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Novel concepts for cold rolled hot dip galvanized dual-phase steels with high hole expansion

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Summary

Dual-phase (DP) steels are nowadays a standard material for automotive applications and will also play an important role in future vehicle concepts. They are known for their excellent combination of strength and formability, involving a low elastic limit, high initial strain hardening rate and continuous yielding. Furthermore, they exhibit a considerable bake-hardening effect. This combination of mechanical properties allows thickness reductions without sacrificing passenger safety. Therefore, the development and widespread application of DP steel grades is a significant contribution to weight reduction and to save fuel consumption. Achieving the requirements of a standard DP500 to DP1000 (according to VDA 239-100: CR290Y490T-DP, CR330Y590T-DP, CR440Y-780T-DP and CR590/700Y980T-DP) with conventional rolling and annealing lines is state of the art. However, there are increasing customer demands on specific properties beyond the standard, like hole expansion and edge crack sensitivity, due to increased integration of functions in formed parts. This requires a reconsideration of alloying concepts and processing parameters. In this study, different concepts are introduced to improve formability and hole expandability of dual-phase steels. An efficient concept is based on lowering the carbon and manganese contents. As these elements are preferentially enriched in martensite, they promote excess strains in ferrite and excess stresses in martensite, thus possibly leading to an early failure. The reduction in strength due to lower C and Mn levels has to be compensated for by other means. Methods to introduce strength without deteriorating formability comprise grain refinement, precipitation control of microalloying elements, solid solution strengthening by silicon and the introduction of a certain fraction of bainite that leads to stress reductions at ferrite/martensite interfaces. The benefits of these concepts are described and compared based on tensile tests, hole expansion tests and microscopy. Furthermore, potential adaptations of the galvanizing process to maintain high quality zinc and zinc magnesium coatings are discussed.

Keywords

dual-phase steels, hole expansion, formability, grain refinement, silicon, microalloying, microstructure, precipitation

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Introduction

For the past decades, the demand for advanced high strength steels (AHSS) in the automotive industry has been steadily increasing [1]. Dual-phase (DP) steels play a major role in this group, especially due to their low elastic limit, continuous yielding and high work-hardening rate. On the one hand, strength increase is desired for weight - and thus CO_2 - reductions and improved crash performance. On the other hand, formability needs to be enhanced to cope with the increasing complexity of forming operations. Edge cracking as a result of stretching, flanging or bending stamped parts is a typical failure mode and therefore receives much attention in current research studies. DP steels are particularly in the focus because the ferrite-martensite microstructure is prone to stress localization at the interphase boundaries and thus to early failure during edge forming.

There are different testing operations for edge crack sensitivity, the most common being the hole expansion test, which best resembles the industrial process of stretch-flanging a punched hole. The correlation between the hole expansion ratio (HER) and other mechanical data or microstructure is a matter of controversial discussions [2, 3]. It was repeatedly observed that a high yield ratio has a positive effect on HER [4]. This is evident when comparing bainitic steels (higher yield ratio but lower elongation) with DP steels. A low hardness difference between the phases has the most beneficial effect on HER [5]. This can be achieved by tempering of martensite [6], grain refinement [7], or the partial replacement of martensite by bainite [8]. Microstructure banding also lowers the HER [9]. Silicon was found to have positive effect independent of the microstructure, while carbon tends to deteriorate hole expandability [4]. The effect of Nb is not clear, as it influences both grain size and phase fractions and can therefore exert either a positive or negative effect on HER [10].

In this paper, several metallurgical concepts are introduced that aim at a better hole expandability of DP steels. Technical aspects like edge condition [5] or testing speed [11] are of critical importance as well [3, 12] but shall not be treated here. Information on chemistry and processing conditions of the materials are given in the respective chapters. Standard tensile specimens were tested according to DIN EN ISO 6892-1. Hole expansion was performed on punched holes and tested according to ISO 16630:2009(E) [13]. Light optical microscopy was performed after standard grinding and polishing techniques finishing with slight Nital etching.

