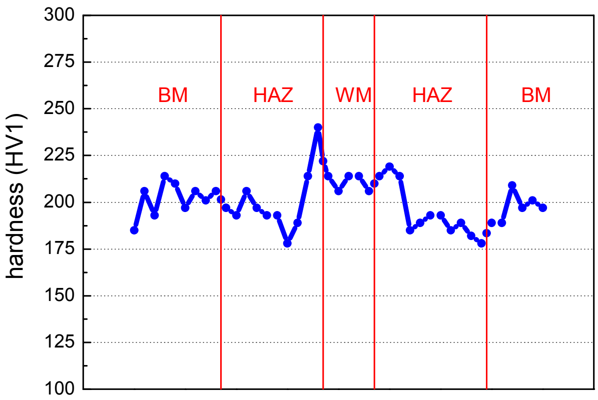

Fig. 16: Hardness of a GMAW butt weld of the ferritic bainitic steel grade HR60 (distance between indentations: 0.5mm for base material (BM) heat affected zone (HAZ) and 2.0mm for weld metal (WM); EMK6/Corgon18; $t_{8/5}$ = 35s)

As can be seen elsewhere [10] the kinetic of the carbon enrichment is dependent on the austenite grain size. Small grains (~5µm) reach equilibrium within few seconds whereas large grains (~30µm) need about one minute to build up a homogeneous distribution of carbon across the austenite grain. Therefore, during the full scale production with around 15s time for C diffusion large grains build up a carbon profil - high carbon contents at the outer parts of the grains lower amounts of C in the centers. Lower carbon contents mean higher martensite start temperatures and higher critical cooling rates. Thus in the centers of large grains autotempered martensite or even bainite is formed. Therefore, one key point in the production of hot rolled dualphase steel grades is beside a homogeneous austenite grain size the ferrite formation. It determines the type and amount of second phase and particularly the carbon content in the martensite – the main factors for the mechanical properties of dualphase steel grades. The specific properties of dualphase steels like continuous yielding behaviour, low 0.2% yield strength, high tensile strength, outstanding work hardening behaviour and high uniform and total elongation values derive from the mixture of hard martensite and soft ferrite. Already during the transformation of austenite into martensite mobile dislocations are generated in the adjacent ferrite grains. Together with local residual stresses caused by the shear displacement and volume expansion associated with martensitic transformation this mobile dislocations cause the low yield strength values. One explanation for the high work hardening values and therefore also high tensile strength and high elongation values during deformation of dualphase steel grades is the concept of geometrically necessary dislocation by Ashby [11]. These dislocations are generated to allow the hard martensite and soft ferrite to deform in a compatible way. The resulting increase of dislocation density is made responsible for the remarkable work hardening behaviour.

The DP600 steel grade of voestalpine is based on a C-Mn-Cr alloying concept as indicated in Table 7. Small amounts of microalloying elements help to reduce austenite grain size and therefore get a uniform martensite distribution within the ferritic matrix. Nevertheless, a certain amount of larger grains with autotempered martensite or bainite can be observed as can be seen in Figure 17.
Table 7: Chemical composition of the dualphase steel grade DP600 (mass %)

