Archives of Materials Science and Engineering

Volume 88
Issue 2
December 2017
Pages 68-74

International Scientific Journal published monthly by the World Academy of Materials and Manufacturing Engineering

High strength steels and aluminium alloys in lightweight body manufacturing

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ABSTRACT

Purpose: of this paper: The main objectives of this paper are to give an overview about the application of various kinds of high strength steels and aluminium alloys in the automotive industry to produce lightweight car body elements to achieve significant reductions in harmful emissions to provide more environmental friendly vehicles which simultaneously fulfils the increased safety requirements, too. In these respects, both high strength automotive steels (e.g. DP, TRIP, TWIP and HPF steels), as well as high strength aluminium alloys (e.g. AA6082, AA7075, etc.) are more and more widely applied in the vehicle manufacturing.

Design/methodology/approach: The contradiction between the increased strength and lower formability of these high strength metallic materials is one of the main issues in their application in the automotive industry. Therefore, in this paper primary focus will be placed on the formability properties of these materials, concerning first of all the limits of formability in various cold and hot forming conditions. To fully utilize the potentials of these materials in forming processes the numerical modelling of forming with FEM simulation is of utmost importance.

Findings: Recently in the automotive industry the Hot Press Forming of high strength boron-alloyed manganese steels become an industrially established process, while the Hot Forming and Quenching (HFQ) of artificially ageing high strength aluminium alloys now become the focus of scientific research. The paper will analyse the main process parameters and gives comparisons of automotive applications.

Research limitations/implications: There are still certain shortages of industrial applications, namely the limits of economic cycle times for economical mass production which needs further research activities in these fields.

Practical implications: Since both the materials mentioned above and the forming processes usually applied, furthermore the available benefits are extremely important for the automotive industry these results have significant practical involvement.

Originality/value: The applied research methods and the introduced new findings will show the originality of the paper.

Keywords: High strength steels – HPF, Aluminium alloys – HFQ, Formability, Automotive industry, FEM modelling and simulation

Reference to this paper should be given in the following way:

M. Tisza, High strength steels and aluminium alloys in lightweight body manufacturing, Archives of Materials Science and Engineering 88/2 (2017) 68-74.

MATERIALS MANUFACTURING AND PROCESSING

1. Introduction

Low cost manufacturing in the automotive industry is one of the main targets in most of the industries due to the ever increasing global competition. It is particularly valid in the automotive industry and often strongly connected with the term lightweight manufacturing. Low cost lightweight manufacturing in the vehicle industry is in the forefront of research for several reasons: there are very strict and even further increasing rigorous environment restrictions concerning the amount of harmful emissions and simultaneously higher safety requirements. In the fulfilments of these requirements, the weight reduction has an important role. Concerning the overall weight of an automobile the car body has a decisive role. Since sheet metal forming is the main manufacturing process in production of car body elements, therefore, sheet metal forming is regarded as one of the most important key technologies in the automotive industry. Therefore the elaboration of new, innovative low cost manufacturing processes is one of the main objectives in sheet metal forming as well. Low cost manufacturing is often linked to lightweight construction principles, too. There are two main trends for producing lightweight automotive parts with low cost manufacturing which are particularly valid for car body elements production by sheet metal forming. Application of high strength steels is one of the possibilities. The application of lightweight materials – particularly various aluminium alloys – is regarded as the other possible solution.

In the next section, we will overview these two main directions with special emphasis on the research activities at the Institute of Materials Science and Technology at the University of Miskolc.

2. Researches in lightweight manufacturing at the University of Miskolc

First, we will shortly overview these researches from the point of view of applied materials. There are several ongoing research projects in these fields at the Institute of Materials Science and Technology at the University of Miskolc, as well. Application of high strength steels is the main concern in one of the big projects called AutoTech [1]. The application of lightweight materials – particularly various aluminium alloys – is the main topic in the LoCoMaTech H-2020 project [2].

