DUAL PHASE STEELS FOR AUTO BODY:
DESIGN, FORMING AND WELDING ASPECTS

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ABSTRACT

There is an obvious trend of increasing material strength in the BIW. The good combination of strength, formability and weldability of DP steels provides a possibility to reduce weight and improve crash performance. Necessary considerations regarding strength, energy absorption and fatigue are outlined in this paper in order to serve as a help for obtaining the best design solutions.

High strength DP steels have superior formability when compared to microalloyed steels of the same strength, but inferior formability when compared to deep drawing steels. This can lead to design problems for the engineer who only has experience in mild stel constructions. In order to identify the strengths and limits in terms of formability, results from several formability tests are presented and compared to deep drawing steel.

Dual phase steels can be welded with all conventional welding methods currently used in the automotive industry (resistance spot welding, laser welding, arc welding). In resistance spot welding conventional single pulse welding can be used. Best results are here achieved with increased electrode forces and longer weld times.

KEYWORDS

Dual phase steels, design, formability, spot welding, laser welding, arc welding.

INTRODUCTION

The microstructure of dual phase steels consists of ferrite and martensite. Simply spoken the ferrite, which is a soft phase, gives a low yield point and the martensite, which is hard, gives the strength. The strain hardening of dual phase steels is much higher than for HSLA steels, which is beneficial both in terms of formability and energy absorbtion capacity.

There is an obvious trend of increasing material strength in the BIW. The good combination of strength, formability and weldability of DP-steels provides a possibility to reduce weight and improve crash performance.

The high strength of DP-steels is favourable from a design point of view. However, the high stresses and thin gauges put increased focus on finding a solution where the sheets are loaded in skin action and where local plate action can be avoided. Further challenges are local buckling effects, loss in stiffness, robustness and fatigue issues. Fortunately there are measures to be taken in order to deal with the challenges mentioned above, but the matter calls for appropriate attention.

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The formability of high strength dual phase steels is in general superior to microalloyed steels of comparable strength. But the concept of formability is very complex and not possible to describe with a single number or parameter. Still today, formability is described by a number of comparative tests, such as the Erichsen test and the limiting dome height test. A more recent formability measure is the forming limit diagram. In this paper a series of formability tests on high strength dual phase steels are presented, with the objective to give a wide picture of their formability.

Resistance spot welding is the main joining method currently used in the automotive industry. Laser welding and arc welding are also used. All these welding methods can be used for joining of dual phase steels. In the paper results from welding tests together with welding recommendations are presented for the dual phase steels.

The denomination of the DP steels in this article is as follows. Docol stands for cold rolled steel, Dogal stands for hot dip galvanised. The digits in the denomination stands for the minimum tensile strength in the transverse direction. The ending DP, DL or DPX refer to standard, low yield point and reverse bending quality respectively.

1. DESIGN ASPECTS

1.1 STATIC STRENGTH AND STIFFNESS

Dual Phase steels are available with high initial yield strength. In addition to this they exhibit a very pronounced work hardening and also a bake hardening effect in case of an increased temperature subsequent to deformation, i.e. painting of formed parts.

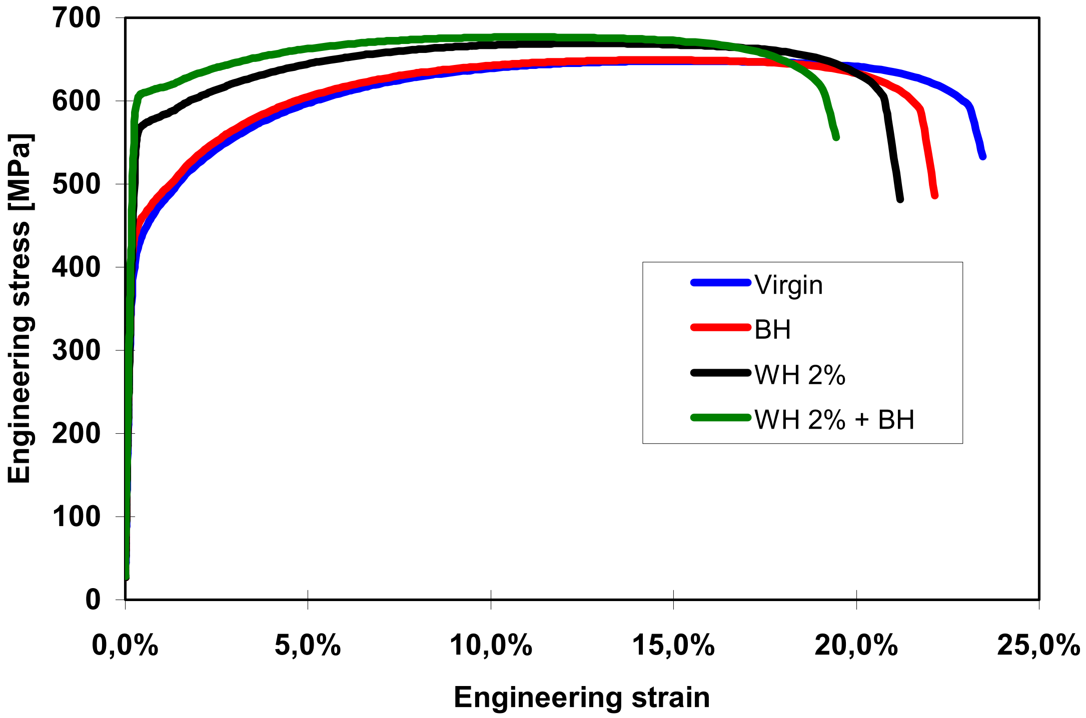

Figure 1: Engineering stress versus engineering strain for Dogal 600DP.

