A SUPER-HIGH STRENGTH FE-MN-C AUSTENITIC STEEL WITH EXCELLENT FORMABILITY FOR AUTOMOBILE APPLICATIONS

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ABSTRACT

Reduction of gas emissions through lightweighting is among the most important goals of steel users. In general, an increase in tensile strength for a given metallurgy is obtained to the detriment of ductility. ARCELOR and TKS have developed a new super-high strength steel with TWinning Induced Plasticity (TWIP) for weight reduction and improved crash resistance named X-IP 1000. This austenitic product, which is based on a high manganese alloy metallurgy, has a tensile strength greater than 1000 MPa for a total elongation superior to 50%. In this paper we present the various mechanical properties and compare them with conventional high strength steels (HSLA, DP, TRIP, etc.) and formable grades (DDQ). The tensile and forming properties are studied using standard test methods (stretching, bending, etc.). In addition, spot welding parameters and the mechanical behaviour of spot welds are presented. The crash resistance potential is investigated using dynamic tensile testing and dynamic drop weight tests at low temperature. The exceptional mechanical characteristics of this product are perfectly adapted to innovative steel design solutions for automotive body in white components.

KEYWORDS

TWIP, twinning, manganese, austenitic steel, mechanical properties, forming, crash, weight reduction, X-IP.

INTRODUCTION

A variety of steels have been developed for the automotive industry in the last decades, achieving significant progress on safety, fuel economy, dent resistance and comfort. However, safety and comfort considerations involve supplementary equipment and can be in contradiction with the pursuit of lighter weight. In order to contribute to these objectives and to solve these contradictions, formability and high strength requirements of steels increase continuously, leading to the development of new steel grades that could combine both requirements.

High manganese austenitic alloys could form the next generation of ductile high strength steels. Although they were discovered by Sir R. Hadfield as long ago as 1880, they have not yet been proposed in cold rolled format for the automotive industry. Extensive studies have been conducted on the phase diagram and the physical deformation mechanisms of Fe-Mn-C steels (Schumann [1], Rémy [2]). Here also the work of Kim *et al* on Fe-Mn-C-Al [3] and of Grässel *et al* on Fe-Mn-C-Al-Si [4] should be mentioned. ARCELOR & TKS have developed a family of high manganese alloyed steels named **X-IP™** steels [1] in an attempt to achieve the best possible mechanical and in use-properties for the automotive industry [5].

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[1] X-IP™ steels = Xtremely formable + Xtremely high strength steels with Induced Plasticity.
X-IP has been applied for a trademark registration by Arcelor and TKS.

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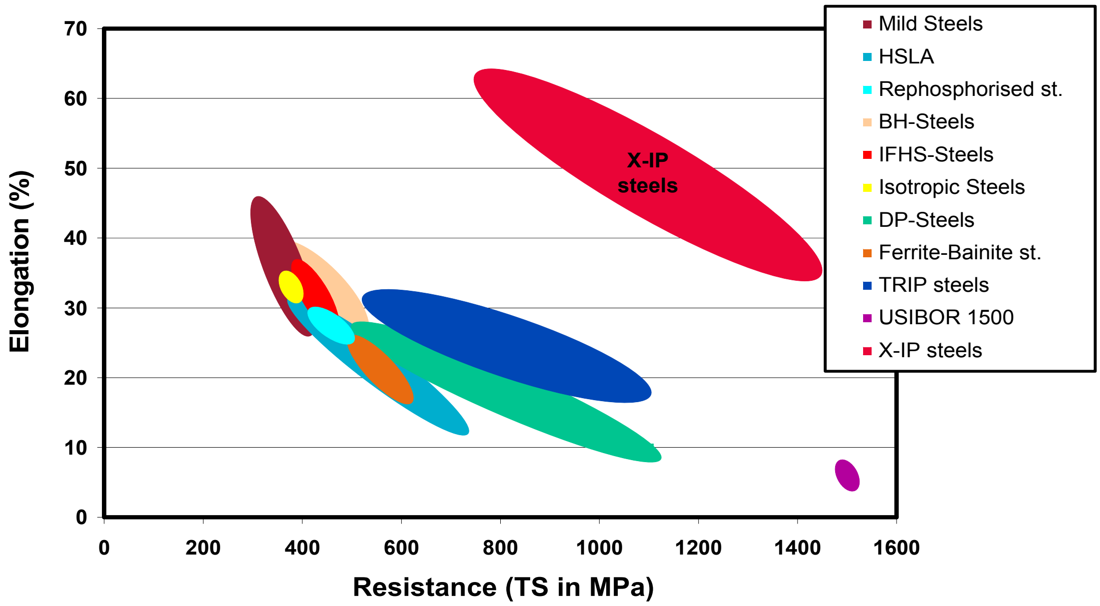

Fig. 1. X-IP steels offer a great improvement of the balance between strength and ductility. The first target material to be implemented is the X-IP 1000 grade.

X-IP steels exhibit the best combination of strength and ductility over the whole range of ductile steel grades for car manufacturing (see fig. 1). Their capacity to be drawn into complex parts is comparable and sometimes even better than the one of mild DDQ steel, but for a strength two to five times higher. Similarly, their tensile strength lies in the range of heat treatable (hardened) boron steels, but their ductility is ten time higher.
A more detailed description of the tensile properties of X-IP 1000 is given in a first part. The unexpected combination of strength and formability is simply explained in a second part through the study of the peculiar microstructure and deformation mode of X-IP steels. Formability and weldability are then discussed. The last part is dedicated to the dynamic properties regarding crash application. Simulations of achievable weight reduction on a simple structure made of X-IP 1000 grade are proposed.