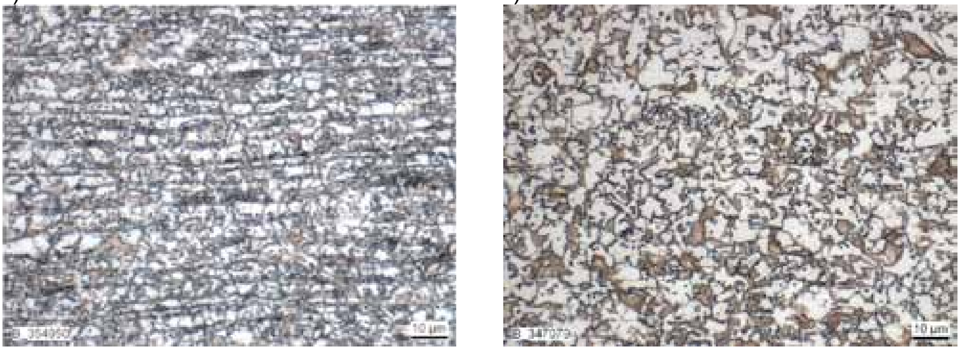
Concept 1: Reduction of carbon and manganese content

A highly efficient way to reduce the hardness difference between ferrite and martensite is to lower the C and Mn contents. As Mn is an austenite stabilizing element and reduces the carbon activity, these elements are preferentially enriched in martensite. This partitioning increases the hardness differences. As a consequence, excess strains in ferrite and excess stresses in martensite are generated during forming. The ferrite-martensite interface is then characterized by a high dislocation density and internal stresses, which facilitate the formation of voids and microcracks. To test this effect, two melts were produced with the nominal composition listed in Table 1. As C content is reduced from 0.15 to 0.10 wt.% and Mn from 2.0 to 1.5 wt.%, strength of the DP has to be maintained by other means. Here, microalloying with Nb, Ti and optionally B combined with adjusted processing parameters is applied to achieve the strength of a DP800.

Table 1: Nominal composition (wt.%) of the steels used to study the effect of lower C and Mn contents.

Steel	C	Mn	Si	Cr+Mo	Nb+Ti+V+B
DP800-15C	0.15	2.0	0.25	0.35	-
DP800-10C	0.10	1.5	0.25	0.35	>0.01

The microstructure of the steels after typical annealing process in the hot dip galvanizing line is shown in Fig. 1. It is obvious that the most striking difference between the steels is the distribution of martensite, which is much more banded in the DP800-15C due to manganese and carbon segregation during processing.


a) Microstructure of DP800-15C

b) Microstructure of DP800-10C

Fig. 1: Microstructures of two steels with different C and Mn contents after intercritical annealing.

The mechanical properties are compared in Fig. 2. The yield strength is slightly higher for DP-10C while the tensile strength is almost the same. However, the HER is almost doubled, increasing from 22% to 42%. Obviously, the more homogeneous microstructure allows reducing stress concentration and delays failure. It was observed that the cracks on the DP-10C samples showed clear evidence for necking before failure, while DP-15C failed in a brittle way.

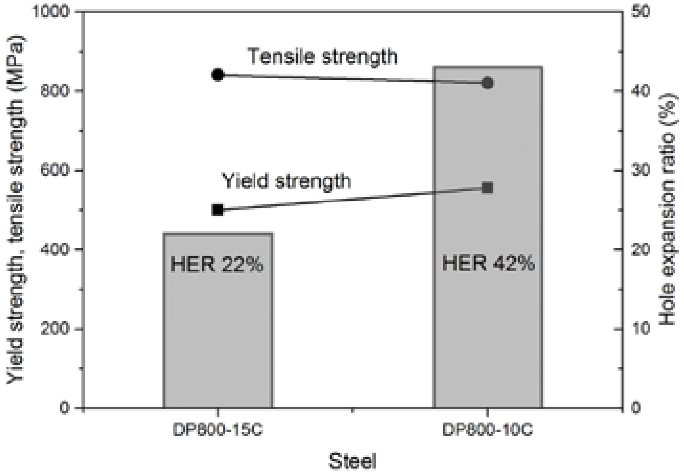


Fig. 2: Mechanical properties of the steels DP-10C and DP-15C.

Lowering the C and Mn content has other beneficial effects on technological properties. For example, welding performance is improved due to the reduced hardness increase in the weld. A smoother hardness gradient in the weld profile means less stress concentrations and thus better failure resistance.

Concept 2: High silicon content

Silicon is a ferrite stabilizing element that contributes substantially to solid solution strengthening (around 10 MPa per 0.1 wt.% Si). Up to 2 wt.%, Si was shown to have little effect on formability. Furthermore, the tendency for segregation is less pronounced than in case of Mn. Si also suppresses the formation of carbides that are detrimental for ductility. In this example, two high-silicon (0.6%) melts are compared to reference grades with low silicon content, Table 2.

Table 2: Nominal composition (wt.%) and mechanical properties of the investigated steels with varying Si content. YS: Yield strength ($R_{p0,2}$, MPa), TS: tensile strength (R_m, MPa), TE: total elongation (A_{80}, %).