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As can be seen in Figure 1 the level of work hardening is significant already at moderate levels of strain, i.e. comes into play also when mapping the result from the forming stage. Typically the work hardening effect is about 200 MPa at a strain of two percent and the corresponding bake hardening effect about another 50 MPa for a typical painting process.

The high strength levels of DP-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 case of skin action there is a membrane stress state and in case of plate action there is a bending stress state, c.f. Figure 2.

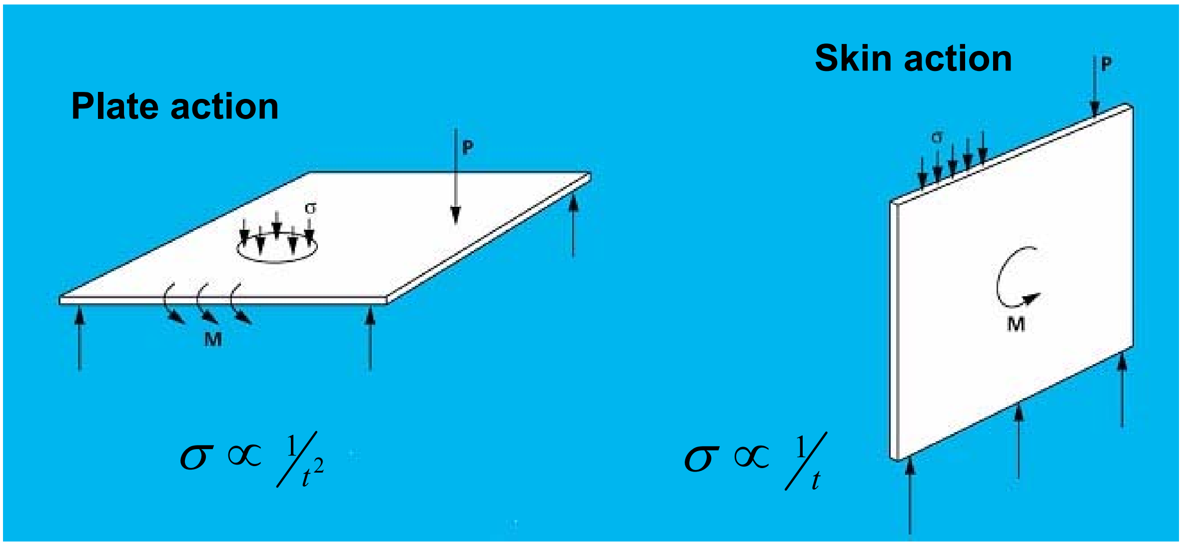

Figure 2: Plate- and skin action.

In case of skin action the stress is linear 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 1 this effect is presented as the level of weight reduction for different steel grades. The numbers within brackets are the yield strength at two percentage strain and after bake hardening. In many true cases the possible weight reduction is between these two extremes. The bending case is not a conservative lower limit due to the fact that local buckling may occur in slender designs.

Table 1: Possible weight reduction for skin- and plate action.

Steel grade	Possible weight reduction assuming **skin** action	Possible weight reduction assuming **plate** action
Mild steel (200MPa)	-	-
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 bending.

Since Young’s modulus is equal for mild steel and high strength steel, stiffness is lost in the same proportion as the reduction in gauge. This will also affect the NVH characteristics (Noise, Vibration and Harshness).

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Challenges and measures

As mentioned above local buckling may occur when reducing the gauges in an upgrading process. This is initially an elastic instability phenomenon and there is no influence of the strength of the material. Local buckles will form at compressed (and sheared) regions at stresses below the plastic limit and the full potential of the material will not be used. Fortunately there are measures to be taken. All sorts of stiffeners may be introduced in order to reduce the slenderness of the compressed regions, c.f. Figure 3.

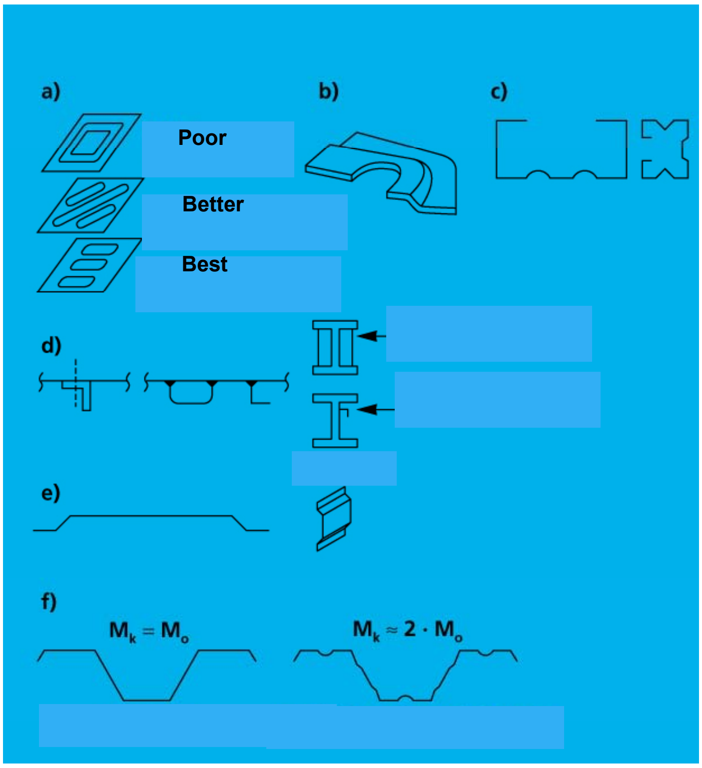

Figure 3: Examples of stiffeners. a) indentations b) stiffening by pressing c) grooves and edge folds d) additional stiffeners e) joggling f) example where the bending moment capacity is doubled by use of stiffeners [1].