1. TENSILE PROPERTIES

Table I shows X-IP 1000 typical mechanical properties compared with micro-alloyed, dual phase and TRIP steels.

Quality	YS (MPa)	YPE (%)	TS (MPa)	TS at U.El (MPa)	U. El (%)	Total El (%)	n (4% -> Ag)	r (4%->Ag)
HSLA320	342	1.5	428	496	16.0	24.0	0.17	1.27
DP590	342		629	727	15.6	25.9	0.15	2.05
TRIP800	478	0.1	825	998	21.1	27.3	0.22	0.93
DP980	644		1009	1112	10.2	15.0	0.11	1.06
X-IP 1000	**599**		**1162**	**1776**	**52.8**	**52.8**	**0.36**	**1.08**

Table I. Typical tensile properties (transverse direction) of different steel grades and X-IP 1000.

Despite their strength, X-IP steels present a very ductile behaviour and particularly a high uniform elongation. As a consequence, the comparison of X-IP 1000 with other grades becomes a lot more impressive when expressed in terms of true stress, as its strength overcomes 1750MPa (see 5th column on table 1). This is more obvious on a true strain - true stress graphic (fig. 2).

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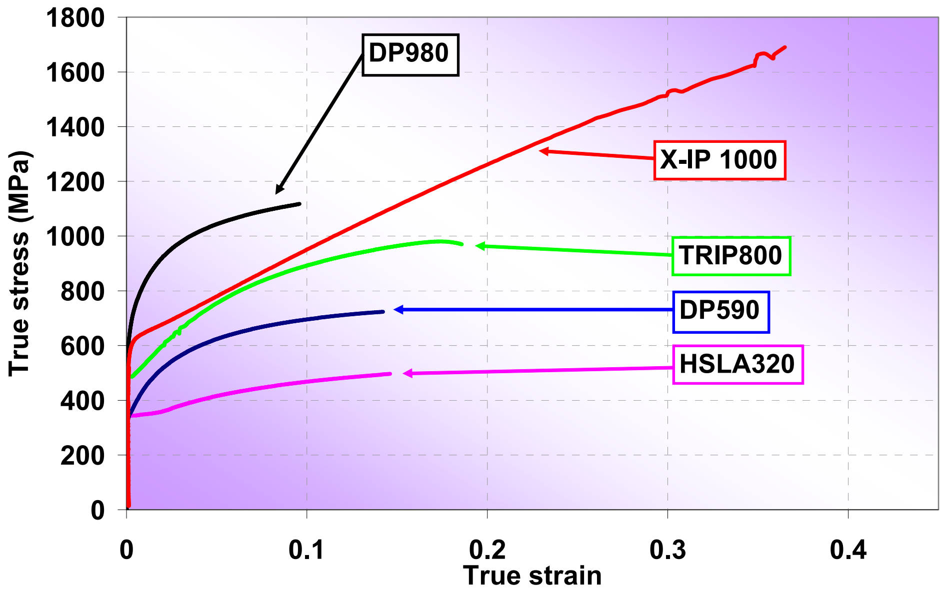

Fig. 2. True strain-true stress curves up to uniform elongation.

This first approach of the tensile properties of X-IP steels already gives a major trend in their use : they have to be highly deformed (>15%) to reach exceptional high strengths on parts. Applications of X-IP steels that could take advantage the most of their potential should thus consider pieces with complex shape obtained by drawing rather than bending. In the particular case of parts for crash application, the energy absorption will be all the more efficient since the design of the fusible piece favors a strong deformation.

This exceptional strain hardening capacity can be more precisely described by plotting the evolution of the instantaneous hardening rate n as a function of the strain (fig. 3).

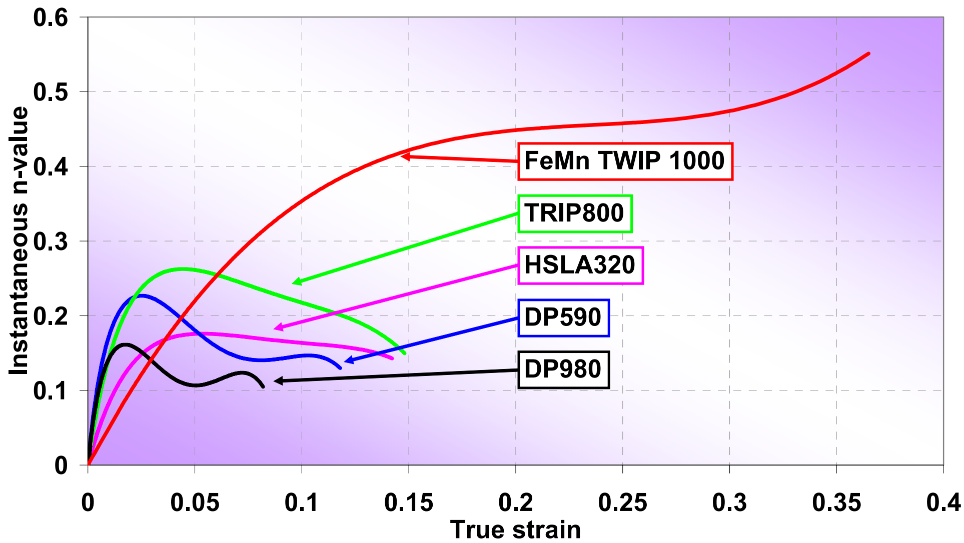

Fig. 3. Instantaneous hardening rate n as a function of the true strain (polynomial fit analysis).

