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To cite this article: M Tisza and Zs Lukács 2018 *IOP Conf. Ser.: Mater. Sci. Eng.* **418** 012033

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High strength aluminum alloys in car manufacturing

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Abstract. In recent decades, there are many requirements stated against car manufacturing both from the customers' side and also as legal requirements to reduce harmful emissions to provide increased environment protection, as well as to achieve increased safety, higher comfort and more economical vehicles. To meet these often contradictory requirements, application of light weight design principles is one of the most widely applied solutions. There are two main trends for producing lightweight automotive structures with low cost manufacturing which are particularly valid for car body elements produced by sheet metal forming. Application of high strength steels is one of the main possibilities. Various generations of high strength steels (e.g. DP-steels, TRIP steels, XHSS and UHSS advanced high strength steels) were developed in the last decades which are already successfully applied in the automotive industry. The application of lightweight alloy materials – particularly various aluminum alloys – is regarded as the other possible solution to meet the requirements of lightweight car body constructions. Aluminum has even higher weight reduction potential than steel materials, but aluminium has lower formability than steel; replacing steel with lighter materials such as aluminum can be costly and is not simply straightforward. Aluminum sheet, in particular, has lower formability at room temperature than typical sheet steels. This is one of the main reasons that recently the hot forming of aluminum alloys came to the forefront of research activities. In this paper, some recent results obtained within a joint European project entitled *Low Cost Materials Processing Technologies for Mass Production of Lightweight Vehicles* will be introduced.

1. Introduction

Considering the main development trends in car manufacturing on the one hand the main customers' demands, e.g. lower consumption to get more economical vehicles, increased safety together with increased functionality and enhanced comfort should be mentioned. On the other hand, more strict legal requirements as lower harmful emissions for environmental protection and increased crashworthiness have to be mentioned [1]. Some of these requirements are even contradictory, however to meet most of these requirements weight reduction may be regarded as the most general solution. In this paper, we will review the main possibilities to meet these requirements including materials and process developments, and we will also compare the possibilities and development trends in future car making solutions.

2. Development trends in car manufacturing

2.1. Body concepts in car making

If we consider the weight ratio of various vehicle components we can state that the car body elements and the vehicle chassis are responsible for nearly 50% of total weight [2], therefore we have to focus first of all on these issues. There are various car body concepts applied in car manufacturing by OEM



car makers, e.g. the so-called integral design, space-frame, hybrid design, tube frame or monocoque structures. These different car body concepts are significantly depending on the production volume and the car categories particularly if we take into consideration the economy of production as well. For example, the integral design concept can be regarded as economic solution in compact class category and line production in mass production volume, the monocoque or tube frame concept is usually applied in low volume production and in luxury car categories, while space-frame and hybrid design principles are applied in middle range production volume as it can be seen in Figure 1 [3].

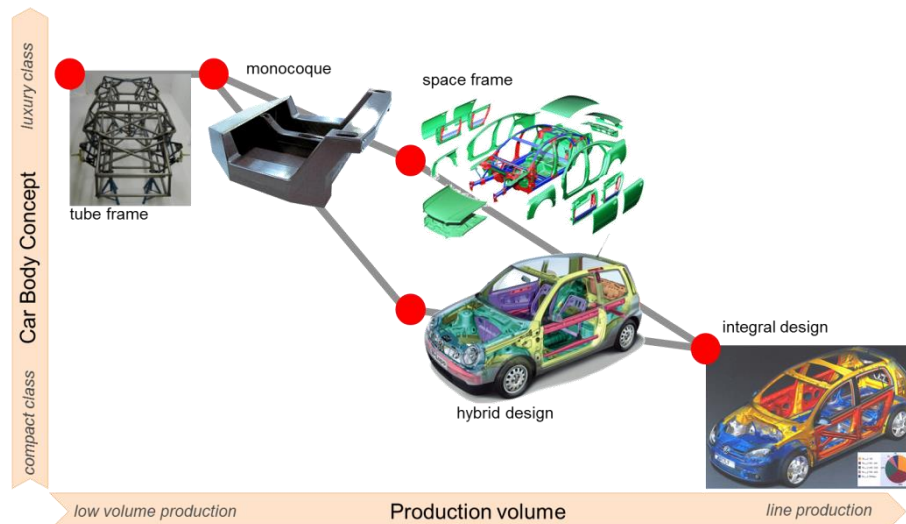


Figure 1. Car body concepts as a function of production volume.

