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HyTens® Creates new Opportunities for High Strength Stainless Steel Applications

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The future growth of the stainless steel market is expected to be greatly influenced by new applications of high strength stainless steel. Major contributions will come from applications using temper-rolled grades where the extreme properties of these grades compete with other high strength materials.

*In order to promote the use of temper-rolled grades in new applications, AvestaPolarit has introduced a new product family, **HyTens,** accompanied with advanced technical support to facilitate material choice. New HyTens value added products have also been developed to further promote the grade.*

Introduction

High strength steel is gaining ever greater attention in advanced product design. Many driving forces can be identified, such as decreased weight and increased safety of components or constructions as a whole, especially in the transport sector. However, the cost factor is just as important; using high strength steel often means a lowering of the gauge, which in turn often means a lower final component cost.

This trend is as important for stainless steel as for carbon steel. For many years AvestaPolarit has successfully promoted duplex stainless steel in applications where weight and / or cost have been important issues. This trend is steadily increasing. In duplex steel, strength is obtained through alloying, which creates a favourable microstructure. This is also the main method for producing high strength carbon steel. With stainless steel, cold working also offers a way of increasing strength, a method that is not as effective for carbon steel.

Cold working is a tried and tested technique in the stainless steel world. Well-known products include temper-rolled grades and other prestretched products such as AvestaPolarit grade 304CCS.

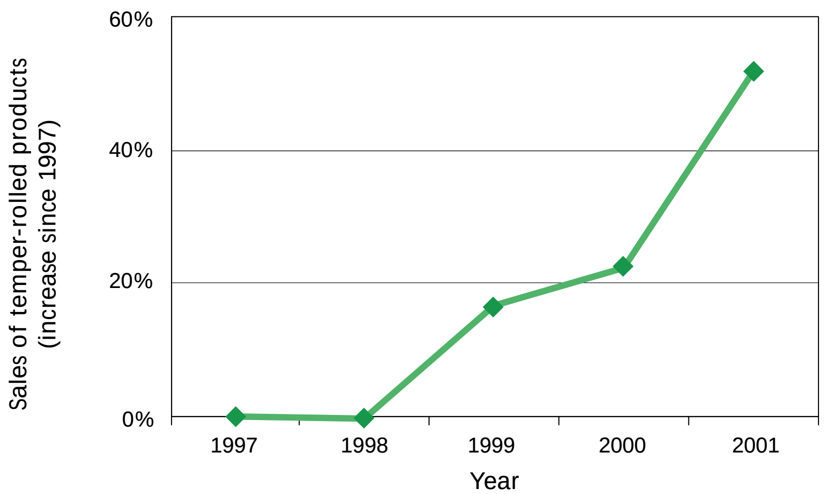

Fig 1. *Temper-rolled sales for AvestaPolarit 1997–2001*

The use of temper-rolled products has increased considerably over the past years, as shown in Fig 1. This growth, which accelerated greatly in 1998, is due both to the introduction of new applications for temper-rolled grades and to the fact that AvestaPolarit has widened the product range up to 1.5 m width and 6 mm thickness. This growth is expected to continue in the future and will be significantly affected by new, high strength applications for temper-rolled products.

An interesting example can be found in the Building & Construction (B&C) sector due to the revision of important standards such as Eurocode 3 parts 1–4. Today, this B&C standard regulates the use of cold-worked stainless steel in constructions up to a proof strength of 2480 MPa. It is also known that on certain markets, steel with a higher proof strength can be used. Work is underway to increase the maximum permitted proof strength in the B&C standard up to 850 MPa, which will give major opportunities for stainless steel to compete in this sector.

Other important contributions to the continued growth of temper-rolled grades are expected to come from the transport, agricultural and construction sectors. Common for most of these new applications will be the challenge of decreasing weight.

In order to further promote the sales of temper-rolled grades, AvestaPolarit has worked actively to find new applications where the focus has been on mechanical properties. An important part of this work has been to introduce a new product family called HyTens. As part of the product package, customers are offered advanced technical support focussing on areas such as design, and forming and joining techniques. Spin-offs from this work have been a number of HyTens value added products.