Geometrical aspects also play an important role when it comes to finding a high strength solution with good stiffness and NVH characteristics. For instance the loss in stiffness from reducing the gauge may be compensated for in a weight effective way by increasing the height of a beam subjected to bending. Among other actions, continuous joining (laser welding, adhesives etc), closed sections and geometrical stiffeners may be mentioned.

1.2 ENERGY ABSORPTION

The high strength levels mentioned above ensure a potential for good energy absorption, favourable 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 1, is the area below the stress-strain curve up to a limited level of strain, say 10%. 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).

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$$E \propto R_m^{0.5} t^{1.5} \qquad (1)$$

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.

DP-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.

Challenges and measures

A challenge when it comes to using advanced high strength steels for energy absorption is to secure a robust behaviour. For instance progressive folding gets harder to achieve in axial crushing as the material strength increases. Aspects of interest are triggers (mechanical or thermal, soft regions at natural folding distances), the global geometry and inserts or foams.

1.3 FATIGUE STRENGTH

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. So 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.

Challenges and measures

However, there are several actions to be taken in order to use Dual Phase 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).

2. FORMING ASPECTS

It is difficult to rank different materials according to their formability. This is due to the concept of formability, which includes varying forming modes such as bending, deep drawing and hole expansion. In this paper the formability of selected DP steels are described according to different tests commonly used to describe formability. Results from tests for bending, reverse bending, deep drawing, stretching and hole expansion are presented and compared to a deep drawing quality, DC04. All results are for 1 mm thick material. Forming limit diagrams of the same steels are also presented. A collection of test samples is given in Figure 4.

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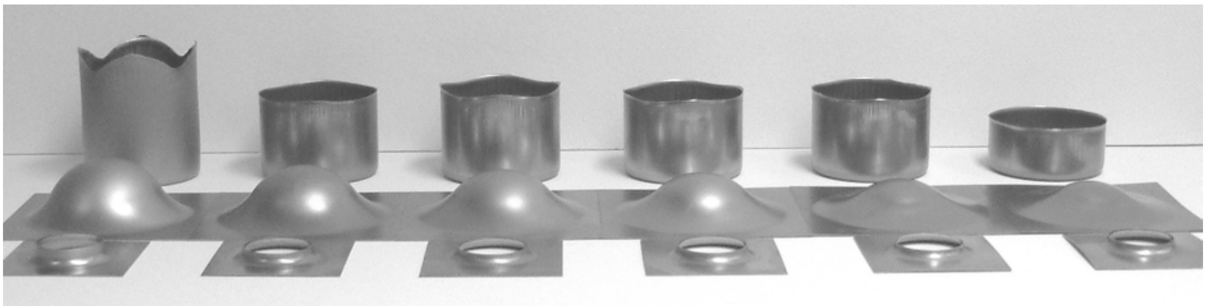


Figure 4. Test samples from deep drawing tests, stretchability tests and hole expansion tests. Materials are from left to right DC04, Docol 600 DL, Docol 600 DP, Docol 800 DP, Docol 1000 DP, Docol 1400 M.

Quite often the formability of a given material is related to the total elongation or the n-value. The total elongation for cold rolled materials is normally measured in a tensile test, as the percentual elongation before fracture of an 80 mm reference length. The n-value is the exponent in the Ludwik-Hollomon expression, Equation (2), determined from the true stress-true plastic strain curve.

$$\sigma = K\varepsilon^n \tag{2}$$

The total elongation and the n-value can give an indication to the formability of a material, but they are insufficient to completely characterise the formability of any material. Minimum total elongation and typical n-values for a selection of DP steels are given in table 2.

Table 2. Mechancial properties of selected steels. All values are minimum transversal values except Rp02 and Rm for DC04 which are maximum. K and n-values are typical.

Material	Rp02 MPa	Rm MPa	A80 (%)	n-value @ true plastic strain range	K MPa
DC04	210	350	38	0.20 @ (0.10-0.15)	470
Docol 600 DL	280	600	20	0.17 @ (0.002-0.16)	1030
Docol 600 DP	350	600	16	0.15 @ (0.002-0.10)	1070
Docol 800 DP	500	800	8	0.11 @ (0.002-0.08)	1250
Docol 1000 DP	700	1000	5	0.09 @ (0.002-0.06)	1440
Docol 1400 M	1150	1400	3	0.07 @ (0.002-0.03)	2060

2.1 BENDING

Bendability is defined as the minimum internal radius to which the material can be bent without any tendency to cracking. It is measured by bending the sample to 90˚ or 180˚ after unloading and then inspecting the sample for cracks. Mild steel, such as DC04, can be bent to a sharp radius in 90˚ bending and even in 180˚ degree bending. Also the DP steels can be bent to a sharp radius in 90˚ bending up to the 600 MPa tensile strength level. Above this strength level a certain minimum internal bending radius must be used to prevent fracture. At the 800 MPa level, the minimum recommended internal bending radius is one time the thickness of the sheet. At the 1000 MPa level, the minimum recommended internal radius is three times the sheet thickness. The martensitic steel Docol 1400 M has a minimum internal bending radius of four times the sheet thickness.

