Mass production-line and process route to enable the use of high strength aluminium alloy materials in car body engineering

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Abstract. Hot stamping of sheet metal materials provides advantages such as application for mass production lines and net shape manufacturing at economical cost. Recent regulations by governments world-wide on environment, emission controls and safety determine the need to provide complete lightweight solutions in the transport industry particularly for the automotive sector. These regulations are influencing multi-material-design concepts in automotive body engineering and the use of high strength aluminium alloy materials: 6xxx and 7xxx series in the development of electric and non-electric vehicles. The use of high strength aluminium alloy materials to manufacture car body parts is increasing in the lightweight solutions mainly due to weight-strength ratio advantage. Due to different material behaviours such as formability and strengthening mechanism, compared with high strength steel alloys, an industrial proven redefined hot forming process route, HForm™ will be needed to ensure high productivity and return on investment in the manufacture of parts using the aluminium alloys sheets. The produced parts will also satisfy functional requirements in the automotive industry such as surface quality, tight tolerances, strength, crashworthiness, corrosion resistance as well as ease-to join in the body-in-white (BiW) structure and e-coat. However to implement the HForm™ process and manufacture functional automotive body parts requires dedicated furnace for aluminium alloy materials, intermediate cooling station, handling/transport systems, a servo hydraulic press, and coated dies with integrated lubricant metering system. Presented in this paper is a complete solution to enable paradigm-shift in the car body engineering.

1. Introduction

The lightweight potential of high strength aluminium alloy materials cannot be over emphasized and according to the Aluminium Association, replacing steel in modern vehicles aluminium can enable the reduction of approximately 44 million tons of CO2 emissions per year due to reduced total weight. Aluminium alloys are three times lighter than high strength steel alloys, thus can provide one of the alternative material solution to achieve the weight-strength ratio advantage in multi-material car body structures. Furthermore, the favorable energy balance makes aluminium an excellent product to recycle, since the main cost of the production of primary aluminium is electricity.

The unique behaviours such as formability and strengthening mechanisms of aluminium alloy materials compared to steel alloys, require an industrial proven hot forming process route such as HForm™ illustrated in Figure 2 below, to ensure high productivity and return on investment (ROI) on manufactured parts. In addition, the parts will need to be manufactured to satisfy tight automotive industry functional requirements such as surface quality, tight tolerances, strength, crashworthiness,
corrosion resistance as well as ease-to join in the body-in-white (BiW) structure in a multi-material body structure as well as e-coating in conventional paint-bake shop process chain. In contrary to conventional uni-material car body structure architecture based mainly on steel alloy body parts, the current multi-materials solutions will require smart and holistic approach to select the right material, part geometry designs and process routes. While press hardening of steel (PHS) represents an effective lightweight process route solution using steel alloys materials, HForm™ process routes, depending on part geometry shape and alloy grade, can provide the most suitable manufacturing method using high strength aluminium alloy blanks.

To achieve these goals will require particular a dedicated furnace for aluminium alloy materials, intermediate cooling station, handling/transport system, and servo hydraulic press, as well as tool system with advanced surface engineering. Presented in this paper is the HForm™ process and the required equipment to enable paradigm-shift in lightweight solution for the car body engineering.

2. Precipitation hardening in industrial process definition and HForm™ process

The achievable properties of steel and aluminium alloy materials used in the automotive industry can be significantly influenced through precise heat treatments. To obtain strengthening of heat-treatable aluminium alloys, the following heat treatments are applied: solutionizing with subsequent quenching (rapid cooling), room temperature storage and ageing [1]. Hence, similar to press hardening of steel alloys, hot forming can provide an adequate process route for high strength aluminium alloy blanks.

Different hot forming process configurations currently applied in the manufacture of automotive and non-automotive parts using aluminium alloy materials are depicted in Figure 1 and detail in [2].

![Figure 1. Schema of hot forming processes using high strength aluminium alloy blank sheets [2]](image1)

In the current work, a hot forming process, termed HForm™ is implemented for a production line design for volume manufacturing. The main objective of the HForm™ process is to enable a hot forming process that can be integrated into an existing automotive ecosystem process chain at economical cost to manufacture parts to satisfy functional requirements in the car body engineering. Figure 2 depicts the process flow of the HForm™ process.