HyTens®

HyTens is the trademark for a new product family from AvestaPolarit. HyTens can be supplied either as ultra high-strength coil or sheet, designated by a suffix to the brand name expressing the tensile strength (e.g. HyTens 1500), or as coil, sheet or tube, designated HyTens X, where the strength is created during the shaping of the final product. "X" represents the strength level of choice by the designer, see Tables 1 and 2 for mechanical properties.

HyTens grades have a unique combination of strength and ductility compared to carbon steel grades, see Fig 2. They can also be further increased in strength in a controlled manner during cold forming. This can be utilised in various innovative ways with HyTens X as demonstrated below.

The extreme properties of HyTens X can most easily be demonstrated through tensile testing, where the strain axis represents the degree of shaping and the flow stress axis represents the strength of the final component.

Fig 3 shows the increase in strength with the degree of forming (left axis) and the development of the martensitic phase during the test (right axis). Also shown are the possibilities for controlling the final strength, both through the degree of shaping

Table 1: *The HyTens grades*

Grade	$R_{p0.2}$ (MPa) Min., typical	R_m (MPa) Min.	A_{80} (%) Min.	Min. bending radius (*)
HyTens 800	600, 715	800	26	0.5 x t
HyTens 1000	800, 960	1000	17	1.0 x t
HyTens 1200	1000, 1130	1200	13	1.5 x t
HyTens 1400	1200, 1370	1400	5	3.0 x t
HyTens 1600	1400, 1580	1600	3	6.0 x t
HyTens 1800	1600, 1780	1800	1	Do not bend
HyTens 2000	1800, 1980	2000	<1	Do not bend

(*) Bendability of HyTens grades refers to standard bending procedures. However, as a result of patented AvestaPolarit techniques (see BlancForm overleaf), all HyTens grades are bendable to radii less than the sheet thickness, as normally stated for soft annealed grades.

Table 2: *The HyTensX grade*

Grade	Condition	$R_{p0.2}$ (MPa)	R_m (MPa)	A_{80} (%)
HyTens X	As received	300	800	50
	After forming	>1500	>1500	–(*)

(*) Elongation after forming of HyTens X depends on the attained local strength level. This is affected by the component design and often varies over the component (see TensForm overleaf).

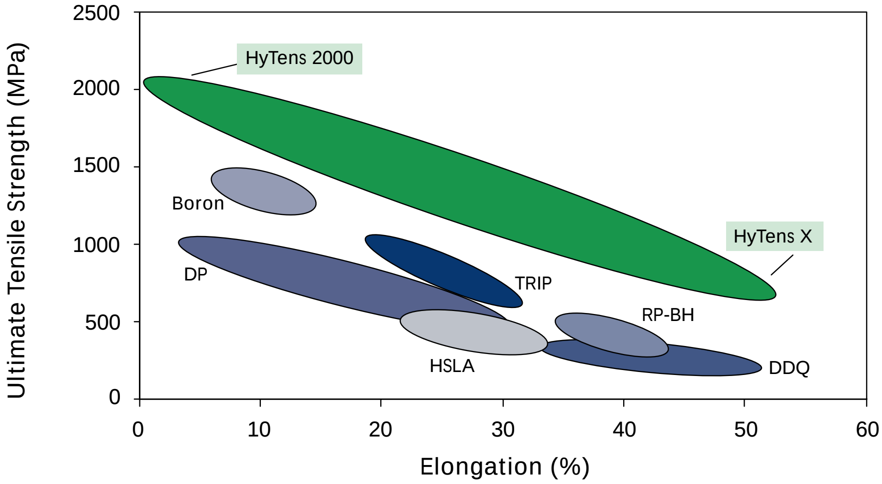

Fig 2. *Strength-ductility combination for HyTens in comparison to carbon steel grades (DP = dual phase steel, TRIP = complex phase steel, HSLA = micro-alloyed steel, RP-BH = rephosphorised steel with bake hardening, DDQ = deep drawing grades).*