DP and TRIP steels show higher n-value in the first stage of straining (for low elongation). Due to strain-induced transformation of retained austenite in TRIP steels, n-value is uniformly high during loading. For X-IP steel, n-value continues to increase up to a strain of 0,25 and while other steels encounters necking, it remains constant at an exceptional n-value of 0.45. This very high and uniform n-value leads to a good ability to cope with local strain peaks and so to a good strain distribution on part (great security against local necking). The reasons for this very peculiar hardening behavior of X-IP steels are explained in the next part.

2. X-IP STEELS : MICROSTRUCTURE AND DEFORMATION MODE

The mechanical properties of X-IP steels comes basically from two main features :

- the crystallographic structure is fully austenitic at all temperatures,
- twinning is the principal deformation mechanism.

Most of the flat rolled steel grades used in car manufacturing have a microstructure composed either of a soft ferritic matrix (e.g. IF steels) sometimes hardened by microalloying precipitation (e.g. HSLA steels), or a hard martensitic structure (e.g. heat treatable steels), or sometimes a mix of both ferrite and martensite (DP steels). The bainitic phase can also be found in some products and has an intermediate mechanical behavior between ferrite and martensite.
The microstructure can also contain a certain fraction of residual austenite phase like in TRIP or in multiphase steels. This phase offers an interesting combination of strength and ductility, but requires the addition of alloying elements and/or a complex thermomechanical processing path to be partially or fully stabilized at ambient temperature.

ARCELOR & TKS have developed a fully austenitic carbon steel by controlling the concentrations of manganese in the range of 17 to 24% and carbon in the range of 0,5 to 0,7%. The solubility of carbon being much higher in austenite than in ferrite, carbon alloying can be used without any problems to stabilize the austenite and also to strengthen the matrix by solid solution hardening.
The chemical composition was optimized to offer not only the best formability for a given strength level, but also a very stable mechanical behaviour over the range of in service temperature (-60°C to + 80°C).

Another important feature of X-IP steels is their mode of deformation : in addition to the classical mechanism of dislocation gliding, they deform also by twinning inside the grains (see fig. 4). Twin boundaries behave like obstacles to dislocations movement in a similar manner as grain boundaries do [2]. While straining, the density of twin boundaries increases. The instantaneous hardening rate *n* is maintained at a high level (>0,45) as the microstructure becomes finer and finer and consequently necking is rejected to higher strain. This mechanism is thus called Twinning Induced Plasticity (TWIP).

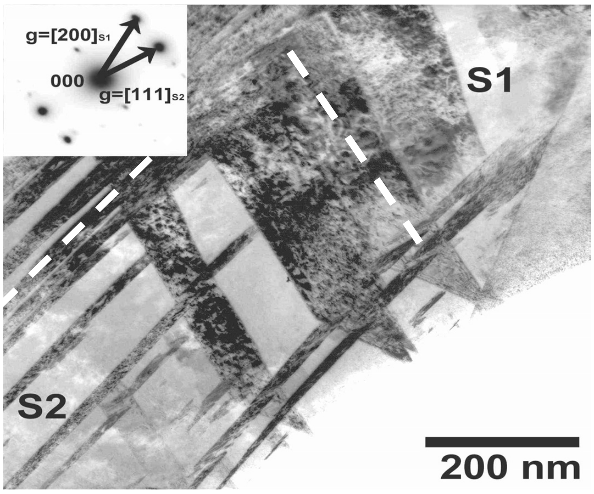

Fig. 4. Dark field TEM micrograph from a X-IP sample strained at room temperature. Microtwins appears in dark. Two competitive twinning systems represented by dotted lines are activated.

TWIP efficiency depends on the chemical composition, the microstructure and the temperature. The challenge ARCELOR & TKS managed to meet was to determine a robust domain of chemical composition and thermomechanical process parameters which lead to a steel grade that extracts the maximum benefits from the TWIP effect.

Outside this domain, TWIP efficiency will diminish and the deformation mechanism will partially or totally move to dislocation gliding or to plasticity assisted by martensitic transformation (TRIP effect). Both mechanisms are less effective than twinning which is a continuous strengthening mechanism: dislocation gliding does not provide a sufficient hardening rate to reach high strength and the TRIP effect cannot lead to such high elongation as it disappears when all the residual austenite is turned into martensite.

3. FORMING PROPERTIES

Uniaxial tensile test results are not sufficient to describe the material behaviour during complex forming operations. This paragraph presents some results on standard stamping trials showing the excellent formability X-IP steels compared with other grades (HSLA320, DP600, TRIP800 and DP980).
A 100mm Marciniak punch and a die of 150mm with lock beads were used to determine the Forming Limit Curve (FLC). The testing speed was 1mm/s and the deformation was recorded online by an optical system monitoring a 2mm rectangular grid applied on the specimen. The FLC thus obtained exceeds largely the one of conventional high strength steel such as TRIP 800 (fig.5). It is even comparable or better than the FLC of deep drawn quality steels like DC06.