Steel	C	Mn	Si	Cr+Mo	Nb+Ti+V+B	YS	TS	TE	n-value	HER
DP600-0.1Si	0.15	1.5	0.10	0.65	-	381	650	21.0	0.15	54
DP600-0.6Si	0.10	1.5	0.60	0.35	-	372	630	24.7	0.18	67
DP800-0.2Si	0.15	2.0	0.25	0.35	-	510	830	15.8	0.12	22
DP800-0.6Si	0.10	2.0	0.60	0.35	>0.02	501	803	18.0	0.12	38

As Si affects the transformation behavior of the steels substantially, adjustments of other elements are necessary. Carbon is reduced to compensate for the strength increase and to improve edge crack sensitivity. In case of DP600-0.6Si, Cr+Mo could be reduced as well. In case of DP800-0.6Si, microalloying was necessary to achieve the required strength. The mechanical properties are shown in Fig. 3. While yield strength and tensile strength are on the same level, hole expansion is substantially increased in the high-silicon steels. Total elongation is also enhanced, while an improvement of the n-value could be found for the DP600. For both the DP600 and the DP800, a beneficial effect of the decreased carbon content (from 0.15 wt.% to 0.10 wt.%) can be stated as well.

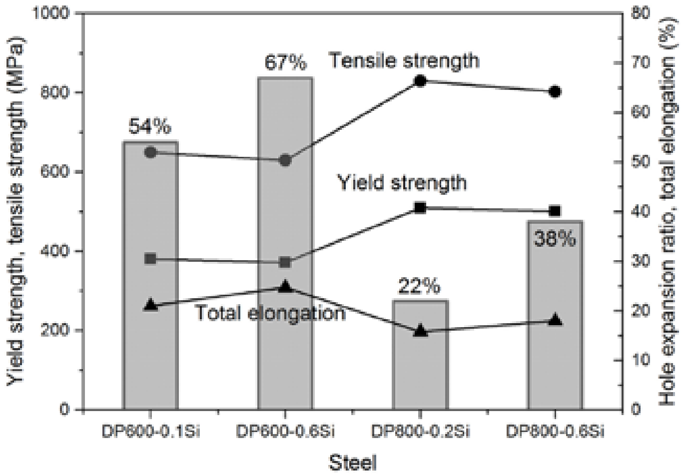


Fig. 3: Mechanical properties of the steels with varying silicon content.

As hot-dip galvanizing (HDG) with zinc or zinc magnesium of steels with high Si content is challenging, the fundamental aspects of the coating process shall be briefly explained. The HDG process combines two metallurgical processes: recrystallization annealing and coating deposition. Alloying elements such as Si, Al, Mn, and Cr are less noble than iron and therefore may segregate to the surface and consequently undergo selective oxidation in the furnace atmosphere. Particularly Si and Mn may be used in concentrations that can lead to pure or mixed external oxides, which possibly deteriorate the wetting behaviour by liquid zinc. This may result in bare spots or insufficient coating adhesion. Selective oxidation depends on a combination of the alloying composition and the annealing atmosphere. Adjusting the oxidation potential in the annealing furnace is a helpful measure to achieve good wetting [14, 15, 16, 17, 18].

Laboratory tests and production line trials were performed to determine the galvanisability of the newly developed DP steels bearing higher Si contents in comparison to actual DP steels. The reactivity of the steel surface in the zinc bath can be evaluated by characterizing the intermetallic Fe_2Al_5-layer by selective dissolution of the zinc coating. An important criterion is the coverage of the original steel surface by the intermetallic crystals. Good reactivity and coating adherence usually correlate with adequate Fe_2Al_5 coverage [18].

Fig. 4 depicts the intermetallic layers of a standard grade (Si 0.25%) in comparison to a new steel of the same grade with increased Si content (0.6%). The Fe_2Al_5 inhibition layers are closed in both cases. The steels were industrially produced and hot-dip galvanised without any adaptations of the galvanising process.

