A pilot prototype production line for the hot-forming of aluminium alloy sheets with fast contact-cooling and multi-point tooling

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Abstract. This paper reports the study of the process chain for sheet metal forming using multi-point tooling for stamping at elevated temperatures and developing a complete production line integrating heating, intermediate fast-cooling, forming and aging. It aims to deliver a high-efficient and cost-effective sheet-metal forming technology with improved process capability and flexibility for the forming of high-strength sheet metal parts. Multi-point tooling sets are employed to test the flexibility of hot/warm-forming the lightweight high-strength metal sheets with fast tooling reconfigurability. The intermediate cooling with high cooling rates was achieved with a contact cooling system recently developed at the University of Strathclyde. With this pilot line, the aluminium sheets heated to the solution heat treatment (SHT) temperature were subjected to the intermediate cooling prior to forming with multi-point tooling. The cooling step is fast and controllable, with different cooling rates tested. The tests conducted on the pilot line demonstrated significant enhancement of the forming limit and manufacturing flexibility.

1 Introduction

As lightweight materials, aluminium alloys are popularly used in many industry sectors, including the Aerospace/Aerodynamics industry [1]. Nevertheless, due to the poor formability of high strength aluminium alloys there are still significant challenges in converting aluminium sheets into complex geometries [2-3]. Hot stamping technology has been intensively used for forming of engineering components from aluminium sheets as this helps to reduce the forming force and the springback incurred during forming, while maintaining structural integrity and impact safety [4-5]. However, hot stamping of high strength aluminium alloys still encounters some problems associated with the forming of complex shapes and the forming die conditions as well as the need for high productivity. These challenges are particularly reflected in the relatively low material forming limits and hence, the achievable component forms [6-7]. However, although intermediate cooling has been introduced to the hot stamping of aluminium alloys as a means of addressing the

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constraints to the forming limits, either the cooling rates achievable to-date, such as air/spray cooling, are still too low, or the designs for fast-cooling are not viable for production environment applications.

Efforts made at the University of Strathclyde aim to address these issues by developing a prototype pilot production line that combines the hot stamping of aluminium alloys and fast contact-cooling. In addition, the employment of multi-point tooling enables the application of flexible forming and testing of different forming configurations, which are inappropriate for solid dies. Multi-point tooling forming is a special category of flexible sheet metal forming in manufacturing that saves the costs of making specific dies by adjusting the pin heights on each set along the machine ram direction to form the desired forming-tool surface contours.

The tests conducted so far demonstrated that the integration of fast-contact-cooling into a production process is feasible and that its associated cost could be relatively low. They also showed that introducing a high temperature forming configuration into a multi-point tooling forming process is feasible and extends the existing process capabilities. The test results indicated that proper cooling rates, which are easily achievable with the facility developed, could improve the forming limits of the high strength aluminium alloys greatly, and, in general, the higher the cooling rate the better results are obtained. Generally, the fast-cooling configuration design could potentially lead to significant process time saving, due to the extremely short cooling time involved.

The Centre for Precision Engineering (CPM) has been working on this hot forming technology for several years, but little work has been done on testing the integration of fast cooling into an industrial forming process chain. At the same time, multi-point tooling offers opportunities for flexible forming and for testing different forming configurations.

2 Overview of the prototype production line

The proposed idea of the pilot line consists of a furnace box, a control and measurement panel, and an integrated hydraulic press with a contact cooling station as well as a multi-point tooling machine, as depicted in Figure 1. A complete process chain of heating, intermediate cooling, forming and quenching can be achieved step by step.

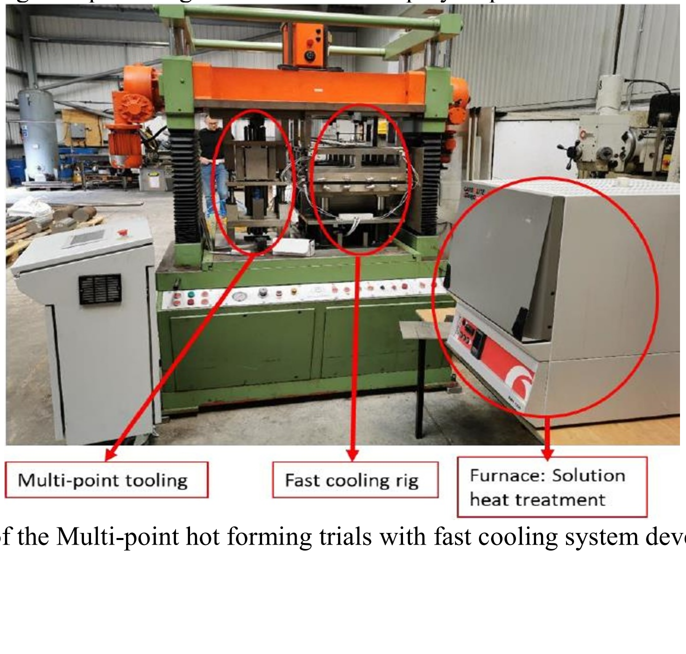

Fig. 1. Setup of the Multi-point hot forming trials with fast cooling system developed.

