



Industry case study: process chain for manufacturing of a large hybrid hot stamping tool with conformal cooling channels

R. Muvunzi¹ · D. Hagedorn-Hansen¹ · S. Matope¹ · X. Madyibi¹ · C. B. Swart¹ · M. Nagel²

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Abstract

Conformal cooling channels introduced into manufacturing tools is fast becoming an industry standard, as it has proven to significantly reduce cycle time during operation. Introducing conformal cooling channels into a metal tool (such as a hot forming punch or injection moulding core) is a challenge on its own and often requires expertise in both additive and subtractive processes to execute efficiently. Another issue is that of the inherent constraints of both the additive and subtractive processes, which prohibit the effective use of these processes for manufacturing of specific tool designs. Thus, often a balance needs to be met, where a hybrid process is sought to utilise the advantages of both processes while limiting the disadvantages. This study suggests a viable process chain for manufacturing a large hybrid tool using milling and selective laser melting processes. A large (745 × 174 × 78.7 mm) hot forming punch with conformal cooling channels was produced by splitting the tool into four sections to fit into the build envelope of the M2 cusing machine from Concept Laser GmbH. Various considerations and challenges are highlighted.

Keywords Conformal cooling · Punch · Hot stamping · Hybrid manufacturing · Process chain

1 Introduction

The conventional method of drilling cooling channels in hot stamping tools prolongs the cooling period for parts with complex features. At least 30% of the cycle time is spent during the cooling phase [1]. Many of the studies regarding the design of tools with conformal cooling channels focus on injection moulding tools and there is limited literature on the design procedures for hot stamping tools. According to the results of a study on the manufacturing of a cutlery drainer tool for injection moulding, the cooling time was reduced by 31% using a tool with surface cooling channels [2, 3]. The purpose of this paper is to investigate the design and manufacture of a large hot stamping tool with conformal cooling channels. The first section of the paper explains the hot stamping process and the conformal cooling design. Secondly, the details of the simulation are given. Thirdly, the manufacturing process

chain is described. This includes the challenges encountered during manufacturing and how they were resolved. Finally, the results of the tests on the conformal cooling tool are explained and compared with the conventional tool.

2 Hot stamping

The hot stamping process is necessary for the production of high-strength and low-weight components [4]. Thus the process is preferable in the manufacture of automotive parts due to the need for reducing fuel consumption and increasing safety [5]. The commonly used blank material is the boron-manganese steel (22MnB5) [6]. The hot stamping process can either be a direct or indirect process [6]. For the direct process, the steel blank is firstly heated in a furnace to 950 °C and transferred to a press where it is simultaneously formed and cooled [7]. The cooling medium circulating in the channels helps to extract heat from the tool system as shown in Fig. 1.

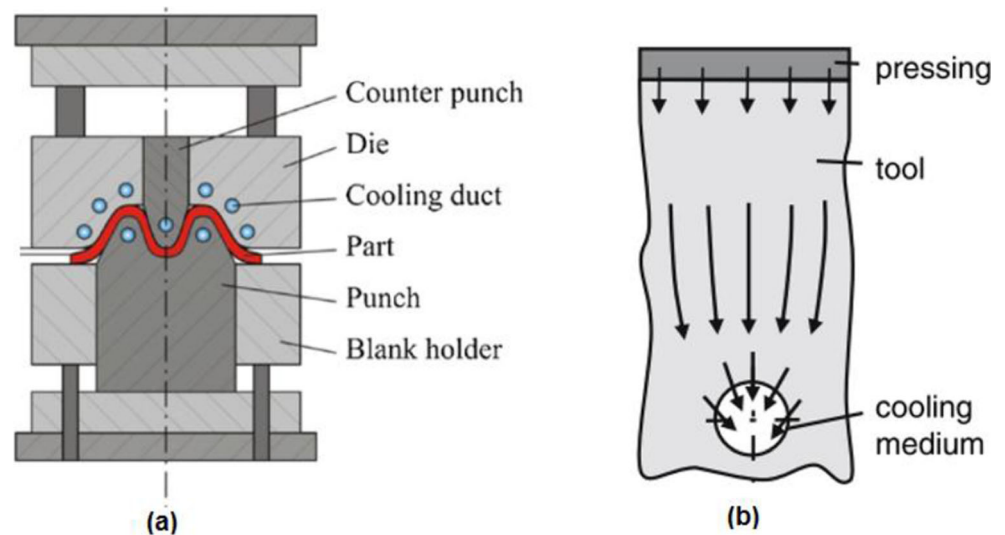
The cooling of the tools, usually performed at a rate above 27 K/s, causes the blank to develop a hard martensitic structure [6]. Thus, in hot stamping, cooling plays a vital role in controlling the quality (hardness) and cycle time. One major disadvantage of the hot stamping process is the complexity of the cooling system design [9]. The most commonly used method of producing the

