Application and development trends in high strength steel and aluminium

Zs Lukacs, M Tisza
University of Miskolc, Institute of Material Science and Technology
lzsolt@kugli.met.uni-miskolc.hu

Abstract. Due to increasing competition globally among car manufacturing companies cost optimization is one of the major concerns in the automotive industries right from inception stage to the final product delivery along with maintaining its highest quality. Nowadays, rising demand for concept car, automobiles with latest technology, aesthetics of vehicles with safety concern, high strength and light weight results technological advancement in sheet metal forming and innovative material development like different grades of high strength steels and lightweight aluminium alloys. In 2015 with the initiative of the Imperial College London a research consortium was established under the umbrella Low Cost Materials Processing Technologies for Mass Production of Lightweight Vehicles. The primary aim of this project is to provide affordable low cost weight reduction in mass production of vehicles considering the entire life-cycle. The technological process solution for HFQ™ of Al-alloys is presented which greatly helped in reducing weight and increasing the strength.

1. Introduction

The globally raising awareness toward CO2 reduction and resource efficiency concerning to climate change have significantly increased the importance of this topic over the last few years. Lightweight materials development and design have always been an important topic in product design across several industries. Developments of different high strength steel and aluminium help in the improvement of powertrain efficiency like small turbo-charged engines, alternative powertrain/hybridization, efficient transmission. The global automotive industry is more challenging than people think. In addition, the automotive industry has benefited as developed economies, have enacted many monetary policies to stimulate growth, pushing interest rates lower. As interest rates decreasing, consumers were more preferring to purchase a new vehicle due to the more affordable financing options available and due to rising incomes of the working class. In the last few years, due to the increased demands of vehicles in the market there were very intense developments concerning the applied materials in car body manufacturing especially different grade of high strength steel and aluminium. AHSS is one of the latest and fastest growing steels in the automotive sector. It leads not only to mass reduction but also reduces greenhouse gas emissions of vehicles. Stringent fuel efficiency regulations have facilitated R&D to develop lightweight & cost effective materials for the automotive sector. Affordability and excellent properties of newly developed high strength steel grades are likely to have positive effect its utilization in the automotive sector over the upcoming years. Aluminium has been witnessing major and crucial growth in the demand from automotive industry due to its weight reduction potential, improved strength and high recyclability as compared to steel. Aluminum can absorb twice the crash energy as compared to mild steel and provides weight reduction of up to 50%, which is expected to propel its demand over the upcoming years [1]. According to the European Union progress report 2017 (United4climate), European Union members states agreed on commitment to reduce their domestic emissions by at least 40 % between 1990 and 2030. But according to the recent
Projected data based on existing measures, the 20% target for 2020 will be met. In 2030, emissions are expected to be 30% which is lower than in 1990 if there will be no additional policies are implemented. Therefore, EU is currently negotiating new legislation to ensure that it will meet its objective of reducing emissions by at least 40% between 1990 and 2030 [4]. Following the adoption of the Paris Agreement at COP 21, efforts and resources will be further concentrated on fighting climate change and decarbonizing the economy. A new EU’s focus area, as known as ‘Building a low-carbon, climate-resilient future’, will specifically support the implementation of the Paris Agreement for 2018-2020 [4].

In the European Union, current climate targets require a 60% reduction in transport emissions by 2050. Pursuing these objectives could be facilitated by enhancing knowledge on the evolution of existing car fleets (hereafter defined as fleet dynamics), examining the impact of changes in material composition, weight and drivetrains of new cars, the energy system and consumer behavior. The greatest emissions savings seem to be achieved only by significant weight reduction and development of more efficient engines. So, advanced high strength steel is the fastest growing steel category in the automotive sector not only because it leads to significant weight reduction but also reduces the greenhouse emission from the vehicles. Powertrain comprises of various forged metal parts like transmission shafts & gears, clutch hubs, drive shaft, and universal joints. In addition, the engine also have forged piston in order to increase its durability. Suspension and body frame also need the use of high strength materials to ensure vehicle safety [1]. Concerning the continuously increasing requirements on the improvement of crash resistance of vehicles, high strength materials like high strength steel and high strength Al-alloys are more and more widely used. Among these high strength materials Manganese-boron steels are the most often used in hot-press forming. Hot-press formed parts offer very high resistance against deformation during crash thank to their very high strength (Rm = 1500 to 2000 MPa). These high strength steels besides the excellent crash-resistance and safety properties are also important from mass reduction point of view. that is, reducing the fuel consumption and harmful CO2 emissions.

