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MICROALLOYED HIGH STRENGTH STEELS FOR REDUCED WEIGHT AND IMPROVED CRASH PERFORMANCE IN AUTOMOTIVE APPLICATIONS

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Abstract

Reduced weight and improved crash performance are two important targets for the automotive industry today. Reduced weight means reduced fuel consumption, reduced CO_2 emissions and improved driving performance. More than 50 % of the weight can be taken away by using high strength steel instead of conventional mild steel on single components. Improved crash performance is important in order to produce safer vehicles and to reach five stars in international crash tests, such as the EuroNCAP. With microalloyed high strength steels, these two targets can be achieved simultaneously in a cost effective way compared to other lightweight materials. These steels show good formability, weldability and parts can be manufactured with conventional forming and welding equipment.

The main microalloying element used in high strength steels at SSAB Swedish Steel is niobium. The range of niobium alloyed steel grades includes precipitation hardened hot-rolled grades, precipitation hardened cold-rolled grades, dual phase cold-rolled grades and martensitic cold-rolled grades. Cold-rolled grades are produced uncoated and hot-dip galvanized. This paper shows some examples of how these grades are produced, their properties in forming, welding and design as well as their current applications in the automotive industry.

Introduction

Reduced weight and improved crash performance are today two important targets for the automotive industry. Reduced weight means reduced fuel consumption, reduced CO_2 emissions and improved driving performance. More than 50 % of the weight can be taken away by using high strength steel instead of conventional mild steel on single components. Improved crash performance is important in order to produce safer vehicles and to reach five stars in international crash tests, such as the EuroNCAP. With microalloyed high strength steels these two targets can be achieved simultaneously in a cost effective way compared to other lightweight materials.

The main microalloying element used in high strength steels at SSAB Swedish Steel is niobium. Since the start of SSAB Swedish Steel in 1978 microalloyed Nb-steels has been a crucial part of the product program. Today, the product range of Nb-alloyed steels at SSAB Swedish Steel spans from yield strength levels of 280 MPa to 1150 MPa.

This paper shows some examples of how these grades are produced, their properties in forming, welding and design as well as their current applications in the automotive industry.

Steel Grades

General information

Domex MC is a range of hot-rolled high strength cold-forming steels. All grades are microalloyed with Nb, available in yield strength levels from 315 MPa up to 700 MPa.

The Docol and Dogal YP grades are typical high strength microalloyed cold-rolled and hot-dip galvanized steels intended for general presswork, forming and bending operations, offering consistent properties that assist modern rapid production methods.

Docol and Dogal DP are cold-rolled dual phase steels. These steels are subjected to heat treatment in the continuous annealing line or hot-dip galvanizing line, which produces a two-phase structure in which the ferrite, that imparts unique forming properties, is one of the phases, and martensite that accounts for the strength is the other. The strength increases with increasing proportion of the harder martensitic phase.

Compared to normal dual phase steels the Dogal DPX steel has improved formability properties especially at bending and are superior in reverse bending operations.

Docol M is cold reduced fully martensitic steels. The ultra high strength is produced by water quenching from an elevated austenitic temperature range.

Alloying

SSAB offers a wide range of steel grades alloyed with niobium. All these steels are of high strength. The main purposes of alloying with niobium are grain refinement and precipitation hardening. Niobium is used in all Domex MC grades in varying amount up to 0.07 %. There are eight different strength levels from 315 MPa to 700 MPa minimum yield point. Typical compositions of three examples are given in Table I. Other microalloying elements such as vanadium and titanium are added for the highest strength levels.

In Table I the typical alloying composition of the cold-rolled and hot-dip galvanized Nb-alloyed steels at SSAB are presented. All of the Nb-alloyed steels at SSAB are aluminum-killed.

Table I. Typical chemical composition of high strength Nb-alloyed steel grades

Grade	Steel type	C (wt.%)	Mn (wt.%)	Nb (wt.%)	Others	
Domex 500 MC	HR-MA	0.07	1.4	0.04	V, Ti	HR-MA – Hot-rolled microalloyed
Domex 600 MC	HR-MA	0.07	1.4	0.05	Ti	
Domex 700 MC	HR-MA	0.07	1.8	0.06	Ti	
Docol 280 YP	CR-MA	0.05	0.40	0.01	-	CR-MA – Cold-rolled microalloyed
Docol 350 YP	CR-MA	0.05	0.40	0.03	-	
Docol 420 YP	CR-MA	0.05	0.60	0.04	-	
Docol 500 YP	CR-MA	0.06	1.20	0.05	-	
Docol 800 DP	CR-DP	0.13	1.50	0.02	-	CR-DP – Cold-rolled dual phase
Docol 1000 DP	CR-DP	0.15	1.50	0.02	-	
Docol 1200 M	CR-M	0.11	1.60	0.02	-	CR-M – Cold-rolled martensitic
Docol 1400 M	CR-M	0.17	1.60	0.02	-	
Dogal 350 YP	HDG-MA	0.08	0.70	0.01	-	HDG-MA – Hot-dip galvanized microalloyed
Dogal 420 YP	HDG-MA	0.08	0.80	0.04	-	
Dogal 500 YP	HDG-MA	0.13	1.60	0.04	-	
Dogal 800 DP	HDG-DP	0.15	1.80	0.02	Cr	HDG-DP – Hot-dip galvanized dual phase
Dogal 800 DPX	HDG-DP	0.15	1.80	0.02	Cr	