✉ S. Matope
smatope@sun.ac.za

¹ Department of Industrial Engineering, Stellenbosch University, Stellenbosch, South Africa

² Fraunhofer Institute for Machine Tools and Forming Technology IWU, Chemnitz, Germany

Fig. 1 **a** Hot stamping tool [6]. **b** Heat flow to coolant in channels [8]



tools in industry is straight drilling [6]. Due to restrictions in machining, the straight channels cannot conform to the geometry of complex parts, causing inconsistent cooling. This prolongs the cooling time and leads to inconsistent hardness of formed parts. Thus, a lot of effort is put into research targeted towards developing of models for improving cooling system design [8, 10–14]. However, the challenge with the models is that they are difficult to apply in real life. Also, the problem of straight channels not conforming to part geometry is not addressed. On the other hand, additive manufacturing (AM) technologies such as a laser powder bed fusion (LPBF) have been successfully applied in the manufacture of conformal cooling channels to improve thermal management of production tools. This was mainly investigated for the injection moulding and casting industry and there is limited information on hot stamping [3, 15, 16]. Hot stamping is more challenging because of the forming loads and high temperatures involved. A case study on the manufacture of a hot stamping punch with innovative cooling channels using hybrid manufacturing is presented. Hybrid manufacturing is a combination of AM technologies with subtractive processes such as machining. In this case, selective laser melting (SLM), a LPBF process, is used because of its capability to produce near full dense parts with mechanical properties comparable to parts manufactured conventionally. Only the punch was considered for the conformal cooling design since its geometry makes it easier to apply metal-based AM processes in its manufacture. The details of the steps involved in the design of conformally cooled tools are beyond the scope of this paper.

3 Tool design and simulation

The punch considered for the study is shown in Fig. 2. The overall tool length required is 745 mm when used in the hot stamping process. The manufacturing and design processes

limit the use of the full tool as a single part. Thus, the tool is composed of four inserts with lengths of 225, 150, 150 and 220 mm respectively.

Hot stamping tools are usually segmented to allow easier drilling of the conventional cooling channels. Figure 3a shows the punch with straight drilled channels and Fig. 3b shows the one with conformal cooling channels. The model in Fig. 3b shows that the complex sections of the channels are occupying the top section of the inserts. According to the computer-aided design (CAD) model, the height occupied by the complex section is 15 mm. However, previous studies have shown that increasing build heights in the SLM process leads to increased residual stresses [17]. According to Mugwagwa et al. [18], residual stresses can lead to distortions, warping and cracking. Thus, there was a possibility of high stresses if the whole 15 mm height was to be built additively considering the broad width of the inserts (174 mm). Further analysis was done on the model to seek portions that could be machined. From the analysis, it was concluded that only 2.5 mm of the complex structure could be machined. This left a height of 12.5 mm which needed to be built with LPBF.

