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PROSPECTS FOR THE USE OF NEW-GENERATION STEELS OF THE AHSS TYPE FOR COLLISION ENERGY ABSORBING COMPONENTS

PERSPEKTYWY WYKORZYSTANIA STALI NOWYCH GENERACJI TYPU AHSS NA ELEMENTY POCHŁANIAJĄCE ENERGIĘ ZDERZEŃ

This paper discusses major problems relating to the design of collision energy absorbing components. The analysis is based on in-house research and the literature. The possibility of using advanced high-strength steels (AHSS) for such components is explored. It has been found that in order to fully exploit the potential of the TRIP and TWIP steels, the components should be manufactured by mainly hydroforming and deep drawing, instead of bending which has predominated till now.
Keywords: controlled body crushing zones, TRIP and TWIP steels, deep drawing processes

W pracy na podstawie własnych badań oraz literatury przedstawiono najistotniejsze problemy związane z projektowaniem elementów absorbujących energię zderzeń oraz przedstawiono możliwości zastosowania stali typu AHSS na tego typu elementy. Prowadzona analiza wykazała, że aby w pełni wykorzystać możliwości, które stwarzają nowe stale typu TRIP i TWIP, należy zmienić technologię wykonywania tych elementów i stosować główne hydroformowanie i głębokie tłoczenia zamiast gięcia, które dotychczas dominowało.

1. Introduction

New car models have to meet two key requirements: lower fuel consumption and improved passive safety. Today most car assemblies which have a direct or indirect bearing on car safety in road traffic are subjected to strict international standards. In the US often more stringent legal safety requirements than the ones in Europe are in force. Some of them constitute the basis for formulating new requirements adjusted to the European conditions [1]. The improvement of the car with regard to safety is a continuous process. Recently, it has become an element of competition between car manufacturers. Although research on increasing collision energy absorption has been conducted all over the world for many decades there are still numerous unresolved problems relating to both energy absorbing components and measuring techniques [2 - 4].

One of the major areas of research connected with the safe car design are energy absorbing structures. In a car they are located in the so-called crushing zones and their task is to absorb impact energy during collision and in this way to ensure safe values of the loads acting on the passengers.

The design of a crushing zone is highly complicated since besides the loads acting during a collision, one must also take into account the geometric conditions determined by the vehicle design and its material characteristics. Thus, the design and construction of energy absorbing zones is a great challenge for car designers and manufacturers.

2. Energy absorbing structure of vehicle

Research has shown that a proper vehicle load-bearing structure – a rigid, undeformable safety cage surrounded by the energy absorbing zones – is the basis of passive safety during a collision. A schematic of the safety cage with controlled crushing zones is shown in Fig. 1.

The way in which the car body deforms during a collision (and so the ability to absorb energy) is determined by its structural components (in the case of head-on collisions, mainly by the longitudinal members

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of the frame). They carry the load, cushion the impact and absorb its energy. Their geometry and properties determine the overloads during a collision and so the safety of the vehicle users. As regards human safety inside the vehicle, it is not so much the absolute value of the force acting on the human body, but the acceleration (deceleration) and its duration are rather critical. The relation between the allowable acceleration and the duration of its action on the human body is represented by the Patrick curve (Fig. 2) [5]. The diagram shows that the acceleration which the human body experiences during a collision should not exceed 90 g at 4 milliseconds, which corresponds to about1000 HIC - Head Injury Criterion [1].

Fig. 1. Controlled crushing zones with typical impact elements – light gray color [6]

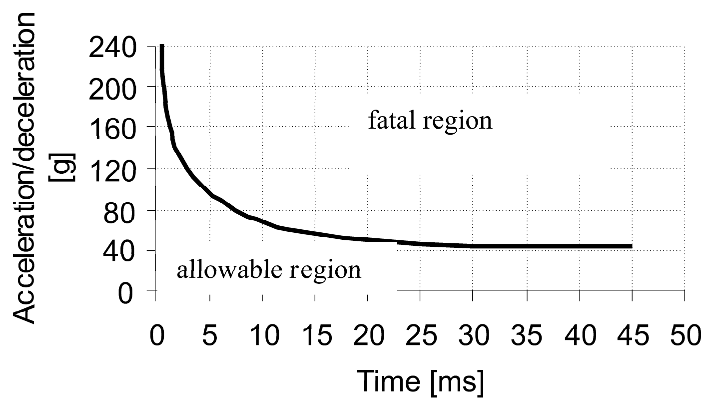


Fig. 2. Relation between allowable and fatal region according acceleration and duration of its action (Patrick curve) [5]