2.1. Application of high strength steels in car manufacturing

For several decades the application of conventional cold rolled steels dominated the car body manufacturing. However, in the last 20-30 years there were very intensive developments in steel making mainly initiated by the requirements to produce lightweight car body structures with lower harmful emissions, better crashworthiness and higher safety.

In Figure 1 the so-called first, second and third generations of high strength steels can be seen where the total elongation (A_{80}) is shown in the function of ultimate tensile strength (R_m).

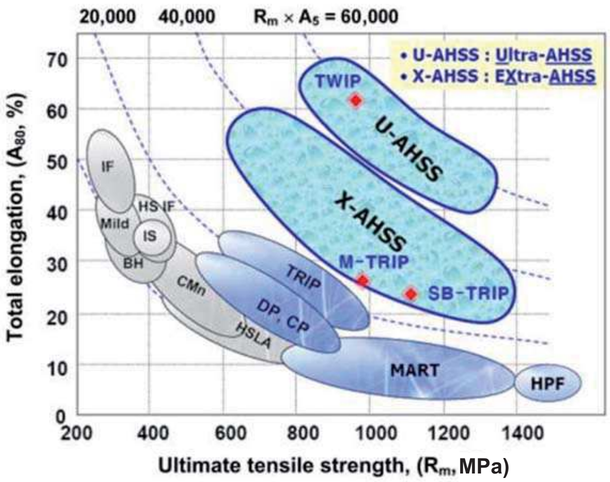


Fig. 1. Total elongation vs Ultimate Tensile Strength for various generations of high strength steels

As it can be seen from Figure 1, increasing the strength parameters the ductility parameters – and thus the formability is significantly decreasing. Therefore, for these high strength steels the extension of formability limits is another important issue.

In the AutoTech project referred above [1] we performed wide scale experimental investigations to analyse the formability of different DP-steel grades (e.g. DP600, DP800 and DP1000) which are already widely used in the automotive industry. For these test results we refer to Research Reports, papers and book [1], [3] published from these investigations.

Among the new, high strength materials like different grades of DP-, TRIP- and TWIN-steels, we had also an important research work on the Press Hardening Steels (PHS) and their application to produce high strength structural body elements (e.g. A and B-Pillars, etc.) applying hot forming processes.

From this latter material grade – i.e. the Press Hardening Steels – different kinds of boron alloyed manganese steels should be mentioned that are also widely used already in car body manufacturing in hot forming conditions – particularly the 22MnB5 alloy which is regarded as the basic type of PHS steels. Since for the light metals we will focus on a new hot forming process (Hot Forming & Quenching – HFQ^{TM}) we will shortly analyse the hot forming of Press Hardening Steels for comparison.

2.2. Hot Forming of Press Hardening Steels

Nowadays, the hot stamping of high strength boron alloyed manganese steels (e.g. 22MnB5) is a well-established, industrially applied process. It is called as Hot Forming of Steels (HFS) or often termed as Press Hardening of Steels (PHS).

This technology was invented in Sweden [4], then further developed in Germany [5], [6] and France [7]. Industrial plants are working all over the World [8], [9] among them in Hungary: the Kirchhoff Automotive is the main supplier for Hungarian OEM car makers with components produced by Press Hardening of boron alloyed manganese steels [9].

Hot Press Forming (HPF) – even it is already widely used in the automotive industry – 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.

Though, it is already an industrially well-established process, there are still many fields for further research activities, thus intensive research works are in progress on the application of various grades of high strength steels. 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.

There are two main technological process variants applied in hot press forming of steels: one of them is called direct hot forming, the other is the indirect hot forming. In direct (or often termed as single stage) hot press forming the blank sheet is directly austenitized, then transferred to the stamping tool and cooled down rapidly with the forming tool, providing the excellent strength properties. This process cycle is shown in Figure 2. It is absolutely essential that the forming could be finished above the M_s temperature (characteristic for the given material) to have suitable formability. After forming, the component is cooled down together with the tool: this cooling should provide the critical cooling rate to get high strength martensitic microstructure as shown in Figure 3.