![Figure 2. Schema of HForm™ process for high strength aluminium alloy blanks.](image2)
The HForm™ process involves 6-process stations (A-F) in a production line layout. The last station G will be implemented at the facilities of the OEMs, Tier1s, etc. as illustrated in Figure 2, depending on the supply chain model employed. Importantly, the temper of the blank material supplies namely: T6-, T4-, F-, 0-tempers has no influence in the application of HForm™. This encourages the use of most cost effective material temper for an economical volume manufacture of automotive parts.

3. Tempering of Automotive Alloy Material AMAG AA7075 Blank Sheets

Solutionization or solution heat treatment of aluminium alloys represents the first step in the heat treatment process and is conducted at elevated temperature to dissolve hardening alloying elements into the aluminium lattice. Depending on the alloy grade of the blank sheet material used, the solution heat treatment temperature (SHT-T) is mostly between 470 and 570 °C. Figure 3 shows a typical solution heat treatment curve for 1.5 mm gauge AA7075 sheet heated in the dedicated AP&T Multi-Layer Furnace (AP&T MLF-ALU) for aluminium hot forming processes such HForm™. The volume manufacturing furnace enables short cycle times at low energy cost.

![Figure 3. AP&T MLF-ALU: Temperature versus time profile of AMAG 7075.](image)

To deal with the high emissivity of aluminium, the AP&T MLF-ALU is based on a forced convection principle for the heat transfer and ensures homogenous heat distribution across the blank sheets at an average heat transfer rate of 6 K/s in the temperature region from room temperature (RT) to 400 °C and an average of 2.5 K/s in the region from 400 °C to 550 °C. A soaking period is necessary to achieve homogeneous solid solution of the alloying elements. Heat-up and soaking zones represent critical considerations in the choice of an industrial furnace in the hot forming process.

Temperature higher than Z-SHT have to be avoided due to local melting of low melting phases. Too low temperatures (below the Z-SHT) results in insufficient dissolution of the hardening elements and lead to reduced strengthening potential. Particularly 7xxx alloy series require a tight solutionization process window. A temperature distribution tolerance of ±3 °C will be recommended to prevent solutionization above the critical SHT-T.

To avoid precipitation that degrades the mechanical properties and corrosion resistance, the solutionized blank must be cooled rapidly (quenched) in an intermediate cooling station immediately after exit from the furnace. In the HForm™ process, the intermediate station was adopted instead of in-die quenching to enable precise process control and ensure homogenous temperature distribution across the blank cross section. In addition, specific different cooling rates are also easier to achieve and enable target precipitation kinetics required for different alloy grades and compositions.

According to [3], much other literature and aluminium material suppliers, resistance to corrosion, strength and toughness of high strength aluminium alloy blanks can be improved applying a cooling rate above 100 K/s. Results presented in section 6 proved that low cooling rates ≤ 50 K/s are not favourable to functional requirements such mechanical properties of the manufactured parts. Other properties such as resistance to corrosion behaviour are also influenced by cooling rate after solutionization before forming process.

Transfer or handling systems between the stations influence significantly the productivity and part quality in the hot forming of aluminium. Particularly critical is the transfer from the furnace to the
intermediate cooling station. Based on many results from trials, transfer time \( t_T \) is the most important in the design parameter of the handling systems for the hot forming process. This time is associated with the hot forming process for different aluminium alloy materials through the definition of the temperature gradient, given as:

\[
\frac{dT}{dt} \leq 8 \, ^\circ\text{C/s}
\]  

(1)

where \( dT \) represents change in aluminium alloy blank temperature during transfer. The transport and handling systems should be operated at a speed of 5.1 m/s and an acceleration of 11.5 m/s² based on a load of 115 Kg. In standard production lines these enable an evaluated temperature gradient of less than 5.6 \( ^\circ\text{C/s} \).