The most important crashworthy parameter is the total energy that a given profile can absorb. It depends on many geometric and material parameters resulting in folding modes. Crushing force is changed during deformation of thin-walled sections according to folding modes. Therefore, the maximum energy absorption is obtained in a given sample if progressive collapse mode is sustained in a profile throughout the whole deformation process (Fig. 3a). On the other hand, the regular folding process is often disturbed by a global buckling caused by incorrectly designed profiles and geometric and material imperfection (Fig. 3b).

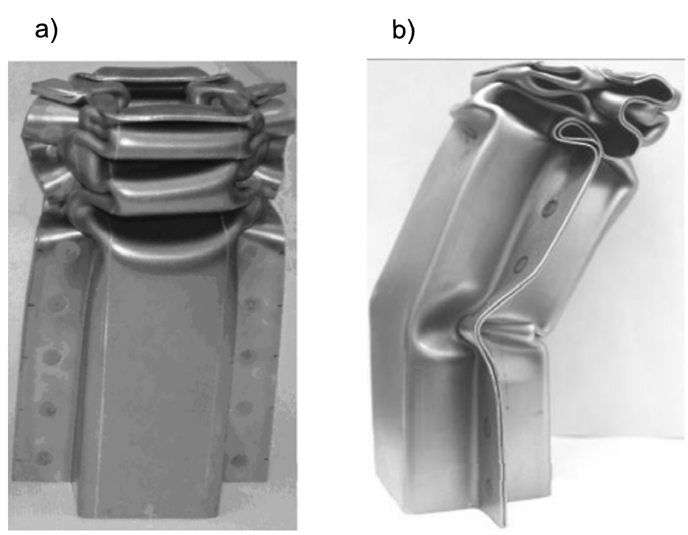


Fig. 3. Folding modes of thin-walled sections: a) progressive folding [7] b) global buckling [8]

For progressive folding it is possible to correlate the size and numbers of the folds formed during deformation with the oscillating course of crush force (fig. 4).

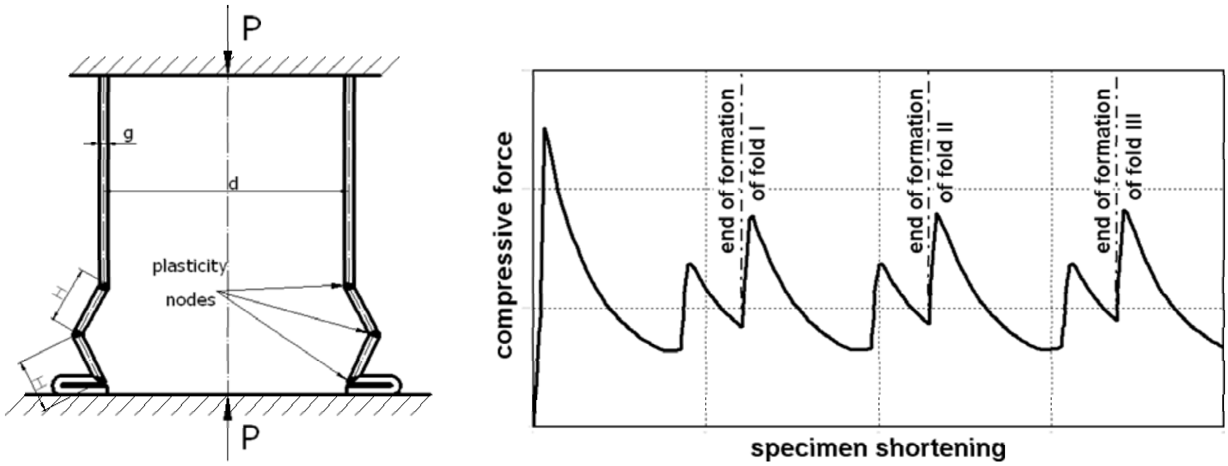


Fig. 4. Folding mode and corresponding force trace during compression of thin-walled axially symmetric specimens [8]

The capacity to absorb the kinetic energy by the different sections used in the car body's controlled crushing zone is the subject of much experimental and theoretical research. Components with different cross sections (circular, square, polygonal), made of different materials (steel, aluminium, composites) and with different mechanisms triggering the formation of regular buckling folds are investigated. The first significant research in this field was published by Alexander [9] who showed that the force upsetting tubular specimens versus time have an oscillatory character.