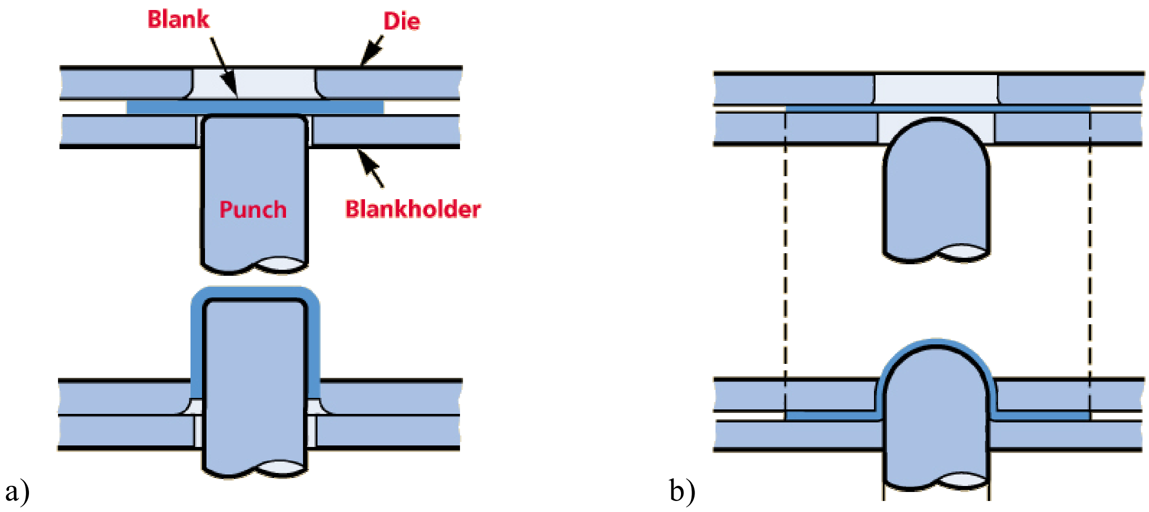
The bendability is in general lowest when the bend is made parallel to the rolling direction. The values stated above refer to bending parallel to the rolling direction. The bending radius can therefore in general be made somewhat sharper if the bend is made in the transverse direction.

2.2 REVERSE BENDING

If the bending is made back and forth, similar to when the sheet glides over a draw bead, the process is known as reverse bending. Reverse bending can also occur in forming operations involving more than one forming step. If reverse bending is done many times the material can fracture even if the minimum bending radius is safe in single bending. In such cases the minimum radius may have to be increased compared to the single bending case. Another possibility is to choose a DP steel specially adapted for reverse bending. SSAB Tunnplåt has developed a range of hot dip galvanised DP steels especially suitable for reverse bending. These steels are denoted DPX. In other forming operations than reverse bending, these steels have the same formability as the conventional DP grades.

2.3 DEEP DRAWING

The deep drawing test consists of drawing a circular blank down into a die with the use of a punch. Figure 5a shows the process. The drawing ratio is defined as the ratio of the diameter of the blank and the diameter of the punch. The punch diameter is normally 100 mm. The limiting drawing ratio, LDR, is the maximum drawing ratio that can be obtained, that is, the largest blank that can successfully be drawn into a cup without fracture.



a) b)

Figure 5. a) Deep drawing test. b) Stretching test

Deep drawing qualities can have limiting drawing ratios of up to 2.5. The LDR’s of high strength DP steels are lower but are almost independent of strength level. From the 600 to the 1000 MPa tensile strength level a limiting drawing ratio of about 2.0 is achieved. DP steels at the 500 MPa strength level reach drawing ratios of 2.1 – 2.15. The martensitic steels however have lower LDR. Docol 1200 M and Docol 1400 M for instance only reach drawing ratios of about 1.7.

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2.4 STRETCHING

If the blank is clamped between the die and the blank holder, for instance by the use of draw beads, no material can be drawn into the die opening. In this case the material that is initially in the die opening area will be stretched by the punch, see Figure 5b.

The ability to stretching is defined as the height of the stretched dome, H, divided by the diameter of the punch, d. H is the maximum height that is possible to stretch without fracture. The stretchability, H/d, of selected materials are shown in Figure 6. A hemispherical punch with 100 mm diameter was used. The stretchability of the DP steels decrease with strength, but it is still considerable at the 600 MPa tensile strength level.