2. Application of high strength steel of car manufacturing

There is an intensive research ongoing on the application of various grades of high strength steels. Steel dominated the global market in term of revenue share. Affordability and excellent properties of new steel grades including advanced/ultra-high strength steel are likely to positively affect its utilization in the automotive sector over the forthcoming years [1]. For several decades, the application of the conventional cold-rolled steels have dominated in the car body manufacturing. However, in the last 20-30 years due to the increasing demands and growth in the automotive sector, there were very intensive developments in the steel sector with more emphasis given on lightweight materials development with better strength, higher safety. These improvements kept in view the regulation of EU norm of CO2 emission according the Paris agreement at COP 21. Some examples for the so-called advanced High Strength Steels (AHSS steels), X- AHSS, U-AHSS. As it can be seen in figure 1, different phases of development of steel called as first, second and third generation steel respectively because of its advancement in terms of increasing strength parameters, the ductility parameters and thus the formability is significantly decreasing. Therefore, the high strength steels have the limited extension of formability that is another important issue.
Figure 1. Total elongation vs. Ultimate Tensile Strength for various generations of high strength steels.

We can also see in figure 1 that the total elongation (A₈₀) is a function of ultimate tensile strength (Rₘ). Among the various new, high strength steel grades like DP steels, TRIP steel, TWIP steel, there were various other grades available and further works going on to develop innovative materials that bring revolution in the automotive sector in terms of cost, quality and sustainability. According to figure 1, we can conclude that strength increases from 1st generation to 3rd generation but elongation gets lower and lowered. Also, there is one important material developed called Press Hardening Steels (PHS) and it is widely used to produce high strength structural body elements (e.g. A and B-pillars, etc.) applying hot forming processes. From this material grade, different kinds of boron alloyed manganese steels should be mentioned that are also commonly used already in car body manufacturing in hot forming condition. That is particularly the 22MnB5 alloy which is regarded as the basic type of PHS steels. This PHS steel is important from our main point since we focus on a new hot forming process (Hot forming & Quenching-HFQ™) developed for light metals.

Even though the application of hot press forming in the automotive industry just started in the recent days, the process itself dates back to 1977 when Erland Lundström, a Swedish scientist patented a process to produce sheet steel products such as a reinforcement element in a larger structure [1].

The next important milestone in the application of hot-press forming in the automotive industry was in 1984. The Swedish SAAB company introduced this technology first time in serial production for manufacturing the side impact beam in SAAB 9000 series [2]. Since then, the use of hot-press forming was widely used in producing parts offering an extra high level of strength. Manganese-boron alloyed steel (22MnB5) as one of the most important typical grade was used as blank material.

2.1. Hot Forming of Press Hardening Steels (PHS)
Hot forming is a unique metal forming technique. Hot press forming is also known as press hardening and it is a relatively new forming process. It was developed particularly for the application of high strength steels in car body manufacturing in the automotive industry. This technology was invented in Sweden [5], then further developed in Germany [6], [7] and France [8]. Many industrial plants are working in the world among them in Hungary; the Kirchhoff Automotive is the main supplier of components produced by Press Hardening of boron alloyed manganese steels for Hungarian OEM car makers [9].

This process may be shortly summarised as follows: the material is heated up to a sufficiently high temperature up to the austenitic zone and holding temperature is selected in the homogenous γ-zone above the A₃ temperature of the given steel until the carbon fully dissolve producing homogeneous austenite microstructure. Then, hot forming occurs and the part is cooled down rapidly in the forming tool with the critical cooling rate to prevent the carbon diffusion, thus resulting in martensitic
microstructure (as shown in figure 2, N=1500X) leading to significant increase of the strength parameters. Since the martensitic transformation – i.e. the hardening process – occurs in the forming tool, this is the reason that this process is often termed as press hardening.

The important process cycle of hot press forming (HPF) of 22MnB5 steel can be seen in figure 2. Boron-alloyed manganese steels are the most suitable group for hot press forming. This group includes the 22MnB5 steel as the most typical one for this application, but some other types as 8MnCrB3, 20MnB5, 27MnCrB5 and 37MnB4 can also be used in hot press forming.

Figure 2. Temperature vs. time for hot press forming (HPF) of 22MnB5 steel.