2.2. Material developments

The applied materials may be regarded as another approach in development trends if we focus on car body elements. Steel was for a long time – and still it is – the most widely applied material in the Body in White (BIW) manufacturing. However, there are significant changes in steel application as well. Cold rolled plain carbon steels were the most widely applied materials in car manufacturing, though they have relatively low strength properties but together with their good formability properties, they were accepted as general solution for many decades. In Figure 2, the estimated weight reduction potential of different steel grades and aluminum is shown [4].

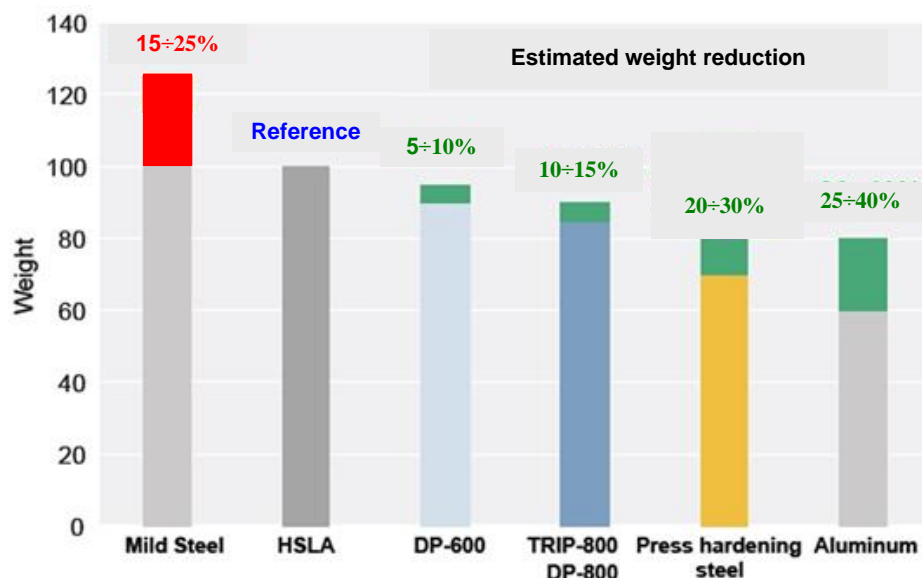


Figure 2. The weight reduction potential of various high strength materials in car body manufacturing.

During the last decades – due to the increased requirements listed above – there were very intense developments concerning the applied materials in car body manufacturing. Among steel developments the various generations of high strength steels should be mentioned. As it can be seen from Figure 2, applying these Advanced High Strength Steels (AHSS) about 20-30% weight reduction may be achieved. Besides steels an increasing application of lightweight alloys among them first of all high strength aluminum alloys are more and more widely applied. The available weight reduction with aluminum alloys can be even higher: it is around 25-40% compared to the reference HSLA material grade as shown in Figure 2.

Besides the aforementioned metallic materials composite materials are also more and more widely applied: this is particularly valid for the monocoque body concepts. Application of so-called multi-material concept is also increasingly present in today's car body manufacturing [5].

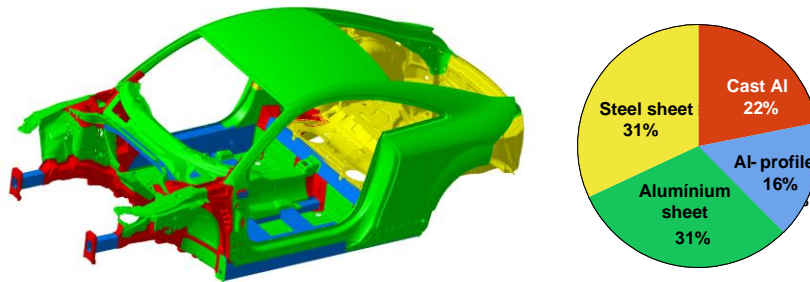


Figure 3. Multi-material concept in car body manufacturing.

