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Material and technological developments in sheet metal forming with special regards to the needs of the automotive industry

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ABSTRACT

Purpose: Of this paper is to give a general overview about the recent developments in sheet metal forming, with special regards to the needs of automotive industry as the main driving force behind these developments.

Design/methodology/approach: First a general overview of material developments concerning the sheet metal forming will be given including the latest results on material developments concerning the recent results in advanced high strength steels, as well as in light metals as the main target materials in weight reduction, then reviewing some process developments in sheet metal forming.

Findings: Some research results achieved with these materials in a national project concerning their formability and some innovative new forming methods particularly applied for these advanced materials will also be introduced.

Research limitations/implications: Further researches with these advanced materials exploring they formability limits and most potential application fields in car manufacturing.

Practical implications: The findings and results will contribute to reduce the harmful emissions by automobiles and as an overall consequence it will also contribute to the increase of global competitiveness of car manufacturing.

Originality/value: A very concise general overview of recent material and process developments providing a good theoretical and practical knowledge for those involved in sheet metal forming.

Keywords: Sheet metal forming; Advanced steel developments; Light metals; Innovative forming processes; Automotive industry

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MATERIALS MANUFACTURING AND PROCESSING

1. Introduction

The automotive industry is always the key industry behind sheet metal forming thus the requirements and developments in car manufacturing have decisive role in the development of sheet metal forming, too. The automotive industry faces with very contradictory demands and requirements: better performance with lower consumption and less harmful emissions, more safety and comfort; these are hardly available simultaneously with conventional materials and conventional manufacturing processes. The fulfillment of these often contradictory requirements are the main driving forces in the automotive industry and thus in the material and process developments in sheet metal forming, as well. To meet these manifold requirements the application of light weight construction principle has an important role. To reduce the weight of automobiles and simultaneously assure the increased safety requirements higher strength metallic materials have to be applied. But it is also well-known that by increasing the strength of materials the formability is significantly decreasing: however the formability of automotive parts is regarded as one of the key issue in car manufacturing.

During the recent years significant developments can be observed in the application of both high strength steels and various light metal alloys. In this respect, among the high strength steels the application of various dual-phase steels while among the light metals the aluminum alloys are the best examples to meet the above requirements. However, the application of both high strength steels and aluminum alloys often leads to formability and manufacturing problems.

In this paper, first a short overview of recent material developments concerning the sheet metal industry will be overviewed then some new innovative forming processes will be described. The results shown in this paper are mainly based on a national research project jointly financed by the European Union and the Hungarian Government.

2. Material developments in sheet metal forming industry

As it was mentioned in the Introduction the material developments in the sheet metal industry are mainly stimulated by the demands and requirements stated against the automotive industry. Some decades ago, design engineers mainly focused their attention on structural and dimensional stability and durability. In recent years, the reduction of fuel consumption together with increasing comfort requirements led to the intensive development of innovative new materials. Enhanced stiffness together with weight reduction resulted in the development and wide application of various grades of high strength steels and various light metals. To meet those often contradictory requirements the application of higher strength metallic alloys with sufficient formability can be regarded as one of the most suitable material developments. In this respect both high strength steels and high strength aluminium alloys are promising alternatives [1].

2.1. Steel developments in sheet metal forming

Nowadays, several micro-alloyed and phosphorous-alloyed steels both with and without bake-hardening are frequently used. An increasing use of interstitial-free (IF) steels, dual-phase and TRIP-steels, as well as the ultra low and super ultra low carbon steels can also be observed. We can state that from the elaboration of various micro-alloyed steels in the mid-seventieth of the last century, there is a continuous pressure on material development leading to the appearance of new advanced steel materials with higher strength properties practically in each five year [2].

However, it is also well-known that with the increase of strength properties a decrease of the ductility parameters can be observed, as it is illustrated in Fig. 1, however, it is worth mentioning that for these new high strength steels the increase of strength parameters is much more significant than the decrease of the ductility parameters.