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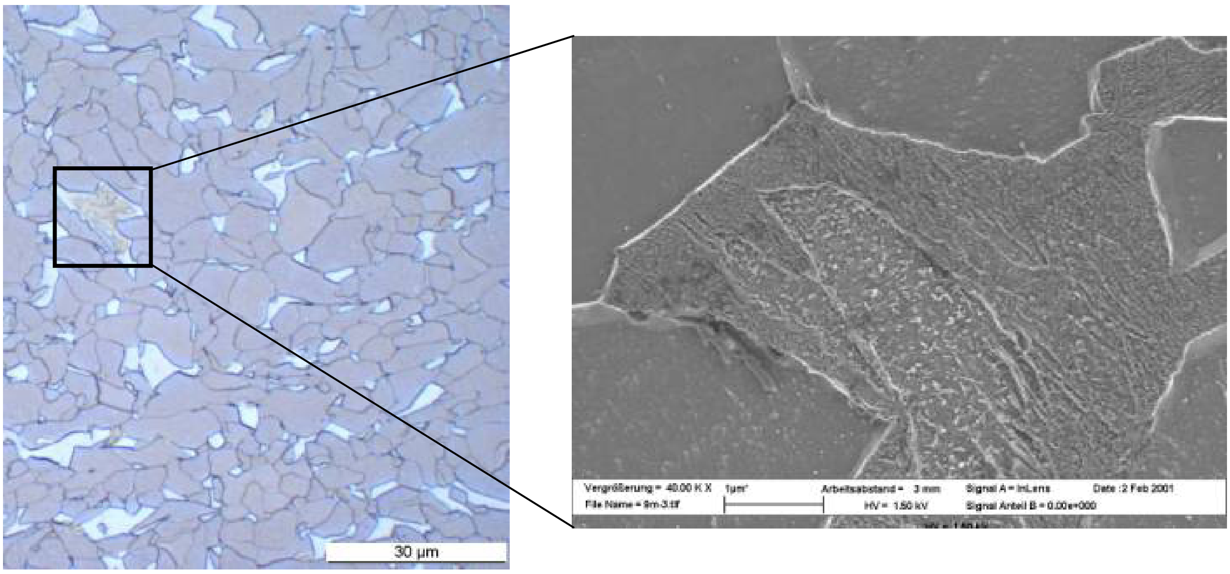
steel grade	**C** max.	**Mn** max.	**Si** max.	**P** max.	**S** max.	**Cr+Mo+B** max.	**Nb+Ti** max.	**N**
DP600	0.12	1.4	0.5	0.085	0.008	1.3	0.05	~0.0050

A typical temperature-time curve for the multi stage cooling on the runout table calculated by the computer aided quality control system (CAQC) of the hot strip mill is shown in Figure 18. Intermediate temperatures of about 700°C promote ferrite formation. Afterwards high cooling rates and coiling temperatures below martensite start temperature ensure martensitic transformation. The achievable mechanical properties are summarized in Table 8 for the transversal direction. The DP600 exhibits rather isotropic properties with slightly higher yield strength and slightly lower elongation values for the transversal direction in comparison to the longitudinal direction. Work hardening values are at about 90MPa (T) and 100MPa (L). Additionally, a BH effect of about 50MPa (BH_2 after 2% prestraining) can be expected. The yield ratio R_p/R_m lies at around 0.68 and is therefore higher than for cold rolled and annealed DP grades. Consequently, also n values are not so high than for cold rolled and annealed dualphase steels (e.g. hot rolled DP600: $n_{4\text{-}6} \sim 0.14$).

Welding of dual phase grade DP600 can be performed without any problems with laser and GMAW processes. All laser and GMAW made I-butt welds achieved in the tensile test transverse to the weld the same strength level as base material. The bending specimens met the specified standards (180° 4a). Because of the low carbon content the material is - in case of laser welds - characterized by a low hardness of maximal 350 HV10 in HAZ and molten base metal. No softening zones can be found.

Due to the pronounced work hardening behaviour one of the most important application fields for hot rolled dualphase steel grades is the production of wheel discs. Here also the high fatigue strength of dualphase steels can be utilized. Furthermore, parts like front rails are known to be produced from hot rolled DP steel. In general, further application fields are parts where a high amount of stretch forming occurs.



(a) LOM (etching: LePera) (b) SEM

Fig. 17: Ferritic martensitic microstructure of the dualphase steel grade DP600 (in the center of larger grains autotempered martensite can be observed).

