MATERIAL DEVELOPMENTS IN SHEET METAL FORMING

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Abstract
Sheet metal forming is one of the most important key technologies in manufacturing industry. It may be reasoned by several facts, among them the economy of the sheet forming processes concerning the material and energy consumption, as well as the overall cost efficiency. To keep this key role of sheet metal forming in manufacturing industry, a continuous development is necessary concerning the materials, the development of new innovative forming processes, the tooling and manufacturing equipment. The ever increasing requirements stated by the automotive industry may be regarded as one of the main driving forces behind sheet metal forming innovations. In this paper, some recent developments in sheet metal forming will be overviewed concerning the sheet materials.

Keywords: sheet metal forming, car development trends, new materials

1. Introduction
Sheet metal forming is one of the most important manufacturing processes. This is particularly valid for the automotive industry where sheet metal forming has an even more important key position. The automotive industry is the leading sector in many countries and the main driving force behind the sheet metal forming developments as well [1].

The competition in car manufacturing is extremely strong leading to larger model variety, and shorter model cycles. The increased competition also leads to a very intense development activity to increase productivity and to reduce costs. Application of lightweight design principles is one of the most important trends to meet the above requirements. Obviously, the new design concepts require new materials. The new materials often require new, innovative forming processes and new tooling concepts, as well. The increased competition also requires shortening the lead times from the concept to final realization: to reduce the lead times the application of various methods of Computer Aided Engineering (CAD/CAM/CAE and FEM techniques) are inevitable.

In this paper, from these many-sided development requirements, we will focus mainly on the materials.

2. Main material development tendencies in sheet metal forming
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. 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. These developments in steel materials are shown in Figure 1 concerning the last 30 years. From this figure, it can be seen 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 practically in each five year [2].

Figure 1. Time horizon of steel development in the automotive industry in the last 30 years

These development trends can be seen from another aspect on Figure 2. This figure shows the well-known relationship between strength and ductility parameters for conventional low- and high strength steels, i.e. which illustrates that with the increase of strength properties, a decrease of the ductility parameters can be observed. There are different classifications concerning the strength of steels: in some cases, you may find narrowly defined ranges to categorize steels as low-, medium- or high strength steels. However, these ranges and categories are changing rapidly due to the rapid developments in steel industry. For example, the World Auto Steel [4] in 2009 defined high strength steels above $R_{p0.2} > 550$ MPa and $R_{m} > 700$ MPa.
In Figure 2, some of the steel developments shown in Figure 1 are drawn in $R_m \times A_{80}$ coordinates indicating the relationship between strength and ductility as described before. From Figure 2, it may be seen that the product $R_m \times A_{80}$ is a constant and thus follows a hyperbolic function. The constant ($C = R_m \times A_{80}$) for these steels is changing between 10 000 to 20 000 and we can state that these developments may be regarded as one of the most important results in the second half of the last century in achieving the required mass reduction.

It is also 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 [3]. This is particularly valid for the group of steels marked as Conventional AHSS steels in the figure. Dual Phase steels (DP), Complex Phase steels (CP), Martensitic Complex Phase steels (MART/CP) and TRIP steels belong to this group. In the following, the main features of these developments will be shortly analysed.

2.1. Conventional High Strength Steels

Both manufacturers and users of steel products are in aware of fundamental metallurgy of conventional steels. However, the metallurgy and processing of high strength steels is less common, therefore, first a short description will be given to understand how their remarkable mechanical properties evolve from their unique processing and structure.

2.1.1. High Strength Low Alloyed (HSLA) Steels

HSLA Steels were one of the first results of steel manufacturing to produce high strength with relatively good formability. The main characteristics of these steels may be summarised as follows: high strength ($R_m = 400$-$1000$ MPa), good formability ($A_{80} = 15$-
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30%), good weldability and low transition temperature (i.e. good resistance against brittle fracture). It is very important that all these excellent properties are provided with small amount of low cost alloying elements. They have low carbon content (C = 0.1-0.2), the only alloying element in substantial quantity is the Manganese (Mn = 1.0-1.7%) and very small amount of V, Nb, Ti and Al as micro-alloying elements (i.e. they total amount is below 0.12%).

The low carbon content is necessary for the good formability, weldability and low transition temperature. Up-to-date converter steel-making processes without significant extra costs can assure the low carbon content. Manganese as the main alloying element has important role from many points of view. Solution hardening is one of the most important effects of Mn-alloying in the strengthening mechanism to provide significant increase of strength properties. Micro-alloying elements have also manifold effects and contribute to the increase of strength parameters. From the strengthening mechanisms the solution hardening and the precipitation hardening is equally utilised by forming disperse carbide and nitride particles. This latter effect is mainly due to vanadium, niobium and titanium. These micro-alloying elements – together with the aluminium – also have important effect in producing very fine grain structure, which is also favourable from the point of view of strengthening.

