Industrial based volume manufacturing of lightweight aluminium alloy panel components with high-strength and complex-shape for car body and chassis structures

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Abstract. To achieve the high volume manufacture of lightweight passenger cars at economic cost as required in the automotive industry, low density materials and new process route will be needed. While high strength aluminium alloy grades: AA7075 and AA6082 may provide the alternative material solution, hot stamping process used for high-strength and ultrahigh strength steels such as boron steel 22mnb5 can enable the volume manufacture of panel components with high-strength and complex-shape for car body and chassis structures. These aluminium alloy grades can be used to manufacture panel components with possible yield strengths ≥ 500 MPa. Due to the differences in material behaviors, hot stamping process of 22mnb5 cannot be directly applied to high strength aluminium alloy grades. Despite recorded successes in laboratories, researches and niche hot forming processes of high strength aluminium alloy grades, not much have been achieved for adequate and efficient volume manufacturing system applicable in the automotive industry. Due to lack of such system and based on expert knowledge in hot stamping production-line, AP&T presents in this paper a hot stamping processing route for high strength aluminium alloys been suitable for production-line development and volume manufacturing.

Keywords: Lightweight, volume production, production-line, hot stamping, automotive, 22MnB5, high strength aluminium alloys.

1. Introduction

The growing demand for lightweight passenger cars to enable more fuel-efficiency, reduce energy consumption and CO2 emission represent a challenge and opportunity for the automotive industry. According to [1] 10 % of vehicle weight reduction can result in 8–10 % of fuel economy improvement. Although steel remains the widely used alloy in most categories of automotive industries, light weight material such as high strength aluminium alloys compared to steel alloys show high strength/stiffness to weight ratio, better corrosion resistance, joinability and recyclability, among others. These attributes are the reasons about the shift towards volume manufacturing of intensive aluminium-vehicles using alloy grades such as AA6082 and AA7075.

However, to achieve the high volume manufacture of lightweight passenger cars at economic cost as required in the automotive industry, light weight or low density materials and new process route will be
needed. Conventional hot stamping processes of steel alloys sheet metal blanks offer the advantage to the manufacture of complex shaped components in single-piece design on an economic basis for volume production and can be applied to the aluminium alloy blank sheet grades. Several hot stamping processes of aluminium alloy blank sheets presented in [2, 3, 4, 5, 6, 7 and 8] and others, show the feasibility for a scaling of the conventional press hardening process of steel alloys to the volume manufacture of complex automotive components from high strength aluminium alloy grades.

For the hot stamping of components made of aluminium alloy grade materials, the required fundamentals to conduct the production process and to design suitable tools and machines are not much published. The lack of suitable volume production facilities for hot stamping of automotive components such as A- and B-Pillars made of high strength aluminium alloy grades using AA7075 materials gave rise to the here presented paper, on the development of hot stamping process as well as tools and production systems for volume manufacturing.

2. **Conventional Hot stamping (Press Hardening) of Steel alloys blank sheets**

Practically it is difficult at material yield strength greater than 1000 MPa, to manufacture car components from steel alloys blank sheet with complex structure and shape applying cold stamping method. Due to this limitation, hot stamping technology developed rapidly. Hot stamping process was developed in Sweden in the 1970s and first used in the automotive industry by Saab Automobile AB in 1984 [9]. The increased application of hot stamping forming technology in recent years by OEMs was mainly to provide for the high volume manufacture of lightweight ultra-high strength steel (UHSS) components for the body structures of vehicles.

In the hot stamping of steel alloys process as illustrated in figure 1, a steel alloy blank is heated in a furnace to the austenitization temperature of around 900 °C and transported to the press fitted with internally cooled tool set for stamping. Through cooled tool design, the blank is deformed and quenched parallel under pressure at a minimum cooling rate of 27-30 K/s in the tool cavity. This minimum cooling rate ensures the formation of a martensitic microstructure in the processed alloy sheet blank and imparts high strength that can be in excess of 1500 MPa. Additionally, components with complex geometries can be manufactured through hot stamping without the problem of springback compared to cold forming.

![Figure 1 Hot stamping process (press hardening) of steel alloys blank sheets](image-url)
Through several modification and refinement of this process different variant of hot stamping process exist today aimed to manufacture components from special steel alloy grades, to optimize cost, impact tailored properties etc.[5, 10, 11]. The parameters $v_{St}$ and $u_{St}$ shown in figure 1 represent different cooling rates to achieve different process route and final part mechanical properties from the stamping process. In comparison to cold forming, process thermomechanical control significantly influences the microscopic structure evolution and subsequently the final mechanical properties of the hot stamped components as well as cycle time. The control is achieved through adequate cooling channels design as depicted in figure 1 and the associated process parameters.

During the transfer of the hot blank from the furnace after the austenitization to the press with fitted forming tools, the blank loses heat by convention and radiation to the environmental temperature of approximately 25 °C. The heat loss recorded is usually about 150 °C with modern handling systems and does not cause any microstructural changes. The forming process is usually completed in second fractions and the quenching to the tool design and controlled temperature in 5-6 s. Automotive components currently and widely formed applying hot stamping process include; A- and B-Pillars, rear bumper, frame and roof rails, rear bumper, side member reinforcement among others.