Processing

At SSAB Swedish Steel, high strength steel grades are produced by basic oxygen furnace steel making and subsequent continuous casting. In the metallurgy-process, sulphide-shape control is also included in order to increase formability.

Niobium is by far the most effective element for increasing the recrystallization stop temperature (Figure 1). In the hot strip mill, slabs are reheated in two walking beam furnaces to a temperature of about 1250 °C. After reheating, the slabs are conventionally controlled rolled in a roughing mill and a six stand finishing mill. After roughing, the transfer bar is down coiled in a coilbox giving a uniform temperature before entering the finishing mill. A typical finishing temperature is about 875 °C and the coiling temperature is around 600 °C for all Nb-alloyed grades in order to optimize precipitation hardening.

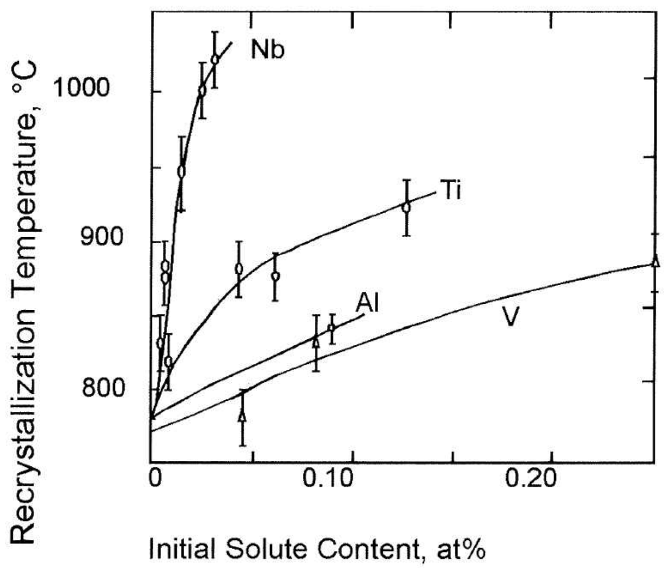


Figure 1. The increase in recrystallization temperature with different microalloying elements in a 0.07C, 1.40Mn, 0.25Si steel [1].

Cold-rolled and hot-dip galvanized grades are pickled and cold-rolled after the hot-rolling. The reduction in the cold-rolling mill is about 65 %.

The microalloyed cold-rolled grades utilize maximum precipitation hardening in the hot-rolling mill. The target for the heat treatment is to recrystallize the brittle cold-rolled microstructure without enlarging the precipitations. SSAB Swedish Steel uses three different production routes for this type of heat treatment, i.e., a bell-furnace, a continuous annealing line or a hot-dip galvanizing line. Figure 2 shows an example of the time and temperature cycle for continuously annealed microalloyed steel.

The dual phase and fully martensitic steels differs from the microalloyed steels. The strength of these types of steel is created in the heat treatment. The dual phase and fully martensitic grades are quenched from the α/γ or the γ region. Figure 3 shows an example of the time and temperature cycle for continuously annealed dual phase steel.

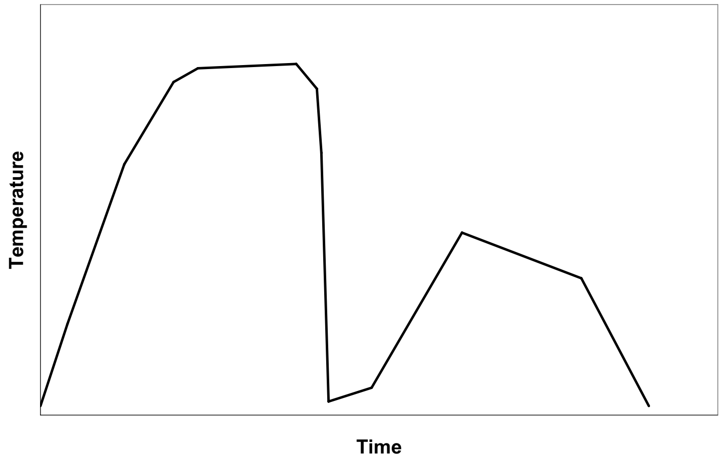


Figure 2. Typical time and temperature cycle for a microalloyed grade.