In Fig. 1 three generations of steel developments can be well distinguished. Among the so-called first generation high strength steels we should mention the conventional high strength steels as IF (Interstitial Free), IS (Isotropic), BH (Bake Hardening) and HSLA (High Strength Low Alloyed) steels. Various grades of Dual-Phase (DP) and Complex Phase (CP) steels as well as several kinds of TRIP-steels belong to the second generation high strength steels. The third generation high strength steels like X-AHSS (Extra-Advanced High Strength Steels) and U-AHSS (Ultra-Advanced High Strength Steels) are the recent and most advanced representatives of high strength steel developments.

It is often usual to characterize sheet materials with the constant value calculated as the product of the ultimate tensile strength (R_m) and the total specific elongation (A_{80}). It is worth mentioning that the different generations of high strength steels can be found along a constant value of the hyperbolic function of this product: $C = R_m \times A_{80}$. This value is about C = 10 000 for the first generation high strength steels, it is about C = 15 000 to 20 000 for the second generation.

As we could see from Fig. 1 an even more pronounced development can be observed concerning this constant (i.e. C = $R_m \times A_{80}$) for the third generation of advanced high strength steels, i.e. for the X-AHSS and U-AHSS group of steels representing an another order of magnitude in the increase of strength properties where the C constant is in the range of 40 000 to 65 000. Obviously, these are mean values; the various subgroups of both X-AHSS and U-AHSS steels cover a broader range as shown in Fig. 1.

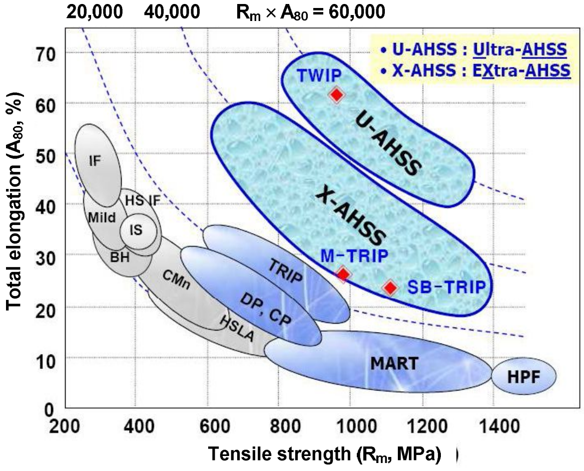


Fig. 1. Tensile strength vs total elongation for various high strength steels [3]

Considering these extreme large values (C = 40 000 to 65 000) it means that with the same value of total elongation the strength can be doubled or tripled, which has a priceless value to meet the increased strength requirements in car manufacturing to reduce the weight.

The extra high strength steels (X-AHSS) may be regarded as the further development of TRIP steels: these X-AHSS steels first appeared in the car manufacturing in the production range of the Far-East car manufacturer superpowers, in Japan and Korea. There are three subgroups in these steels, namely the so-called FB-TRIP, the SB-TRIP and the M-TRIP. The microstructure of FB-TRIP steels contains ferrite (F) and bainite (B) as indicated in their name (FB stands for Ferrite-Bainitic TRIP steel). Ferrite assures large value of stretchability, while the high strength is provided by the bainite produced by extra high grain refinement. This microstructure besides the high strength values results in outstanding strain hardening (n) and in extra-large total elongation. The microstructure of SB-TRIP steels (which is termed as Super Bainitic TRIP steel) has small nano-sized, lamellar bainite matrix with a small amount of retained austenite. Their mechanical properties can be characterised by extra high strength parameters ($R_{p0.2}$ = 900 MPa, R_m = 1600 MPa) with outstanding total elongation (A_{80} = 27-30%) at this extra high strength values [4].

The third subgroup, i.e. the M-TRIP steels contain also small amount of retained austenite but in martensite matrix, which lead to an even higher strength with still relatively good total elongation values. The usual composition of the M-TRIP steels can be characterised by C = 0.15-0.2%, Si = 1.6%, Mn = 1.6%.