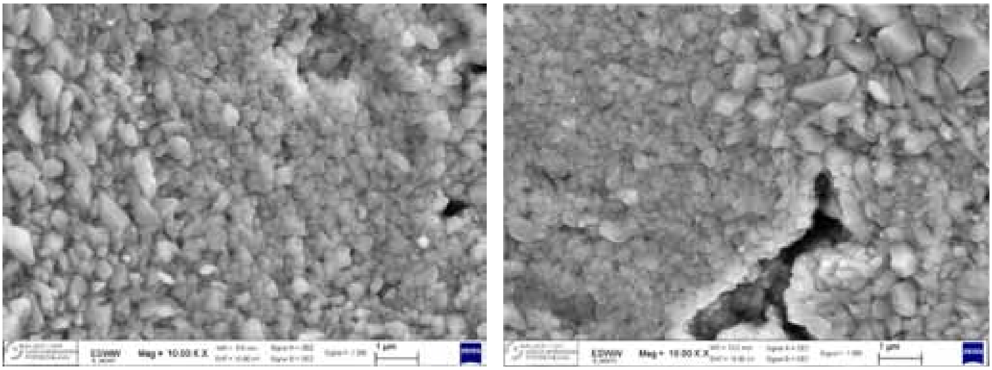


Fig. 4: The surfaces of industrially produced 0,6Si-1,4Mn DP grade (left) and 0,25Si-1,8Mn DP grade (right) are completely covered with Fe_2Al_5 layer.

Adhesion of the zinc coating was tested with standard dynamic impact test according to SEP1931 and a glue bead test, a specific laboratory test introduced by a car manufacturer. Samples showed good coating adherence in both tests. Therefore good galvanisability could be testified for the newly developed grades.

Concept 3: Grain refinement

Grain refinement has several advantages that contribute to high hole expansion. By refining the ferrite grain size, the ferrite matrix is strengthened. Therefore, the hardness difference between the phases is reduced, leading to less pronounced stress concentrations as explained above. The second advantage of grain refinement is that the martensite fraction can be reduced without a loss in tensile strength. Reducing the martensite volume fraction retards crack propagation. Refining the martensite also reduces banding. In the examples presented here, grain refinement is achieved by precipitation control of microalloying elements (mainly Nb and Ti) and by optimization of annealing parameters. A powerful means is the cooling rate. Rapid cooling leads to grain refinement and a more uniform distribution of ferrite and martensite i.e. reduced banding. These effects reduce the potential crack nucleation sites. In case the setup of the annealing line allows doing so, tempering of martensite is helpful for stress relaxation and better coherency between the phases during forming.

Fig. 5 shows the microstructures and mechanical properties of some recent trials for the products DP600, DP800 and DP1000. These grades are optimized based on the considerations described above for a high hole expansion (marked with “E”). It must be stated that all three steels presented in this figure contain less than 0.1 wt.% carbon. One can clearly see the fine grained microstructure of the DP’s.

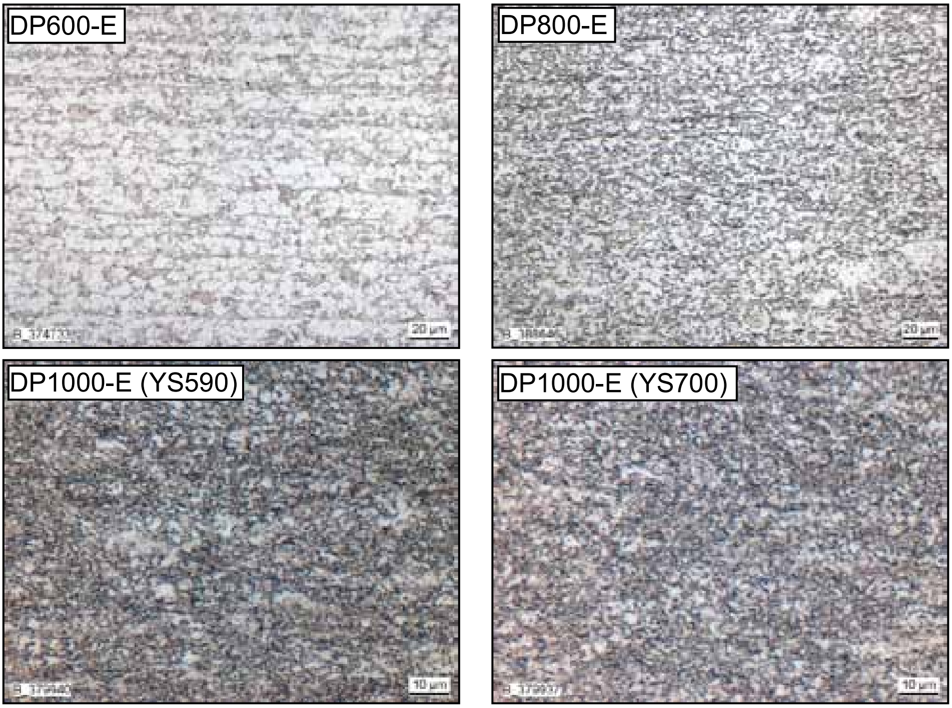


Fig. 5: Microstructure DP600-E, DP800-E and DP1000-E.