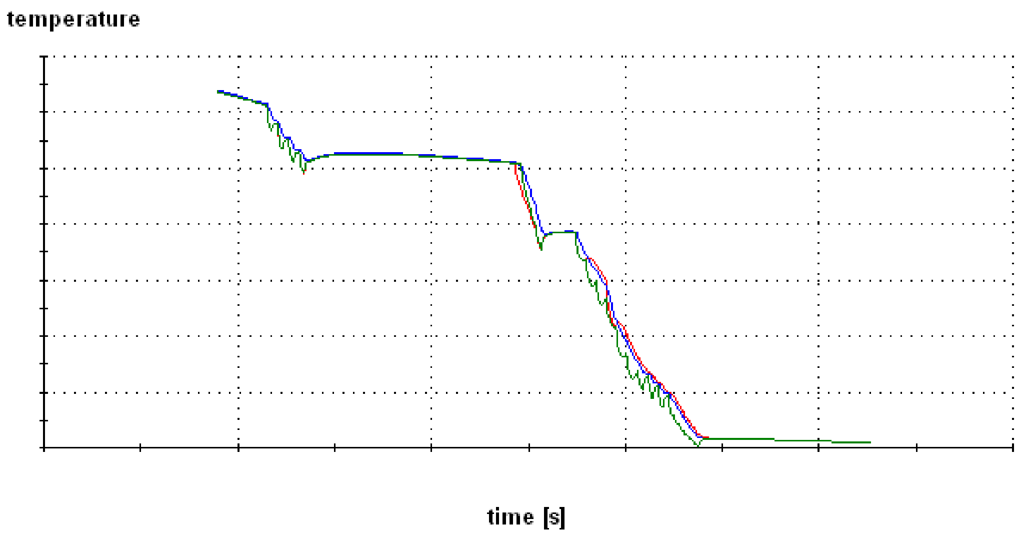


Fig. 18: Temperature-time curve of a segment of a dualphase steel strip on the cooling section of the hot strip mill at voestalpine (calculated by the CAQC system)

Table 8: Mechanical properties of the dualphase steel grade DP600 (transversal)

$R_{p0.2}$ [MPa]	R_m [MPa]	A_5 [%]
300-470	580-670	min. 22

6. DISCUSSION

In Figure 19 the different high and ultra high strength hot rolled steel grades presented in this paper are compared with respect to the amount of transformation hardening and homogeneity of microstructure. The microalloyed and thermomechanically rolled ALFORM® grades, the multiphase and martensitic steel grades show a rather homogeneous microstructure (i.e. a uniform hardness distribution of microstructural constituents). No strain localisation and few nucleation sites for voids occur. Therefore, materials can bear high strains without void formation and are thus predestined for forming operations such as bending, roll forming or stretch flanging. However, strain hardening exponent values and uniform elongation values are lower compared to dualphase steels. Dualphase steels in contrast exhibit excellent work hardening behaviour and high uniform and total elongation values together with low yield strength and high tensile strength values. These properties derive from the mixture of hard and soft microstructural constituents (i.e. heterogeneous microstructure) and make dualphase steels the best choice when drawing parts with a high amount of stretching during forming operation. Nevertheless, also dualphase grades withstand bending operations especially grades with lower strength levels as can be seen in Figure 20. Here the bending behaviour expressed by the bending angle is compared for different steel grades. Even a DP700 (out of a trial production) with about 740MPa tensile strength could be bent to the same angle as the MP800 and a ALFORM700M® without fracture. The martensitic steel MS1200 with a significant higher strength level still exhibits a bending angle of over 70° before fracture. However, from investigations on cold rolled and annealed steel grades with higher strength values it is known that the minimum bending radius of dualphase steels (so called drawing type steels) is significantly lower than for partial martensitic (also called bending type steels). This tendency is indicated in Figure 21 [12]. Nevertheless, the interrelations between microstructure and mechanical properties on the one hand and formability and forming operation on the other hand are mainly empirical and not fully understood yet. Therefore, this topic is a matter of interest for further research work.