The excellent mechanical properties – besides the right chemical composition – are produced by special thermo-mechanical treatment including hot plastic deformation at optimum temperature, which is followed by a severely controlled cooling process. During this thermo-mechanical treatment, both the manganese and the micro-alloying elements have further important roles by delaying the recrystallization process thus enabling significant plastic deformation in austenitic state and providing very fine grain structure. The finer the grain structures of austenite during phase transformation, the better the mechanical properties are after completing the phase transformation.

2.1.2. Dual Phase (DP) Steels

Though HSLA steels have outstanding properties, i.e. relatively good formability besides extreme high strength, they formability in some cases is not sufficient to produce parts requiring large plastic deformation. This led to the elaboration of a newer high strength steel grade, i.e. the DP-steels having practically the same strength values as HSLA steels but with increased formability. DP-steels consist of ferritic matrix containing hard martensitic second phases in the form of small martensite islands. Increasing the volume fraction of hard martensite phases increases the strength. The dual-phase structure (i.e. martensite isles in ferrite matrix) is usually produced by controlled cooling from the two phase, austenite and ferrite zone (i.e. from the temperature zone between the A1 and A3 phase transformation lines).

Figure 3. shows a schematic illustration of the microstructure of DP-steels containing hard martensitic isles (small dark grains) in mild ferrite matrix (light grains in the figure). The mild ferrite forms a continuous micro-structure assuring excellent ductility, whilst the hard martensite isles are responsible for the high strength of DP-steels.
Modifying the ferrite/martensite ratio, the mechanical properties of DP-steels can be changed in a wide interval. The usual amount of martensite isles is about 10 to 20%. During forming, deformation is concentrated in the lower-strength ferrite phases surrounding the martensite isles and thus creating extra high strain hardening of DP-steels. The excellent ductility together with the extra high strain hardening results in much higher ultimate tensile strength compared to conventional HSLA steels [5].

A further advantage of DP-steels that they exhibit a high bake hardening effect (i.e. their yield strength increases significantly due to the temperature ageing created by the curing temperature after painting in the bake oven).

2.1.3. TRIP steels

The elaboration of TRIP steels is regarded as a very important step in the development of high strength steels. As it can be seen from Figure 6., they are located along the hyperbola characterised by a constant value \( C = 20,000 \) (where \( C = R_m \times A_{80} \)) whilst this value for conventional HSLA steels is about \( C = 10,000 \). It means for example that for a tensile strength \( R_m = 800 \) MPa, the total elongation for a HSLA steel is in the range \( A_{80} = 10\div15 \) %, for TRIP steels it is much higher, i.e. \( A_{80} = 20\div25 \) %.

The microstructure of TRIP steels contains at least a minimum 5% residual austenite in a ferrite matrix. Besides the retained austenite, hard bainite and martensite phases are also present in varying amounts. Typical microstructure of TRIP steels can be seen in Figure 4. This microstructure typically requires isothermal holding the steel at an intermediate temperature: this is necessary to provide the required amount of bainite. Then it is followed by a controlled cooling.

During plastic deformation the hard disperse phases in the mild ferrite matrix result in significant strain hardening as described for the DP-steels. However, in TRIP steels the retained austenite more progressively transform into martensite with the increase of strain, thus increasing the strain hardening at higher strains. This is particularly useful when designers take advantage of the higher strain hardening to design parts utilizing higher strength in formed condition.

TRIP steels have higher carbon content compared to DP-steels to retain austenite even at room temperature. Though the higher carbon content is beneficial for stabilizing the austenite, it creates a critical problem during the bainite transformation, namely the precipitation of carbide should be prevented. Adding Si and Al alloying elements are important to avoid carbide precipitation during bainitic transformation.

TRIP steels can be tailored according to the requirements either to provide excellent formability for manufacturing complex parts and by deformation induced phase transformation providing significant increase of strength or exhibit high strain hardening during crash deformation for outstanding absorption of crash energy.
2.1.4. Martensitic steels – MS Steels

Martensitic steels can be found at the highest strength region of strength-elongation hyperbolic curve characterized by the constant $C = R_m \times A_{80} = 10,000$. The ultimate tensile strength for these steels is about $R_m = 800-1500$ MPa. The austenite existing during hot rolling is almost entirely transformed to martensite on the run-out table or in the cooling section of the continuous annealing line. Besides martensite a small amount of bainite or even ferrite can be found. This microstructure can be also provided with post-forming heat treatment. Sometimes, they are subjected to post-quench tempering to increase ductility and to provide relatively good formability even at extreme high strengths.

2.1.5. Hot-Formed HF-HPF Steels

Press hardening is a recently developed application of extra high strength steels to produce very complex parts. In Figure 6., they can be positioned at the high-strength end. Boron-alloyed Manganese hot forming steels (22MnB5) are the most prominent representative of these steels. This is the result of a complex material and technological development often termed as press hardening. It has considerable amount only from manganese (Mn = 1.2-1.4 %), some micro-alloying elements (e.g. Al, Ti) and usually very low amount of boron (B = 0.002-0.005 %). In delivery state, this steel has low yield strength ($R_{p0.2} = 300-350$ MPa) and good formability ($A_{80} = 20$ %). The usual forming procedure is hot forming at $T = 900-950$ °C followed by cooling with $v_h > 50$ °C/s cooling rate together with the tool. The result of this hot forming and subsequent relatively fast cooling is a high strength ($R_m > 1500$ MPa) stable martensitic microstructure. Typical application fields of this hot-formed steels in car body production are shown in Figure 5.