It can be seen that both in the body concepts and in the materials application there are significant changes in the recent decades. Starting from the HSLA steels, the first break-through should be mentioned in the last 70s concerning significant replacement of conventional plain carbon steels by the then newly developed High Strength Low Alloyed steels [6]. Application of HSLA steels resulted in an overall 15-25% weight reduction compared to conventional cold rolled plain carbon steels. Following the introduction of HSLA steels, a very dynamic steel development has been observed. This development includes various generations of high strength and advanced high strength steels: in the automotive industry DP and TRIP-steels gained the widest application in various car body elements. Considering the weight reduction potential of HSLA steels as a reference value, for different DP-steels about 5 to 10% weight reduction may be achieved, while for the TRIP-steels it may even reach 10 to 15%. As a further step, the development of press hardening steel (PHS-steels) may be regarded as one of the most significant development among high strength steels. Applying these PHS-steels the estimated weight reduction may even achieve 20 to 30%. PHS-steels are mainly boron alloyed manganese steels and among them the 22MnB5 alloy is the most widely applied one in automotive applications. Besides the significant material development in PHS steels it should be also mentioned that the wide application is based on the new, innovative forming process developed particularly for these steel grades, namely the hot forming with quenching [7]. This process development is of utmost importance from the point of view of this paper, since the recently developed and patented process for hot forming of aluminum alloys (to be discussed later) has significant similarities but at the same time big differences as well to this process [8].

Besides the increasing application of various advanced high strength steel materials [10], there is an intensive growth in the application of high strength aluminum alloys. This increasing application partly may be reasoned also on the basis of Figure 2. From this Figure it can be clearly seen that using aluminum may have even higher weight reduction potential up to 25 to 40% compared to the reference value of HSLA steels. Aluminum may be applied in the automotive industry in many various fields: here we emphasize the aluminum application in car body elements made by sheet metal forming. However, we have to also mention that aluminum structural elements are extensively used as extruded or casted parts as well [10].

3. Aluminum in the automotive industry

3.1. *Short historical overview of aluminum application in the automotive industry*

Many people think that the application of aluminum in car manufacturing is one of the recent development trends; however, building lightweight cars with the aid of innovative materials like aluminum goes back more than a century. As early as 1913, NSU produced a car with a body entirely made of aluminum [11]. Although steel is preferred by most automakers, in recent years changing fuel economy and recycling regulations have intensified weight-reduction attempts by automakers. Aluminum offers good engineering solution: its density is one-third that of steel and satisfies the torsion and stiffness requirements of an automotive material. However, aluminum by weight is about five times more expensive than steel: this is one of the main reasons that aluminum remained as a solution primarily in the premium segment car manufacturing [12].

Although the use of aluminum in cars has been intensively increasing for the past decades, however, progress has been limited concerning sheet metal parts. In fact, most aluminum substitution has come in the form of castings and forgings in the transmission, wheels, etc. Car manufacturers have developed all-aluminum cars with two competing designs: conventional unibody and the spaceframe concept. However, for a long time aluminum was far from being a material of economic choice for auto bodies. The increase of substitution of aluminum for steel is partly influenced by regulatory pressures to meet fuel efficiency standards by reducing vehicle weight, and to meet recycling standards. The key obstacles are the high cost of primary aluminum as compared to steel, lower formability and added manufacturing costs of aluminum panels. However, both the aluminum and the automotive industries have attempted to make aluminum a cost-effective alternative to steel [13]. In this paper, the cost of manufacturing and assembly of six different car body designs, making comparisons with conventional steel designs at current aluminum prices and using current aluminum manufacturing technologies were analyzed. Authors then attempt to determine if aluminum can be an economic alternative to steel at lower primary aluminum prices, and improved manufacturing processes.

Different car categories were analyzed: small car designs (e.g. VW Lupo and Audi 2), midsize car designs (e.g. Ford Contour steel body and Ford 2000 aluminum body both as a unibody design) and a higher class Audi A8 made of stamped aluminum parts. The two key results of this analysis were higher material costs and higher tooling costs as the main obstacles to substitute steel as body panel.

The use of large amounts of aluminum in mass-produced cars, as distinct from expensive, low-volume models, has been frequently predicted but as yet has not come about [14]. It may be stated that aluminum can displace steel with any significance when aluminum sheet replaces steel as the primary material in the chassis or the body of the car. During the past decades, vehicle manufacturers have repeatedly attempted to assess the status of aluminum vehicles. New types of alloys and advanced production techniques have been tested. Interest has been also focused on testing suitable joining methods.

3.2. *Aluminum in car manufacturing at Audi*

The Audi Hungaria Motor Kft. may be regarded as one of the most important OEM car makers in Hungary. Besides its importance in the Hungarian automotive industry we have to also mention that Audi was always and still is playing an outstanding role in the application of aluminium alloys in car manufacturing. Shortly after that NSU made its first car with a body entirely made of aluminum, in 1923, Audi experimented with a streamlined aluminum car body for its Type K model [11].