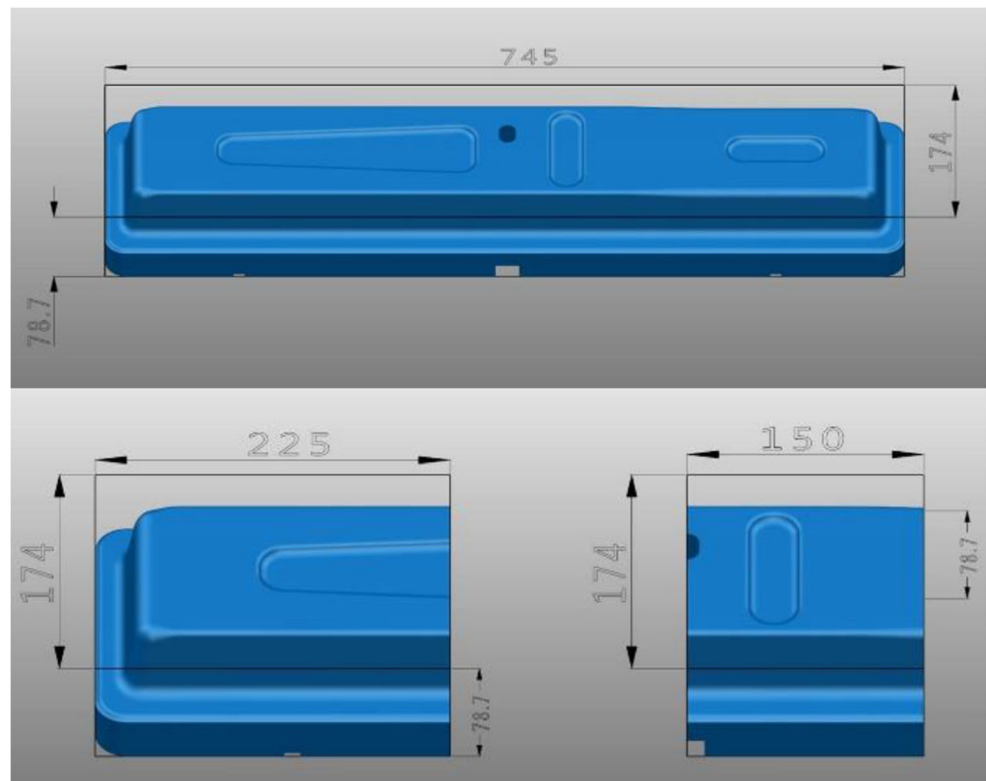
The next stage was to divide the model into two sections: the section to be machined (base body) and that to be built as shown in Fig. 3b.

3.1 Simulation

The conformal cooling system design was simulated to compare the performance of the two cooling systems layouts in Fig. 3. PAM-STAMP 2019 was used for the analysis because it can evaluate the cooling system design through temperature calculations [19]. Table 1 shows the simulation parameters used which depict real-life industrial operating conditions.

Based on the parameters in Table 1, the simulation is composed of two stages, namely, stamping and cooling. During

Fig. 2 Punch geometry of the whole tool compared with two sections of the divided tool



the stamping stage, the punch encounters the blank and die to perform the deformation. The blank is then held between the punch and die at different times of 2–8 s. This is done to measure the effect of cooling time on the conformal cooling layout. Figure 4 shows the temperature profile graphs obtained for the conventional and conformal cooling tool from the simulation software.

According to the graph in Fig. 4, the conformal cooling tool cooled the blank to an average temperature of 200 °C after 6 s. On the other hand, the conventional tool cooled the blank to an average temperature of 200 °C after 8.4 s. This translates to a 28.6% reduction in cooling time. The temperature map of the punch shows that the conformal cooling tool had a more uniform temperature distribution when compared with the conventional tool as shown in Fig. 5.

4 Tool manufacturing process chain for the conformal cooling tool

The tool manufacturing process chain encompassed five stages as summarized in Fig. 6. After the design and simulation step, the CAD geometry for the base body section was used to develop the CAM program for machining the base parts. The next step was to drill the straight part of the cooling channels using a 5 mm TiN-coated carbide drill bit on a 3-axis DMG Mori DMU 65 monoblock milling machine. As seen in Fig. 3, one side of the cooling channels was angled to conform to the shape of the part. Thus, a Hermle C40U 5-axis milling machine was used to drill the angled holes. This process could also have been performed on a 3-axis machine with an angled vice.

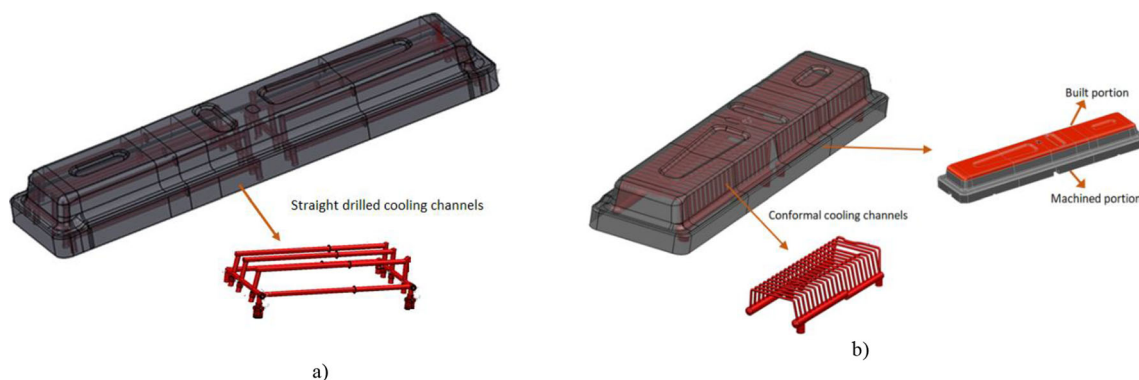


Fig. 3 Punch geometry showing **a** straight drilled cooling channels and **b** conformal cooling channels