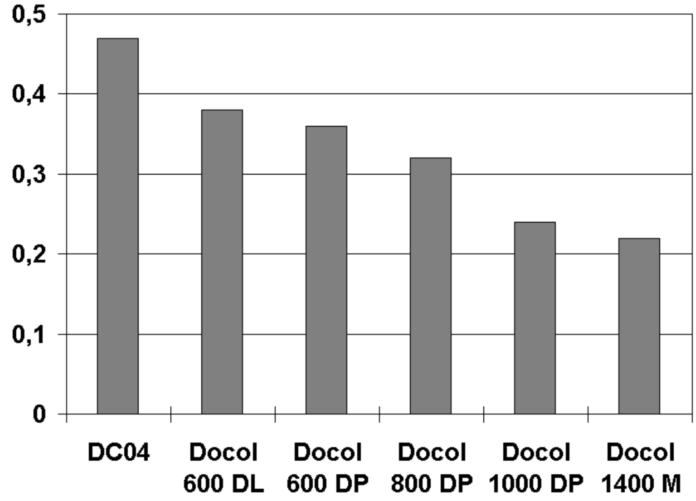

Figure 6. Stretchability, H/d, of selected materials.

2.5 HOLE EXPANSION

The formability of a cut edge in tension can be tested by hole expansion. A cut edge cannot be deformed to the same extent as a continuous sheet surface, due to the crack initiation points on the edge. The hole expansion test was performed on circular punched holes, which were expanded through the use of a cylindrical punch with conical top. The test was considered successful if all of the tool could be driven through the hole without fracture on the edges, see Figure 7a. The hole expansion ratio is defined as the ratio between the diameter of the cylindrical part of the punch and the diameter of the punched hole, or ∅punch / ∅hole. The base diameter of the conical punch was 50 mm, the die opening 54.5 mm and the die radius 10 mm. All results refer to hole expansion with the edge burr facing inwards.

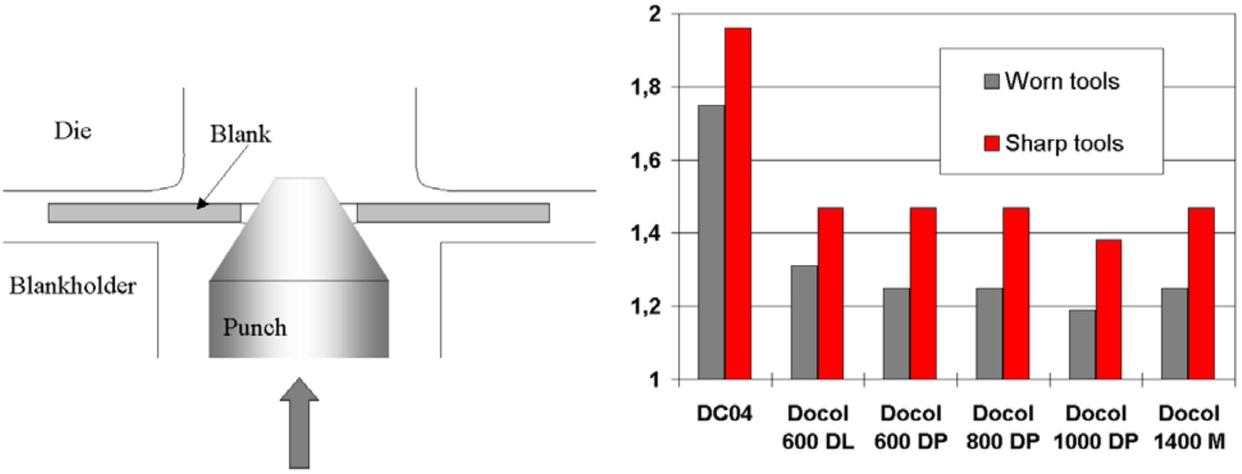

Figure 7. a) Hole expansion test. Arrow indicates punch movement. b) Hole expansion results.

The difference in hole expansion capacity between worn tools and newly sharpened tools can be seen in Figure 7b. It is of great importance to use high quality tool steels when punching DP steels.

2.6 FORMING LIMIT DIAGRAM

The forming limit diagram is used extensively in finite element simulations to judge if a stamping operation can be done without fracture. The forming limit curves of a selection of materials are shown in Figure 8. All curves in Figure 8 refer to 1 mm thick material. The curves were determined by the Nakazima method using a 2x2 mm grid and the samples were oriented so that the fracture occurred in the transverse direction.