Ultra-Advanced High Strength steels (U-AHSS) can be found on the top of today's steel development. TWIP (Twinning Induced Plasticity) steels are the most characteristic representatives of this group. TWIP steels usually contain high manganese content (Mn = 17-24%). This high manganese content provides the fully austenitic microstructure at room temperature. Its deformation mechanism may be characterised by the large number of deformation twinning induced by plastic deformation. It has also very high strain hardening capability (n = 0.4), which is responsible for the extra-large uniform elongation (ε_m = 50%) besides the extreme high strength parameters (R_m = 1000-2400 MPa). It is also worth mentioning that for example at tensile strength R_m = 1000 MPa they have a total elongation of A_{80} = 65%, which means that the product of $R_m \times A_{80}$ may achieve the constant C = 65 000, which is the highest value among steels at present [4].

2.2. Application of light metal alloys

Due to the increasing demand for environment-friendly vehicles requiring reduced fuel con-sump-tion and weight, besides steel as structural material, aluminium alloys in automobiles are recently more and more widely used in car manufacturing for body-in-white production, and their ratio will even further increase. According to the European Aluminium Association [5] the average amount of aluminium in today's car bodies is about 140 kg, however, many of premium category car makers produce car bodies made of fully aluminium alloys (e.g. Audi A8, Jaguar XJ, Range Rover, etc.). The amount of aluminium alloys in these cars exceeds 500 kg. Though this high value today is just characteristic for the premium category cars, but according to aluminium application forecasts in the near future it will be significantly increased in the middle and upper-middle car category, too. This forecast is proved by the fact that in 2015 the Jaguar XE model is issued with fully aluminium made body.

Due to this tendency there is an intensive research activity in the development of new aluminium alloys competitive with steels concerning their specific weight ratio, i.e. the ratio of the strength over density values.

Table 1.
Aluminium alloy application in various car models

Type	Structural elements	Inner panels	Outer panels
Audi A2	6181	6014	6016
Audi A8 (D2)	5182	6009	6016
Audi A8 (D3)	6181	6009	6016
BMW 6	6060, 6082	5042, 5182	6008
BMW Z8	6060, 6063, 6082	5754, 5182	6016
Chevrolet Corvette	6063	5745	6063
Ferrari 548 Italia	6005, 6063, 6082, 6260	6181, 6082, 6022	6181, 6082, 6022
Jaguar XJ (X350)	6082, 7108	5182	6111
Jaguar XJ (X351)	6082, 7108	5182	6111
Jaguar XK	6082	5754	6111
Lamborghini Gallardo	6060	6181	6016
Lotus Elise	6063	3105	3105
Lotus Evora	6060	5754	5754
Range Rover	6082	6014	6181, 6451
Rolls-Royce Phantom	6060, 6063, 6082	5182, 5454	6016

Another important issue in the application of aluminium alloys in car manufacturing to improve the formability properties and to elaborate innovative new forming processes to produce aluminium car body elements with relatively ease of use technologies. Among these process developments the various methods of Hydroforming and the forming at elevated temperatures are of important developments: these developments will be discussed later among the forming process developments.

According to the history of aluminium application, the Panhard Z1 model was the first car made of aluminium alloys in series production in 1953 [6]. Following the Panhard Z1, several models made of aluminium alloys appeared in small series production, among them Audi, BMW, Chevrolet, Jaguar, Ferrari, Lamborghini, Rolls-Royce are the most prominent ones. The applied aluminium alloys at the beginning belonged to the 5000 series aluminium alloys (e.g. EN AW 5754, 5182 and 5454) but soon other groups belonging to the 6000 and even to 7000 series were also applied. In Table 1. a summary of aluminium alloys most widely applied in car manufacturing is shown [6].

From Table 1, it can be seen that most car manufactures apply nearly the same or similar aluminium alloys. It is also worth mentioning that the automotive industry continuously started to use those aluminium alloys that were before already applied in the aircraft industry where the application of low weight construction principles is even more prominent. Besides the aluminium alloys other light metals like magnesium and titanium are also applied in car manufacturing to reduce the weight of automobiles.