Table 1 Simulation parameters

Symbol	Parameter	Description
C_b	Specific heat capacity of blank (C_b)	650 J/kg °C
h_c	Heat transfer coefficient	3300 W/m ² °C
L	Thickness of blank	0.0015 m
T_b	Initial temperature of blank	800 °C
$T_{b(t)}$	Targeted blank final temperature	200 °C
T_d	Initial temperature of tool (punch and die)	25 °C
P	Density of blank	7830 kg/m ³
T_w	Initial temperature of coolant	20 °C
	Blank material	22MnB5
	Tool material	H13 tool steel
v	Forming speed	200 mm/s
	Shell type	Quadrilateral shell elements
s	Forming distance	40 mm
F	Press force	100 KN

Figure 7 shows the process of building the top conformal cooling section of the inserts using the laser powder bed fusion process.

The machining was done with an overdraft of 1 mm right round and up to the parting line height. This was performed to allow for final machining after the build process and to give room for any distortion that would occur. The parts were machined and positioned in the SLM machine. The top level of the part was positioned in line with the powder coater to build the top segment as shown in Fig. 7b. To increase fusion of the powder to the base parts during the builds, the inserts were initially sand blasted before building the top section to increase the surface roughness. In order to avoid overheating

the top surface of the part and causing it to become brittle, only two exposure scans were performed for the initial layer.

Various challenges arose during the manufacturing of the tool. As the number of processes increased, so did the complexity of the process chain. The design phase was the most challenging, as a balance had to be struck between the various processes and the process capabilities. The limitations of the LPBF process appeared to be the limiting factor with regards to the cooling channel design, tool segment size and tool heat treatment. The heat treatment process is complex and adds additional steps to the overall procedure, since the tool base and additive section are made with different, but compatible materials. Two heat treatment steps had to be followed: one