Besides the two basic types of Hot Press Forming analyzed above, further process variants may be used. In these process variants, the final microstructure as well as the mechanical properties of the part can be controlled very effectively depending on the holding temperature and the controlled cooling process.

In one of the most common processes, the holding temperature is selected in the homogeneous γ-zone above the A_3 temperature of the given steel (i.e. full austenitization) and the cooling occurs over the upper critical cooling rate resulting in a fully martensite microstructure (see Fig. 4a).

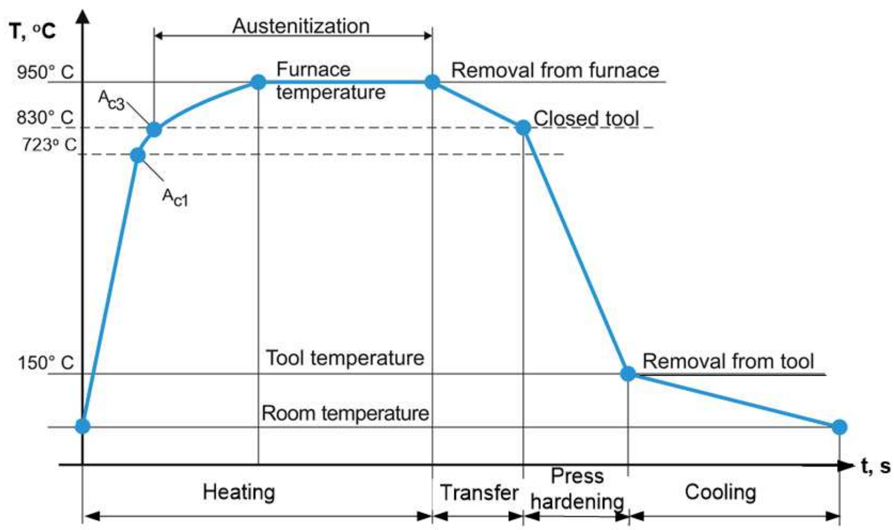
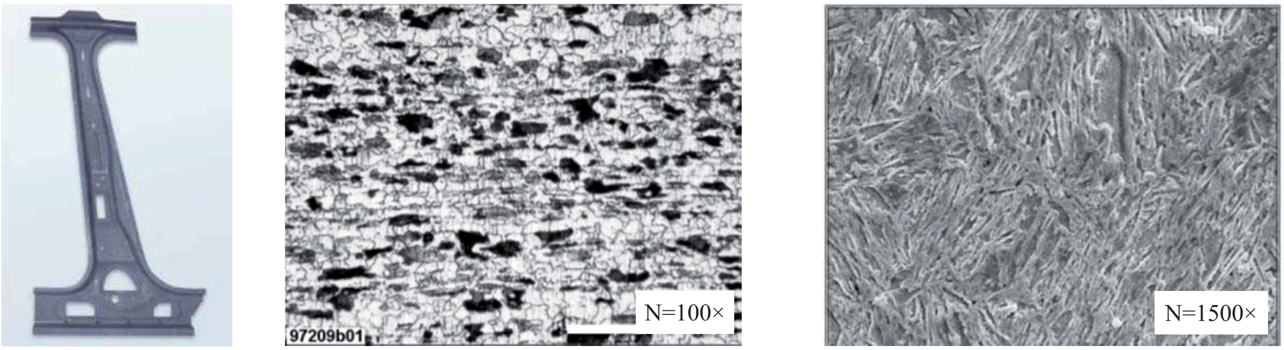