![Figure 5. Typical hot formed parts in a middle class car [7]](image)

2.2. New Generation Advanced High Strength Steels

Besides the before analysed steels, there are even more pronounced steel developments in the last two decades. The two most outstanding representatives of Advanced High Strength Steels are the so-called Extra-Advanced High Strength Steels denoted as X-AHSS, and the Ultra-Advanced High Strength Steels denoted as U-AHSS. There are several subgroups within these steels. The development and application of these X-AHSS and U-AHSS steels is evolving from the ever increasing demand on the car manufacturing to
produce cars with even lower consumption and less harmful emission simultaneously with more safety and higher formability.

As we could see analysing the various grades of conventional high strength steels, the constant of the product of tensile strength times total elongation (i.e. \( C = R_m \times A_{80} \)) for that group was increased from \( C = 10,000 \) to \( C = 20,000 \). These X-AHSS and U-AHSS steels represent another order of magnitude as shown in Figure 6. In this figure, it can be well seen that the constant \( C = R_m \times A_{80} \) has been increased to \( C = 40,000 \) for X-AHSS steels and to \( C = 60,000 \) for U-AHSS steels. Obviously, these values are mean values; the various subgroups of both X-AHSS and U-AHSS steels cover a broader range as shown in Figure 6, too. In this figure, the conventional high strength steels analysed in the previous section are also shown, which provide a good basis for comparison how big development in AHSS steels achieved. Considering these extreme large values (\( C = 40,000 \) to 60,000) 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.

![Figure 6. Tensile strength vs. total elongation for X-AHSS and U-AHSS steels [3]](image)

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 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.

The third subgroup, 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 representative 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 the plastic deformation. It has also very high strain hardening capability ($n = 0.4$), which is responsible for the extra-large uniform elongation ($e_m = 50\%$) 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.

### 2.3. Application of Aluminium alloys and non-metallic materials

Due to the increasing demand for environment-friendly vehicles requiring reduced fuel consumption and weight, besides steel as structural material, aluminium alloys in automobiles are recently also widely used in car manufacturing for body-in-white production, and their ratio will even further increase according to the application trends shown in Figure 7.

![Figure 7. Application trend of Aluminium alloys in car manufacturing](image)

It can be well seen from this figure that the application of aluminium and its alloys has been increased more than four times during the last 30 years. While in 1978, the total amount of aluminium applied in car manufacturing was about 32 kg in an average car, for 2008 it was increased up to 130 kg. It is also worth mentioning that the sort of aluminium alloys has also been significantly changed. While in 1978, the ratio of wrought Al-alloys was more than 90%, for 2008 this ratio has been significantly changed: today nearly 50-
50% is made of wrought and cast alloys. Even more significant changes can be observed if we focus on sheet materials. Due to the obvious advantages of aluminium alloys in mass reduction, there is an overall interest among car manufacturers to use more and more aluminium. Nearly all top car manufacturers has at least one model made of aluminium body. Together with the mass reduction it means simultaneously lower CO₂ emission and the reduction of fuel consumption.

It is also important to note that nearly all top car manufacturers (e.g. Mercedes, Audi, BMW) have at least one model where the body is made of aluminium alloys. Most of these models belong to the luxury car category, but recently there are already aluminium bodies in the compact car category, too. In Figure 8., the Mercedes SL model, in Figure 9. the Audi A2 model can be seen: both are made of aluminium alloys.

![Figure 8. Mercedes SL model with aluminium body](image1)

![Figure 9. Audi A2 aluminium body on the assembly line](image2)

In many cases aluminium alloys are used within the so-called multi-material concept as shown in Figure 10.

![Figure 10. Multi-materials body concept in car manufacturing](image3)

Many analyses also have shown that further significant weight reduction can be achieved in automobiles using fibre-reinforced composite materials. Carbon-fibre reinforced polyamide seems to be particularly suitable for this purpose: it satisfies the requirements of production in large series together with good mechanical strength and shape stability.
3. Conclusions

In this paper the recent development trends in sheet metal forming were overviewed from the point of view of material developments.

Concerning the material research and development the increasing application of high strength steels, low density aluminium alloys, as well as the so-called multi-material concept was emphasized. Among high strength steels both the so-called conventional high strength materials (like HSLA, Dual-Phase, Complex Phase, and TRIP steels) were analysed. Besides introducing the development trends in steel materials in the last 30-40 years, a special emphasis was given of the most recent developments in Advanced High Strength Steels, as the Extra- and Ultra High Strength steels.

It was also shown that the application of aluminium alloys in car manufacturing is rapidly increasing. Finally, the multi-material car concept was introduced.

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5. References