4. Forming of high strength aluminium alloy materials for car body engineering

4.1. Sheet metal forming and materials

The predominant strengthening mechanism during deformation of polycrystalline material such as high strength aluminium alloys is the conventional dislocation movement. The plastic behavior during deformation is significantly influenced by the activation and cross-hardening of different slip planes, depending on the crystallographic orientations [4]. The flow stresses during sheet metal forming are usually characterized by the relationship in equation 2:

\[
\sigma = f(\text{microstructure, } \varepsilon, \dot{\varepsilon}, T)
\]  

(2)

in which \( \sigma \) represents stress (applied load), \( \varepsilon \) is the strain, \( \dot{\varepsilon} \) the strain rate and \( T \) is the working temperature. In reference to Equation 2 varying strain rates and temperature influence significantly the deformation and hardening behavior in the hot forming process. Fundamentally, an increase in strain rates results in higher flow stresses, while high temperatures reduce the required stress level. Further, isotropic and anisotropic material behaviours of the alloy blanks represent microstructural influence in the forming process. Therefore adequate process knowledge, tools and equipment are required to manufacture functional parts with complex geometries in a volume manufacturing of automotive parts using high strength aluminium alloy materials.

4.2. Servo hydraulic press in hot forming of high strength aluminium alloy materials

Due to challenges in the forming of sheet metals with low formability such as high strength steel and aluminium alloy, a servo hydraulic press technology may be needed to apply required forming loads, as well as speed, acceleration positioning of the tools etc. accurately to achieve specified part tolerances. Such press system developed and designed based on the advantages of servo mechanical and hydraulic presses. Due to high degree of software control, servo presses are generally more flexible and equipped with more features especially free motions of slide motion, compared with hydraulic presses. Through the reverse rotation of the servo motor, variable slide stroke can be achieved in a servo press system for optimal forming process irrespective of material behavior. In addition, the new press compared to existing press technologies can be presented as a sustainable and environmental friendly press solution due to achievable outstanding energy efficiency such as operating on half motion in a progressive die application. 50 % lower energy consumption is achievable with servo presses compared to hydraulic presses. In addition, due to low volume of oil used during operations and associated control valves, maintenance work using servo hydraulic press can be reduced to at least 30 % [AP&T Group].

During the press hardening process, the tool dwells for an extended period from 5-10 s for parts thickness: 1-2.5 mm using hydraulic presses. While dwell time above 150 s is difficult to achieve with hydraulic presses, longer dwell time is possible with servo mechanical presses but with limited press force. Servo hydraulic presses offers most cost effective solution at dwell time above 300 s dwell on the bottom and above 1000 press tonnage compared with other press technologies. Dwelling with the require press force represents an important stage in the hot forming process. Furthermore, the combination of variable die cushion pressure and the slide motion control in the design of servo presses can provide
unique feature for improved performance in the sheet metal forming process irrespective of material behaviours.

4.3. Tooling system for hot forming of high strength aluminium alloy blank sheet materials

In press hardening through cooled tool design, the blank is deformed and quenched simultaneously under pressure at a minimum cooling rate of 27-30 K/s in the tool cavity [2]. Manufactured parts using the tools experience insignificant or no spring-back, with dimensional accuracy that requires no further operations. However, tools based on conventional tooling system used in the hot stamping of boron steel for the automotive industry cannot be used directly in the hot forming of high strength aluminium alloy due to different material properties. To enable HForm™ process, a prototype tool is used to develop optimal tool/die solution for the hot forming of aluminium alloy blanks and depicted in Figure 4(a).

![Figure 4](image)

**Figure 4.** HForm™ process: (a) half B-Pillar Prototype tool, (b) Manufactured half B-Pillar part.

During hot forming, the interaction between the tool and hot blank aluminium sheet causes different changes in the physical and mechanical features as well as the properties. These changes can include surface appearance and roughness, resistance to plastic deformation, hardness etc. and can be very severe in volume manufacturing. Figure 5(a) illustrates galling defect due an unsuitable lubricant and uncoated tool as depicted in Figure 4(a).

![Figure 5](image)

**Figure 5.** Manufactured B-Pillar Parts: (a) formed using uncoated and unsuitable Lubricant, (b) formed using coated and suitable Lubricant.

In most cases, galling defects with aluminium are experienced at the flange and side areas of the formed part because of the high temperature and stress working conditions as illustrated in Figure 5. Illustrated in figure 5(b) is the part formed on coated tool with about 20 % lubrication. High friction in the flange area influences the thinning and the eventual failure on the parts side wall in the deep-drawing processes. To avoid abrasive wears and galling at the blank/tool interface, a surface engineering solution employing coated tools and reduced dedicated lubricant acceptable to OEMs will be required.