3. **Aluminum in the Automotive Industry**

To reduce CO2 emission, without compromising safety and at reduced cost, the automotive industries are increasing applying the strategy of weight reduction. As given in [12] Aluminum, replacing steel in modern vehicles, could save approximately 44 million Tons of CO2 emissions/year. Additionally approximately 90 % of the aluminum used in vehicles is recycled at the end of the usage lifecycle. In the manufacture of light weight cars, steel alloys components are increasingly been replaced by aluminium and aluminium alloys. Over a decade now, aluminum has been progressively incorporated into automotive doors, trunks, hoods, and engines more significantly in passenger cars as depicted in figure 2.

![Figure 2 Aluminum in an automobile [Source Aston Martin, DB11, GALM, Birmingham, UK 2017]](image)

The car manufacturer Audi has been for close to 20 years now, manufacturing an all-aluminum structure for its A8 model and Ford has developed an all-aluminium structure for its F-150 pickup that has significant market segment in North America among other brands on the road. According to [14] the incorporation of more aluminium and their alloys in passenger cars by other car manufacturers can cause a 40 % increase in the demand for aluminium material. The trend is expected to continue and in [13] is a predicting 4 % annual growth of aluminium material usage in the automotive industry up to 2025. In
table 1 below, manufacturing and weight-strength ratio attributes were used to illustrate the advantages of aluminium compared to steel material in the automotive applications.

### Table 1 Manufacturing in the Automotive Industry: High strength aluminium alloy against UHSS materials.

| Material      | Elongation % | Forming loads | Energy Consumption | Weight/Strength Ratio |
|---------------|--------------|----------------|--------------------|-----------------------|
| Steel Alloys  | high         | Thermal: high  | high               | high                  | low                   |
| Aluminium Alloys | low         | Force: low    | high               | low                   | high                  |

Lower elongation % and strength of aluminium alloy materials compared to steel alloys represents a major challenge for manufacturing and application. The weight/strength ratio advantage of aluminium alloys over steel alloys will however encourage the increase use in automotive industry in the manufacture of light weight cars. A weight saving comparison between UHSS and AA7075 is given in table 2 below.

### Table 2 Properties of UHSS and AA7075 (Ultralex)-source Constellium (material supplier).

| Material | Tensile Strength [MPa] | Weight Saving [%] |
|----------|------------------------|-------------------|
| UHSS     | 1100                   | -                 |
| AA7075   | 500                    | 17                |

To address the elongation % challenge, high strength aluminium alloy grades such as AA6000- and AA7000-series can be hot stamped to manufacture components with strengths ≥ 500 MPa higher compared to some steel alloys. Through adequate design strategy, components made from these alloy grades after hot stamping process can be structurally compared to mild steel and absorb crash energy two times more [13]. According to AMAG (material supplier) high-strength AlZnMg(Cu) alloys of the AA7xxx series are well-established materials in the aircraft and sports applications, and exhibit tensile strength of up to 700 MPa . The automotive industry has also realized the lightweight potential of this alloy class and explains the present increase push for passenger car bodies of all-aluminium design, multi-material design, or in light-metal doors and closures.

### 4. Hot Stamping process of Aluminium Alloys Blank Sheets

Cast and wrought are the two categories used by the Aluminum Association to classify aluminium alloy semi-finished or as supplied materials. The wrought category applies to alloys produced in ingot, billet form or blank sheets and subsequently metal worked in operations such as rolling, extruding, forging, drawing. The subordination of the wrought alloys are given as heat treatable and non-heat treatable (strain-hardenable). Commercially available high strength aluminium alloys blanks sheets of the 6000- and 7000-series are heat treatable and exist in different temper designation [15], will be the focus in this publication.

Heat treatable aluminium alloy refers to the alloy grades in which the alloying elements provide significant solid solution and precipitation strengthening during solution heat treatment and subsequent
ageing. Solid-solution heat-treatment (solutionization) of an aluminum alloy involves the heating above the solvus line, where only one phase is thermodynamically stable and other solid phases dissolve. Depending on the alloy grade and composition, the blank sheet must be kept at this temperature for an adequate time.

Depicted in figure 3 is a schema of hot stamping of aluminum alloy process of alloy blank sheet defined to enable volume manufacturing of automotive components from different alloy grades.

![Diagram of hot stamping process](image)

Figure 3 Hot stamping process (precipitation hardening) of aluminium alloys blank sheets

As illustrated in this figure, the process starts with the solutionization process to form supersaturated solid solution (SSSS). By rapid cooling (quenching) at the cooling rate $v_{AA}$ against the slow cooling rate $u_{AA}$, the SSSS and excess vacancies are maintained for optimal age hardening process and rapid formation of Guinier-Preston zones (GPZ). Optimal quenching rate and final temperature before transfer to the press for stamping is dependent mainly on the alloy blank grade and composition. The process of precipitation is not instantaneous as is often the case in liquid-solid precipitation and involves intermediate metastable phases as illustrated in figure 3 and listed in table 3 below. The precipitation sequence of most of the high strength aluminium alloys depend on the composition.