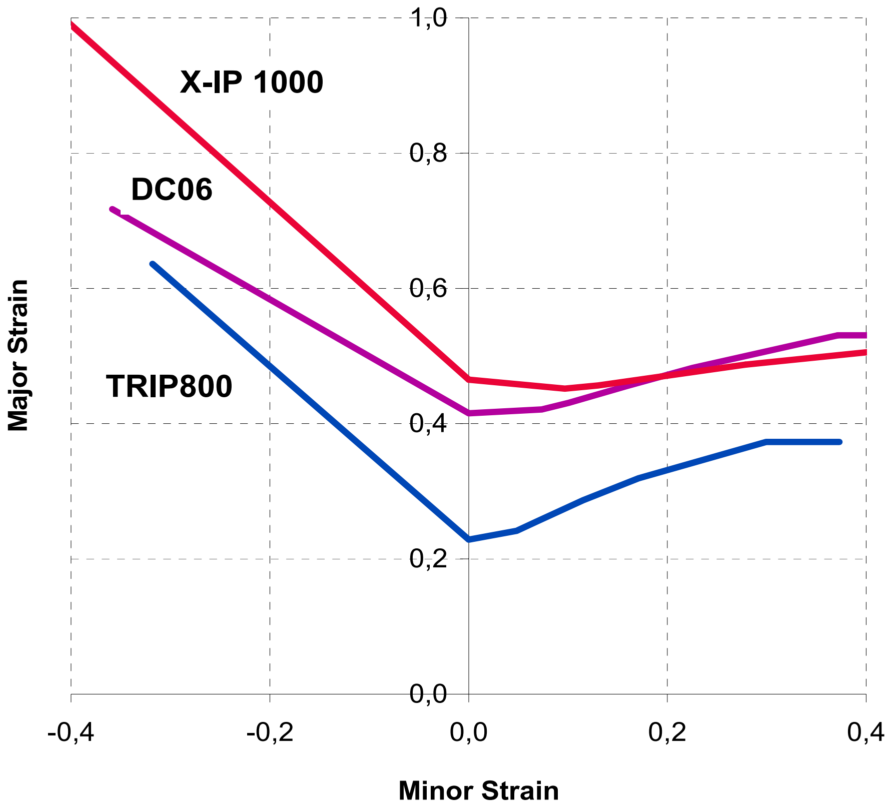

Fig. 5. FLC of X-IP1000 in comparison with DDQ & TRIP steels (thickness = 1.20mm).

This excellent stretch forming capacity comes from the high hardening rate of X-IP that ensures a good strain distribution during press forming. X-IP steel is thus a good choice for deep stamped parts.

The stamping of a piece can encounter difficulties due to an excessive depth to reach. Problems may arise also from the complexity of the shape to be drawn, as the presence on the same piece of areas with different strain paths and strains level favors an early localization of the deformation.

The cross-tool test is well adapted to check this point, as it combines on a single test several deformation modes such as uniaxial tension, plane strain and bi-axial strain.
Results are expressed again as good part height in the most severe case, i.e. for the largest blank size of 300mm x 300mm (fig. 6.).

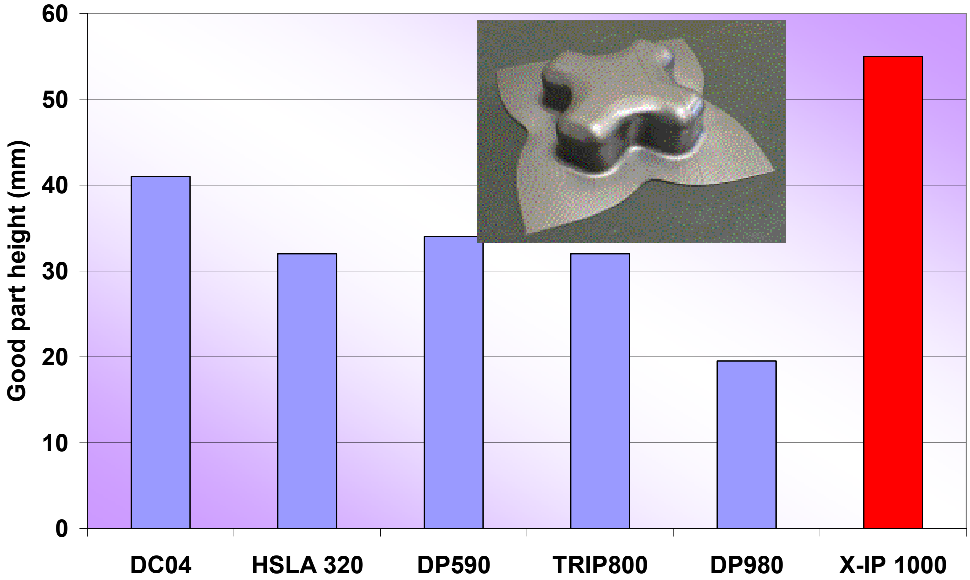

Fig. 6. Good part height in mm as a function of the material in the cross-tool test.

X-IP 1000 steel exhibits very good results when compared not only to grades with equivalent tensile strength but also to mild steels for deep drawing (DC04). The high hardening rate is again responsible of these good results as it delays the occurrence of plastic localization.