5. Fast ageing for industrial application

Due to demand to develop an effective hot forming production line using aluminium alloy materials that will satisfy requirements such as reduced cycle time, increased mechanical properties, better corrosion properties, etc., intermediate cooling, pre-ageing and paint baking process steps were integrated in the HForm™ process definition illustrated in Figure 2 and implemented in the manufacturing layout. The short paint baking time of 20-30 min practised by most OEMs, will not be adequate for optimal hardening required to achieve functional requirements in the car body engineering because of the age
hardening kinetics of these alloy materials. The main objective of the ageing strategy in HForm™ process is to develop a production line that will be suitable in the manufacture of components using all age hardenable aluminium alloys and offer the potential to improve alloy properties such as ductility, toughness, strength, resistance and fatigue as well as reducing costs and process cycle time.

In the conventional automatic process chain, prior to final assembly of the vehicles, the BiW is painted and cured in a furnace under process condition of approximately between 150 and 180 °C for a time period of 20-30 mins. Depending on the specific paint bake cycle, precipitation strengthening of the aluminium part may be achieved. The pre-ageing step as defined in HForm™ process line compliments the product-specific paint-bake cycles. Further, it offers OEMs and Tier1s much flexibility in the material flow and process chain used in the automotive industry. In addition, the improved ductility of formed parts allows for mechanical joining in the body assembly structure before e-coating. Mechanical joining such as piercing riveting is usually difficult for high strength aluminium alloy materials (particularly most 7xxx series) beyond 30 mins after hot forming, due to a strong increase in yield strength during room temperature ageing.

6. Result and discussions: HForm™ process using AMAG 7075
The tests were conducted to evaluate the HForm™ process and verify the influence of ageing steps and intermediate cooling ≤ 50 K/s steps on the mechanical properties of the formed parts using AA7075 material. Collated in Table 1 are different process routes for the tests and were conducted with constant settings for the furnace and press during solutionization and forming steps respectively.

| Table 1. HForm™ Test Matrix with AMAG 7075 material. |
|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| MATERIAL: AA7075 T6          | SUPPLIER: AMAG ROLLING         |                                 |                                 |                                 |                                 |
| SAMPLE                        | PROCESS ROUTE                  | STEPS                           | STEPS                           | STEPS                           | STEPS                           |
| R01_7075                     | MRoute#01                      | Intermediate cooling no         | no                              | Intermediate cooling yes         | yes                             |
| R02_7075                     | MRoute#02                      | Pre-ageing yes                  | yes                             | Pre-ageing yes                  | yes                             |
| R03_7075                     | MRoute#03                      | Storage yes                     | yes                             | Storage yes                     | yes                             |
| R04_7075                     | MRoute#04                      | Paint Baking 30min@185 °C       | yes                             | Paint Baking 20min@180 °C       | yes                             |
| R05_7075                     | MRoute#05                      |                                 |                                 |                                 |                                 |

Each manufacturing route as collated in Table 1 represents a production cycle as illustrated in Figure 2. Intermediate cooling (IMC) step was carried-out at 20 K/s. Pre-ageing (PA) and storage steps condition was constant for all the routes, where indicated ‘yes’ in Table 1. In Table 2 the evaluated mechanical properties are listed, while the relation between these properties are illustrated in Figure 6. The baseline result given in Table 2 represent material properties based on 24 h at 125 °C paint baking after deformation process without intermediate cooling, pre-ageing and storage before paint baking.

| Table 2. Evaluated mechanical properties of manufactured Parts: AMAG 7075 material. |
|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| PROCESS ROUTE                  | SAMPLE                          | AVRG. R$_{0.2}$ [N/mm$^2$]     | AVRG. R$_M$ [N/mm$^2$]         | AVRG. A$_{50}$ [%]             |
| CONVENTIONAL                  | Baseline                        | 500                            | 565                            | 12                              |
| MROUTE#01                     | R01_7075                        | 400                            | 496                            | 11                              |
| MROUTE#02                     | R02_7075                        | 460.5                          | 532                            | 10.6                            |
| MROUTE#03                     | R03_7075                        | 425.5                          | 506                            | 10.9                            |
| MROUTE#04                     | R04_7075                        | 336                            | 465                            | 13.67                           |
| MROUTE#05                     | R05_7075                        | 360                            | 464                            | 10.55                           |

*The results presented in table 2 above are in T6 conditions (ageing for 24 h at 125 °C)
Figure 6. Evaluated mechanical properties AMAG 7075 HFormed parts: yield strength (YS), Ultimate strength (UTS) and Elongation at fracture %. Material: AMAG 7075, thickness 1.5 mm.