2.1 Working Principles

Figure 2 shows schematic procedures of the proposed multi-point hot forming pilot line with a fast-cooling process. At the start, the high strength aluminium alloy sheet is heated to about 500ºC (SHT temperature) in a furnace and maintained at this temperature for a while (10 minutes usually). Then the hot blank is transferred to the lower contact plate of the cooling system. It is crucial to keep the blank transfer time from the furnace to the cooling plate as fast as possible. The press is then operated to bring the upper contact plate down to apply pressure on the blank for the intermediate fast cooling process from approximately 500ºC to 350ºC. The cooling rate can be varied by setting the contact plate to different temperatures. Then the blank is quickly transferred to the stripper plate of the multi-point forming tool with lubricant applied. The blank can be formed to a desired shape and held within the cold die for in-die quenching. Subsequent washing and artificial aging process may follow. The temperature profile of the process chain is given in Figure 3.

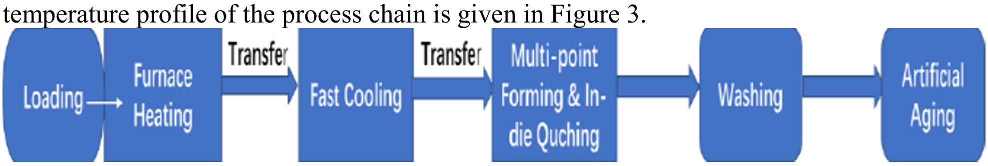

Fig. 2. Illustration of the process chain involved.

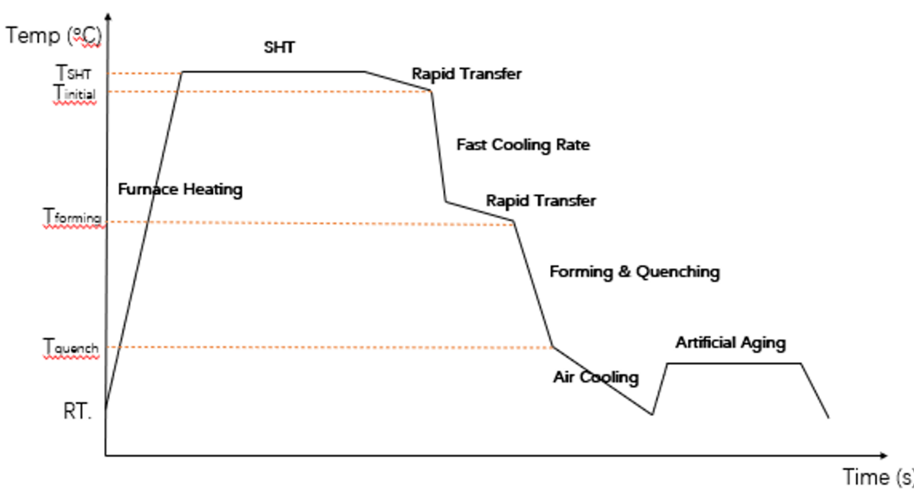

Fig. 3. Temperature profile of the process chain.

2.2 Multi-point tooling

The multi-point tooling consists of 23 tightly packed adjustable dome-like pins with a hexagon cross-sectional area column for each of top and bottom punch-set, as shown in Figure 4. The bottom punch is fixed to the base, while the movement of the top punch is controlled by hydraulic force in the vertical direction along the guide pillars. The heights of the pins can be adjusted by a screw thread. Four blank holders are attached to the top punch-set to control the sliding of the sheet metal along the surface of the die-plate during the forming process.

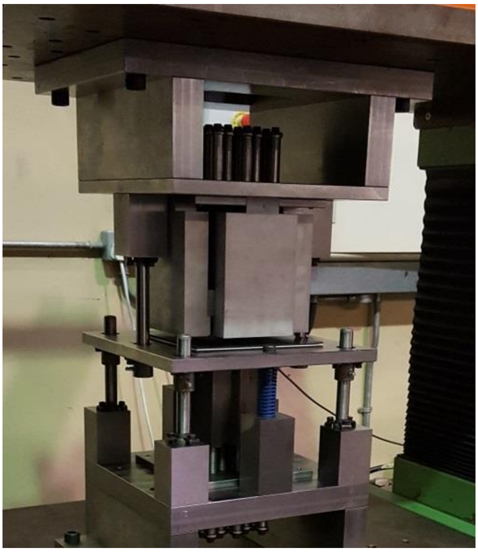

Fig. 4. Multi-point tool used for the forming trials in the pilot line.