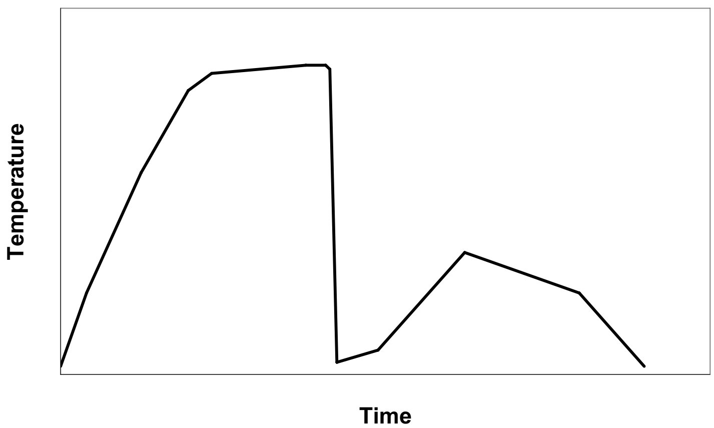
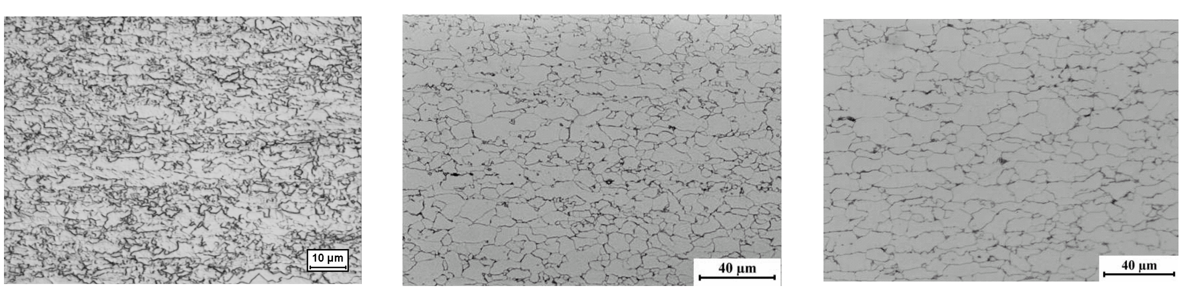


Figure 3. Typical time and temperature cycle for a dual phase grade.

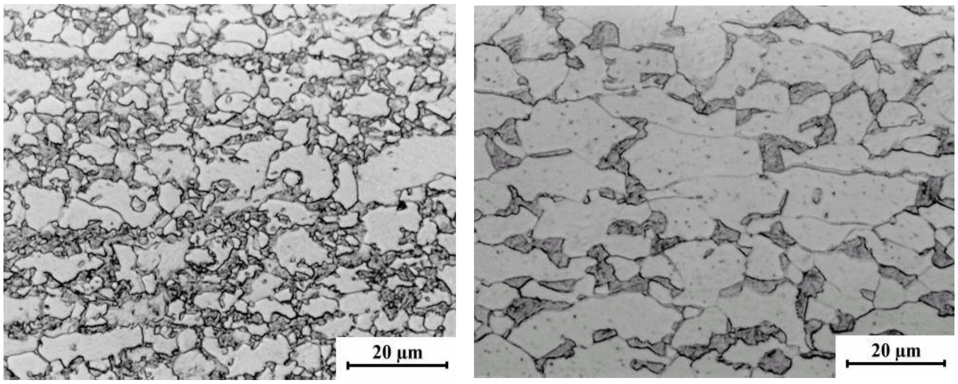
Typical microstructures of the hot-rolled grade Domex 700 MC, the cold-rolled grade Docol 420YP and the hot-dip galvanized grade Dogal 350 YP can be seen in Figure 4. The microstructure of Domex 700 MC is an irregular ferrite with an approximate average grain size of about 3-4 μm. Docol 420YP and Dogal 350 YP consists mainly of ferrite with pearlite at the grain boundaries.



(a) (b) (c)

Figure 4. Typical microstructure of Nb-alloyed steel grades:
(a) Domex 700 MC, (b) Docol 420 YP, (c) Dogal 350 YP.