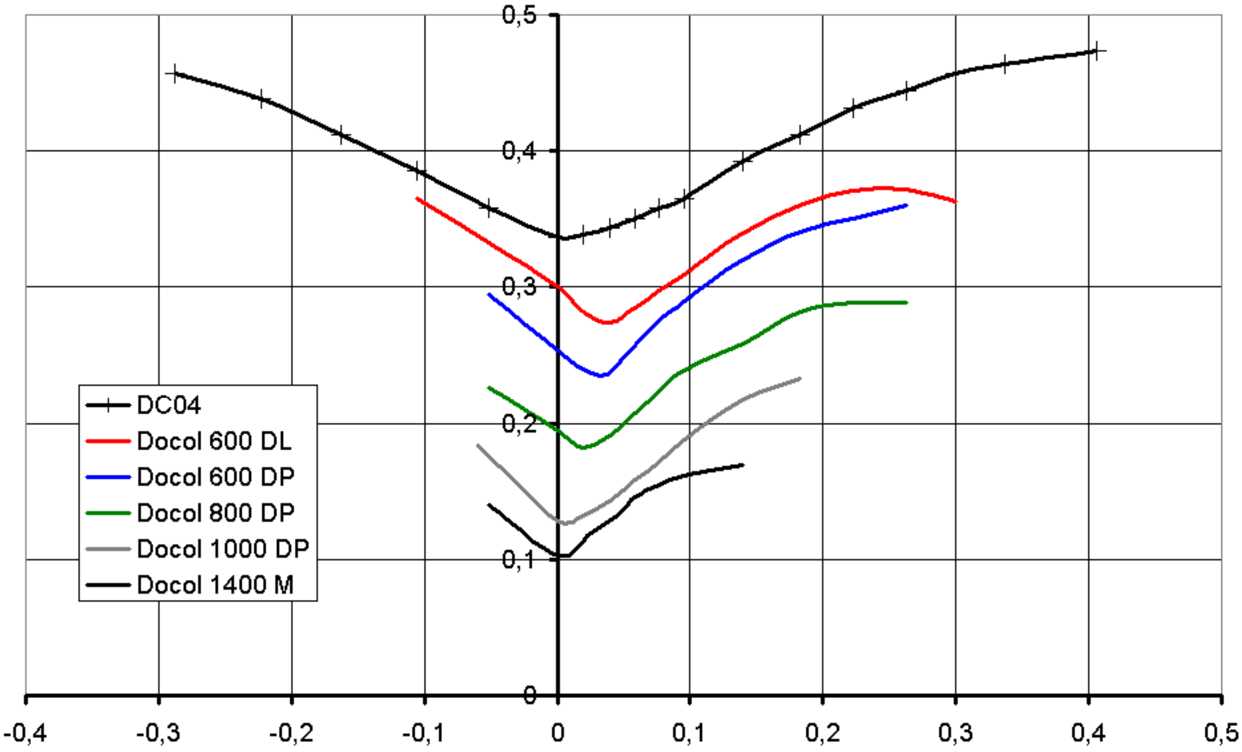

Figure 8. Forming limit curves. Units of logarithmic strain.

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3. WELDING ASPECTS

3.1. SPOT WELDING

Resistance spot welding has been used for many years in the automotive industry. Although other joining methods have been introduced resistance spot welding is still the primary joining process for sheet steels in the auto body production. When using resistance spot welding for joining dual phase steels different issues have to be considered e.g. suitable spot welding equipment, weldability, fracture mode and mechanical properties.

Dual phase steels can be welded with both AC and MFDC spot welding machines and conventional single pulse welding can normally be used. The best results are obtained if the electrode force is somewhat increased compared to what is normally used for mild steels. It is also beneficial to use slightly longer weld times. The dual phase steels can be welded with both truncated cone and domed shaped electrodes.

Weld growth curves (weld size vs. weld current) and weldability lobes form the basis of weldability studies. These give a means of comparing the welding current range capable of producing acceptable welds for a particular welding schedule (electrode force/weld time combination) for different steels. The width of the weldability lobe gives information of the anticipated tolerance of a particular welding schedule in production. The aim is to maximise the welding range to achieve the greatest safety margin on weld quality.

In Table 3 results from weldability studies are shown for some of the dual phase steels (two sheet joints, same steel in both sheets). Besides the available welding current ranges (ΔI) the maximum plug diameter and fracture mode are given. These results show that wide welding current ranges can be obtained for all dual phase steels when optimised welding parameters are used. Dogal 1000 DPX is a new hot dip galvanized dual phase steel from SSAB Tunnplåt, which will be introduced on the market in a near future. Despite a slightly higher amount of alloying elements for this steel in comparison to the other dual phase steels rather good welding results have been obtained. Regarding fracture mode plug failure is often a quality requirement in destructive tests. In the tests described in Table 3 plug failures were obtained for all dual phase steels. In general plug failures are obtained for Docol 600 DP/DL, Docol 800 DP/DL and Dogal 600 DP. For the other steels of higher strength (Docol 1000 DP, Dogal 800 DP and Dogal 1000 DPX) plug failure is also normally obtained but in some cases also partial interfacial failures are observed. It is especially for thick sheets (>1,7 mm) it can be difficult to always achieve plug failures.

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Table 3: Available welding current ranges (ΔI) in resistance spot welding of uncoated (Docol) and zinc coated (Dogal) dual phase steels. Cross tension tests, AC (50 Hz), single pulse, electrode type B (flat tip for Docol steels and tip with radius for Dogal).

Steel 1 / steel 2 (thickness, mm) (coating)	Welding data1)	ΔI2) (kA)	Max plug diameter3) (mm)	Fracture mode
Docol 800 DP (1.5) / Docol 800 DP (1.5)	6/4.0/15/10	2.0	8.0	Plug failure
Docol 1000 DP (1.2) / Docol 1000 DP (1.2)	6/4.0/14/10	2.1	7.2	Plug failure
Dogal 600 DP (1.0) / Dogal 600 DP (1.0) (Z100)	6/4.5/19/20	1.7	8.1	Plug failure
Dogal 800 DP (1.5) / Dogal 800 DP (1.5) (Z140)	8/4.0/17/10	3.1	8.2	Plug failure
Dogal 1000 DPX(1.6)/Dogal 1000 DPX(1.6) (Z140)	8/4.0/22/10	2.0	7.4	Plug failure

1) Electrode tip diameter (mm) / electrode force (kN) / weld time (cycles) / hold time (cycles)
2) Available welding current range (minimum plug diameter = $4\sqrt{t}$ mm).
3) Plug diameter close to the splash limit

