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New Multiphase CP and DP 1000 MPa strength level grades for improved performance after hot forming

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Abstract. Pure martensitic steels have after hot forming limited performance in terms of rest ductility which limits the application in crash relevant parts. New steel grades were designed in the EU project HOTFORM including the corresponding process routes. These steel grades have ferritic-martensitic dual phase (DP) and martensitic-bainitic complex phase (CP) microstructures after hot forming process. The laboratory tests show an improved formability after hot forming. The basic concepts of the new alloys are explained. Furthermore, for validation of upscaling purposes a semi-industrial test is carried out and the results are discussed. The main application is for vehicle safety. This is evaluated by comparing the crash performance of these hot formed grades with cold rolled DP1000 and CP1000 for crash cans in a drop tower test.

1. Introduction

In automotive lightweight design, AHSS components are one of the preferred alternatives, since they allow downsizing vehicle structures in a cost effective manner. Different AHSS grades are used according to the component required functionality, structural, stiffness, crash behaviour, ...

Cold forming of AHSS grades, in the range of 1.000MPa, implies high resulting springback and press force, limited formability, reduced post-forming ductility and low stretch flange-ability, several operations needed for manufacturing complex geometry parts and large scrap is produced after trimming the addendum and blank-holder areas. HOTFORM proposes a new route for manufacturing multiphase AHSS grades (DP type and CP type), where the annealing stage, from the steel processing, is performed at the press shop, heating the blank sheet in a furnace and then hot forming the part, with cooled dies. This will be achieved by optimized steel alloying design and dilatometry testing and characterization, aiming at ensuring the stability of the required phase transformation kinetics over the combined thermal and deformation gradients, produced during hot forming. The benefits of hot forming will be: improved formability, no springback, reduced press forming forces, reduced raw material usage and produced scrap, only one forming operation for complex geometries,...

The total energy usage will be optimized, as the energy used for annealing stage, from the steel processing, will be converted in the heating before the hot stamping. Reduced press forces and number of operations will account for production energy savings.

Experimental tests will validate the new steels. Prototype testing is done by Tecnalia [1]. Edge crack sensitivity at hot forming temperatures is evaluated by VW [2]. An additional pursued benefit will be the possibility of integrating flanging operations during the hot stamping. This will be evaluated with CAE simulations [3].

Semi-industrial hot forming results with subsequent crash performance testing is described in this paper.

2. Alloy design and thermal cycle design

For Dual Phase (DP) alloys, DP1000 steel was taken as reference for developing new alloys with final microstructure consisting of ferrite and martensite. The strategy for designing new DP alloys was based on applying an inter-critical heating and fixing the final microstructure at the end of the inter-critical heating (Figure 1). This approach means that the forming stage is done over two-phase microstructure (ferrite + martensite). The austenite is transformed into martensite on the quenching stage, giving rise to ferrite-martensite dual phase structure. Therefore, it is very important to avoid the presence of any undesired phase (pearlite, bainite) that could appear during transfer and quenching. Alloys with elevated hardenability are needed and this characteristic played an important role in the alloying design.
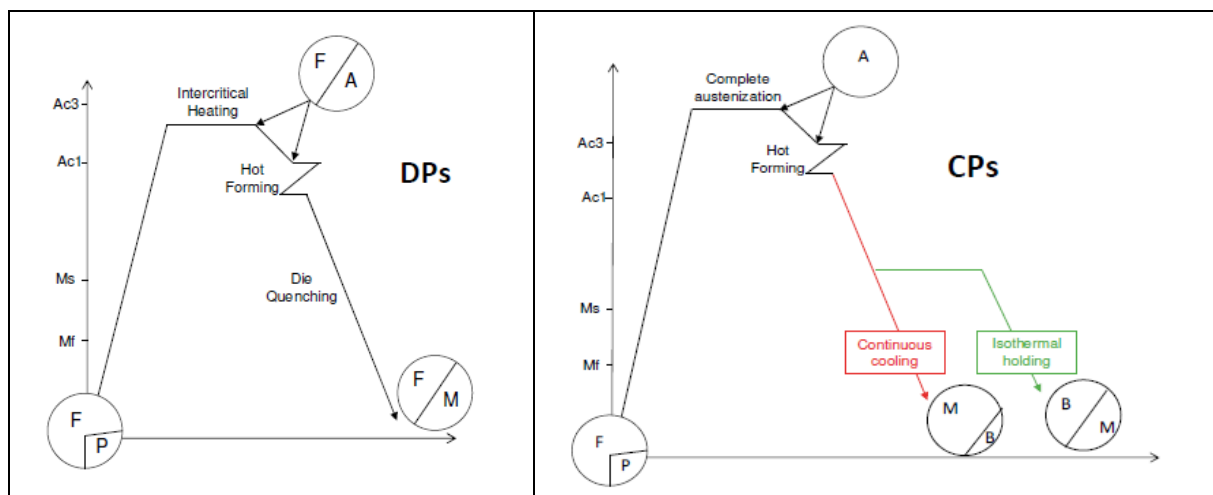