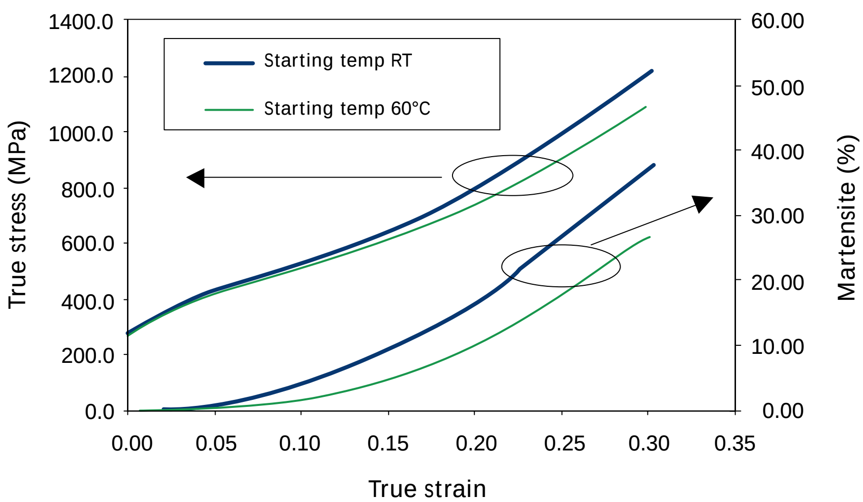

Fig 3. *Stress-strain curves for HyTens X with differing specimen temperatures (25°C or 60°C).*

(strain level) and the preheting/cooling method (thin, bold lines).

Using a hard second phase in the material is a well-known method of producing high strength steel. However, in this case the user of the material, not the material producer, controls the amount of hard second phase. In this way, HyTens X, compared with traditional ultra high strength steels, offers the designer further flexibility.

HyTens Value Added Products

HyTens is used in a series of new products (patents pending). Production of these products has only been possible due to the unique properties of HyTens.

HyTens Stiff

Light, corrugated, ultra high strength. HyTens grades are often used in combination with down-gauging. In such cases, the stiffness of flat planes is a

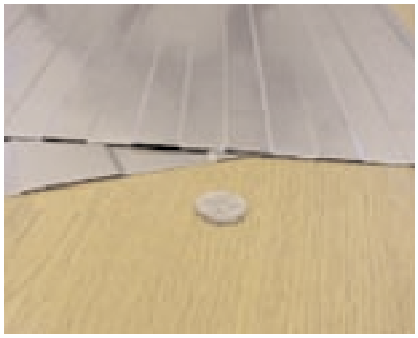

Fig 4. *The HyTens Stiff*

common problem. HyTens Stiff solves this problem by introducing a slight corrugation in the surface.

HyTens Xpand

Expanded metal, ultra high strength.

Expanded metal is a well-known commodity product. HyTens Xpand provides an ultra high strength expanded metal with a large potential for saving weight, see Fig 5.

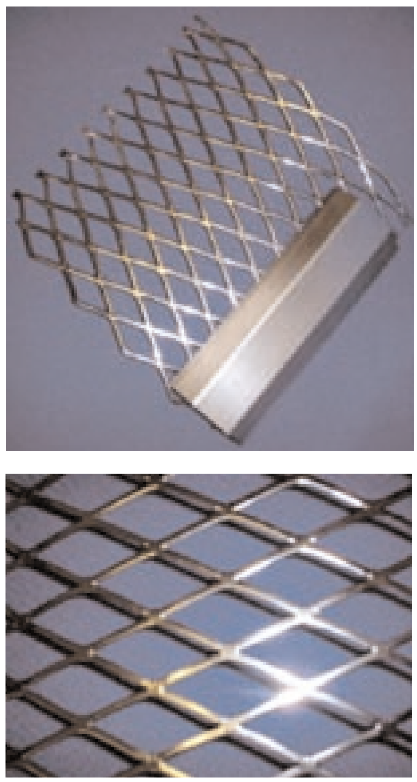

Fig 5. *The HyTens Xpand*

HyTens Acoustic
By introducing a polymer layer between two HyTens sheets, a high-strength sandwich product for sound and vibration damping is obtained.

HyTens Wood
A sandwich with HyTens and veneer provides a new material for various applications such as furniture. Compared to standard veneer products, HyTens Wood is much stronger and also provides superior shape stability.