Table 3 Precipitation sequence of high strength aluminium alloy blank sheet.

| Base Material | Alloy Grade       | Precipitation Sequence                  |
|---------------|-------------------|----------------------------------------|
| Aluminium     | Al-Mg-Si (AA6xxxx) | GPZ (rod) → β' (rods) → β (Mg$_2$Si) (plates) |
| Aluminium     | Al-Zn-Mg (AA7xxxx) | GPZ (spheres) → η' (rods) → η (MgZn$_2$) (plates) |

Precipitation progresses with time, to define the ageing process and stops, when the solution achieves an equilibrium composition limited by the solvus line for the aging temperature of the alloy grade. Compared to the hot forming of steel alloys illustrated in section 2 above, full strength is not achievable
in the hot stamping of aluminium alloys after quenching and forming rather a metastable partially strengthened part is produced. The metastable is subsequently transferred to the ageing station to enable full strengthening.

The distribution of precipitates affects the hardness and yield strength. The hardness and yield strength are greater when the precipitates are small and finely dispersed in the matrix than when the precipitates are large and not finely scattered. Thus, to gain hardness the precise control of the solutionization will be required to produce a fine dispersion of small precipitates (coherent) [16].

Aging process is a function of temperature and the higher the temperature, the wider the spacing of the precipitates that are initiated on cooling (quenching) from the solid-solution heat treatment temperature. Additionally, because coarsening is dependent upon the movement of atoms (diffusion), the maximum point is generally reached sooner at a higher temperature than at a lower temperature.

5. AP&T Multi-Purpose Production-Line for High Strength Aluminium Alloy Grades

In the last decades the influence of hot stamping of blank sheet metal process particularly steel alloys on the body in white (BiW) structure is very significant. AP&T Sweden AB has been part of this history and continue up to date to play global role in the hot stamping technology. Based on the extensive experience and global collaborations with universities, research institutions, material suppliers, OEMs, Tier1s and other associated industries, AP&T present here the first multi-purpose stamping production-line for aluminium alloy grades to enable volume manufacturing for the automotive industry.

The stamping process configurations depicted in figure 4 account for the aluminium alloy grades material behaviors and design considerations in the volume manufacturing for the automotive industry applications. The parameters illustrated in this figure 4 are collated in table 4 below.

![Figure 4 Schema Stamping process configurations of High strength aluminium alloy grades](image-url)
Table 4 Process configuration parameters.

| Stamping Process | Automotive aluminium alloy grades (AAxxxx) | \( t_1 \) | \( t_1- t_2 \) | \( t_2 \) | \( t_2- t_3 \) | \( t_3- t_4 \) | \( t_5- t_6 \) |
|------------------|-------------------------------------------|---------|------------|---------|------------|------------|------------|
| Warm             | 5053, 5182, 5754, 6016 T4, 6022 T4, 6111 T4, 7075 T6 | time to heat-up to SHT | soaking time at SHT | transfer time | forming/quenching time | transfer/air cooling time | ageing time |
| Hot              | 6016, 6082, 6070, 7021, 7075 | | | | | | |

Less heat sensitive alloy grades can also be manufactured without intermediate station as presented in [3, 4] and warm forming, and W-temper process in [2, 17]. Illustrated in Figure 5 is the overview of the AP&T developed production-line at the company head-office in Sweden.

Figure 5 AP&T Multi-purpose production-line for high strength aluminium alloy grades

The multi-purpose production-line is characterized by new press, furnace and tools technologies dedicated to high strength aluminium alloy materials grades. Despite the emphasis here on aluminium the production-line and modules can be reconfigured to process other materials particularly conventional UHSS. The new press is a high performance system and designed to operate at lower energy consumption, speed 350 mm/s, high availability, and accuracy etc. The new AP&T Aluminium MLF furnace offers tight set-temperature tolerance of ±5 °C and achievable higher heating rate compared to conventional furnaces in the market. These attributes make the production-line suitable for volume manufacture high strength aluminium alloys components due to the associated complex thermomechanical behaviour. The developed tools achieved through much trials at AP&T R&D center in Sweden provides adequate tribological and thermal solutions for the stamping processes.

6. Conclusions and Outlook

Stamping processes of high strength aluminum alloys at elevated temperatures are current research topics, AP&T Sweden AB has developed the first world production-line for volume manufacture of automotive components from high strength aluminum alloys. This was achieved partly through global collaborations with the industry, academia and mainly based on the expert as well as the extensive knowledge in press hardening of steel alloys. Hot stamping of boron alloyed high strength steel depicts
much similarity with stamping processes of high strength aluminum alloys at elevated temperatures and explained the success achieved by AP&T in transferring press hardening knowledge to aluminium alloy material grades.

However, despite this success much work still remain to develop and manufacture optimal tools at economics cost. Additionally, more collaborations with material suppliers will be needful to develop less heat sensitive alloy grades that still satisfies functional requirements in the automotive industry after stamping processes.

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