The dual phase and martensitic grades are alloyed with niobium to control the grain size and to obtain a small grain size. This effect can be seen in Figure 5. A more uniform grain size results in more uniform mechanical properties [2]. A smaller grain size contributes to a finer dispersion of the martensitic phase giving a higher tensile strength. A negative effect of alloying with Nb is that Nb promotes ferrite formation during cooling [3]. In SSAB's continuously annealed dual phase and martensitic steels this effect cannot be seen due to the fast water-cooling.



(a) (b)

Figure 5. Microstructure of dual phase steels:
(a) with Nb, (b) without Nb.

Properties

Tensile properties

Mechanical properties of Domex MC grades are based on the European standard EN 10149 specifying different strength levels. Elongation is specified for a thickness less than 3.00 mm by A_{80} and from 3.00 mm and thicker as A_5 according to the standard.

The mechanical properties of all Domex, Docol and Dogal steels are guaranteed within the specified minimum and maximum values. In Table II typical minimum tensile properties for the Nb-alloyed grades are presented.

Table II. Typical minimum tensile properties for SSAB's Nb-alloyed steel grades

Grade	Steel type	Yield Strength (min) [MPa]	Tensile Strength (min) [MPa]	Elongation A_{80} (min) [%] $t < 3.0$ mm	Elongation A_5 (min) [%] $t \geq 3.0$ mm
Domex 500 MC	HR-MA	500	550	14	18
Domex 600 MC	HR-MA	600	650	13	16
Domex 700 MC	HR-MA	700	750	10	12
Docol 280 YP	CR-MA	280	370	26	-
Docol 350 YP	CR-MA	350	410	22	-
Docol 420 YP	CR-MA	420	480	16	-
Docol 500 YP	CR-MA	500	570	12	-
Docol 800 DP	CR-DP	500	800	8	-
Docol 1000 DP	CR-DP	700	1000	5	-
Docol 1200 M	CR-M	950	1200	3	-
Docol 1400 M	CR-M	1150	1400	3	-
Dogal 350 YP	HDG-MA	350	420	22	-
Dogal 420 YP	HDG-MA	420	490	18	-
Dogal 500 YP	HDG-MA	500	600	10	-
Dogal 800 DP	HDG-DP	500	800	10	-
Dogal 800 DPX	HDG-DP	620	800	10	-

Forming properties

It is difficult to describe forming properties in a complete and objective way. There is today no single way to describe formability which can be used throughout. A common misconception is that the elongation value describes formability of a material. This is true in some cases but not in all. In this paper, the forming properties are described in terms of bendability and forming limit curves. Figure 6 shows the results from three different formability tests for a range of products in the cold-rolled family.

Figure 6. Results from deep drawing tests (rear), stretch forming tests (center) and hole expansion tests (front) of various steel grades (rom left to right):
DC04, Docol 600 DL, Docol 600 DP, Docol 800 DP, Docol 1000 DP and Docol 1400 M.

Bendability

Table III shows the minimum internal bending radius that can be obtained without cracks for a specific material and sheet thickness (valid for all bending directions). Microalloyed steels can generally be bent with tighter radius compared to dual phase steel grades of the same yield strength level.

Table III. Typical bending properties for SSAB's Nb-alloyed steel grades.

Grade	Minimum recommended bending radius in 90 degree bend, $t \leq 3$ mm
Domex 500 MC	0.6 x t (0.8 x t)*
Domex 600 MC	0.7 x t (1.1 x t)*
Domex 700 MC	0.8 x t (1.2 x t)*
Docol 280 YP	0.0 x t
Docol 350 YP	0.0 x t
Docol 420 YP	0.5 x t
Docol 500 YP	1.0 x t
Docol 800 DP	1.0 x t
Docol 1000 DP	3.0 x t
Docol 1200 M	4.0 x t
Docol 1400 M	4.0 x t
Dogal 350 YP	0.0 x t
Dogal 420 YP	0.5 x t
Dogal 500 YP	1.0 x t
Dogal 800 DP	1.0 x t
Dogal 800 DPX	0.7 x t