HyTens Tube
Ultra high strength tube.

HyTens is also available as high strength tubes, with strength levels far exceeding those of standard tube grades.

HyTens X Tube
Tube for forming governed strength.

HyTens X tubes constitute a special product since it is the designer who decides the strength of the final component by utilising the material properties shown in Fig 3.

HyTens Methods

FORMING TECHNIQUES

A new grade can only be successfully introduced if it can be shown to be formable to the shapes required by customers. Accordingly, a set of patented techniques has been developed to be used in combination with HyTens grades.

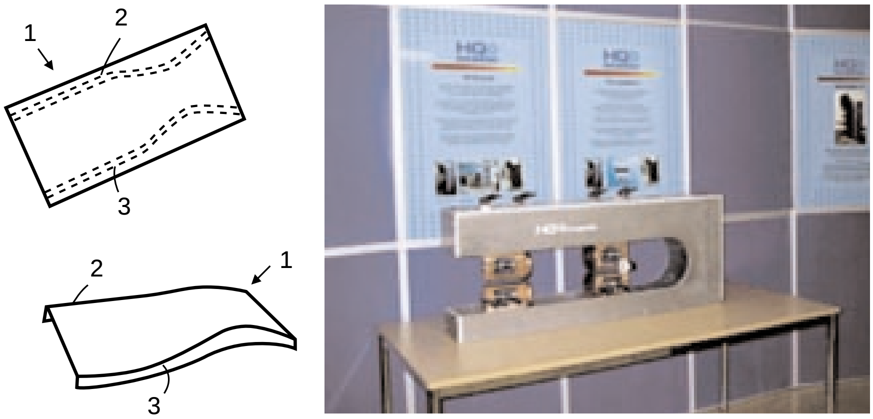

Fig 6. *The BlancForm technique utilised for bending and a prototype machine for blankpreparation of bending lines.*

BlancForm
BlancForm introduces a completely new approach to shaping a component. Traditionally, the component shape is determined by the tooling and / or machinery (as in deep drawing for example). With BlancForm, the blank preparation determines the final shape. A bending application is shown in Fig 6 as an example of the technique.

The blank is softened along the intended bending lines. Since the material is hard around the soft lines, bending can only occur in the soft zones, i.e. the blank determines the shape of the component. As shown in Fig 6, machinery for the blank preparation is also designed in co-operation with other companies.

TensForm
The concept of interaction in designing the product, choice of forming method, tooling design and use of HyTens X is called “forming governed strength” or TensForm. TensForm offers many opportunities for different foming techniques including hydro forming, an interesting technique due to the possibilities for large areas with a high deformation. Either sheet hydro forming or tube hydro forming is possible.

To demonstrate a possible way of using TensForm, a new wheel nut wrench was designed. Typically, a wheel nut wrench weighs about 400 g. By utilising hydro forming of HyTens X tube it has been possible to reduce the weight to about 100 g, a 75% weight reduction, while still fulfilling the physical requirements of torque level and integrity of the hex shape, see Figs 7 and 8.

Fig 7. *A typical wheel wrench weighing about 400 g*

Fig 8. *The new, tubular design in HyTensX, weighing about 100 g*

Fig 9. Hex-A-Beam, a closed-openable profile made of HyTens

Adapted Standard Shaping Techniques for HyTens

As well as the specially designed techniques, standard techniques are also used to shape HyTens grades, such as:

- Roll forming
- Bending
- Spinning
- Hydro forming
- Mechanical tube forming

An example of roll-formed high strenght profiles is the Hex-A-Beam concept.

Hex-A-Beam

This is a pantented closed-openable profile, se Fig 9. Through the spring action of the HyTens grade, the profile is self-closing which can be utilised in various innovative designs, for example space frames.