Fig. 6 shows the specification ranges of the yield and tensile strength as well as the minimum value of the total elongation. The grey bars are the values for the hole expansion ratio that can be additionally achieved for these grades. For the DP1000, different yield strength levels from low (>550 MPa, not shown here), standard (>590 MPa) to high (>700 MPa) can be realized. Increasing the fraction of bainite can be helpful in this case.

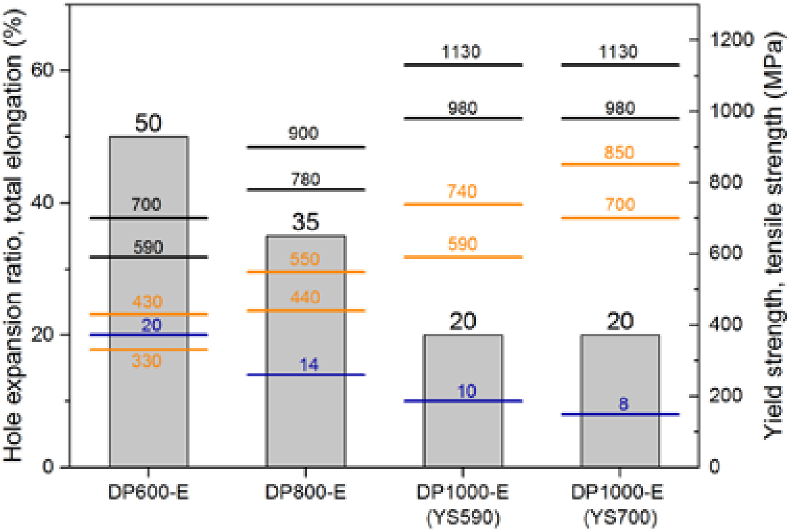


Fig. 6: Mechanical properties of DP600-E, DP800-E and DP1000-E. Ranges for yield strength, tensile strength and total elongation are according to VDA 239-100, hole expansion ratio is a particular definition by Salzgitter Flachstahl GmbH.

Fig. 7 shows the result of a benchmark study that compares the DP600-E with cold rolled and annealed reference materials of the same strength level. While all material fulfill the requirements according to VDA 239-100, the material DP600-E exhibits the highest hole expansion value. This was achieved by careful adjustment of the processing conditions, leading to a fine grain size, reduced hardness difference between ferrite and martensite and avoidance of microstructure banding.

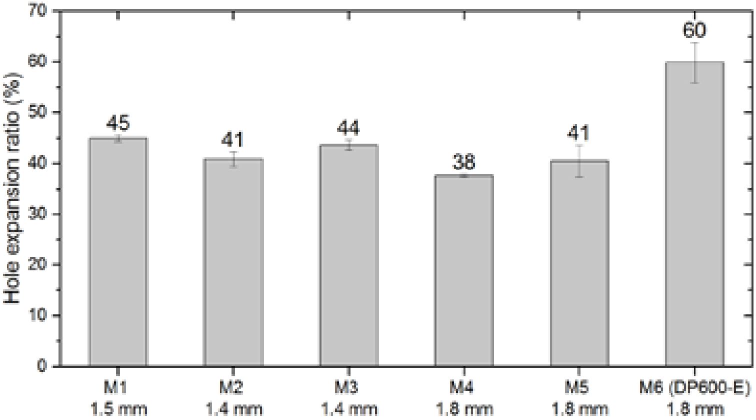


Fig. 7: Benchmark study on hole expansion ratio of DP600, tested according to ISO 16630.

Conclusions

The concepts introduced in this paper led to the development of a new group of cold rolled, hot dip galvanized DP steels that are characterized by high hole expansion ratio (HER). By careful adjustment of the chemistry and the processing conditions, the following hole expansion ratios can be realized:

- at least 50% for a DP600-E
- at least 35% for a DP800-E
- at least 20% for a DP1000-E (YS590 and YS700)

The most relevant mechanism to achieve high HER is the hardness difference between ferrite and martensite, which can be reduced by grain refinement, lowering the carbon and manganese content or strengthening ferrite by silicon and/or microalloying e.g. with Nb. A certain fraction of bainite is beneficial as well, however, it should be limited to avoid the loss of the typical DP steel properties.

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