The results illustrated in Figure 7 and listed in Table 2 above, show that the mechanical properties achieved in HForm™ process route, MROUTE#02 and baseline are closely comparable. However, the reduced ageing time with the associated cost advantage favours HForm™ for volume manufacturing application in the automotive industry. Process route without intermediate cooling (IMC), MROUTE#02 with average YS of 460.5 MPa, UTS of 532 MPa and elongation of 10.6 % presents best properties compared to routes with IMC. The results illustrates the influence of low cooling rate on achievable mechanical properties at T6 conditions using AA7xxx materials. Due very low cooling rate of 20 K/s (less than 50 K/s) employed in the routes: MROUTE#03, MROUTE#04 and MROUTE#05 they showed reduced mechanical properties compared to MROUTE#01 and MROUTE#02. Furthermore, grain structure of HFormed half-B-pillars was analysed using a light microscope. Figure 7 shows the half B-Pillar and the cut sample sections to characterize the process.

Figure 7. HFormed B-Pillar using AMAG 7075 material: Samples R02_7075 and R03_7075. Samples were taken from the bottom section (B) with minimal or no forming and from the sidewall (S) section. The sidewall section represents the deep drawn section. In Table 3 the measured mechanical properties are collected, while the micrographs are depicted in Figure 8 below.

Figure 8. Micrograph of HFormed part cross section parallel to rolling direction along L-S plane. (B and S: bottom and side part sections respectively as shown in Figure 7). Material AMAG 7075, thickness 1.5 mm.
Figures 8 depicts micrograph images of the grain structure of the bottom (B) and sidewall (S) areas of the HFormed half B-piller sections. According to the measured mechanical properties and collated in Table 3, S-cut from sample R02-7075 presented highest mechanical values compared with B-cut from sample R02-7075 and R03-7075. Higher mechanical values of the sidewall areas are a consequence of local strain which occurred during forming after SHT, which can be seen by the reduced thickness of the sidewall section in contrast to the undeformed bottom section. The higher dislocation density enhances the nucleation of the strengthening phase $\eta'$, which leads to higher paint bake response for the sidewall areas.

Table 3. Micrograph of samples R03_7075 and R02_7075: Evaluated mechanical properties of the different cross sections.

| PROCESS ROUTE | SAMPLE     | $R_{P0.2}$ [MPa] | $R_m$ [MPa] | $A_G$ [%] | $A_{10}$ [%] |
|---------------|------------|-----------------|-------------|----------|-------------|
| MROUTE#02    | R02_7075 B | 449             | 527         | 8        | 9.9         |
|               | R02_7075 S | 472             | 537         | 8.8      | 11.3        |
|               | R03_7075 B | 417             | 501         | 8.8      | 10.9        |
|               | R03_7075 S | 434             | 511         | 8.7      | 10.9        |

7. Conclusion, recommendations and future works

It is obvious from Figure 6 that there is an inverse relationship between strength and ductility and the results show adverse effect of low cooling rate on the mechanical properties of formed parts. Further, the tests results illustrate that the pre-ageing and the different ageing routes listed in Table 1 influenced achievable mechanical properties at T6 conditions of the used material. Hence the two-step ageing in the HForm™ process will be recommended for industrial application to reduce cycle time and manufacturing cost.

The results on the properties namely: corrosion resistance, fatigue, toughness etc. will be evaluated in the future trials with intermediate cooling $\geq 50$ K/s. The aim will be to illustrate the adverse effects of low cooling rate $< 50$ K/s and the need for intermediate cooling in the HForm™ process using 7xxx series materials. In addition, the comprehensive crashworthiness of parts will also be evaluated with considerations or combination of % elongation before fracture and a bending test using specifications from OEMs. An analysis on corrosion resistance combined with mechanical properties results will provide comprehensive process and manufactured parts quantification. These will enable expert advice for automotive applications in the car body engineering.

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