In general the spot weld strength increases with increasing sheet thickness and weld size. The material strength has also an influence on the weld strength. This influence is however different for shear and cross tension loading. Fig 9 shows the influence of material strength on shear and cross tension strength for three Docol dual phase steels. The shear strength increases along with the material strength up to the 1000 MPa level. Tests with steels of even higher strength (fully martensitic “Docol M” steels) have shown that the shear strength continues to rise also beyond the 1000 MPa level. The cross tension strength also increases along with the material strength up to the 600 MPa level but the cross tension strength increases less rapidly. Then contrary to the shear strength the cross tension strength does not increase any more. The cross tension fracture load of Docol 600 DP is as high as the cross tension fracture load of Docol 1000 DP. Tests with the martensitic steels of higher strength than 1000 MPa have shown that the cross tension strength for these martensitic steels is even lower than for these dual phase steels. These results demonstrate that the greatest benefit of spot welds is in shear and in design peel or tension loading should therefore if possible be avoided.

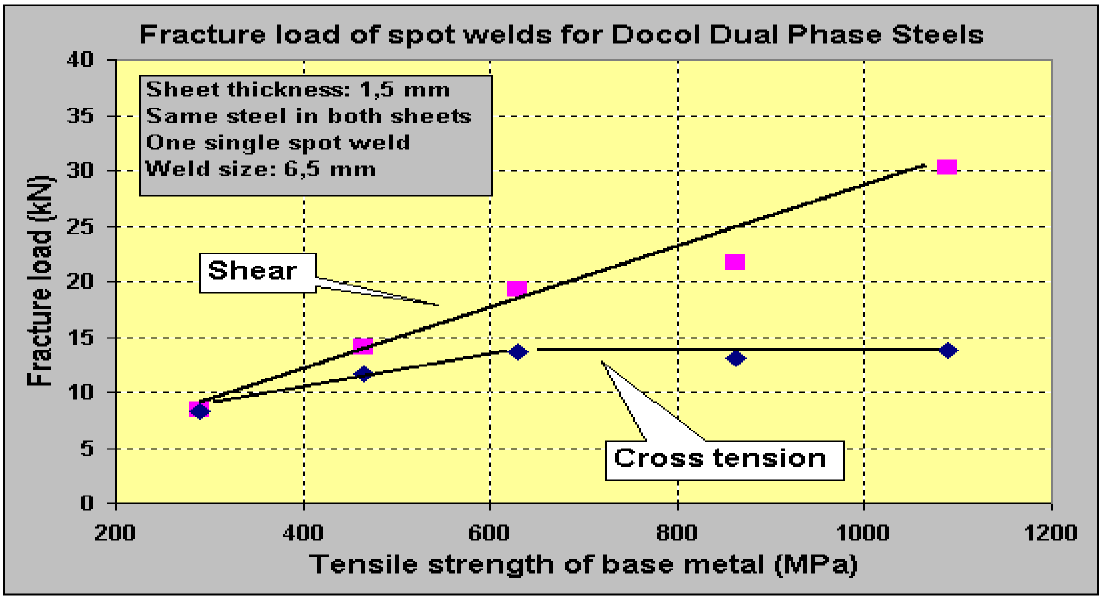

Fig. 9: Fracture load of spot welds (shear and cross tension) for Docol dual phase steels (DP600, DP800, DP1000). Two steels of lower strength included as reference.

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3.2. LASER WELDING

Laser welding can be used for the dual phase steels, both in the production of tailored welded blanks (TWB) and for assembly welding. In the case of laser butt welding and tailored welded blanks a good quality edge and a good fit-up is needed to achieve good results. These requirements are similar for dual phase steels and mild steels. Bad edge preparation can create an undesirable underfill on the topside of the weld.

If a tailored welded product is intended for use in a forming operation a stretchability test (Erichsen cup test) is normally used for the evaluation of the formability of the laser weld. All Docol DP and Dogal DP steels show good stretchability values (see Fig 10, stretchability = 100 x the ratio of stretchability of weld to stretchability of base metal). The hardness of the laser welds for DP steels is higher than for mild steels (see Fig 10) but despite this fact good stretchability values can be achieved for the DP steels. The reason is that the factor, which mainly determines the stretchability is the difference in hardness between weld metal and base metal and these values are not so much higher for dual phase steels compared to mild steels. To obtain such a high stretchability value for Docol 1000 DP, which is shown in Fig 10, it is important to use a high laser welding speed to avoid soft zones in the HAZ. If the hardness of the laser weld for the DP steels is too high a pre- or post heating treatment can be used to reduce the hardness (e.g. with a high frequency induction device close to the sheets).