In the years that followed, weight-saving construction remained one of the key competence areas of automobile manufacturer. 1984 was also the year when Audi began to study aluminum intensively again; an aluminum body based on the Audi 100 was developed. The next important step was in 1993 when the Audi A8 design study revealed an Aluminum Space Frame (ASF) car concept: this vehicle made use of entirely new construction principles that amounted to far more than mere substitution of aluminum for steel as the structural material. The Audi Space Frame (ASF) principle created a high-strength aluminum framework into which the larger sheet aluminum elements were integrated and performed a load-bearing function. However, at this stage the application of aluminum was more or

less the privilege in the premium car segment. The next milestone was in 1997 when Audi exhibited its A12 design study, a vision of an aluminum car suitable for high-volume production.

3.3. The multi-material approach in lightweight construction of automobiles

Besides aluminum as a potential material for significant weight reduction, the multi-material approach is another way for automotive lightweight construction. This principle originated a European project with the title Super Light Car (SLC) – which developed lightweight construction with a multi-material approach [15]. This approach is well illustrated by the Figure 4, where the affordability of weight reduction is shown with the application of various multi-material concepts.

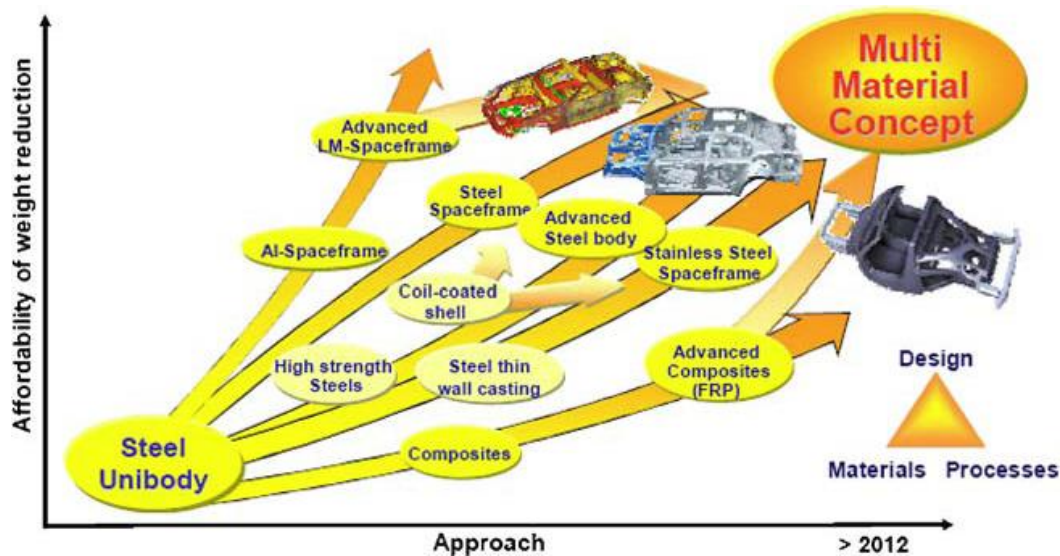


Figure 4. Affordability of weight reduction using various multi-material concepts [15].

4. Process developments for the application of high strength aluminum alloys in car body manufacturing

Application of high strength aluminium alloys is the other possibility to meet the requirements in lightweight car body constructions. However, replacing steel with lighter materials such as aluminum, magnesium, etc. can be costly and is not simply straightforward. Recently several groups of aluminum alloys are applied in car manufacturing, among them for example AA5754 H22 and AA6082 T6; both are widely applied in car manufacturing. AA5754 (AlMg3) alloy is widely used in sports cars like Jaguar XK, Lotus Evora and Chevrolet Corvette. This alloy has medium strength among aluminum alloys [16]. AA6082 is extensively used for structural elements in the form of extrusions in most of luxury cars applying aluminum body components like BMW 6, Jaguar XJ, Jaguar XK, Range Rover and Rolls-Royce Phantom; however the HFQ^R process has unlocked the potential for automotive sheet applications, too.

However, aluminum has much lower formability at room temperature than typical sheet steels. For both aluminum and steel sheet materials we performed several material- and formability testing. Formability investigations were performed with the modified Nakajima test applying a computer controlled universal sheet formability-testing machine equipped with an optical strain measurement system, which records the distortion of the grid; a 2×2 mm square grid is printed on the blank sheet before the tests. The system has 4 CCD cameras to obtain the 3D point cloud from the mesh. From the measurements, the Vialux-AutoGrid software is used to determine the grid deformation and to calculate the strain distribution along the curved surface. With these data, the FLC and FLD can be determined. In these investigations we followed the ISO 12004-2 instructions, to obtain the FLDs of tested aluminum sheets. The results of these experiments are summarized in journals and conference papers [16], [17].