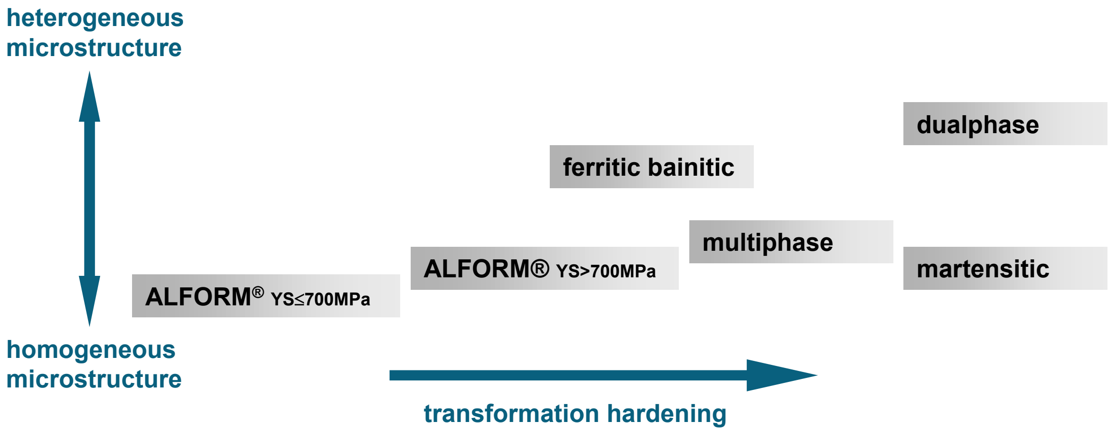


Fig. 19: Comparison of the different high and ultra high strength hot rolled steel grades presented in this paper with respect to the amount of transformation hardening and homogeneity of microstructure

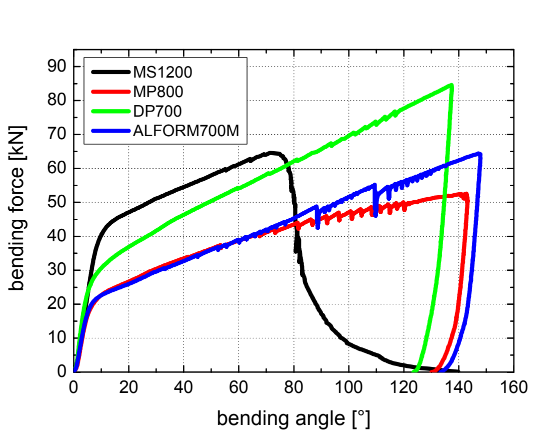


Fig. 20: Instrumented bending test (bending axis: transversal; bending radius: 1mm) for different steel grades with a thickness of 3mm (DP700 out of trial production 4mm thick)

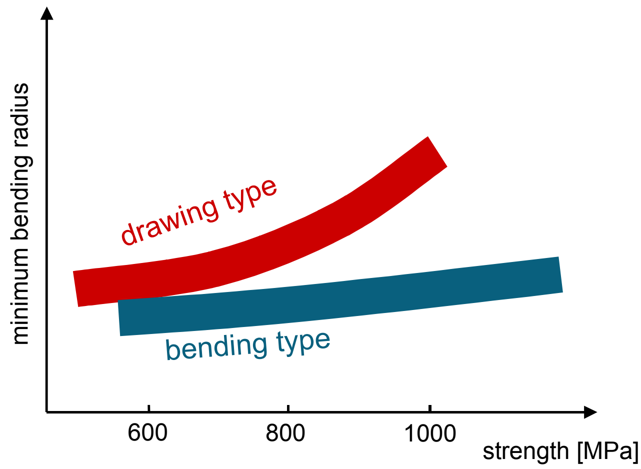


Fig. 21: Minimum bending radius in dependence of strength level for cold rolled and annealed steel grades [12]

Looking at the steel grades with a rather homogeneous microstructure a wide range of strength values is covered due to the contributions of different hardening mechanisms (see Figure 19). With an increasing amount of transformation hardening steel grades get more sensitive in terms of changes in mechanical properties with processing temperatures. Thermal treatments in this context could be for example stress relieve annealing, hot dip galvanizing, semi hot forming and of course also in the heat affected zone of a weld tempering occurs. Figure 22 shows the response of the yield strength and tensile strength on a tempering treatment for three steel grades with different ratios of various hardening mechanisms.