Fig. 2. Temperature vs. time for hot press forming of steels



a) B-Pillar made by Press Hardening

b) Ferrite-perlitic microstructure in as delivery condition

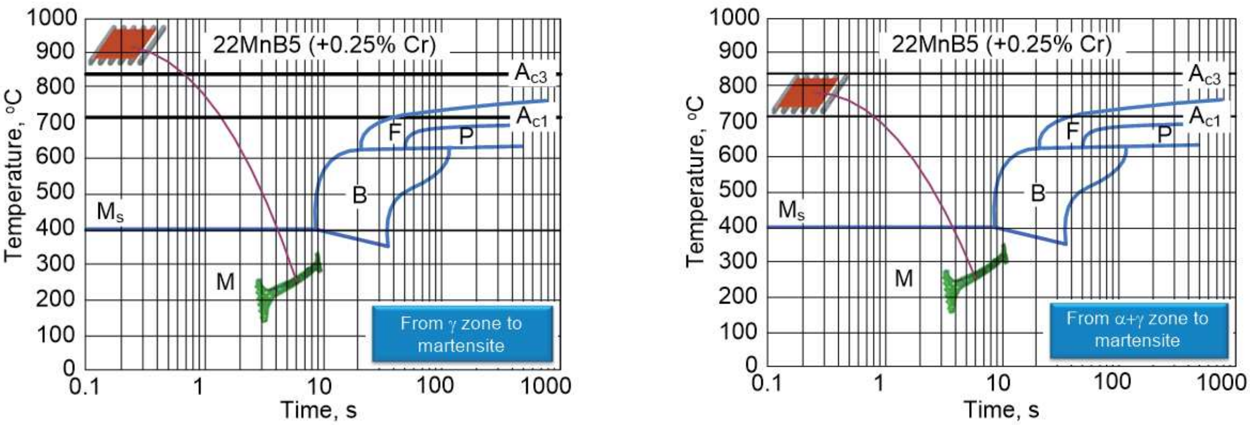
c) Martensitic microstructure after hot forming and quenching

Fig. 3. Microstructure of a typical automotive part made by Press Hardening

In the second subtype (see Fig. 4b) the holding temperature is in the (α+γ) intercritical range (i.e. between the A_1 and the A_3 temperature). Thus the starting microstructure has ferrite and austenite. In this case, just the austenite content can be transformed into martensite and the final microstructure when the forming and cooling completed has a certain amount of ferrite, too. Though, it results in somewhat lower strength compared to the previous process variant, however it also leads to a certain amount of ductility providing better toughness properties.

Also further process variants can be originated by applying a bit lower cooling rate after the forming process. In these cases – since the cooling rate is lower than the upper critical cooling rate – the final microstructure besides martensite also contains bainite. Though, it also results in somewhat lower strength depending on the quantity of bainite, but together with an increased toughness which might be very advantageous for example increasing the crashworthiness of the structural parts due to the better energy absorption properties.

These process variants are widely used in car manufacturing for producing structural elements with high load bearing capacity, like A and B pillar, subplate, side impact beam, etc.



a) Holding temperature in the γ-zone

b) Holding temperature in the (α+γ) zone

Fig. 4. Process variants for Hot Forming of Steels depending on the holding temperature

3. Aluminium alloys in automobiles

As it was mentioned in the Introduction section, in lightweight manufacturing of automobiles the aluminium and its alloys play very significant role [12]. Application of aluminium as base material for car body elements is very beneficial from the point of view of mass reduction. However, aluminium usually has lower formability than steels which leads to serious formability problems in cold forming operations [13]. But it is also well known that the formability is increasing significantly with the increase of the temperature. This is the main reason that significant efforts are made both in the laboratories and in industrial circumstances to apply high strength aluminium alloys in hot forming conditions [14].