Great advance was made by White and Jones [10] who presented the theoretical and ex-perimental analyses of the quasi-static compression of top-hat and double-hat sections. The model was based on superfolding (SE) elements previously proposed by Abramowicz and Wierzbicki [11].

Despite merits of the theoretical models and their usefulness in the investigation of crushing mechanisms, they are seldom put into practice because of their limited accuracy and long computation time. Currently, the mathematical modelling of various processes (including crushing), consisting in a virtual experiment, is becoming the standard in such investigations. Good agreement with reality, no need for expensive tools and materials and short experiment duration contribute to the fact that experiments in the virtual world become a necessity [2, 4, 7]. Thanks to the different (single and multiple) criteria, such virtual experiments provide invaluable assistance in the optimization of both components and complex structures. The available software and the fast increasing computing power facilitate such tasks. Obviously, the agreement between virtual experiments and reality needs to be verified by real tests, but much fewer and less extensive and costly. If material models, boundary conditions and modelling conditions are properly determined, a very good agreement between the mathematical model and the real process can be achieved (figs 5 and 6) [8]. The results presented in those Figures come from ABAQUS Explicite simulations of the crushing of double-hat specimens made of HSLA steel and joined by clinching.

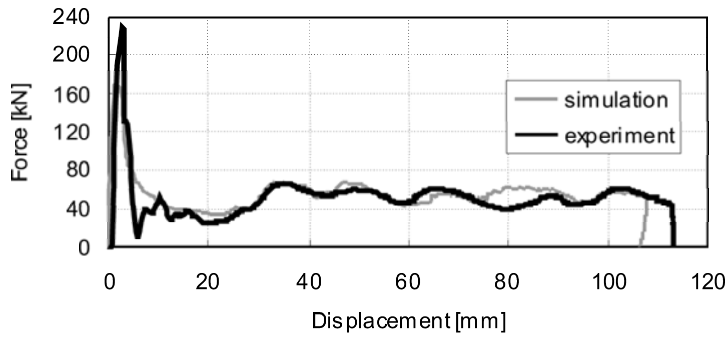
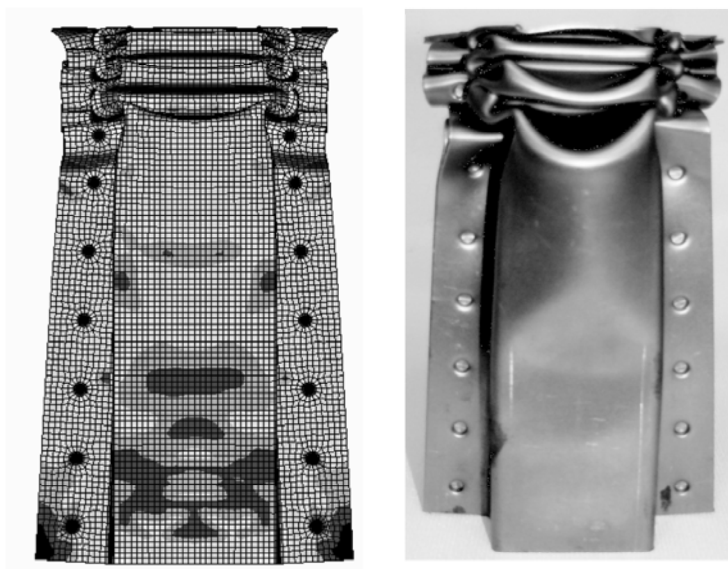


Fig. 5. Force versus steel sheet specimen shortening for real tests and modelling [8]



FE model Real process

Fig. 6. Comparison of thin-walled structure deformation determined for H320LA sheet by respectively numerical simulation and experimental tests [8]

3. Structural energy-absorbing materials

In order to design the energy absorbing structures one must know that they respond to the load and influence of the geometry, the material and method of joining on the crushing mode.