Jaguar XJ is a good example to illustrate it. The Jaguar XJ (X350) is already produced in large series where besides the 5000 (EN AW 5182) and 6000 (EN AW 6082 and EN AW 6011) aluminium series the application of EN AW 7108 from the 7000 series can be also found. Besides these high strength aluminium alloys other materials like magnesium alloys and different grades of steels-even conventional mild steels, high strength steels, hot stamped press hardening steels are also applied realising the so-called multi-material car body construction principle.

The ratio of different material groups applied in the Jaguar XJ (X350) is shown in Fig. 2. It shows that together the 59% of 5000 series and 20% of 6000 series aluminium alloys represent nearly 4/5 of total material usage. It is also worth mentioning that the ratio of hot stamped Press Hardening Steels altogether is 8%.

Production of wheels and rims is regarded as a high-tech application field of magnesium alloys in the automotive industry. Manufacturing of inner and outer panels from magnesium alloys is less common, however we can find such examples [7]. For example, in Fig. 3 a trunk-lid panel made of magnesium alloy can be seen.

Besides the example shown above in the Fig. 3, there are further application examples among body elements, too. Manufacturing of inner structural elements like various seat-frames is another good example for the application of magnesium alloys in car manufacturing.

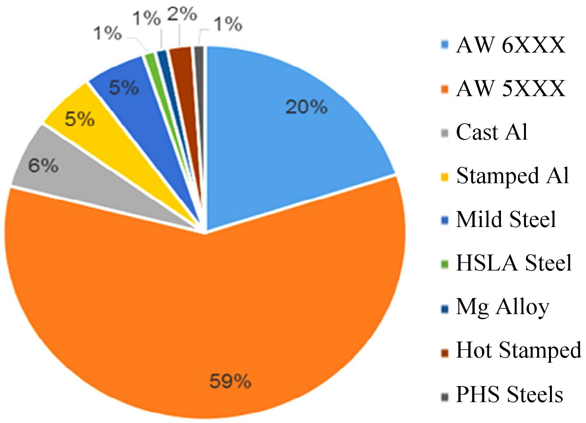


Fig. 2. Ratio of various materials in Jaguar XJ [6]

Fig. 3. Trunk-lid panel made of magnesium alloy [8]

However, the engine block and the gear boxes may be regarded as the most suitable and most common application fields for magnesium alloys [8]. In Fig. 5, a Volskwagen engine block made of cast magnesium alloy can be seen.

Due to their excellent properties, titanium alloys also have good potential for automotive application [9]. Among these advantageous properties, low density ($\rho = 4.5\ kg/dm^3$) and high specific strength ratio (R_m/ρ) are particularly beneficial properties of titanium alloys considering the weight reduction. Besides these properties titanium alloys are often important materials enhancing the power parameters. In this respect the engine winch made of titanium alloy is an excellent example (Fig. 6).

Titanium alloys besides the aforementioned advantageous properties (low density, high specific strength) have higher heat-and corrosion resistance. Thus they are also considered as structural parts where the operation temperature may be higher than 400°C. Therefore titanium alloys may also be used as the material of several engine parts and elements of exhaustive system [10].