Joining HyTens

Joining HyTens is of course a critical issue. Development activities in this area include:

- Spot welding techniques
- Mechanical joining techniques
- Adhesive bonding techniques

Market development – PRINOX

The use of HyTens in applications where stainless steel is not traditionally used and where extreme mechanical properties are the primary interest has made it necessary to find new ways for developing the market. PRINOX is the name of a virtual company created within AvestaPolarit to find and establish new markets. A network has been developed in close co-operation with end-users and their suppliers, machine and equipment manufacturers, software and engineering companies, and internal resources. PRINOX acts as the external customer interface and draws any necessary competence from the network thus creating a virtual company with extensive development capacity.

Development work is being carried out in many different areas such as end-user products, design concepts and forming methods, just to mention a few. Through this type of work, huge market potentials are being identified and consequently opened for future sales of the HyTens product family.

Conclusions

- The growth of sales of temper-rolled grades is expected to increase in the future due to the development of new applications where strength level is the main issue. This is a new and exciting field for application development in sectors such as Building & Construction and Transport.

- AvestaPolarit has expanded its product range of temper-rolled grades to wider and thicker gauges, up to 1.5 m wide and 3 mm thick, to meet the requirements of new applications.

- AvestaPolarit has worked actively to promote the use of temper-rolled grades in new applications through the introduction of a new product family (HyTens) and associated design, shaping and joining techniques.

- Focusing on the extreme mechanical properties and less traditional applications necessitates new ways of working to develop the market and promote sales.

The Applicability of Stainless Steels for Crash Absorbing Components

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To increase crash performance in automotive vehicles it is necessary to use new techniques and materials. Components linked to crash safety should transmit or absorb energy. The energy absorbing capability of a specific component is a combination of geometry and material properties. For these components the chosen material should have high yield strength and relatively high elongation to fracture. These demands have led to increasing interest in the use of high strength stainless steels.

The relative performance of three high strength carbon steels and two high strength stainless steel grades was evaluated through intrinsic and simulative tests. The rear bumper for a Volvo Car model in current production was manufactured using the five sheets tested to verify formability and behaviour under load. The bumpers were clamped in a rig that allowed quasi-static impact tests to be made. The energy absorbing capabilities were evaluated by measuring force versus displacement during the impact test

Introduction

Next generation automotive vehicles must satisfy the conflicting demands for decreased weight and increased crash safety. Since an increase in crash safety usually means an increase in weight. This have led to that car manufacturers around the world have started to consider new innovative manufacturing techniques and new types of materials for structural components [1-5].

Materials themselves have properties such as yield- and tensile strength, elongation to fracture, anisotropy and Young's modulus. Typical loading conditions for a component are axial, bending or torsional. Depending on the loading conditions there is a material-and-shape combination that best resists the applied load. For axially loaded components, the cross-sectional area is important since all sections with the same area will carry the same stress. For bending and torsion loads, the material and overall shape both affect the components ability to resist applied loads [6].

When the applied load reaches a certain level, the material will start to flow plastically and the component will suffer permanent deformation after the load released. For axial tensile loading the material starts to flow when the stress in the material reaches the yield stress [7]. A high yield stress means that the material has high resilience to plastic deformation [8].

For bending, the elastic-plastic transition depends on a combination of shape and material properties. The maximum elastic deflection of a beam under bending is proportional to the materials yield stress and Young's modulus. The stiffness is correlated to the materials Young's modulus and the shape of the component.

There has been an increasing interest in the use of stainless steels in automotive vehicles due to their excellent formability combined with high strength. This means that is possible to press components with shapes that have high stiffness and high energy absorbing capability [9].

In this project rear bumpers of the Volvo S80 have been manufactured using different types of materials and their quasi-static crash absorbing behaviour studied.

Material characterization

The materials chosen for this study were three carbon steels (DP750, DP800 and TRIP700) and two austenitic stainless steel grades (HyTens X and HyTens 1000). Two carbon steels had a duplex microstructure while the third was a TRIP grade. The stainless grades had an austenitic structure with a lean composition; one was totally annealed after the cold rolling process while the other was in a hard condition.

Both the stainless grades and the TRIP grade carbon steel have a meta-stable microstructure. This means that the initial microstructure is able to change during plastic deformation. For the carbon steel, the ferritic microstructure changes to a martensitic structure whilst the stainless grades austenitic microstructure changes to a martensitic structure during plastic deformation.