Concerning high strength aluminum alloys, AA7075 should be first mentioned as one of the most widely used high strength aluminum alloys in transportation industry [18]. Its main constituents are

aluminum, zinc, magnesium and copper. It's one of the strongest aluminum alloys available in sheet form and comparable in that respect with steel; however its density is only a third of the density of steel. The statement that aluminum sheet has usually lower formability at room temperature than typical sheet steels is even more valid for this alloy group. Therefore, the successful application of this alloy requires new processes.

In 2016 a research consortium from 9 European countries with 19 institutions was established with the leadership of Imperial College London (ICL) with the project title Low Cost Materials Processing Technologies for Mass Production of Lightweight Vehicles (with the acronym LoCoMaTech) within a H-2020 umbrella [19]. The overall aim of the project is to elaborate low-cost production technology for manufacturing of high strength lightweight complex-shaped aluminum parts with low environmental impact in mass production. As it was mentioned these high strength aluminum alloys have low formability at room temperature, therefore an economical production process for this purpose is the Hot Forming and Quenching (HFQTM) patented process [19]. The general principle of this process can be seen in Figure 5, which has some similarities to the hot forming of boron alloyed steels already successfully implemented in the automotive industry, but it has significant differences due to the different material science background of aluminum and steel.

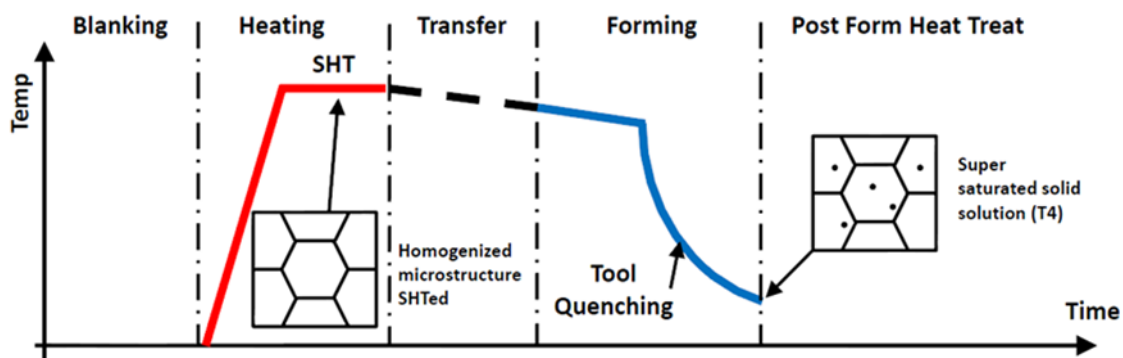
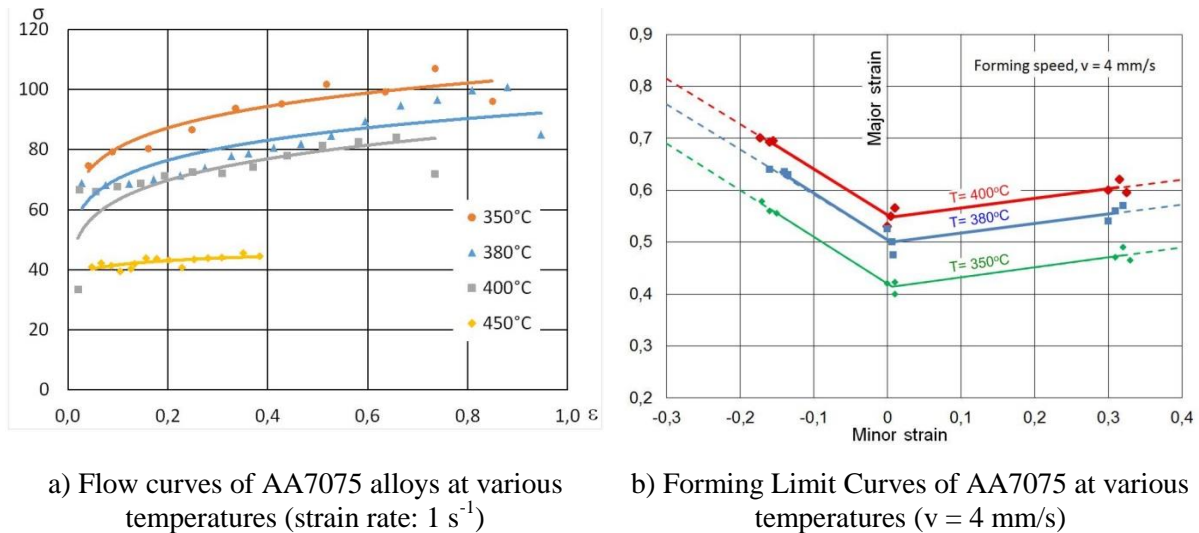


Figure 5. Basic principle of Hot Forming and QuenchingTM of aluminum alloys [19].