During the recent decades several new grades of high strength aluminium alloys were developed. Among them the so-called 5xxx, 6xxx and more recently the 7xxx series are mainly used in the automotive industry. Obviously with the increase of strength the formability of these alloys is reduced. It is also well known that the formability – as for most of the metals and metallic alloys – can be significantly increased at elevated temperatures. In the Imperial College of London together with some other project partners a special process was developed for the hot forming of aluminium alloys. This process is called Hot Forming and Quenching [15], [16]. This new process is patented by the Imperial College of London and the Impression Technologies UK with the name HFQ^R.

The Hot Forming and Quenching of high strength aluminium alloys was developed partly utilising the principles 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 materials science [11]. This principle is shown schematically in Figure 5 with the usual Time-Temperature (T vs t) diagram [16].

The first part of this process is a solution heat treatment (SHT) where all the precipitations are solved above 500ºC (usually between 525-580ºC providing a homogenised microstructure of α-solid solution. Depending on the thickness of the part it usually takes 30-60 min.

After this homogenization a fast cooling (usually water quenching) required to avoid large precipitates. The result is a homogeneous, but super-saturated α-solid solution with very low strength and good formability parameters. The high strength is provided in the second phase by

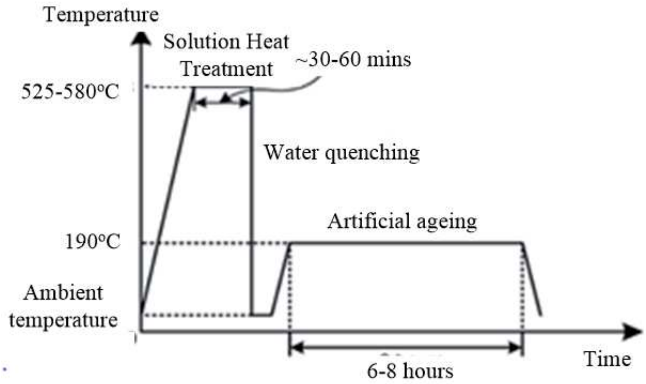


Fig. 5. Time-Temperature (T vs t) diagram for precipitation hardening Al-alloys

a precipitation hardening (often termed as artificial ageing) usually done about 180-190ºC, which may take several hours [16].

The realization of the above described principal heat-treatment procedure together with the forming of Al-alloy sheets is shown in Figure 6. The main differences can be summarized as follows. The real process starts with the blanking of sheet for the necessary blanking shape and sizes. Then it is heated up to the solution heat-treatment temperature and hold to get fully homogenized α-solid solution. After homogenization, the blank transferred to the forming tool. The forming is done in this solid solution state and cooled down fast (Tool Quenching stage, Fig. 6). However, at the end of it 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. However, it is usually a long procedure taking several hours, which may be reduced if we utilize the time of other processes, e.g. part of this precipitation hardening may occur during the paint baking of body elements .

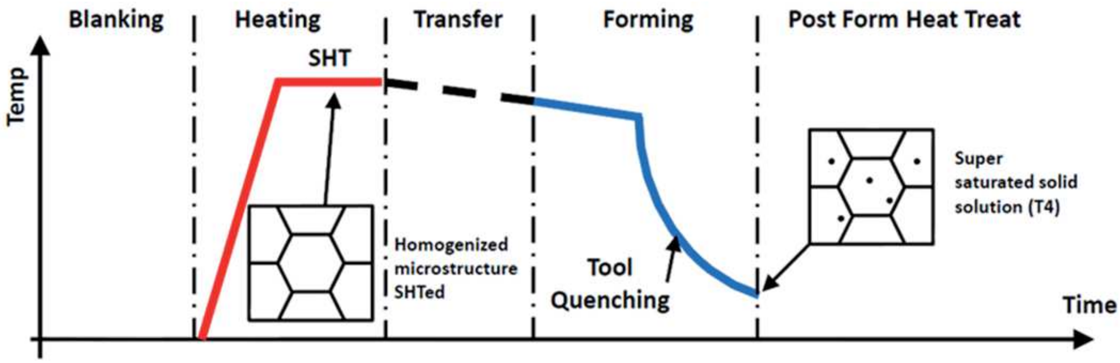


Fig. 6. Basic principle of Hot Forming and Quenching^{TM} of aluminium alloys [2]

This basic principle is realised with the technological process solution shown in Figure 7. The 4^{th} step is also 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.