UNIAXIAL TENSILE TEST

Uniaxial tensile tests were made to evaluate the mechanical and plastic properties of the materials. The test specimens (ASTM-standard E 8M-96 geometry) were cut out from the blanks using a ROFIN-SINAR 6kW CO_2 laser and the edges polished by hand using emery paper.

The uniaxial tensile tests were made at a crosshead speed of 0.1 mm/s in a Dartec 50kN tensile testing machine. The extensometer was an Epsilon model number 3542-050M-025-ST. The European standard EN 10 002 defined the initial gauge length of the extensometer, which was proportional to the initial cross-section area.

The engineering stress-strain curves obtained for the materials are shown in figure 1 and the true stress-strain curves up to maximum tensile strength given in figure 2 and the mechanical and plastic properties are presented in table 1.

From table 1 it can be seen that the stainless grades have highest true stress at ultimate tensile strength and the greatest uniform elongation. The table also shows that the softer stainless grade is much thinner then the other materials used in this study.

A materials capability to absorb energy during uniaxial deformation is equal to the total work absorbed by the tensile specimen during deformation up to fracture (i.e. the area under the stress strain curve). This is the

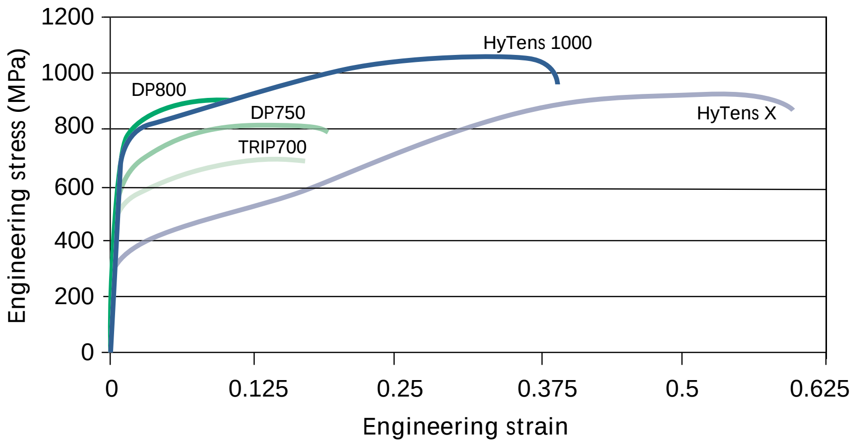

Figure 1: *The engineering stress-strain curves for the materials in this study.*

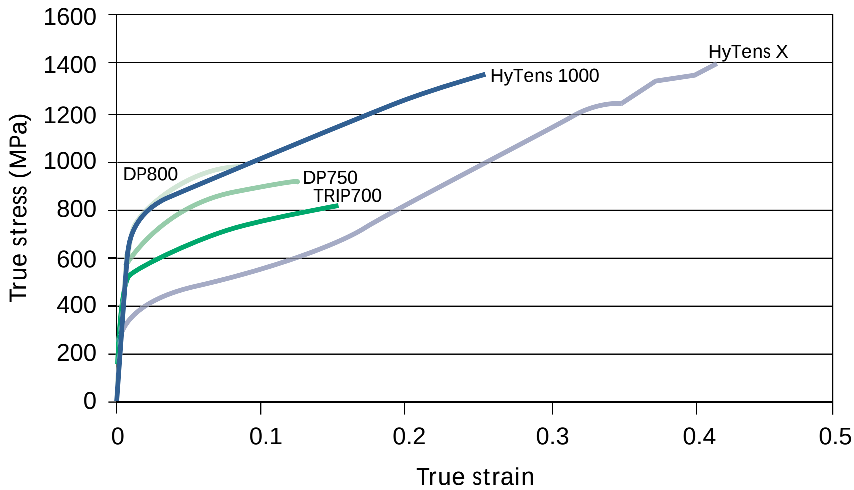

Figure 2: *The true stress-strain curves up to maximum tensile strength for the materials in this study.*