3. High strength Aluminium alloys in the automotive industry
Significant progress has been witnessed in the demand of Aluminium from automotive industry due to its lightweight and high recyclability as compared to steel. Aluminium can absorb twice the crash energy as compared to mild steel and provides weight reduction of up to 50.0% which is expected to propel its demand over the coming years [1]. The 1st generation high strength steel are very closer properties to the high strength Al alloys, it is clearly seen from figure 3. Aluminium is also commonly used as base material for car body elements. It is very important from mass reduction point of view. However, there is an important concern that it has lower formability than steels which leads to serious formability problems in cold forming operations. It is well known that the formability is increasing significantly with the increase of the temperature. This is the main reason that significant efforts and steps are made for both in the laboratories and in industrial circumstances to apply high strength aluminium alloys in hot forming conditions.

During the recent years, several new grades of high strength aluminium alloys were developed [10]. Among them, the so called 5xxx, 6xxx, and more recently the 7xxx series are mainly used in the automotive industry. Also, with the increase of strength the formability of these alloys is also reduced. So, the formability as for most of the metals and metallic alloys can be significantly increased at elevated temperatures. Constellium is one of the major suppliers of different grades of high strength aluminium in the world and in the European automotive sector as well, providing different grade of aluminium alloys with different trade names like Sufalex®, Stronglex®, Ultralex®. These grades of aluminium alloys with different trades name have very close mechanical properties to the first generation AHSS as seen from the figure 3.
The Ultralex® offers inter-granular, filiform structure and stress corrosion resistance best-in-class among the 7xxx family, provides approx. 15% weight savings vs. UHSS and formable using press hot forming & warm forming, and joinable using adapted mechanical fasteners.

Table 1. Compare of 22MnB5 vs. Ultralex® Al-alloy T6 condition.

| Side impact beam product | YS, MPa | UTS, MPa | A50, % | Gauge of ISO crash performance | %-light-weighting vs. 22MnB5 |
|-------------------------|---------|----------|--------|-------------------------------|-----------------------------|
| 22MnB5                  | 1100    | 1500     | 6      | 1.2                           | -                           |
| Ultralex®               | 500     | 550      | 15     | 2.9                           | -17%                        |

In order to compare the UHSS (e.g. 22MnB5) and Ultralex® mechanical properties for side impact beam product as presented in table 1, we can conclude that Ultralex® Al-alloy in T6 condition has more than twice the total elongation and crash strength as compared to 22MnB5. The Ultralex® Al-alloy is 17% lighter than UHSS (e.g. 22MnB5) because of its lower density. Hot forming techniques helps in dissolving the precipitates.

3.1. Theoretical background of forming of high strength Al-alloys

The hot forming and quenching of high strength aluminium alloys was developed partly utilising the principle of Press Hardening of Steels but due to the very different material science background of aluminium alloys, it requires the usage of several other concepts. The basic principle behind this process is based on the unique behaviour of ageing aluminium alloys during heat treatment which is well-known from material science [11]. This principle is shown schematically in figure 4 with the usual Temperature- time (T vs t) diagram [12]. The first part of this process is a solution heat treatment (SHT) where all the precipitations are dissolved above 500 °C (usually between 525-580 °C) providing a homogenised microstructure of $\alpha$-solid solution. Depending on the thickness of the part, it may take 30-60 min.

After this homogenization, a fast cooling (usually water quenching) has been required to avoid large precipitates. The result is a homogenous but super-saturated $\alpha$-solid solution with very low strength and good formability parameters. The high strength is provided in the second phase by a precipitation hardening (often termed as artificial ageing) usually done about 180-190 °C, which may take several hours [13]. However, at the end of the hardening, the formed aluminium part has low strength properties due to the super-saturated solid solution state. Therefore, it is followed by a post forming precipitation hardening (artificial ageing) heat treatment to achieve the required high strength. But, it is usually a long procedure that takes several hours.
3.2. Hot Forming and Quenching Technology HFQ©

The Hot Forming and Quenching (HFQ©) process was patented by the Imperial College London (ICL) and the Impression Technologies (ITL). However, this innovative new process may only be competitive if it can offer production time cycle comparable to PHS of high strength steels. The general principle of this process can be seen in figure 4. This new technique helps the manufacturers to form deep drawn complex shapes from high and ultra-high strength aluminium using a fast process with cycle time suitable for a range of volumes low to high. The technological process solution for HFQ™ of Al-alloys is shown in figure 5. In this process, blank is heated in solutionising oven, then transferred to high speed hydraulic press to make form panel and in the same high speed hydraulic press perform quenching in tool. Finally, it brought into the ageing oven that is the last stage 4. It is an important part of this process since after the solution heat treatment and fast cooling aluminium alloys have low strength properties, therefore a precipitation hardening (often termed as artificial ageing) is necessary to provide the high strength properties.