One of the major (most promising) factors having a bearing on the energy absorption capacity of the structure is the material and its properties. Considering the vehicle weight, the materials should be characterized by the high specific strength and good plasticity. Because of the costs and properties, low-carbon steels and higher-strength steels dominated up to the end of the last century. Today, more and more often light materials, such as aluminium alloys and magnesium alloys, are used for car bodies. However, a new generation of multiphase steels with high and very high strength – advanced high-strength steels (AHSS) – is gaining dominance. AHSS grades are characterized by the very high strength and high plasticity, much higher than those of the typical stamping steels. Using AHSSs for the components critical for passenger safety one can build the safer structure and at the same time reduce the vehicle weight [12 - 14]. The properties of the modern materials are shown in Fig. 7. Owing to their properties the new high-strength materials have been introduced for the car bodies at a rate much exceeding the forecasts from just a few years ago.

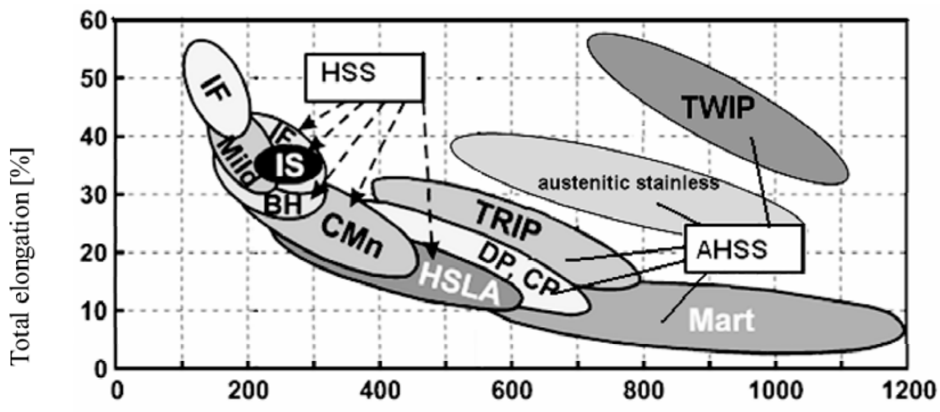


Fig. 7. Dependence between yield point and total elongation for different steels [12, 13]

A long-term forecast (made in the 1990s) for the use of such materials is shown in Fig. 8. Already in 2005 AHSSs replaced the low-carbon steels to a substantially greater extent than the one predicted by that forecast. It is anticipated that the use of low-carbon steel sheets for car bodies will be marginalized and that of HSLA steels considerably reduced.

The group of advanced high-strength steels (AHSS) includes:

- ferritic-martensitic (DP – Dual Phase) steels,
- CP (Complex Phase) steels,
- TRIP (Transformation Induced Plasticity) steels,
- Mart (Martensitic) steels,
- austenitic TRIP (high-manganese) steels,
- TWIP and TRIPLEX steels,

The specific desirable properties result from the type of microstructure determined by the phase components and their number and morphology. AHSSs are multi-phase steels which contain martensite, bainite or bainite and retained austenite within the soft ferrite, in amounts ensuring the required mechanical properties characterizing the technological and functional qualities of drawing sheets. In comparison with typical micro-alloyed steels, the modern AHSS grades show an exceptional combination of the high strength and good deformability. This combination of properties is mainly the result of low (in relation to tensile strength) yield point and the high work hardening whereby the steels are highly suitable for the press forming.

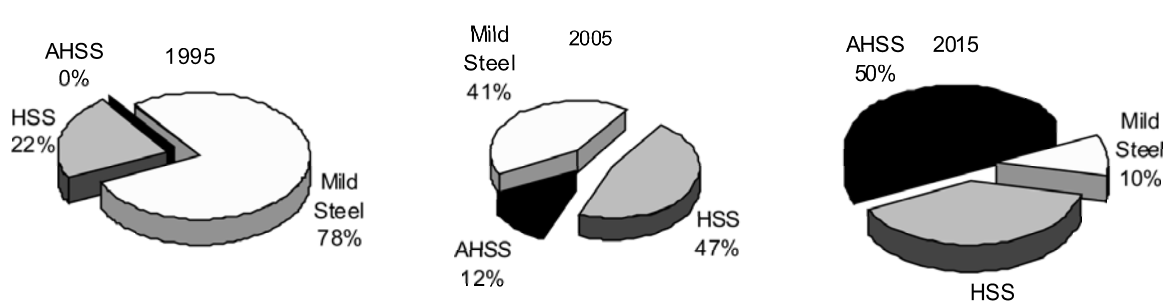


Fig. 8. Forecasted use of AHSS in car construction by 2015 [15]