Bending capacities were also investigated through a free bending test (folding through 180°). This test is based on the ECCA or NCCA tests to define organic coating formability (flexibility and adherence).Results are given in Table II.

			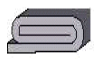	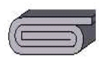
	OT	0,5T	1T	1.5T
HSLA 320	OK			
DP590	OK			
TRIP800	µcracks	OK		
DP980	Failure	Cracks	OK	
X-IP 1000	Cracks	OK		

Table II. Results of bending tests. Specimens were cut in the rolling direction

The behavior of X-IP steel is at least similar to TRIP800 and better than DP980, which have tensile strengths of the same order. Bending in finishing process can thus be applied to X-IP steel without major difficulty.

As a conclusion of these forming tests, X-IP 1000 steel has an extremely good forming behavior compared with other grades with similar or even lower tensile strength, and thus offers an attractive combination of strength and formability for structural and safety automotive parts.

However, it should not be forgotten that due to its high mechanical properties, X-IP steel may exhibit some drawbacks shared with other very high strength steels. An increase of the stamping forces and the tool wear has to be considered. The increase of spring back tendency due to higher strength level must be taken into account as well, although efficient forming techniques can be used to control it (small die radius and die clearance, high blank holder load in case of U-shape for example, overbending, coining radius, restriking tool,…). Stiffness increase of "open" parts using ribs in non-functional areas can also be easily conducted with X-IP due to its very good formability.

4. SPOT WELDING CHARACTERISTICS

Spot welding ability of two-side electro-galvanized 1.5 mm thick X-IP grade was studied in homogeneous and heterogeneous configuration. The mechanical strength of the spot is controlled through cross tensile tests. Both welding configurations were presented in the following table.

	Homogeneous	Heterogeneous
Current type	50Hz	50Hz
Welding force (DaN)	450	450
Welding time	3(7+2)	5(9+2)
Holding time (Cycle)	20	20

Table III. Welding configurations

In spite of a low current level of welding in homogeneous configuration, we obtain an interesting welding range in heterogeneous one (Fig. 7).

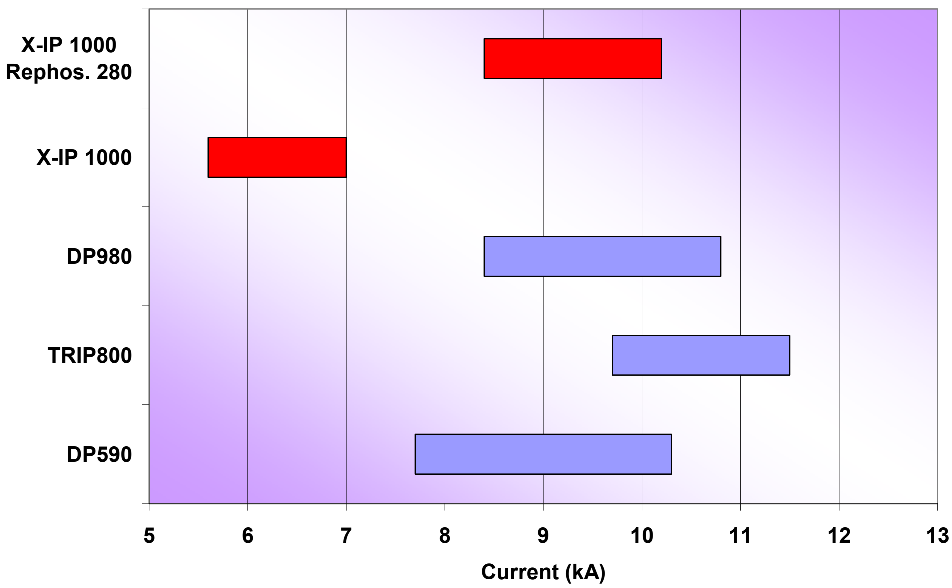

Fig. 7. Welding range in the Cross Tensile Test.

Although the shape of nugget is asymmetrical (Fig. 8), a metallurgical bond is created by element diffusion (C, Mn, …) during welding in heterogeneous configuration. This asymmetrical shape is due to the shift of physical constant of X-IP1000 steel (Electrical resistivity is 3 times higher than ferritic steel)