Advantages:
The major advantages of this technology are the following:

- It is easily adaptable for aluminium parts without simplifying or changing the geometry while replacing the steels.
- It is well-capable in using high-strength grades for down gauging (reduce weight, reduce material usage).
- This technology completely eliminates the need for springback-compensation in tool and part design.
- It also eliminates the use of reinforcement panels which are required to add strength, otherwise.
- This technology helps in substituting the high strength Al extrusions with high-strength HFQ© pressings.

![Figure 4. Basic principle of Hot Forming and Quenching™ of aluminium alloys.](image)

![Figure 5. The technological process solution for HFQ™ of Al-alloys.](image)
4. Conclusions

Besides the increasing application of various advanced high strength steel materials, there are many new technological development and an intensive growth in the application of high strength aluminium alloys in the automotive sector. In this paper, we briefly summarized the application and development trends in high strength steels and aluminium alloys for producing lightweight automotive parts. The major concern besides weight reduction is to increase the strength, crashworthiness, the vehicle fuel efficiency and to reduce the carbon dioxide emission according to EU norm. The recent developments in the application of lightweight design concepts in the automotive industry were analysed from the viewpoint of hot forming of metallic materials. Firstly, basic principles of hot forming of steels, widely known as Press Hardening of Steels, were introduced and then hot forming and quenching of aluminium alloys were presented. PHS-steels are mainly boron alloyed manganese steels and among them, the 22MnB5 alloy is the most widely applied in automotive applications. Also, comparison has been made between the first generation AHSS (22MnB5) and the new generation high-strength Al-alloys (Ultralex®). The development of the latter unique process brought revolutionary change to the usability of aluminium and cost effectiveness along with the higher safety.

References

[1] Automotive Metal Market Analysis by Product (Aluminium, Steel, Magnesium) by Application (Body structure) by End-use and Segment Forecasts 2018-2025 (2017), Report ID: GVR-1-68038-560-1
[2] Rick P, Reid W, Evan H, Akshay S (2017) 2017 Automotive Trends
[3] Ruth H, Nicolai M, Wolff van S, Anne S, Andreas T (2012) Lightweight heavy impact McKinsey&Company 2012
[4] Report from the commission to the European Parliament and the Council – Two years after Paris: Progress Towards meeting the EU’s climatec commitment (2017) Brussels 7.11.2017
[5] Tisza M (2013) Recent development trends in sheet metal forming, Int. J. Microstructure and Material Prop. 8. No. 1-2. pp. 125-139.
[6] Tisza, M (2014) Advanced materials in sheet metal forming, Key Engineering Materials, 581 pp. 137-142. DOI:10.4028/www.scientific.net/KEM.581.137
[7] Ghassemieh E (2011) Materials in Automotive Application – State of the Art and Prospects, in New Trends and Developments in Automotive Industry, InTech Open Publications, DOI: 10.5772/1821
[8] Banik J et. al (2013) Warmumformung im Automobilbau, Süddeutsche Verlag, Munich, p. 84.
[9] Keeler S, Kimchi M and Mooney, P (2017) Advanced High Strength Steels – Application Guidelines 6.0, World Auto Steel April, pp. 314.
[10] Sam C (2017) Constellium gets it right with AutoForm-Thermosolver AutoForm Blog-Customers Stories
[11] Audi AG.: Historical background on use of aluminium at Audi, https://www.audiworld.com/news/02/aluminum/content1.shtml
[12] European Aluminium Association (2012) Aluminium in cars-unlocking – The light weighting potential http://www.alueurope.eu/publications-automotive/
[13] LoCoLite (2013), An industry system enabling the use of a patented materials processing technology for Low Cost forming of Light Weight structure for transportation industries EU FP7 NMP Project ID No. 604240

Acknowledgments

The authors express their grateful thanks to the European Commission for their support on the H2020 project entitled “Low Cost Materials Processing Technologies for Mass Production of Lightweight Vehicles (LoCoMaTech)”, Grant No: H2020-NMBP-GV-2016 (723517). HFQ is a registered trademark of Impression Technologies Limited. Impression Technologies Limited is the sole licensee for the commercialization of the HFQ technology from Imperial College London.