The latest steels: TRIP and TWIP deserve special attention. TRIP steels contain considerable amounts of retained austenite which transforms into the martensite in the course of deformation, causing substantial work hardening of the steel whereby its drawability and deformability improvement (Figs 9, 10).

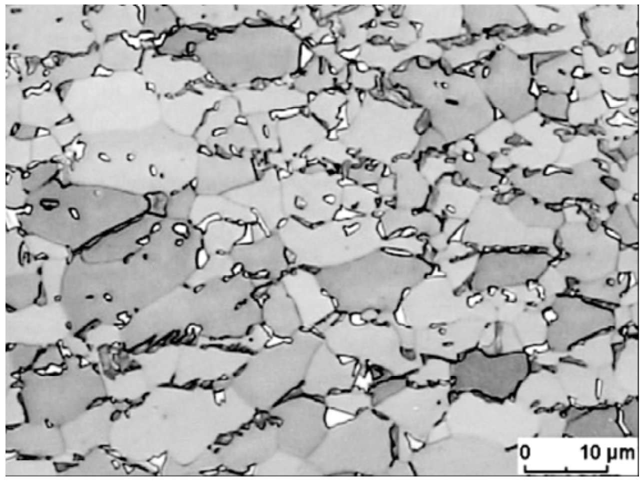


Fig. 9. Microstructure of TRIP steel (light areas - retained austenite) [16]

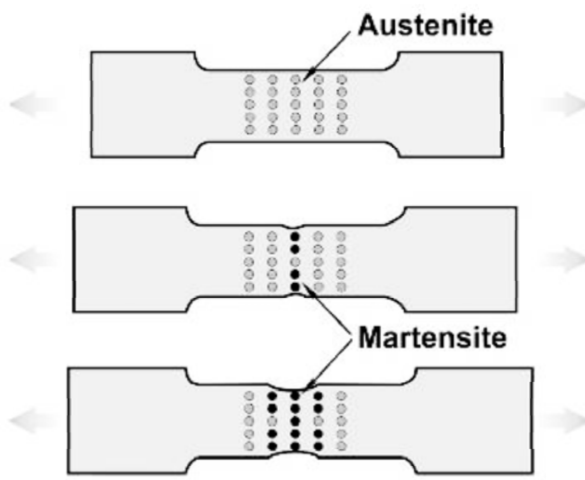


Fig. 10. Illustration of TRIP effect during tensile test [16]

The TWIP steels, whose deformation mechanism is based on the twinning (Fig. 11), show even higher work-hardening intensity at very high plasticity.

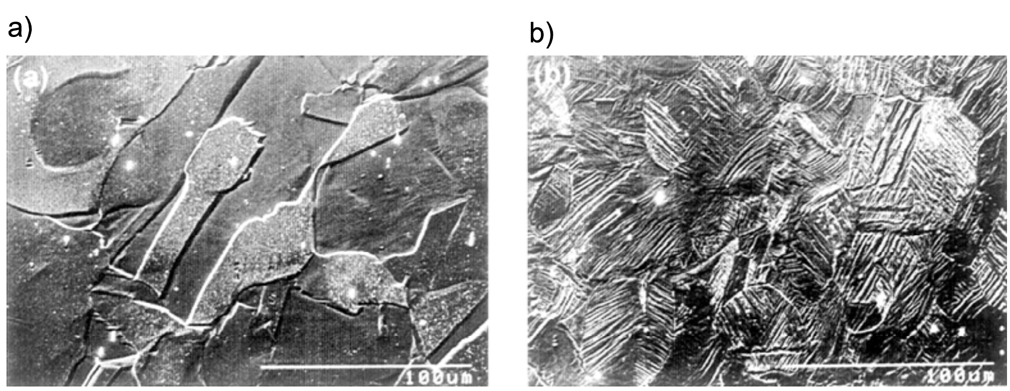


Fig. 11. SEM micrographs of Fe-25Mn-Si-3Al TWIP steel in deformed state: (a) T 400°C, strain 40%; (b) T 50°C, strain 68% [17]