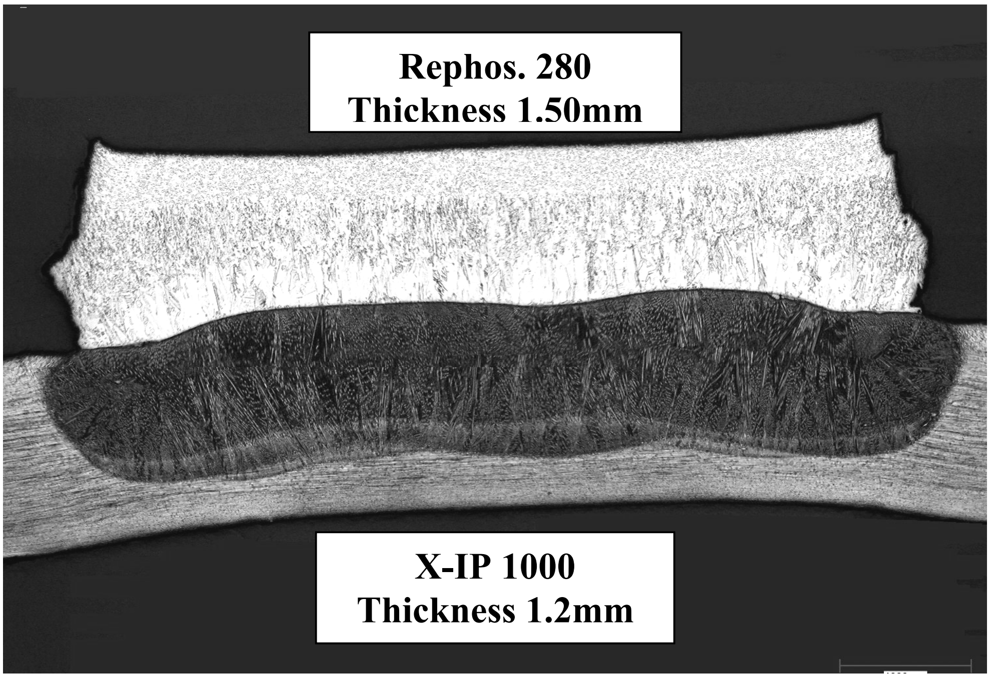

Fig. 8. Unplug and nugget obtained on heterogeneous spot weld X-IP 1000 on a Rephosphorized 280 steel grade. The strips were Zn coated on both faces.

In spite of this difference, the cross tensile rupture is performed by unplug (Fig. 8) and results of this test in homogeneous and heterogeneous are good (Fig. 9).

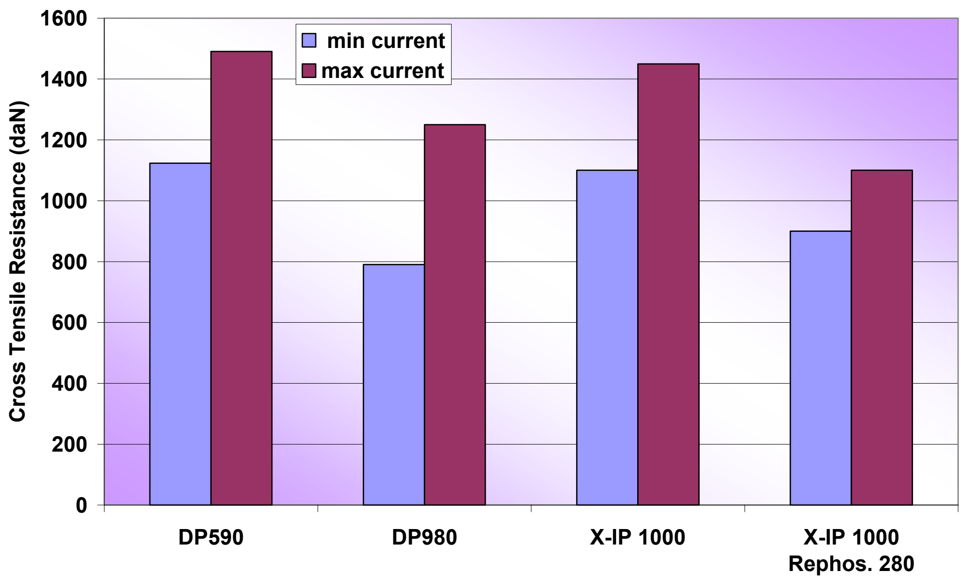

Fig. 9. Good Cross-tensile resistance of spot welds of X-IP assemblies.

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4. CRASH PERFORMANCES

An important criterion for the use of steels in crash application is a ductile dynamic behaviour even at low serving temperatures. The sensitivity to crack formation was examined in dynamic drop weight tests performed at low temperatures from –80°C to +20°C . Deep drawn cups with drawing ratio of 1.8 and 2.0 were placed on inverted cones and impacted by the drop of a 27kg hammer. Details of the test can be found in [5]. Figure 10 illustrates that no cracks were detected even at -80°C. This fact clearly indicates that these steels show enhanced impact toughness and are not sensitive to embrittlement even at very low temperatures and high deformation rates.