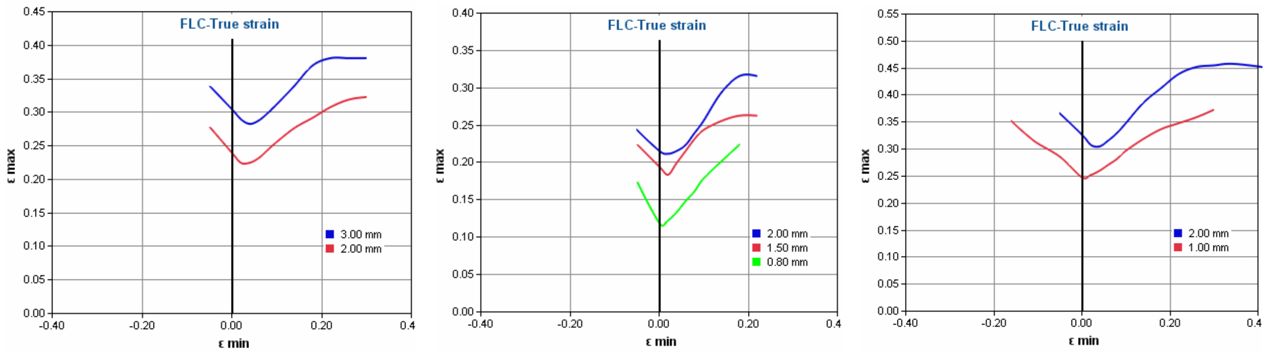
* For thickness $3<t\leq 6$ mm

Forming limit curves, FLC

Forming limit curves show the amount of deformation a material can withstand without fracture, under certain conditions. At SSAB Swedish Steel, the forming limit diagrams are determined according to the Nakazima method. The influence of both material strength and thickness can be seen in the curves.

The left side of the forming limit curve corresponds to a forming condition where the degree of drawing increases leftwards. In the same way, the right-hand part of the curve corresponds to an increasing degree of stretch forming.

In Figure 7 examples of forming limit curves for some of SSAB's Nb-alloyed steels are presented. Domex 700 MC and Docol 1000 DP in 2 mm have more or less the same plane strain properties.



(a) (b) (c)

Figure 7. Typical forming limit curves for Nb-alloyed steel grades [4]:
(a) Domex 700 MC, (b) Docol 1000 DP, (c) Dogal 420 YP.

Welding properties

All high strength steels produced by SSAB Swedish Steel are capable of being welded with conventional welding methods due to lean chemical compositions. These welding methods include spot welding, seam welding, MIG/MAG welding and laser welding. Microalloyed grades are even easier to weld due to a very low carbon equivalent.

In spot welding, wide current ranges are achieved in combination with a ductile fracture behavior of the spot weld even for dual phase and martensitic grades. In some cases, the failure mode can be partial plug failure, but the dominant failure mode is full plug failure. Figure 8 shows typical welding parameters for the Nb-alloyed dual phase grade Docol 1000 DP when it is spot-welded to itself. This figure also shows that the current range becomes wider when the electrode force is increased.

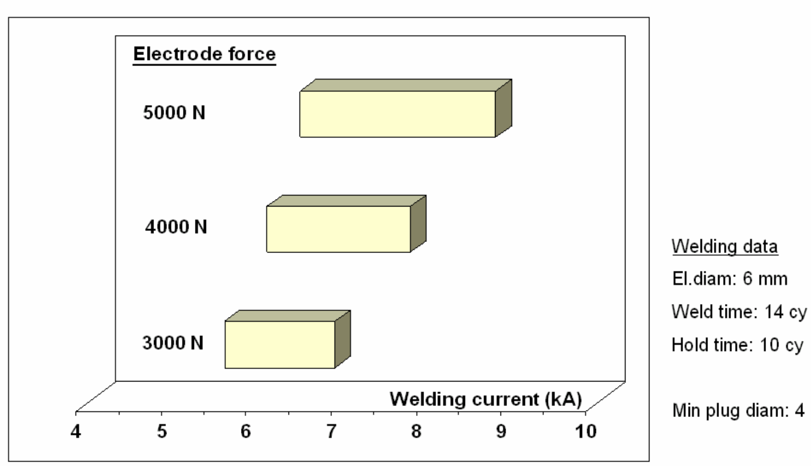
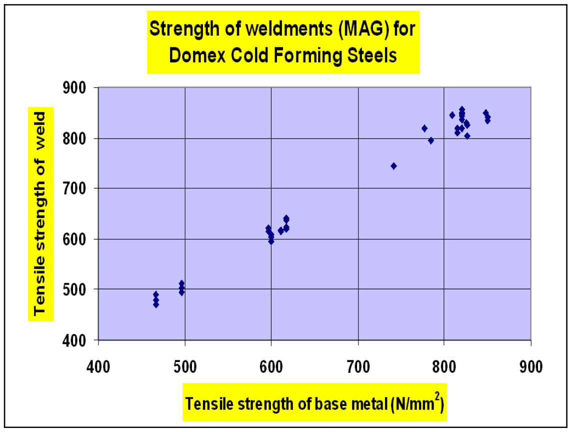
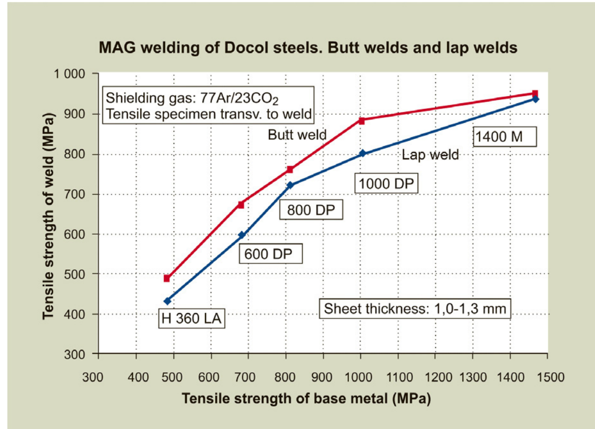