As can be seen the ALFORM700M® grade with a low amount of transformation hardening shows an increase in yield strength when tempering at elevated temperatures whereas the tensile strength hardly is changed over the whole temperature region. This behaviour can be attributed to strain ageing. In contrast for the ALFORM900M® grade with a more pronounced transformation

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hardening but also more precipitation hardening potential as ALFORM700M® the tempering treatment leads to a higher increase in yield strength but at the same time to a significant decrease of the tensile strength values. That means that precipitation during annealing raises the yield strength but cannot fully compensate the loss of tensile strength due to tempering of the transformation hardened microstructure. The third steel shown in Figure 22 is the martensitic steel MS1200. Its strength is solely based on transformation hardening. No precipitation hardening potential exists. Therefore, the strong decrease of strength values by tempering can be explained.

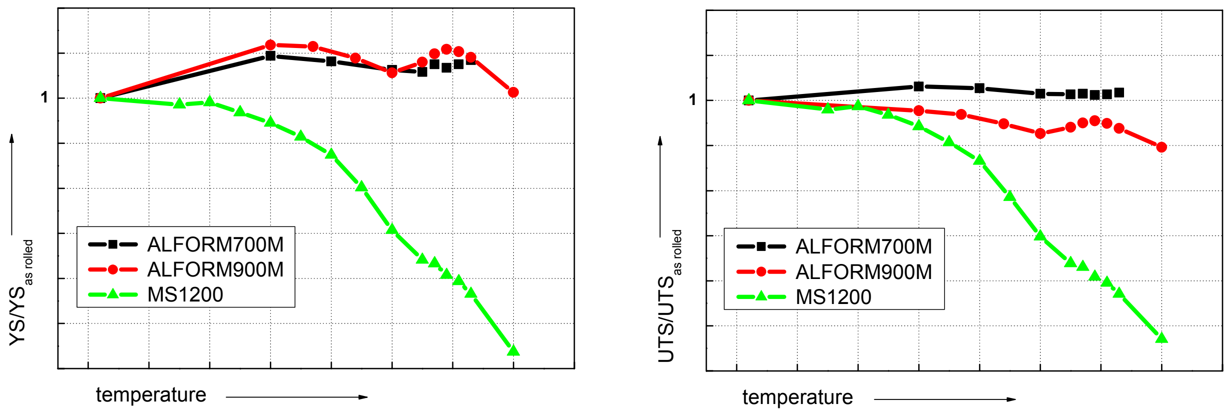

Fig. 22: Response of the yield and tensile strength on a tempering treatment for three steel grades with different ratios of various hardening mechanisms

7. SUMMARY

An overview of the hot rolled high strength and ultra high strength steel grades (microalloyed and thermomechanically rolled ALFORM®, ferritic bainitic, dualphase, multiphase and martensitic steels) produced at voestalpine Stahl GmbH was presented in this work. These steel grades were classified with regard to the portion of transformation hardening and the homogeneity of the microstructure. Out of that the typical properties and application fields were highlighted. Some aspects of application engineering properties such as bending, welding and response to thermal treatments were discussed in more detail.

The specific mechanical and mechanic-technological properties of these high strength steel grades are derived from the complex microstructures consisting of ferrite, irregular ferrite, bainite, martensite and M/A constituents. To adjust the different microstructures of each steel group large efforts in the hot rolling process have to be done. Especially when utilizing a large amount of transformation hardening multi stage cooling, high cooling rates and low coiling temperatures adapted to the different alloying concepts must be applied. At the end products with increased strength levels and well balanced formability can be offered to the customers for a wide range of application fields such as automotive and truck but also construction engineering or crane industry. Nevertheless, as was shown in this work one steel grade cannot meet all demands. Therefore, for a successful use the steel grade has to be carefully adjusted to each specific application.

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