Fig. 4. Automotive seat-frames made of magnesium alloys

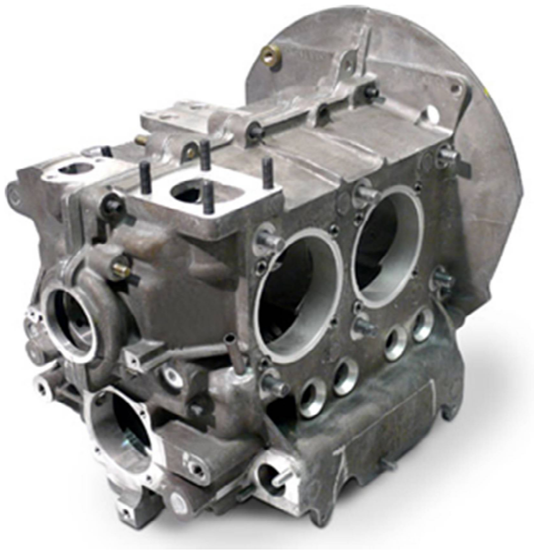


Fig. 5. Automotive engine block made of magnesium alloy

Fig. 6. Engine winch made of titanium alloy

The good heat-shock resistance of titanium alloys may be regarded as further advantage of them. The heat-shock resistance of a material may be well characterized by the product of thermal expansion coefficient and the Young-modulus: this parameter is about three times better for titanium alloys than that of the good quality stainless steels. A good example for this application is shown in Fig. 7.

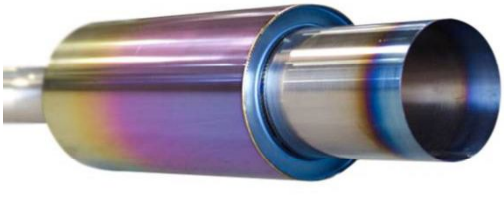


Fig. 7. Elements of exhaust system made of titanium alloys

3. Process developments in sheet metal forming industry

To elaborate new, innovative sheet forming processes, the automotive industry always played key role [11], and on the other hand, car manufacturing as a mass production would be unthinkable without innovative forming technology: they have a mutually advantageous effect on each other resulting in a synergic interdisciplinarity of various sciences. Due to the limited extent of this paper, only a few, but representative examples will be shown from the recent developments [12,13].

3.1. Hydroforming in the automotive industry

One of the research targets in the project mentioned in the Introduction was the application a various methods of hydroforming.

In the automotive industry, tube hydroforming is already an industrially proven technique: various load bearing components produced by this method can be found in several cars. In Fig. 8, an engine cradle and some elements of exhaust system can be seen as a typical examples for tube hydroforming [14].

The development of hydroformed parts for large series production requires efficient methods both in the design and in the manufacturing phase to meet the requirements to produce high quality parts in a cost effective way [15]. In most cases, the initial workpiece is a semi-finished product-usually a roll formed tube made of hot- or cold rolled, longitudinally welded strips.

Depending on the complexity of the component to be produced, hydroforming usually applied together with additional preforming operations. These preforming operations often include pre-bending as also can be seen from Fig. 8.

Engine cradle made from DP600

Elements of exhaust system made of stainless steel

Fig. 8. Hydroformed automotive parts

Recently, hydroforming of double sheets has also been developed and seems to be also a promising process to produce complicated sheet metal parts [16]. An example for hydroforming sheet metal parts is shown in Fig. 9.

Fig. 9. Complicated sheet metal part produced by sheet hydroforming

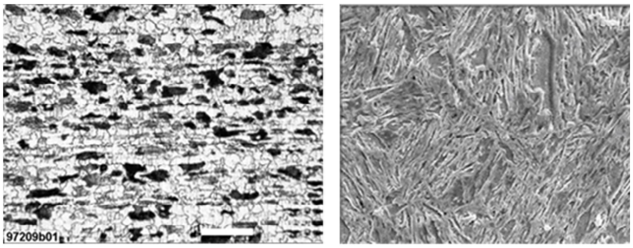
3.2. Hot forming of high strength steels

To meet the increased requirements stated against the automotive industry the Hot Press Forming (HPF) of Press Hardening Steels (PHS) has an utmost importance [17]. The Press Hardening Steels were developed to produce a relatively low alloyed high strength steels with good formability. These PHS steels are mainly boron-alloyed manganese steels. They contain very low amount of micro-alloying elements, among them the Boron element is the most important one. Besides these micro-alloying elements these steels contain only manganese in relatively low quantity (usually the manganese content is about 1.2-1.4%). The 22MnB5 alloy (e.g. MBW 1500) is the most characteristic representative of these alloys having a moderate carbon content (C = 0.22-0.25%) and boron element approximately 10 to 15 ppm. Whilst the relatively low manganese content (Mn = 1.2-1.4%) basically determines the basic hardness of martensite, the very low amount of boron is responsible for the low cooling rate ($v \leq 3$°C/s) thus enhancing the martensite formation. This steel in as delivery state has a moderate yield strength ($R_{p0.2}$ = 450-600 MPa) and sufficient formability (specific elongation A_{80} = 15-20%) with a ferrite-perlite microstructure [18].