Figure 1. Hot forming cycle for Dual Phase steels (left) and for Complex Phase steels (right)

For Complex-Phase alloys, CP1000 steel grade was the reference for designing alloys with a microstructure consisting of carbide-free bainite (> 90 %), martensite (< 10 %) and few amounts of retained austenite. This microstructure provides high ductility while maintaining the strength. The combination of carbide-free bainite and the TRIP (Transformation Induced Plasticity) effect produced by residual austenite provides the material with improved elongation, whereas the presence of martensite islands contributes to increasing the strength. However, the definition of the process for CP steels is more complicated than for DP steels (Figure 1). The heating stage and the transfer from furnace to the forming die are planned to be as in conventional hot stamping processes (full austenitisation followed by a transfer of the blank sheet in air, avoiding ferrite/pearlite transformation). But, once the blank sheet is located within the dies, a so-called isothermal holding route is followed: first, a quenching within the dies is applied until reaching a given temperature (Tq), at which an isothermal holding is performed. Stopping the quenching above Ms is the preferred option, but a Tq slightly below Ms could be also beneficial, because the formation of a certain percentage of martensite thanks to lowering the temperature below Ms is reported to accelerate bainite formation, acting martensite as nucleation sites for bainite.

For each type of steel 4 variants were evaluated. Based on dilatometer testing and flat tool testing for each steel type 1 composition was selected: DP-A and CP-B

3. Characteristics

3.1. Final properties
The basic properties of the materials after hot forming according to thermal cycles given in figure 1 are listed in table 1 [1].

TABLE 1: Mechanical properties, bending values and microstructure of flat tool samples

Alloy	YS	TS	A80	L Bending (VDA238)	Microstructure
DP-A	613MPa	1186MPa	10.6%	60º	33% ferrite 67% martensite
CP-B	693MPa	1079MPa	7.5%	101º	95% bainite/martensite 5% retained austenite

The mechanical properties are aimed at the specifications of e.g. the VDA239 standard but strength levels are outside the limits. However elongation is much better than specified. Be aware that these are the properties after applying the hot forming cycle for a flat tool. In a real part (e.g. the omega part) the forming will influence the phase transformations and thus properties can vary in the part.
Bending is not specified in standards. The behaviour is as expected: Due to the dual phase character of the DP steel the bending is less than for an almost single phase steel as CP.

3.2. Springback
The advantages of the hot forming operation are improved formability, no springback and reduced press forming forces. This is general and also applies for DP-A and CP-B. Shown here (figure 2) is the end result of a hot formed omega shape with DP-A and CP-B versus cold formed part with DP1000 and CP1000. Clearly visible is the reduced springback.
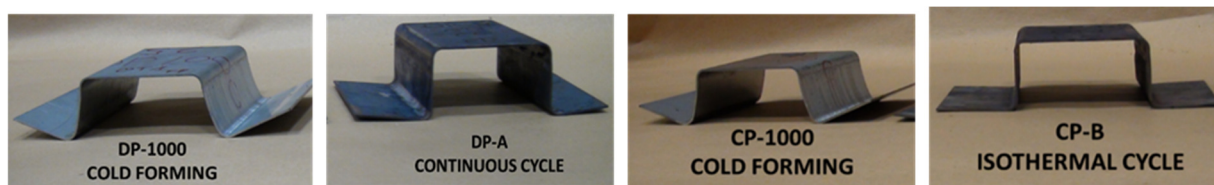

Figure 2. Hot formed parts (DP-A and CP-B) and cold formed parts (DP1000 and CP1000)

Furthermore to be mentioned is that hot forming is crash forming resulting in limited thickness reduction. For these omega parts the thickness reduction of the walls is smaller than 7%.