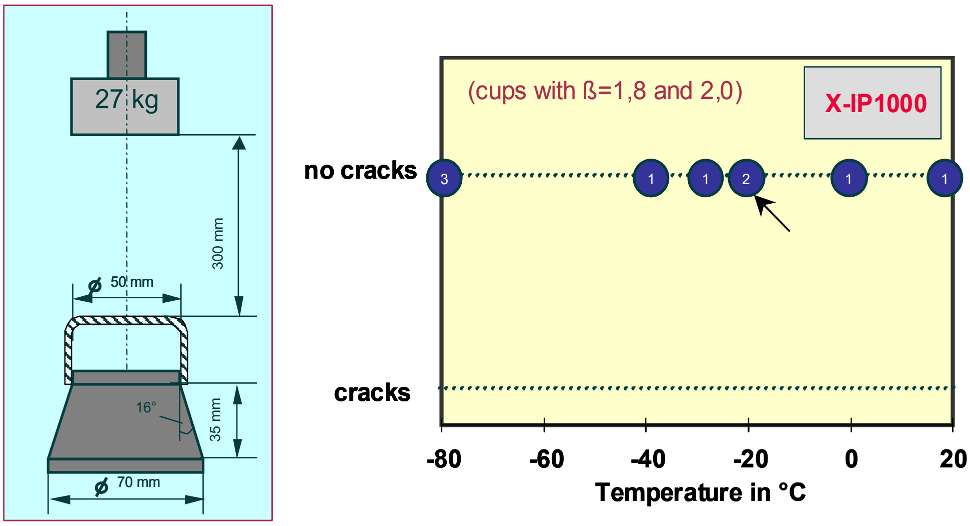
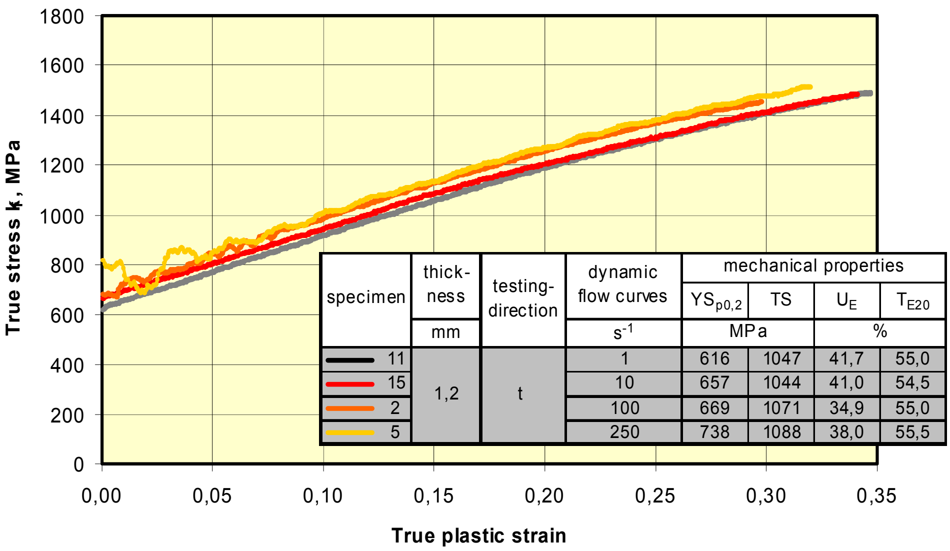


Fig. 10. Results of dynamic drop weight test.

The dynamic characteristics of X-IP steels are of particular interest with regard to the crash behaviour. Tensile tests were therefore conducted at strain rates up to approximately 250s^{-1}. The yield stress of conventional steels increases with increasing strain rate. This increase is less pronounced in the case of X-IP steels (fig. 11) whose strain rate sensitivity is close to 1. The energy absorption potential can be approximated by the area under the dynamic tensile curve. Usual X-IP values are superior to 0,5 J/mm^3 what is at least two times higher than for conventional deep drawing qualities and modern multiphase steels.



specimen	thick-ness (mm)	testing-direction	dynamic flow curves (s^{-1})	mechanical properties: $YS_{p0,2}$ (MPa)	TS (MPa)	U_E (%)	T_{E20} (%)
11	1,2	t	1	616	1047	41,7	55,0
15			10	657	1044	41,0	54,5
2			100	669	1071	34,9	55,0
5			250	738	1088	38,0	55,5

Fig 11. The dynamic flow curves denote a positive strain rate sensitivity of X-IP 1000 in the range of 1s^{-1} to 250s^{-1}.

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Axial compression tests conducted on spot welded hat shaped structures and 3 points bending tests on open cross section structures showed a very good crash behavior of X-IP steel (Fig 13). The figure 12 gives the dimension of the crash sample for the two kinds of crash test. The input speeds are respectively 58km/h for axial compression tests and 29km/h for 3-point bending tests.

Fig. 12. Axial compression tested structure and 3-point bending tested structures after crushing

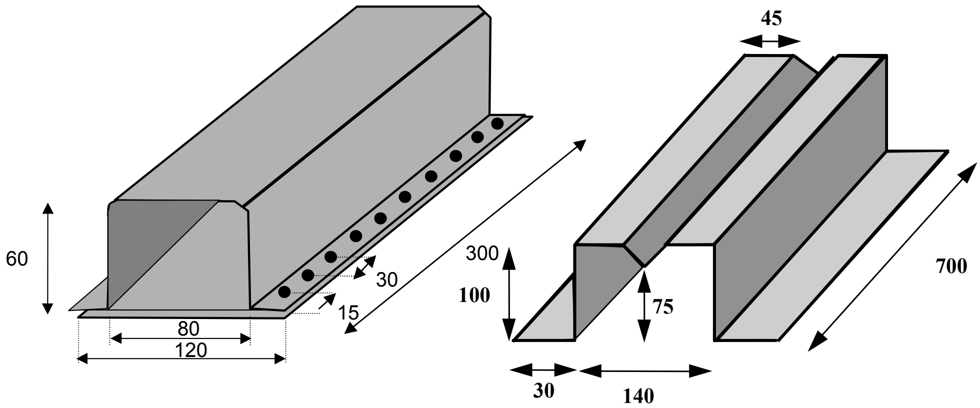

Fig. 13. Axial compression and 3 point-bending tested structures

The following graph (Fig. 14) shows, for the X-IP steel, the level of absorbed energy in axial compression compared to other steel grades with the same thickness (1.5mm). This one is expressed in terms of average crushing force, given for a 150 mm crushing distance. Clearly, X-IP leads to the better results than TRIP800 and similar results than DP980 in the configuration of non-prestain specimens. On this type of fusible parts (compression collapse), X-IP steel permits to obtain great weight reduction in relation with Deep Drawing Quality: 30% without prestrain.