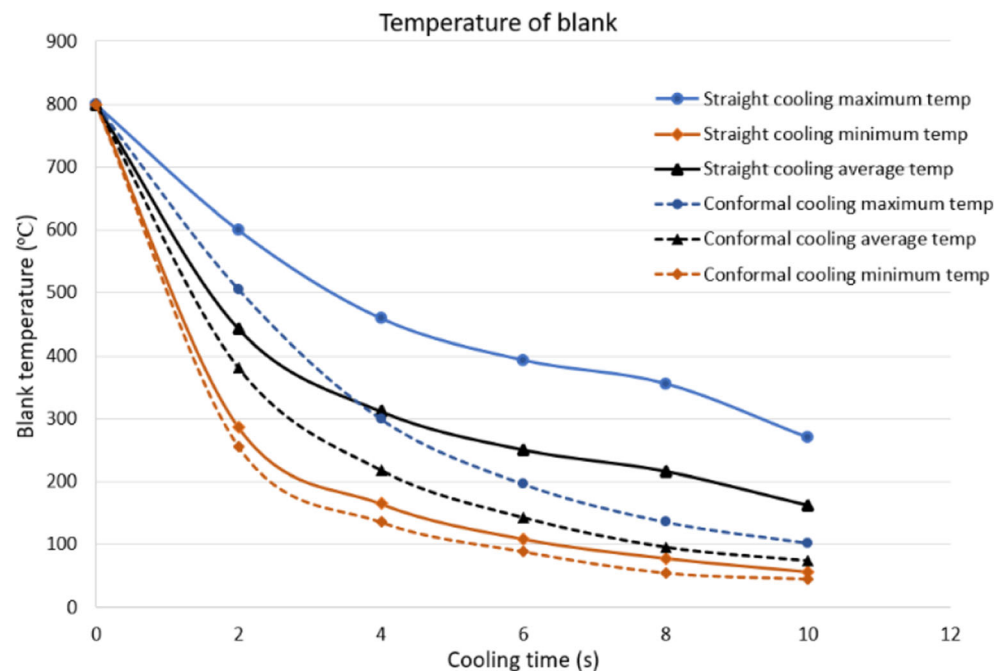
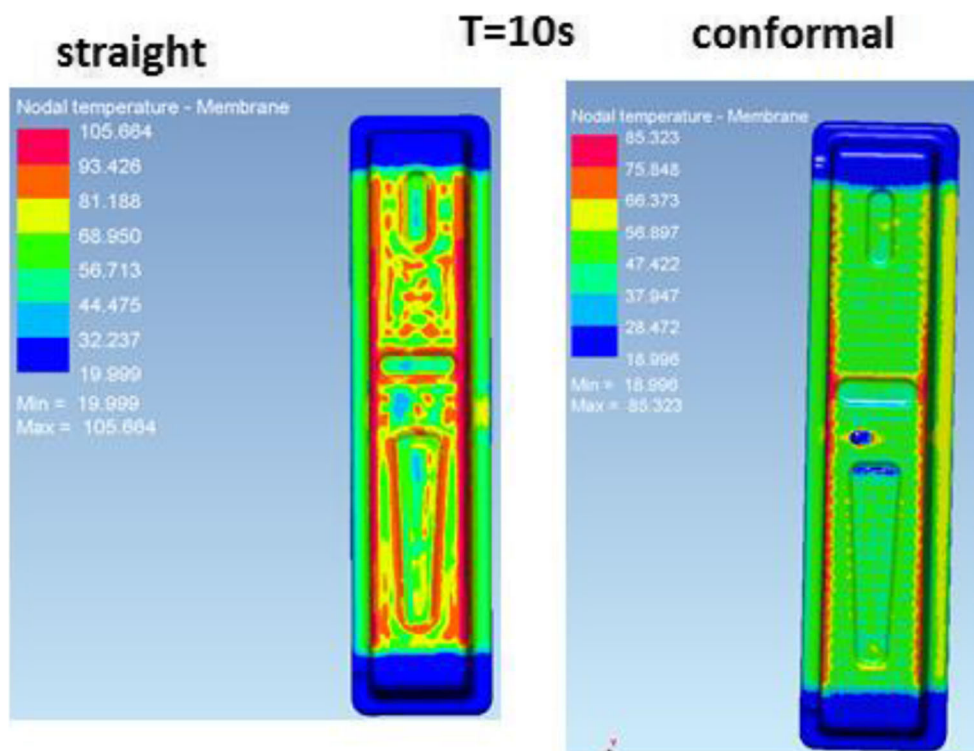
Fig. 4 Temperature curves for conventional and improved conformal tool

Fig. 5 Temperature map of (left) the conventional tool and (right) the conformal tool



for the base materials and one for the SLM material. This also added extra machining setups for skimming of the oxidation layer from the top of the base plate after initial heat treatment. This is done to avoid fusing the conformal cooling section to a compromised top surface of the base part.

Other challenges that surfaced during the manufacturing of the tool include lining up the physical base plate to the digital model for the SLM process. Although substantial stock material (1 mm) was added to the outside surfaces of the tool for machining, the cooling channels cannot be easily machined after

the SLM process. So, the cooling channels need to be lined up properly before building commences. It is crucial that precision grinding be performed on the bases and mating areas of the tool after the additive manufacturing process. Failure to do this results in the tool channels and tops not lining up on final assembly of the tool. This step is also very important for the proceeding machining process. The final finishing of the tool had to be performed on the entire tool setup on the milling machine. This was done to reduce any errors between the tool segments, and to assist with a consistent surface finish across the entire tool.