There are two basic types of hot forming of these steels: direct and indirect hot forming. In both cases, the hot forming is performed at about T = 950°C where due to the small sheet thickness a full austenitization occurs within a few minutes. From the furnace the blank is transferred to the preheated tool and the forming occurs before the martensitic phase transformation starts. Then the hot formed part is cooled down to T = 150°C together with the tools, then removed and cooled down to room temperature. At the end of this hot forming process the part has fully martensitic microstructure, with significantly increased ultimate tensile strength ($R_m \approx 1500$ MPa). The microstructure of this steel before and after hot forming is shown in Fig. 10.

The time-temperature cycle of the hot forming process for boron-alloyed manganese steel (22MnB5) is shown in Fig. 11 including the total heating-forming and cooling cycle.

The application of hot forming of PHS steels is more and more widely applied in the upper and upper-middle category cars among the European carmakers. As an example, the Volkswagen Passat is shown indicating those load bearing parts that are made of press hardening steels by hot forming [19].



Ferrite-pearlite microstructure in as delivered state

Martensite microstructure after hot forming

Fig. 10. Microstructure of 22MnB5 Press Hardening Steel

Among these typical application fields the B-pillar has an outstanding role as one of the first examples using boron alloyed manganese steels (Press Hardening Steels) but there are many further significant applications in the automotive industry like rail roof inner, side impact beams, tunnel and subplate elements, etc.