In the case of TRIP steel and TWIP steel (especially the latter one), the magnitude of limit strains deserves notice. As the true stress – true strain curves for the steel sheets (Fig. 12) show, the limit strains are substantially greater than for the other materials.

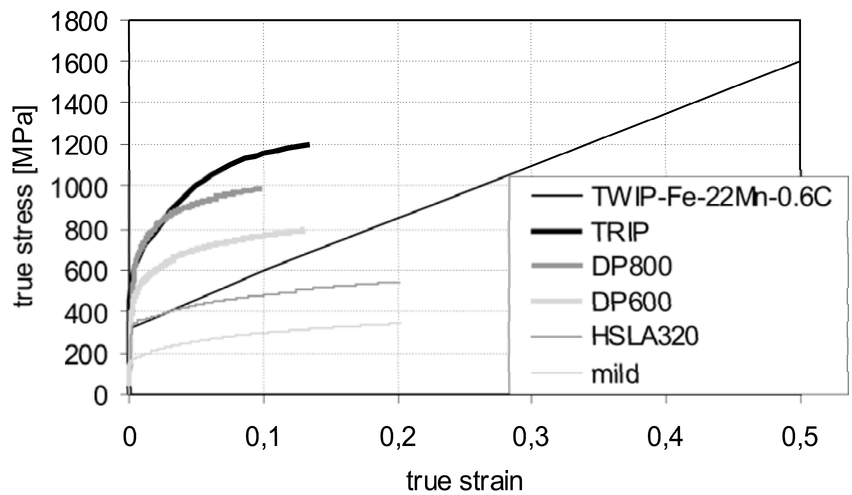


Fig. 12. True stress – true strain curves for different steels [7, 18, 19]

The research projects: ULSAB (Ultra Light Steel Auto Body) and ULSAB-AVC (Advanced Vehicle Concepts), which represent the offer of the world steel industry and a challenge for designers and manufacturers to increase the efficiency of cars by reducing their fuel consumption, improving driving safety and reliability, have significantly contributed to the development of new grades of steel for cars.

It seems to be natural that as AHSSs are introduced to build the car bodies, they should also be used for controlled crushing zone components. It turns out that in recent years only DP sheets have been increasingly used in the controlled crushing zones (Fig. 13).

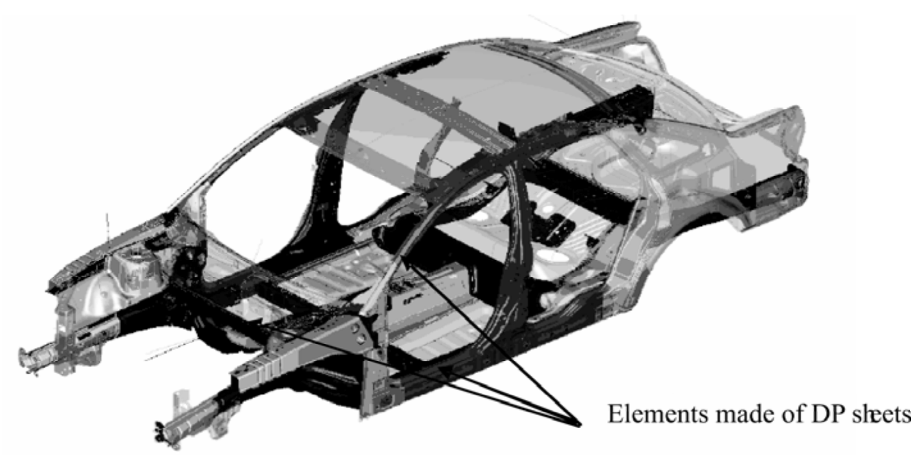


Fig. 13. DP sheets used to build Ford 500 [20]

The special properties of TRIP and TWIP steels should lead to very good designs of energy absorbing materials but practically they have not been used for the typical collision energy absorbing materials, yet. No ideas of how to use such steels for controlled crushing zones have appeared. In the generally available literature one can find only little information about the research conducted in this area.