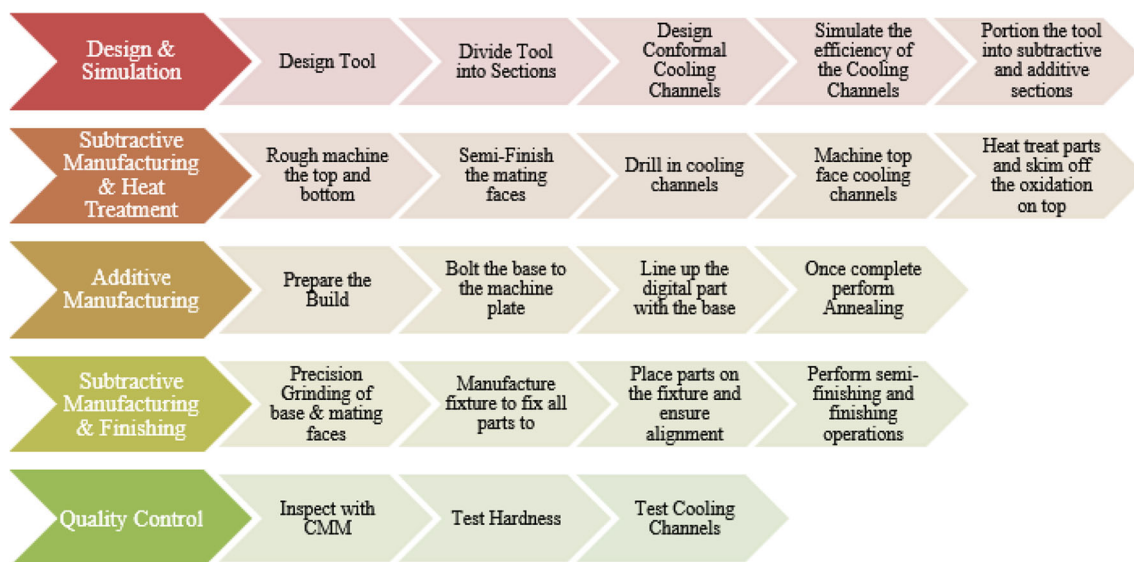
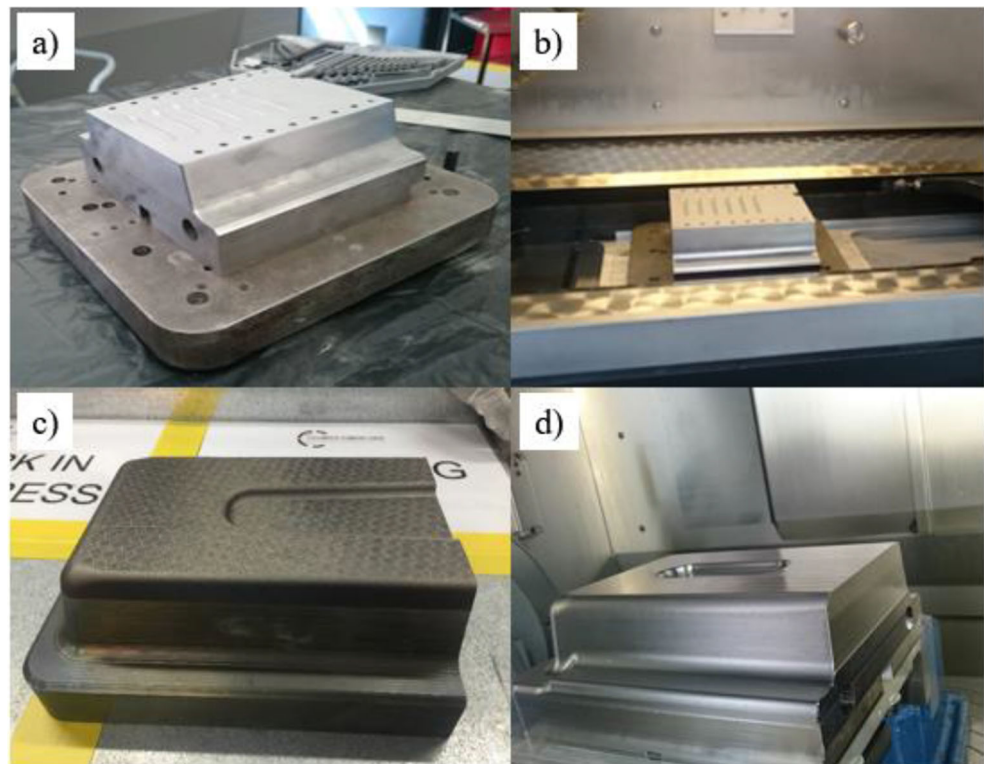


Fig. 6 Hot stamping tool with conformal cooling manufacturing process chain

Fig. 7 Process of building hybrid tool with **a** attaching base of insert to machine build plate, **b** fastening build plate to machine and loading powder, **c** hybrid part with grown conformal cooling channels after heat treatment and **d** machining the insert on CNC milling machine



5 Results from tool testing

Using the full factorial method of designing experiments, a total of 18 experimental runs were conducted in order to test the efficiency of the conformal cooled tool vs the conventionally cooled one. This involved two replicates, three levels of cycle time (2, 5 and 8 s) and three levels of coolant flow rates (11, 15 and 19 l/min). The blanks were each heated to 1000 °C for 10 min, transferred to the forming press manually for 10 s, formed and cooled for 2–8 s. Figure 8 shows the stages in the hot stamping process.