***Table 1:** The material properties evaluated from the uniaxial tensile tests.*

Type	Thickness (mm)	Rp02 (MPa)	Ultimate tensile strength (UTS) (MPa)	True stress at ultimate tensile strength (MPa)	Uniform elong. Ag (%)	Total elong. A80 (%)
Carbon steels						
TRIP700	1.58	473	703	818	16.4	17
DP750	1.48	513	811	920	13.4	18.8
DP800	1.44	573	896	976	8.9	9.9
Austenitic stainless steels						
HyTens X	1.16	306	937	1429	52.5	59.3
HT 1000	1.55	639	1068	1377	28.9	38.6

***Table 2:** The toughness and resilience per volume unit for evaluated from the uniaxial tensile curves.*

Type	Resilience (J/m^3)	Toughness (J/m^3)
Carbon steels		
TRIP700	0.996	105
DP750	1.131	101
DP800	1.32	74
Austenitic stainless steels		
HyTens X	0.536	364
HyTens 1000	1.726	269

toughness of the material, the toughness being equal to the sum of the absorbed elastic energy, the resilience, the plastic energy and the ductility of the material [10]. A high resilience is desirable if a structures function is to transmit impact energy to other structural parts while high ductility is advantageous for absorbing energy.

The toughness and resilience for the different materials are given in table 2.
Table 2 shows that the stainless grades have either highest resilience or highest toughness.

This means that if a structural component subjected to axial loading was made with equal initial thickness then the stainless steel component should absorb most crash energy. If the loading condition was bending then the stainless steel component should deflect elastically the most before permanent deformation and transmit most energy. If the loading condition was torsional then the component made from stainless steel could be twisted the greatest angle before plastic deformation occurs.

Mechanical tests

In this study a rear bumper from a Volvo S80 car was chosen, figure 3.

The rear bumper must transmit crash energy to the vehicle structural frame but should not be so stiff that a low speed impact would deform material behind the bumper or in the structural frame. This means that the bumper should both transmit and absorb crash impact energy. The ideal condition bumper material would have an intermediate yield stress with strong work hardening behaviour up to a high ultimate strength. The bending property of a rear bumper is both shape and material dependent. The elastic behaviour of a rear bumper

***Fig 3.** The rear bumper from the Volvo S80 was used in this study.*

depends on moment of inertia (I), Young's modulus (E) and yield stress (Rp02).

Test blanks were cut using a laser and the test bumpers drawn, slit and punched in a transfer line at Volvos car body component plant in Olofström, Sweden. A picture of two bumpers is shown in figure 4.

For the carbon steel grade DP800 it was not possible to successfully complete the deep drawing operation. The material has low elongation to fracture and bad formability causing the material cracked at the corners of the bumper. The shape of initial blank and lubricant used during forming were changed but without success. The fracture caused during forming of a DP800 bumper is shown in figure 5.

The carbon steel grade with highest strength, which allowed bumpers to be formed without fracture, was DP750.

The stainless steel grades showed on no problems during the forming process.

QUASI-STATIC IMPACT TEST

The bumpers were mounted in a testing rig using the standard mounting holes in the component. A half-spherical beam used to simulate an impact was forced into the centre of the bumpers by a hydraulic cylinder. A load-cell was used to measure the absorbed energy, see figure 6 and 7.

The ram speed was 100 mm/s and the force and displacement data was collected on a micrcomputer. From the force-displacement curves of the punch the absorbed energy of the bumpers could be calculated.

The peak force in the load-displacement curve depends on loading condition, the shape of the bumper and thickness of the sheet, the Young's modulus and the yield stress. In this study the loading condition, Young's modulus and shape of the bumpers were the same in all cases.

Figure 8 show that the high strength austenitic stainless steel HyTens 1000 has highest energy absorbing capability. Whilst the softer stainless grade made of thinner material and with lower yield stress gave the lowest peak force value.

The point where the load-displacement curve reaches its maximum is known as the elastic-plastic transition. After this the bumper starts to deform plastically and acquire a permanent deformation. The energy absorbed during plastic deformation depends on the materials work hardening behaviour and the shape of the bumper. The amount of absorbed energy for the different materials is presented in table 3.