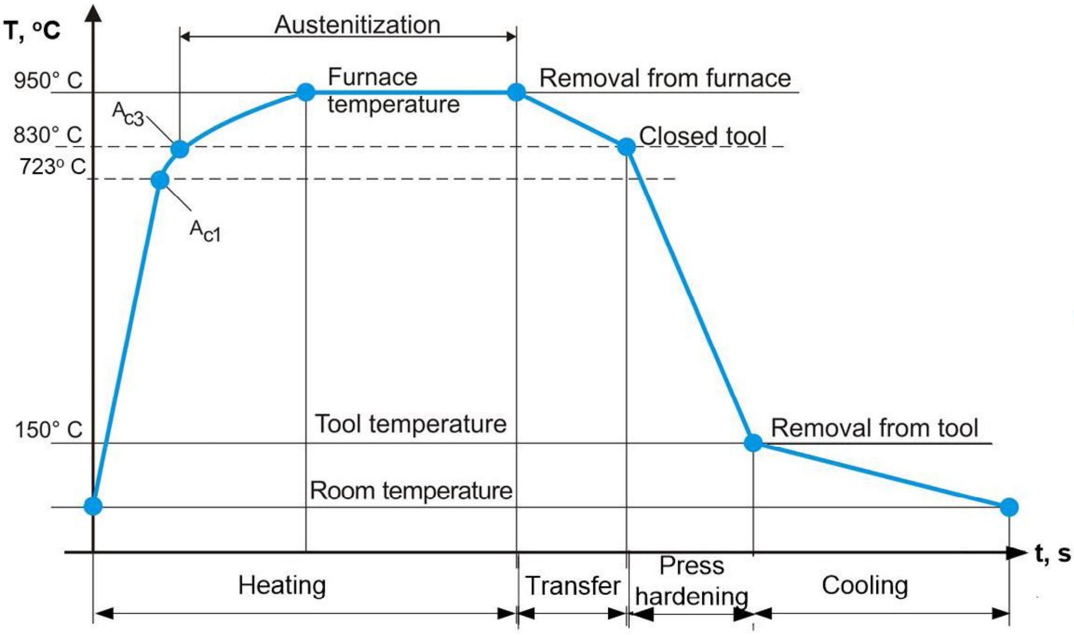


Fig. 11. The time-temperature cycle of the hot forming process

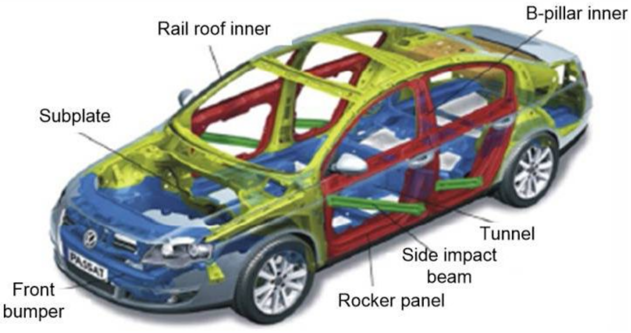


Fig. 12. Typical application fields of Press Hardening Steels

Fig. 13. Hot press forming of a B-pillar applying the so-called Hot Tailor Welded (HWB) concept

In Fig. 13 a unique Tailor Welded approach of B-pillar manufacturing can be seen. The B-pillar is the most important functional part concerning the side impact load bearing capacity. Therefore the upper 2/3 section of the B-pillar requiring the largest rigidity is made of high strength press hardening steel, whilst the lower 1/3 section is made of HSLA steel which also has a relatively high strength but comparing to PHS steels it is significantly lower, however, it has better ductility properties which is beneficial from the point of view of energy absorption capacity. The two different materials are joined by laser welding creating a transition zone possessing high strength and rigidity and simultaneously good energy absorption capability [20].

Applying PHS steels by hot forming can result in significant weight saving. The weight saving potential in PHS steels is about 30-40% compared to conventional mild steels widely applied in the automotive industry in former years [21].

4. Description of achieved results

As it was mentioned before, these results were achieved within a national research project. Within this project we performed several experimental investigations with these new high strength steels, particularly with several grades of DP steels most widely applied in the automotive industry (from DP600 to DP1400).

Among these investigations we performed conventional materials testing to determine the basic mechanical properties, formability testing including various types of deep-drawability tests (e.g. Erichsen-test, cup drawing test, Limit Dome Height test, etc.).

We also determined the Formability Limit Diagram (FLD) for these materials and collected these data in a book published recently [23]. In Fig. 14 the experimental testing system for determination of Formability Limit Diagrams is shown. This sheet formability tester machine is equipped with an optical strain measurement system for fast and accurate determination of strains even during the testing process.

Fig. 14. Complex formability testing machine equipped with Vialux optical strain measurement system

A Forming Limit Diagram of three different advanced high strength DP steels (DP600, DP800 and DP1000) is shown in Fig. 15. The experiments were performed with modified Nakajima specimen [24].

Besides the formability investigations, we performed several experiments to analyse innovative forming processes. Among the many investigations we have analysed the effect of various state factors (e.g. stress state, temperature and strain rate) on the formability of high strength steels.

Concerning the effect of stress state we also performed various experiments with hydroform and hydromech processes to analyse the optimum process parameters for these new materials both in sheet- and tube hydroforing. A schematic view of applied hydroform process for double sheet hydroforming is shown in Fig. 16.