The results of one of the first crushing tests carried out on sections made of different grades of AHSS are presented in Fig. 14. One can notice that the results for the TWIP steel do not differ from those for the DP 980 steel, whereas those for TRIP steel are markedly lower.

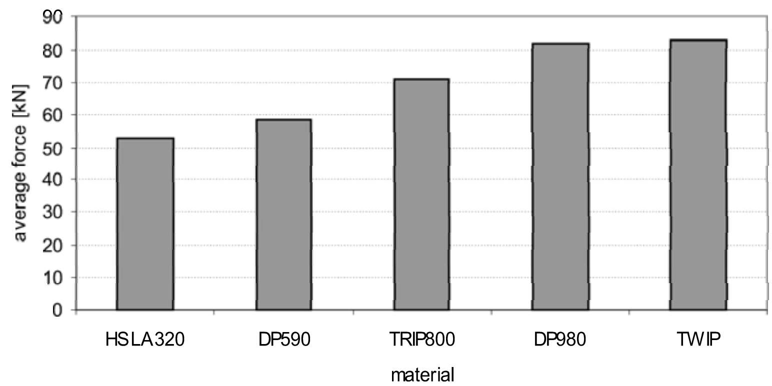


Fig. 14. Average load for 150 mm crushing in axial compression for different types ofsteel [21]

4. Therefore, the question arises: are we really able to exploit the good deformability of TRIP and TWIP steels in the controlled crushing zones?

Currently, most energy absorbing components are made by bending or shallow drawing during which only zones in the vicinity of the bending line or near the corner of the die stamping undergo deformation. The distribution of strains in such a section after crushing clearly shows that most of the material volume underwent deformation in an interval of 0.0-0.2 (Fig. 15). The results together with the work-hardening curves (Fig. 12) indicate that in this manufacturing technology, the potential of TRIP and TWIP steel sheets (especially of the latter) is unused. For such components it is advisable to use the ferritic-martensitic steel or even martensitic steel. These steels are characterized by very high strength and sufficient plasticity.

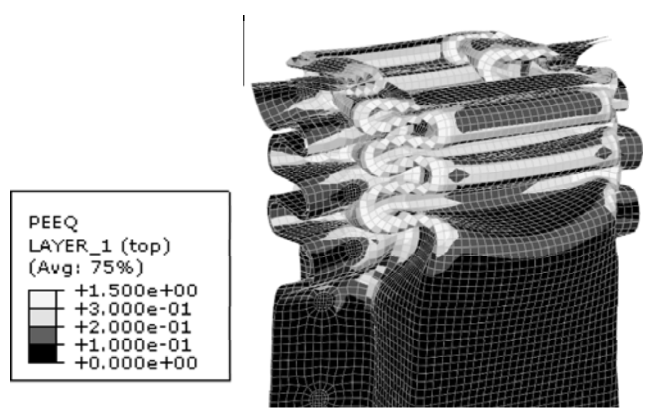


Fig. 15. Distribution of strains in energy absorbing section after dynamic deformation (FEM)

The potential of TRIP and TWIP steel sheets, which are characterized by the greater work-hardening than the materials used so far, can be fully exploited in the energy absorbing components only when the latter are manufactured by the deep drawing or hydroforming. Owing to the fact that the material prestrain occurs in these processes, the prehardened components are more able to absorb energy during dynamic deformation.

Hydroforming (Fig. 16) is increasingly often used to manufacture car bodies. The full section, with no need for joining or collars, facilitates progressive crushing. The section can be quite easily differentiated along its length whereby it can be well fitted to the body and a gradient structure can be obtained without additional joining. So far the conventionally stamped steels with relatively low strength have been used for such components.

Unfortunately, the design of such structure made of TRIP and TWIP steel will be more laborious since these materials are characterized by the greater spring-back which makes it more difficult to obtain a more accurate shape or when the prestrains obtained in the deep drawing or hydroforming are too large the material may crack in the course of dynamic deformation. Therefore, many

FEM optimization procedures will need to be applied in order to produce a correct energy absorbing structure.