The data in table 3 confirms that the high strength austenitic stainless steel has the greatest crash energy absorbing capabilities due to its high yield strength and greater work hardening behaviour. The low value for the softer austenitic stainless grade is due to the thinner material used and lower yield stress.

Fig 4. *Two of the rear bumpers that were made in stainless steels.*

Fig 5. *The fracture on the bumpers made with DP800.*

Fig 6. *The configuration used to test the energy absorbing capabilities of a rear bumper.*

Fig 7. *Nearing the completion of a test.*

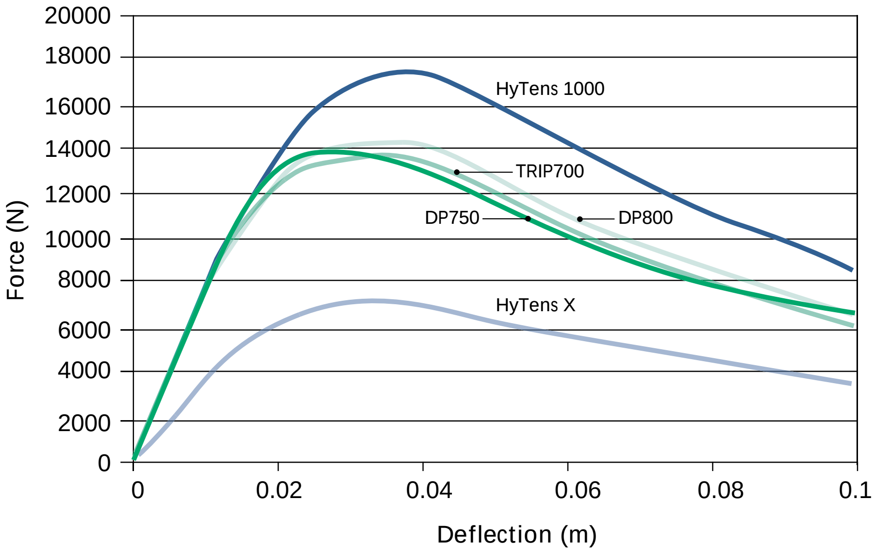

***Figure 8:** Force-displacement curves from the quasi-static impact test for the five different materials.*

***Table 3:** The energy absorption of the tested materials for quasi-static bending of a rear bumper.*

Type	Energy absorption during deflection to maximum load (J)	Energy absorption during deflection 0-99 mm (J)
Carbon steels		
TRIP700	262	969
DP750	333	967
DP800	345	1005
Austenitic stainless steels		
HyTens X	177	518
HyTens 1000	426	1239

Conclusions

This study used a half-spherical beam to simulate an impact into the rear bumper of a Volvo S80 car. The loading condition in this study is bending caused by a quasi-static point load. The absorbing energy was measured during the tests.

The variation of absorbed energy between the materials during the tests was lower then in the uniaxial tensile tests. The reason for this is the shape of the tested component since the amount of absorbed energy in bending is related to both material and shape. If the loading condition is bending and the component required transmitting impact energy in the sub frame, it should have as high stiffness as possible. The most important shape parameter for components stiffness is the moment of inertia (I). Hence, the moment of inertia should be as high as possible.

To increase the moment of inertia thicker material or a more complex shape must be used.

Producing a more complex shape during the deep drawing of a bumper could require too severe forming condition for the chosen material. In the worst case, increasing the strength of the material will leads to a decrease in formability, meaning that less complex shape can be manufacture hence decreasing the maximum moment of inertia.

The formability of DP800 was very poor; resulting in cracks occurring at the corner of the bumper during the forming process.

The carbon steel grade with highest strength, which allowed bumpers to be formed without fracture, was DP750.

The stainless steel grades showed on no problems during the forming process.

The study showed that HyTens 1000, a high strength austenitic stainless had the best impact energy absorbing capabilities of the materials tested. This is because of its high yield stress combined with excellent work hardening behaviour.

This study showed also that DP750 was better as far as absorbed impact energy then TRIP700.

This study has shown that HyTens X, an annealed austenitic stainless grade, has the highest elongation to fracture, which indicates that it has best formability. This material would probably be the best alternative for a new bumper designed with a complex shape and high moment of inertia.

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