Nevertheless, the high yield strengths on parts, resulting of this high work hardening capacity have to be taken into account during crash simulation in order to use the whole weight reduction potential of X-IP steels.

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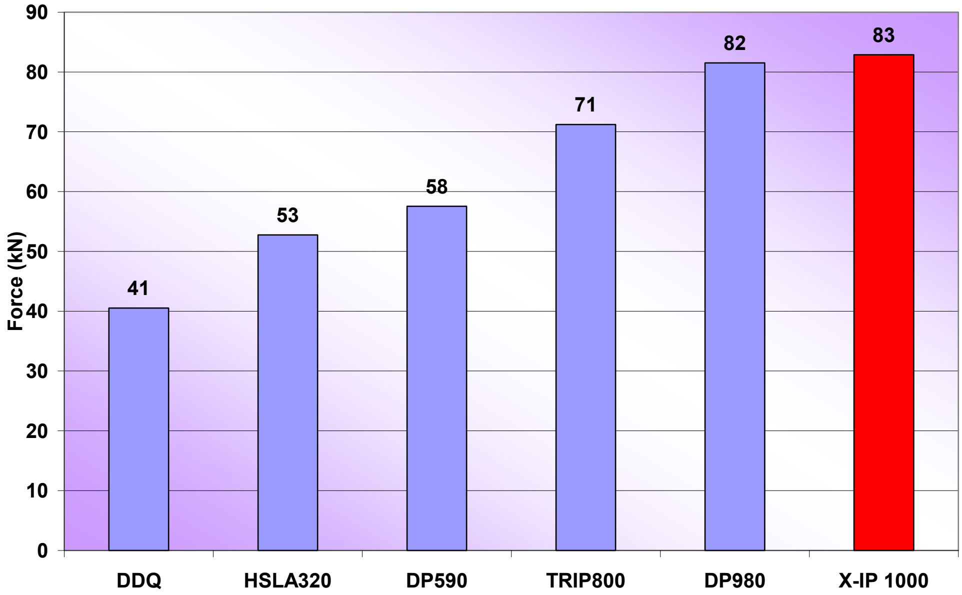

Fig. 14. Average load for 150mm crushing in axial compression

The following graph (Fig.15) shows ultimate load before crushing in 3-point bending for X-IP compared with other qualities with 1.5mm thickness. This test is dedicated to classify our steel grades for intrusion components application.

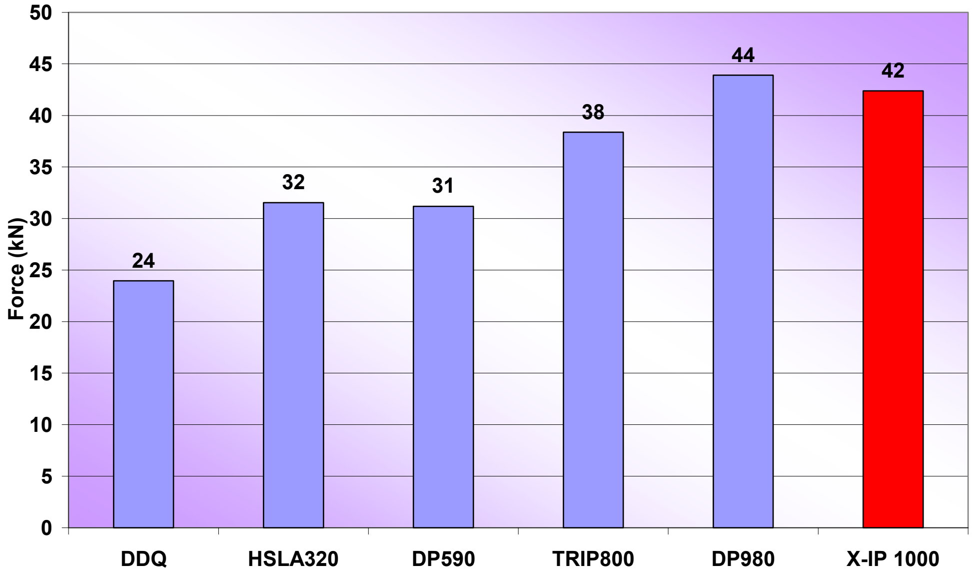

Fig. 15. Ultimate load in 3-point bending (SAE180 filter)

Again, X-IP leads to the better results than TRIP800 and similar results than DP980 in the configuration of non-prestain specimens. On this type of reinforcement parts (bending collapse), X-IP steel permits to obtain great weight reduction in relation with Deep Drawing Quality: 27% without prestrain.

Supplementary progress in safety improvement and lightness is possible with a coordination of product design and steel performance. Space precludes any serious discussion of the possible automotive applications of X-IP^{TM}1000 steels here. A detailed description can be found in reference [6].

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CONCLUSION

X-IP steels are newly developed super high strength steels based on an austenitic Fe-Mn-C metallurgy that deforms by TWIP effect. Their main characteristic is the combination of high strengths with excellent deep-drawing, stretch forming and impact resistance properties that should enable major weight reduction on automotive parts while improving the crash safety.

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