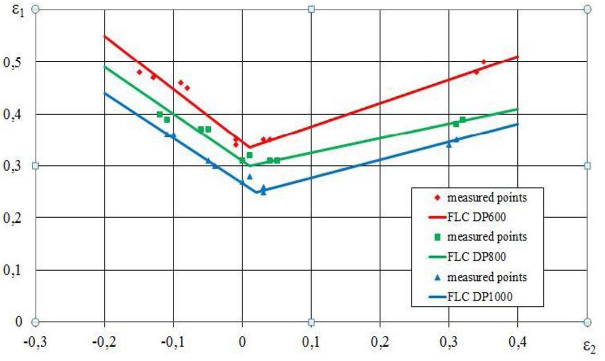


Fig. 15. FLD for high strength steel DP steels (t = 1.2 mm)

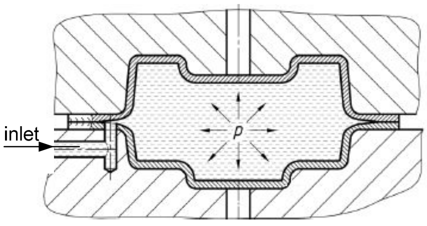


Fig. 16. Hydroforming of double sheets joined on their flange

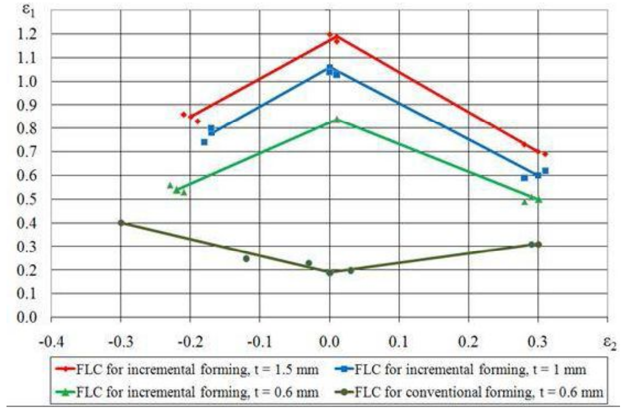


Fig. 17. FLD for Al-1050 sheets with different thicknesses

We have performed also several experiments concerning rapid prototyping processes applying incremental sheet forming. Incremental sheet forming is a powerful process to produce complicated parts in small batch production [26]. Together with our partner institutions we have elaborated a new method for the determination of forming limit diagram for aluminium sheet incremental forming [27]. Forming Limit Diagrams for an Al-1050 aluminium is shown in Fig. 17 for different thicknesses.

From this Figure it can be seen that in incremental forming much higher formability can be achieved. The maximum value of main principal strain (ε_1) in plain strain condition (i.e. when $\varepsilon_2 = 0$) might be three times higher than in conventional forming.

5. Conclusions

In this paper some recent material and process developments were overviewed first of all from the perspectives of automotive industry. Then some research results achieved within a national project were summarised. Concerning the material developments it is stated that to meet the increased demands against the automotive industry the application of advanced high strength steels and light metal alloys have the greatest importance.

Among the high strength steels three generation of steel developments are overlooked with particular emphasis on DP steels as the most widely applied high strength steels in the automotive industry. A special attention was paid to the so-called press hardening steels (PHS steels) as one of the most outstanding developments concerning the load bearing elements in automotive structures. The latest results in Advanced High Strength Steels (X-AHSS and U-AHSS) are the most advanced materials developments concerning the balance between extra high strength properties and formability which is also extremely important in car manufacturing.

Besides high strength steels light metal alloys like aluminium-, magnesium- and titanium-alloys are also very important in fulfilling the ever increasing demands and challenges stated against the automotive industry to improve the global competitiveness.

Following the material developments some recent achievements in process developments are also summarised including innovative forming processes as hydroforming, hydro-mechanical drawing, hot forming of press hardening steels, and some of the rapid prototyping processes, like sheet incremental forming were analysed.

Acknowledgements

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Additional information

Selected issues related to this paper are planned to be presented at the 22nd Winter International Scientific Conference on Achievements in Mechanical and Materials Engineering Winter-AMME'2015 in the framework of the Bidisciplinary Occasional Scientific Session BOSS'2015 celebrating the 10th anniversary of the foundation of the Association of Computational Materials Science and Surface Engineering and the World Academy of Materials and Manufacturing Engineering and of the foundation of the Worldwide Journal of Achievements in Materials and Manufacturing Engineering.

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