The basic principle behind this process is based on the unique behaviour of age-hardenable aluminium alloys during heat treatment, which is well known from materials science [20]. The first part of this process is a solution heat treatment (SHT) where all the precipitations are solved above the solvus temperature (which is alloy dependent typically between 480-580°C) providing a homogenized microstructure of α -solid solution. Depending on the thickness of the part it usually takes 30-60 min. However, for aluminum alloys, the material is in a supersaturated state after the solution heat treatment and quenching in the tool having very low strength parameters and good formability; furthermore, the process requires much longer cycle time. To have sufficient high strength still we have to apply a precipitation hardening (tempering, artificial ageing) with an even much longer cycle time. Therefore, to apply this process economically in mass production in the automotive industry these cycle times should be decreased significantly. Fast heating and fast cooling methods are regarded as one of the possibilities to reduce the cycle times: these are among the most important targets in the LoCoMaTech project. Another possibility to reduce the long cycle time is the utilization of other inevitable necessary processes in the production line, e.g. using the paint baking as part of the artificial ageing process.

The good formability at high temperatures is utilized with the hot forming process shown in Figure 5. However, for successful hot forming and also for the accurate and reliable numerical modelling of HFQ process we have to know the formability parameters of the alloy at different elevated temperatures and various strain rates. To determine the optimum forming conditions we have to perform various material testing and formability investigations. However, in hot forming the material properties and thus the formability is also dependent not only the temperature but also on the strain rate applied during the hot forming. Determination of these parameters at various temperatures and strain rates were done by the University of Miskolc. Results of these experiments are shown in Figure

6. It can be seen from both diagrams that the formability is increasing with the increase of temperature. As it can be also seen from Figure 6.a, above this temperature (i.e. $T > 400^{\circ}\text{C}$) the true stress is further decreasing with the increase of temperature (e.g. flow curve at $T=450^{\circ}\text{C}$) however, the failure strain is also decreased. Analyzing the FLC curves determined at various temperatures (see Figure 6.b) it can be also concluded that by the increase of the temperature the FLC curve is moved upwards, i.e. the limit strain was increased in the temperature range between 350 to 400°C . Since the failure strain in hot uniaxial test was decreased above this temperature, it can be stated that the optimum hot forming temperature for AA7075 alloys can be found around 400°C .



a) Flow curves of AA7075 alloys at various temperatures (strain rate: 1 s^{-1})

b) Forming Limit Curves of AA7075 at various temperatures ($v = 4 \text{ mm/s}$)

Figure 6. Flow curves and Forming Limit Curves for AA7075 alloy at various temperatures

5. Conclusions

In this paper, first we shortly summarized the main requirements and challenges in today's car manufacturing. Due to the increased environment protection and safety regulations these challenges may be met by applying various lightweight body concepts. Analyzing the different car body concepts it can be concluded that the applied car body concepts are strongly dependent on the production volume and the economy of production.

It can be also concluded that applying the lightweight construction principles in car manufacturing both different grades of high strength steels (DP, TRIP and AHSS) and high strength aluminum alloys are potential metallic materials; however applying the multi-material concept may be often the most favorable solution. Focusing only on metallic materials we studied the weight reduction potential of different grades of high strength steels and high strength aluminum alloys, too.

Analyzing these results it can be found that the largest weight reduction potential can be found applying the innovative hot forming processes both in the case of Press Hardening Steels (PHS) and Hot Forming and Quenching of high strength aluminum alloys. Concerning the hot forming of steel and aluminum it can be said that these two innovative forming processes have important similarities and at the same time great differences arising mainly from the different material science background of the two material groups.

Applying hot forming, the peculiarities of hot forming processes, i.e. the temperature and strain rate dependence of material properties and the forming limits should be taken into consideration. In this paper, some results on the hot formability of high strength aluminum alloy (AA7075) were introduced. It was also shown in this paper that the application of high strength aluminum alloys (like AA7075 for example) is significantly increasing due to the increasing requirements both from the customers' side and legal requirements.

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.

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