The measured blank temperature profile for the different cooling system layouts is shown in Fig. 9.

An infrared temperature gun was used to measure the blank temperature after the cooling stage. According to previous experimental results, the blank temperature should be 200 °C or less to attain the required hardness properties [12, 20]. According to Fig. 9, the conformal cooling tool cooled the blank to an average temperature of 163 °C after 5 s, which is acceptable since it is below 200 °C. Consequently, it was concluded that 5 s is enough to cool the blanks to the required specifications using the conformal cooling tool. No cracks or any other signs of damage were observed on the tool. For the conventional tool, the blanks reached an average temperature of 211 °C after 5 s. Accordingly, the conformal cooling tool caused an increase in the cooling rate by 9.6 °C/s in the first 5 s. Thus, the current cooling time of the blanks can be reduced from 7 to 5 s when conformal cooling is incorporated. This

shows the potential to reduce cooling time by 28.6%. The conformal cooling system allowed for the diameter of the cooling channels to be reduced and to increase their number as compared with the straight drilled system. This increase in cooling channels and reduction in diameter significantly contributes to the increased cooling performance.

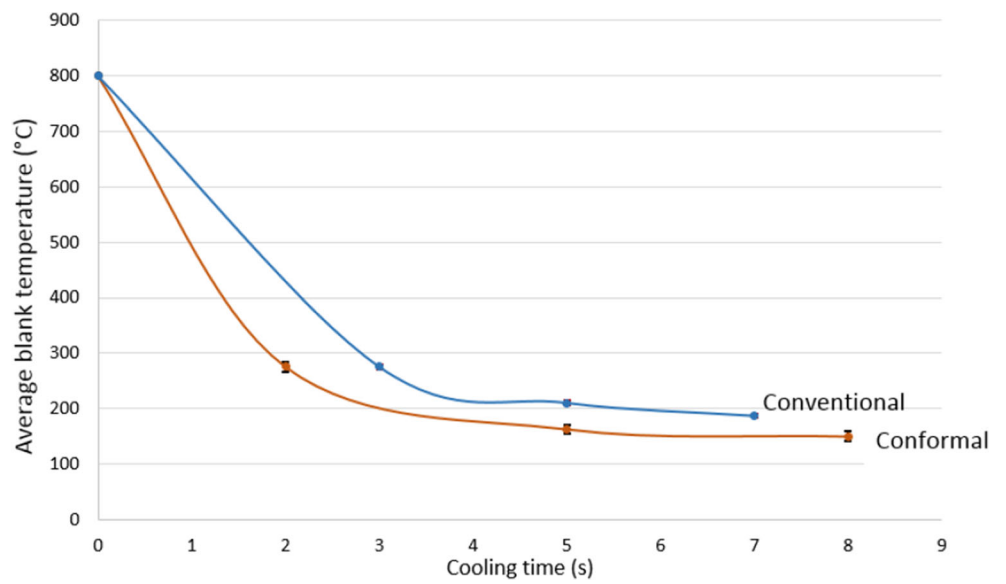
6 Conclusion

The paper presents a case study of manufacturing a large hot forming punch with conformal cooling channels using a combination of subtractive and additive processes. The first and second stages of the paper present the introduction and literature on the hot stamping process. The third stage of the paper presents the CAD model of the tool and the conformal cooling system layout. Only the top section of the tool cooling system has a complex geometric structure to minimise the manufacturing costs and issues. The fourth stage of the paper presents the simulation analysis to compare the cooling stage of the conformal and conventional tool. According to the simulation results, the cooling time of the blank can be reduced by 28.6% using the conformal cooling tool. A process chain for manufacturing the large hybrid tools was presented and the various considerations and challenges were highlighted. The final stage involved experimentation with the manufactured tool. According to the results, the cooling time can also be reduced by 28.6% using the conformal cooling tool. The

Fig. 8 a Developed punch tool on press setup. b Blank placed in furnace. c Blank retrieval. d Blank placed on press in forming position. e Blank formed



Fig. 9 Average blank temperature



manufactured tool was shown to withstand the high forming loads in hot stamping, since there were no cracks present on the tool after rigorous testing was performed.

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