Figure 8. Typical spot welding parameters for spot welding Docol 1000 DP 1.20 mm to itself. Failure mode is full plug failure.

In MAG welding of high strength steels, the tensile strength across the weld can be maintained up to a tensile strength of 800 MPa. Above this strength level some softening occurs in the heat affected zone but the increased strength of the steel still contributes to the strength of the weld. This can be seen in Figure 9.





(a) (b)

Figure 9. Tensile strength of MAG weld as a function of tensile strength of base metal for (a) Domex microalloyed cold forming steels. Butt welds, matching electrodes have been used. (b) Docol microalloyed, dual phase and martensitic steels. Butt and lap welds.

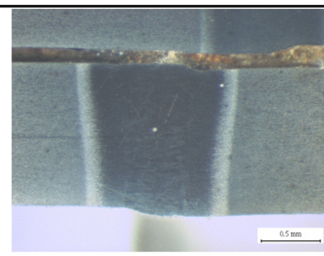
Laser welding can be easily performed on microalloyed, dual phase and martensitic grades. The formability of laser welds is good for microalloyed and dual phase grades. Good formability is expressed as an Erichsen value in the welded zone being 70 % or more of the Erichsen value in the base metal. Figure 10 shows an example of a laser weld in Docol 1000 DP 1.20 mm laser.

Welding data:

- 6 kW CO_2-laser / gas He
- Spot: 0.5 mm/on surface
- Focal length: 200 mm
- Welding speed: 10 m/min

Results:

- Good weld quality
- E=0.81-0.88



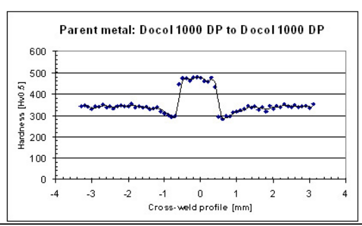


Figure 10. Formability results and hardness profile of typical laser weld in Docol 1000 DP 1.20 mm. E=Erichsen value expressed as formability of the weld divided with formability of the base metal.

Design

Static

Microalloyed high strength steels are available with high initial yield strength. Dual phase steels on the contrary exhibit a very pronounced work hardening and bake hardening effect in the case of a deformation followed by an increased temperature, i.e., paint baking of formed parts.

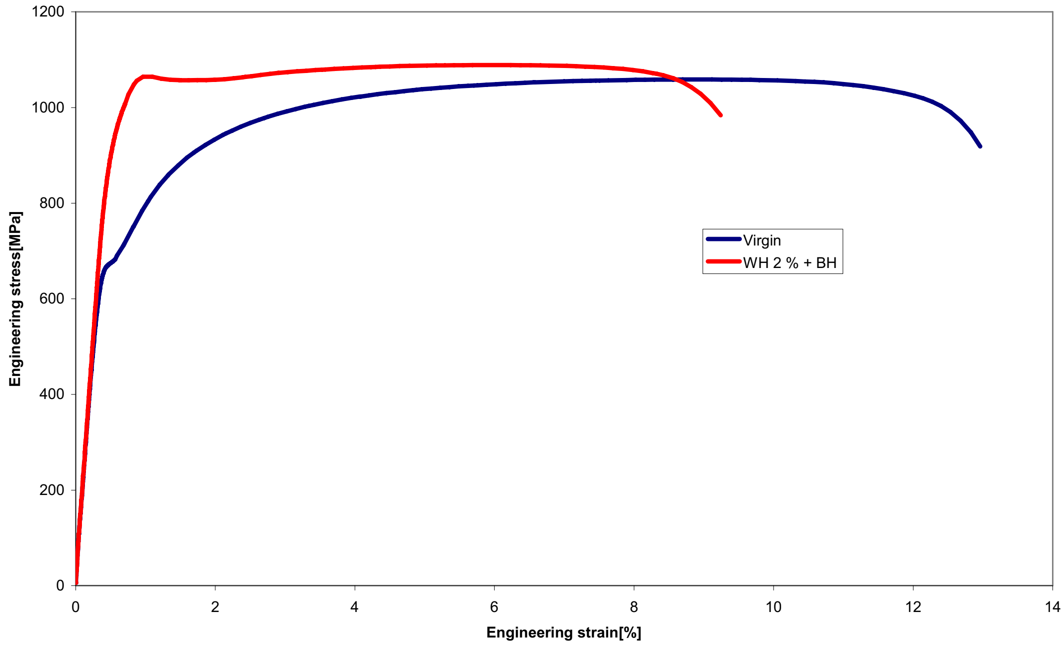


Figure 11. Engineering stress versus engineering strain for Docol 1000DP.