3.3. Edge-forming behaviour at elevated temperature
Besides bending the edge crack sensitivity is another important phenomenon of local formability. It is important to evaluate these local formability aspects for AHSS as the performance for these aspects for AHSS are limited compared to mild steels and can give rise to (unexpected) failure of forming parts. These aspects of local formability are not captured in standards that only focus on global formability aspects.
The edge crack sensitivity is determined with the hole tension test at relevant elevated temperatures for DP-A (700º), CP-B (800º), 22MnB5 (800º), and compared with DP1000 and CP1000 at room temperature [2]. Measure for high edge ductility determined in this test is the major strain as is shown in figure 3
The low values for major strain for DP1000 and CP1000 is indicating that indeed local formability can be an issue when cold forming parts. The value for DP is lower than for CP due to its dual phase

microstructure. It is obvious that for elevated temperatures the edge ductility is excellent. The values for CP and boron are slightly higher than for DP related to the dominant single phase character of these steels.
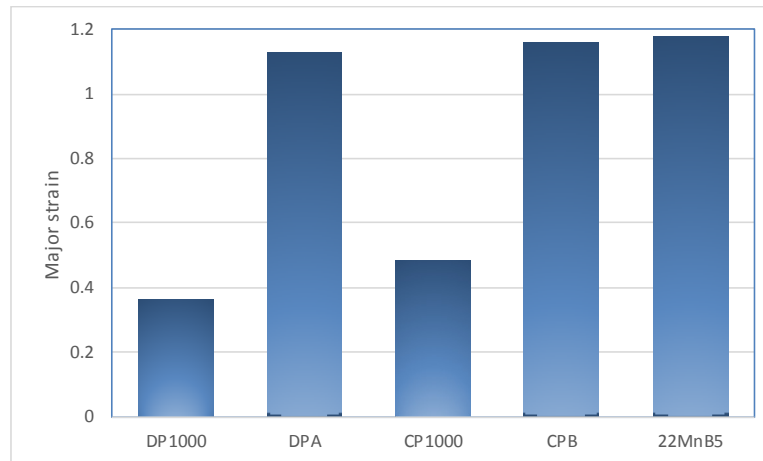

Figure 3. Major true strain values from hole tensile tests

4. Performance

Corrosion performance is a critical driver for automotive applications. For hot forming at present an AlSi coating is applied. However, the main reason for applying this coating is preventing scale formation during hot forming. At the final part this coating is transformed in a AlSiFe layer and gives only passive corrosion protection. A Zn coating is preferred due to its active corrosion protection. Similar to the AlSi after hot forming the Zn coating will be transformed into a ZnFe layer but due to the Zn it will still have active corrosion protection [4]. Main problem why Zn is not applied for hot forming is the sensitivity for microcracking: When the metal is hot, liquid Zn can penetrate or solid Zn can diffuse on the grain boundaries of the substrate giving rise to embrittlement of these grain boundaries. During hot forming the stresses can cause cracks that go into the substrate due to the embrittlement. These microcracks can have an influence on the final performance like crash of a part. This prevents the industry at present to apply Zn coatings for hot forming. It is of interest to investigate the microcrack sensitivity of the new hot form grades. The microcrack sensitivity is dominated by the hot forming cycle. Therefore the microcrack sensitivity was investigated for the two hot forming cycles as shown in figure 1 for the same Zn-coated DP steel. The microcracking was investigated for the walls of hot formed top-hat samples like the ones shown in figure 2. Figure 4 shows a typical image of the cross section for the two hot forming cycles. Clearly visible besides the regular needle like cracks in the coating are the micro cracks down to the substrate
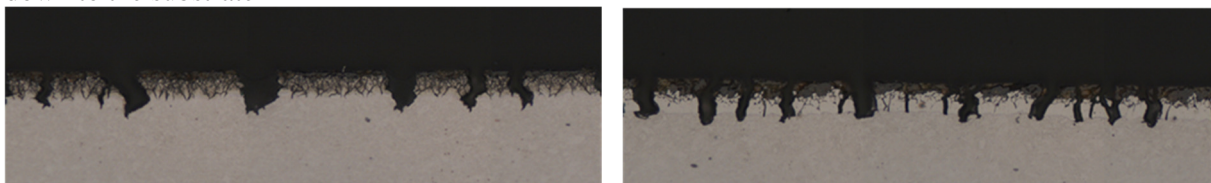

Figure 4. Microstructure of Zn-coated hot formed steel according to DP hot forming cycle (Left) and CP hot forming cycle (right) ; field of view is 500 μm x 150 μm

The quantitative assessment of the microcracks penetrating the substrates is presented in Figure 5. Although the CP cycle used much higher top temperature of 930ºC (see figure 1), surprisingly the crack depth was lower than with DP cycles. The reason behind this peculiar behaviour is that in the intercritical temperature range where the top temperatures of the DP cycles lay, ferrite was present in addition to

austenite. On the other hand, for the CP cycle only austenite is present at the top temperature since the temperature of 930ºC is above the Ac3 temperature of the steel. As Zn diffusion in ferrite is faster than in austenite [5], more liquid phase is formed during reheating during the DP cycles than in the CP cycle, leading to larger microcrack formation in DP.
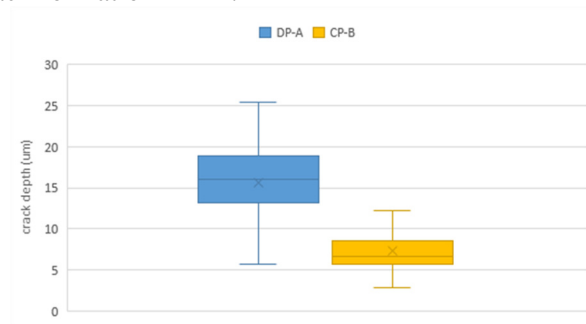