The process shown in Figure 7. has some similarities with the hot forming of boron alloyed manganese steels. The substantial difference between the hot stamping of steels and the aluminium alloys mainly based on the differences of material science background and can be summarized in the followings: applying the boron alloyed manganese steels in hot forming and quenching the part is cooled in the tool with a cooling rate sufficient to provide hard martensitic microstructure having very high strength properties (usually around R_m = 1500-2000 MPa) without any further heat-treatment, thus providing high strength properties within an industrially acceptable production cycle time t = 5 to 10 seconds.

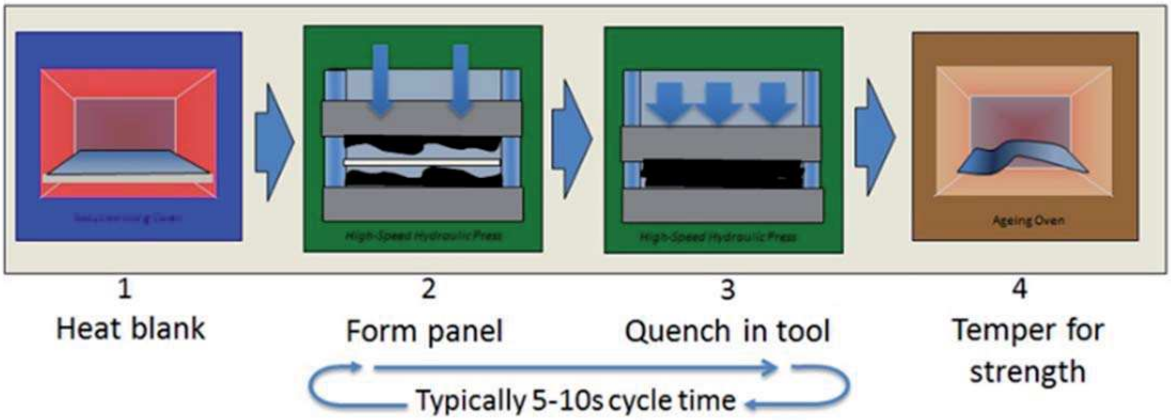


Fig. 7. The technological process solution for Hot Forming and Quenching™ of aluminium alloys [17]

However, for aluminium 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 successfully and 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 [18]. Another possibility to reduce the long cycle time is the utilization of other inevitable necessary processes in the production line, i.e. using the paint baking as part of the artificial ageing process.

As it was mentioned before, this process is principally based on the hot stamping of steels, and it is also aimed in the project to develop a similar production line which already exists for the Press Hardening of boron-alloyed manganese steels. This is the final objective of the LoCoMaTech project.

4. Conclusions

In this paper, some recent developments in the application of lightweight design concepts in the automotive industry were analysed from the point of view of hot forming of metallic materials. First, some basic principles of Hot Forming of Steels widely known as Press Hardening of Steels were introduced, then the Hot Forming and Quenching of aluminium alloys was analysed. Since the automotive industry requires the application of higher strength materials to overcome the reduced formability of these materials the hot forming is a promising solution. In this paper, the hot forming of steels and aluminium alloys was analysed demonstrating their similarities and differences, too.

Acknowledgements

The research results introduced in this paper were partly achieved in a Hungarian National project called AutoTech *New materials and innovative manufacturing processes in the automotive industry* and partly in a European H2020 project called LoCoMaTech entitled "Low Cost Materials Processing Technologies for Mass Production of Lightweight Vehicles (LoCoMaTech)", Grant No. H2020-NMBP-GV-2016 (723517). Authors express their grateful thanks to the financial support of both projects.

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