As can be seen in Figure 11, the level of work hardening and bake hardening is significant already at moderate levels of strain, i.e., it is important when mapping the result from the forming stage. Work hardening is highly dependent on the amount of deformation and on the steel grade. Typically, the work hardening effect can be up to 200 MPa at a strain of two percent and the corresponding bake hardening effect adds up another 50 MPa for a typical painting process.

The high strength levels of dual phase steels may be utilized in order to reduce weight. Considering the two extreme cases of skin- and plate-action may highlight the potential for weight savings.

In the case of skin-action, there is a membrane stress state and in case of plate-action there is a bending stress state. In case of skin-action, the stress is linearly proportional to one over the gauge, while in case of plate-action the stress is proportional to one over the square of gauge. In Table IV this effect is presented as the level of weight reduction for different steel grades. The value within brackets is the yield strength at two percent strain followed by bake hardening. In most true cases, the possible weight reduction is between these two extremes. The plate-action case is not a conservative lower limit due to the fact that local buckling may occur in slender designs. If local buckling occurs, the real weight reduction may be lower than given in Table 4.

Table IV. Possible weight reduction for skin- and plate action.

Steel grade	Possible weight reduction assuming **skin**-action	Possible weight reduction assuming **plate**-action
Mild steel (200 Mpa)	-	-
600DP (500 MPa)	60%	37%
800DP (650 MPa)	69%	45%
1000DP (850 MPa)	76%	51%
1400M (1350 MPa)	85%	62%

Designing for use of advanced high strength steels puts increased focus on measures to avoid local buckling, loss in stiffness and fatigue failures.

Fatigue

Increased yield strength is positive for the fatigue strength and the fatigue life in base metal testing. For smooth specimens this effect is significant, but also notched specimens show a positive influence of the yield strength. The increase in fatigue strength is equivalent no matter if the increase of the yield strength is due to work hardening, bake hardening or caused by upgrading the steel grade. The edge conditions are of crucial importance both in testing and in true life.

The fatigue strength of welded joints is however in general not affected by the strength of the material. Thus allowing for higher stresses by using high strength steels will result in reduced fatigue life in a case where every other parameter is kept constant.

However, there are several actions to be taken in order to use microalloyed high strength steels also in highly fatigue loaded applications. There are several aspects, such as smart design (changing from plate- to skin-action, placing joints at lower stressed regions etc), increased spot weld density and/or diameter, improved weld quality and/or post treatment for continuous welds and the usage of alternative joining methods (laser, adhesives, weld bonding).

Energy absorption

The high strength levels mentioned above ensure a potential for good energy absorption, favorable in a car crash situation. A relevant measure when it comes to determining the potential energy absorption from a tensile testing curve, as depicted in Figure 11, is the area below the stress-strain curve up to a limited level of strain. Integrating the complete curve is not relevant. As a consequence there is in many cases a good correlation between the tensile strength and the energy absorption. For instance, for axial crushing of a quadratic tube the absorbed energy depends on the gauge and the tensile strength [2], see Equation (1).

$$E \propto R_m^{0.5} t^{1.5} \tag{1}$$

This relation indicates the potential for weight reduction. If the tensile strength is doubled from a reference case the weight may be reduced by about 20% with equivalent energy absorption.