Figure 5. Box plot summarizing the results of microcracking for DP/CP hot forming cycle

The main driver for the application of AHSS in cars is safety. Therefore crashworthiness of the materials is an important properties of the materials. The crashworthiness is evaluated by a crash-test which in this case is a drop test of a weight of 1000kg 1m above a crash-profile. The crash-profile is this case are two omega profiles spot welded together (see figure 6). Figure 6 also shows some examples of crashed crash-profiles

Figure 6: Dimensions and examples of crashed crashcan for DP-A (top) and CP-B (bottom)

There are two important issues to be evaluated from a crashtest: The crashworthiness and the energy absorption. Concerning the crashworthiness it is important that the integrity of a crashprofile is maintained. This means that the crashed profile should be regularly folded without cracks. As can be observed in figure 6 there are no cracks in DP-A and CP-B. Thus crashworthiness of DP-A and CP-B is OK.. The energy absorption can be determined from the recorded profiles from the crash test. Examples are shown in figure 7
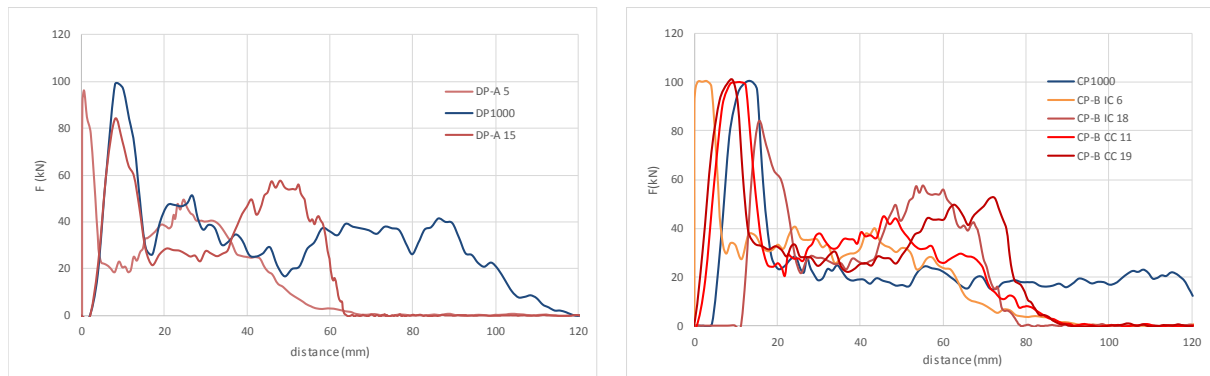
Figure 7. Force-displacement curves for DP-A (left image) and CP-B (right) (value indicates trial number and IC, CC explained in figure 1)

At first glance it looks from figure 7 that the hotformed materials have a much better crash performance as the cold formed DP1000 and CP1000. Unfortunately the comparison cannot be done so straightforward because the gauges of the cold formed materials are thinner (1.2 mm for DP1000 and 1.3 mm for CP1000) than the gauges of the hot formed materials (1.5mm). A general guideline for crash absorption energy is that the axial crush force scales with $t^{1.6}$. Correcting results with this factor unfortunately still does give scattered results. The reason for this remaining large scatter is that there was no trigger applied in the crashprofiles due the limited height of the profiles. This causes a non-uniform folding of the crash-profiles resulting in scatter of the displacement curves which makes the assessment of the energy absorption for the various grades impossible. Nevertheless the crash distance is small due the high strength of the different grades thus the crash energy absorption is good. In general the energy absorption over distance will scale with strength and thickness. The importance of the crash test is not to validate this scaling but to check crashworthiness. This is problematic with hot formed boron steels. Now with these hot formed materials a good crashworthiness can be obtained

5. Conclusions
Two new steels of the dual phase (DP) and complex phase (CP) families and their associated hot forming thermal cycles to be applied on them have been developed as alternative materials for automotive parts that are currently made of cold stamped steels in the range of 1000MPa for tensile strength. Stamping at high temperatures is evaluated and shows benefits compared to cold forming. In terms of application performance the new steels show good crashworthiness

Acknowledgment

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