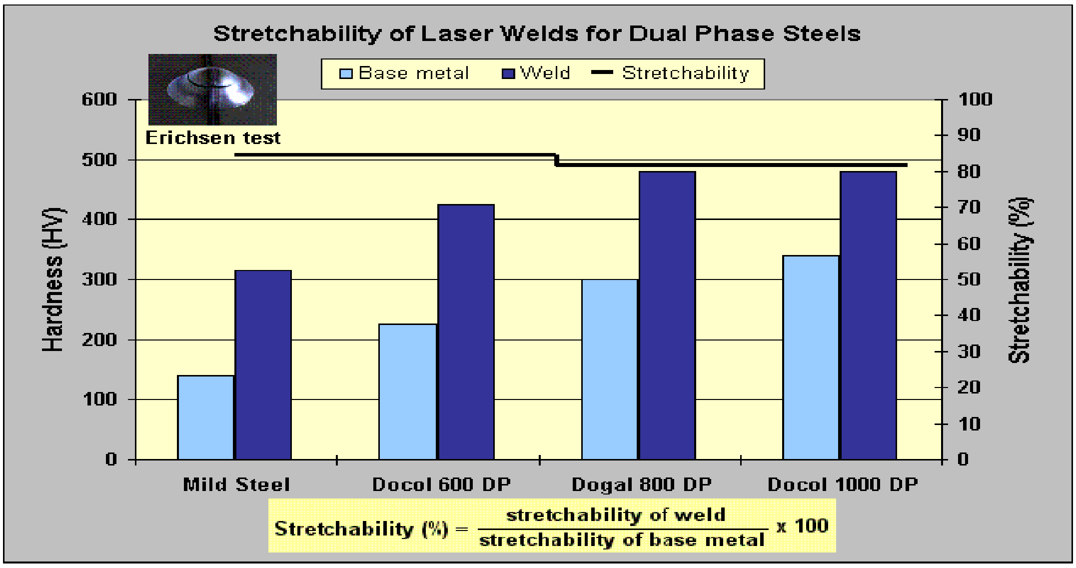

Fig. 10: Hardness and stretchability of laser welds for Docol DP and Dogal DP steels. Butt welds with both sheets of the same thickness (1,2 mm). The Erichsen test is used for describing the stretchability.

In assembly laser welding different kind of overlap joints are often used. It can be a fillet weld (edge weld) or a conventional overlap weld. For overlap welds with thin sheets often full penetration in the lower sheet is utilized due to an easy quality control process in this case. For overlap welds with thicker sheets approx. 50% penetration in the lower sheet can be recommended. In the case of overlap welds in combination with zinc coated steels a small gap (0,1-0,2 mm) between the sheets is beneficial. In this way pores and other defects can be avoided as the zinc can disappear away from the melt. To avoid underfill on the topside of the overlap weld an excessive gap should be avoided.

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3.3 ARC WELDING

Docol DP steels (uncoated)
All common arc welding methods (MAG, TIG and plasma) can be used for welding of uncoated dual phase steels. The same welding parameters and shielding gases as are used for mild steels can also be used for dual phase steels. Normally there are no problems with cracks and other defects.

The strength of the welds for Docol DP steels increases with increasing base metal strength. For the DP steels of very high strength (e.g. Docol 800DP/1000 DP) the strength of the welds may be slightly reduced in comparison to the base metal strength. The reason is small soft zones in the outer HAZ. In the automotive industry single-sided welded lap joints are often used. The strength of a lap joint is lower than the strength of a butt joint. This is due to the unsymmetrical loading and the extra bending moment associated with this type of loading for the lap joint. With an increased strength of the filler metal it is possible to reach only a slightly higher weld strength for the lap joints. In the case of butt joints there is no difference between a low strength filler metal and a high strength filler metal for DP steels (the weakest zone is located to HAZ). Due to these facts often conventional low strength filler metals (e.g. solid wire AWS A5.18 ER70S-6) are used when DP steels are arc welded.

Dogal DP steels (hot dip galvanized)
Zinc coated dual phase steels can be welded in the same way as zinc coated mild steels.
For thin coatings conventional solid wires can often be used and the recommendation in this case is to reduce the welding speed to avoid problems with pores and spatter. For difficult joint geometries (e.g. lap welds and fillet welds) and/or thick coatings a special flux cored arc wire especially developed for welding of zinc coated steels can be used.

4. SUMMARY & CONCLUSIONS

For most components in the BIW, a solution made of DP-steel, with the appropriate grade, can be found. The strength limit, from a design point of view, is given by effects such as local buckling and loss in stiffness, robustness and fatigue. These challenges can in general be dealt with by use of local stiffeners (grooves, folds, flangings etc) to restrain local buckling and increase the stiffness. The loss in stiffness may also be dealt with by geometrical changes and/or by decreasing the pitch distance for spot welding or introducing continuous laser welds. These measures also improve the fatigue situation as well as adhesive bonding.

The formability of high strength dual phase steels has been compared to that of a mild steel and a martensitic steel. The formability of the mild steel is always superior to that of the high strength steels, but in some cases the difference is not so big. The stretching capacity of the dual phase steels is significant, at least in the lower levels around 600 MPa tensile strength. Bending to 90° can likewise be done with a sharp radius at the 600 MPa tensile strength level. The limiting drawing ratio is lower for the dual phase steels than for mild steel, but remains constant up to a tensile strength level of 1000 MPa. The ability to hole expansion is much lower for the high strength steels, and actually goes through a minimum at 1000 MPa tensile strength level. The fully martensitic steel has better hole expansion capacity than the 1000 MPa tensile strength steel, which probably is due to its homogeneous microstructure. The importance of good tool quality and maintenance is obvious. The forming limit curves of the investigated steels look as expected, with levels decreasing continuously with strength.

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DP steels can be welded with all conventional welding methods currently used in the automotive industry (resistance spot welding, laser welding, arc welding). In resistance spot welding of DP steels conventional single pulse welding can be used. It is recommended to increase the electrode force and to use slightly longer weld times in comparison with the welding data used for mild steels. With such an optimisation of the welding data wide welding current ranges can be obtained for all DP steels.

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