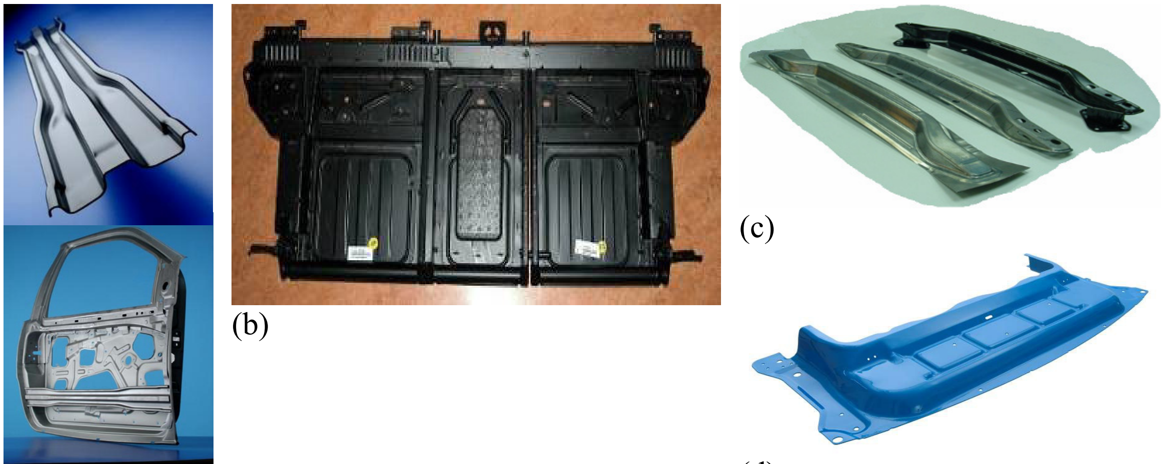
In crash boxes, the microalloyed steels might be a better choice than dual phase steels due to the fact that too high peak of a load might damage the back-up structure.

Further, microalloyed high strength steels exhibit a strain rate hardening effect, i.e. sustain higher stresses at increased deformation speed. This effect corresponds to about a 100 MPa increase at strain rates involved locally in a car crash, about 500 /s.

Applications

Typical applications for Nb-alloyed high strength steel grades in the automotive industry include traditionally bumper reinforcements, door impact beams, seat structures and seat mechanisms. New applications include different energy absorbing structural parts in the body of the car. This trend was clearly pointed out in the ULSAB-AVC (Ultra Light Steel Auto Body-Advanced Vehicle Concept) project which showed the possibility to use as much as 83 % advanced high strength steels (of which 75 % was dual phase steels) in the body of a mid-size sedan car.

Maximum amount of advanced high strength steels in the body of already existing cars in Europe is reported to be in the range of 20-30 %. Figure 12 shows some typical examples of current use of microalloyed, dual phase and martensitic steel grades.



(a) (b) (c) (d)

Figure 12. Typical applications for Nb-alloyed steel grades:

(a) Door impact beam stamped in dual phase steel Docol 1000 DP.
(b) Rear seat frame with horizontal member in Docol 420 YP, horizontal tube in Docol 800 DP, vertical members in Docol 1000 DP and brackets in Docol 420 YP, Domex 600 MC and Domex 700 MC.
(c) Stamped bumper reinforcement in dual phase steel Docol 1000 DP.
(d) Stamped structural part in martensitic steel Docol 1200 M.

Applications for microalloyed grades include mainly chassis components and seat frames and mechanisms. Other applications are bumper reinforcements, door impact beams and structural body components such as crashboxes. Main advantages are an excellent weldability in combination with a very good bendability. From a structural point of view, it is also an advantage that a high yield strength is achieved in the whole cross section of a component also without work hardening.

Dual phase grades are used more and more in a lot of different applications including seat frames and mechanisms, bumper reinforcements, door impact beams and different energy absorbing body components. With dual phase grades it is possible to reach a higher tensile strength compared to microalloyed grades and this is achieved with an attractive combination of formability and weldability.

Martensitic grades are used for highest tensile strength and also highest weight reduction potential in seat frames and mechanisms, bumper reinforcements, door impact beams and specific body components. Despite a lower ductility compared to dual phase grades components can be produced using both stamping, bending and roll forming. Weldability is very good for these grades in relation to the high strength level, which is possible to achieve.

Conclusions

Reduced weight and improved crash performance are more and more important in the development of new cars. Increased use of advanced high strength steels is one important way to meet these requirements. At SSAB Swedish Steel, microalloying with Nb is used extensively to meet the requirements from the automotive industry on higher strength, improved formability and improved weldability. The following conclusions can be drawn:

- The role of microalloying with Nb in high strength steels includes precipitation hardening and grain refinement. This effect is directly used in the microalloyed grades to increase the yield strength.
- In dual phase grades microalloying with Nb is used to reduce and control the grain size resulting in a finer dispersion of the martensitic phase, a higher tensile strength and more uniform mechanical properties.
- In martensitic grades Nb microalloying is mainly used for grain size control.
- Due to low alloying content in these grades, attractive combinations of formability and weldability can be achieved in the full tensile strength range from 370 to 1400 MPa.
- The strength increase in these grades can be used for considerable weight reduction and/or improved crash performance when designing car components.
- Applications include chassis components, body parts, bumper reinforcements, door impact beams and interior parts like seat frames and mechanisms.

Acknowledgement

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