2.3 Fast cooling system

As shown in Figure 5, a contact fast cooling system with a dedicated control unit has been developed. Cartridge heaters and thermocouples are used to achieve a variable die temperature. The cooling station is divided into an upper and lower die, each with its own cooling plate. Both dies are mounted on a movable hydraulic press and connected to the control cabinet. The upper and lower dies are identical, while damping components and sprung pins are designed for the lower die to lift the blank for an automated robot. The tool design allows the contact material to be changed to achieve different thermal conductivities, thus obtaining various heat transfer and cooling rates. In this process copper is used for all tests due to high thermal conductivity for high cooling rates. The sub-frame is thermally isolated from the cooling plate for each die to reduce the thermal mass and ensure that the only hazardous components of the tool are the contact plates. Both dies feature four 2kW heating cartridges fixed within the copper contact plate. Pressurised air can be channelled through the dies to cool the contact plates. When the temperature across the plate reaches the set limit, the cooling system can engage automatically. The control cabinet is designed for temperature control and data recording. Up to sixteen thermocouples can be connected to the cabinet to measure live temperatures. All data and controlled functions are displayed on the screen.

(a) (b)

Fig. 5. Tooling used for fast contact cooling: (a) upper and (b) lower.

3 Hot forming experiment results and discussion

AA6082-T6 is used as the material to investigate the forming capability with the proposed pilot line. The blank sheets are cut into 200mm * 200mm square plates with a thickness of 1.5mm. Thermocouples are mounted at the edges of all plates to monitor the temperature change during the entire heating, cooling and forming process. As all four edges are constrained for the square plates, the stress and strain conditions can represent the most universal industrial applications.

A total of nine groups of square plates were formed and these were classified in three general categories, representing increased pressing strokes of 20mm, 22mm and 24mm. In each category three samples were labelled as 'SHT+NC', 'SHT+FC' and 'SHT+EFC', with cooling rates of 5°C/s, 50°C/s and 100°C/s respectively before being formed using the multi-point tools.

Fig. 6 Square samples from hot multi-point forming with cooling process.

From the test trials, when formed to the same depth, there is little difference in the final shape of the plates with different cooling rates. This is partly due to the similar Young's modulus and maximum elongation under different cooling rates. Nevertheless, reduced wrinkling can be observed for the plates that were cooled at a higher cooling rate while large transverse shrinkage on the edges can be seen in the plates that were naturally cooled. This can be due to the restriction of a lower UTS of aluminium alloys with decreased cooling rates.

Table 1 illustrates the final conditions of the edges where cracking propagates with increasing formed depth. Also cooling rates are important to the final shape condition and for AA6082-T6, the formability can be improved by increasing the cooling rate. In this case samples under solution heat treatment and extra fast cooling perform the best. One possible reason is the strength differences under different cooling rates. Based on the HFQ concept, the underlying reason is that when aluminium alloy is heated close to the solution heat treatment temperature, the material becomes very soft, ductile and easy to deform because the crystalline particles become an unstable supersaturated solid solution, which is desirable for high post-form strength. However, fast cooling is necessary to obtain the optimal mechanical properties by freezing the supersaturated solid solution and maximising the effect of strain rate hardening. Various cooling rates also impact the forming performance. Since the material microstructure is unstable near its solution heat-treatment temperature and strain hardening effects, too much decrease in strength may cause the material to be softer, making the sample easier to damage when the elongation at the break point remains the same. Therefore, a suitable cooling rate needs to be taken with a balance between formability and ductility.

Table1. Final shape edge performance of square samples

Curve depth	Heat treatment and cooling status	Final shape edge performance
20mm	SHT+NC	Thinning
	SHT+FC	No damage
	SHT+EFC	No damage
22mm	SHT+NC	Crack
	SHT+FC	Thinning
	SHT+EFC	No damage
24mm	SHT+NC	Propagated crack
	SHT+FC	Crack
	SHT+EFC	Thinning

4 Conclusion

This paper reports an innovative pilot line that was developed for hot sheet-metal forming which introduces an intermediate 'fast-cooling' step between heating and forming steps for forming of high-strength aluminium alloys to fulfil industrial needs. The application of multi-point tools at elevated temperatures was also introduced for the first time. The results prove that introducing the intermediate fast-cooling can greatly improve the formability of high strength aluminium alloy sheets in multi-point tool forming, while the cooling rate used can have a significant effect on the material deformations, making it crucial to the forming limit of the sheet metal as well as final output of the formed component, including defects.

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