However, the advantage will be the creation (through controlled deformation during hydro-forming or deep drawing) of the structure with nonuniform work hardening along the length of the section whereby a gradient controlled crushing zone will be obtained. So far, such structures have been produced as, for example, tailored banks (Fig. 17). Because of the difficulties in the joining materials having different properties and the introduction of considerable nonuniformity in the form a laser weld, structures of this type are today very seldom used.

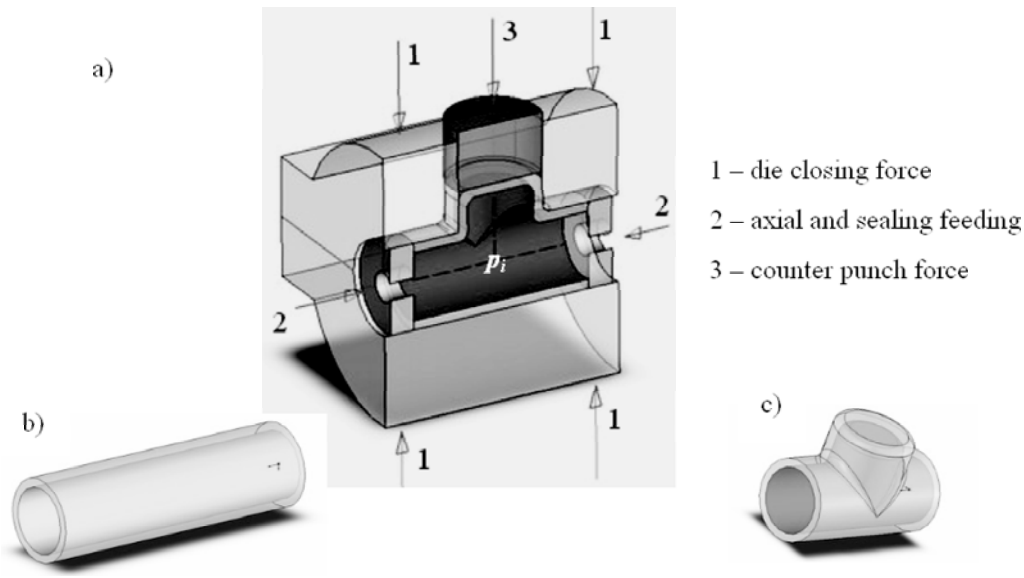


Fig. 16. The hydroforming principles: a – tool setup, b – initial tube, c – final product (T-joint) [22]

Fig. 17. Thin-walled tailored blanks made of two kinds of steel: steel USB with lower strength and steel DC01 with higher strength. Specimen before and after deformation [23]

5. Summary

Problems involved in the design of controlled crushing zones have been discussed. The design of such zones is highly complex since besides the loads acting during a collision one must take into account the geometric conditions determined by the vehicle design and the material characteristics. Owing to the great advances made in the field of new materials, today light materials (such as aluminium alloys and magnesium alloys) are increasingly often used for car bodies. However, the new generation of high and very high strength multiphase steels (AHSS) is gaining the dominant position, especially for building light structures. AHSSs are very strong and at the same time highly plastic (as plastic or even more plastic than typical drawing steels). The peculiar properties of the steels should lead to very good designs of energy absorbing components. It turns out, however, that despite their advantages AHSSs are still not used for typical collision energy absorbing components. There are no ideas of how to use such steels for controlled crushing zones. In the generally available literature one can find only little information about the research conducted in this area.

The preliminary FEM and experimental analyses of the deformation of thin-walled sections show that TRIP and TWIP steel sheets (characterized by the greater work hardening than the conventional materials) can be fully exploited to produce the energy absorbing components only when the latter are manufactured by the deep drawing or hydroforming. The material is pre-strained in these processes whereby the components have a greater capacity to absorb energy during dynamic deformation.

An additional advantage of producing sections by hydroforming and deep drawing will be the formation of structure with the nonuniform work hardening of the material along the length of the section and so the creation of the gradient zone of controlled crushing.

Acknowledgements

The licences of programmes ProEngineer of Wrocław Centre for Networking and Supercomputing was used in article.

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Received: 10 September 2009.