GF Machining Solutions

Singapore Institute of Manufacturing Technology
SIMTech

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Additive Manufacturing

Metal AM for Mold and Die: Overcoming production challenges

Executive Summary

Additive manufacturing has gained popularity over the last decade but has limited impact leading to adoption in injection molding industries. The rise in additive manufacturing (AM) was accompanied with a common misconception that it will eventually replace traditional manufacturing processes. However, that is far from reality. In this white paper, Univac Precision Engineering Pte Ltd, a company specialising in tooling and molding assemblies, worked with Singapore Institute of Manufacturing Technology & GF Machining Solutions Pte. Ltd to leverage the remarkable benefits of additive manufacturing and harmonise with traditional manufacturing in a full end-to-end AM workflow to produce high-quality tooling inserts at a lower cost and shorter lead time.

Introduction

Additive Manufacturing (AM) has been gaining attention, driving innovation in supply chains with sustainable net-shape manufacturing. The rise in AM corresponds to a worldwide shift towards industry 4.0 through enhanced system integration and intelligent technologies. The adoption of AM technologies has increased over the last decade in aerospace and automotive industries, mainly in the United States and European countries. On the contrary, AM original equipment manufacturers (OEMs) have struggled to penetrate the Asia market despite dedicated support from various government funding bodies. Majority of AM technology users in Asia originate from institutes of higher learning (IHLs) or research institutes, with technology readiness levels (TRL) in the low to medium range. Although a handful of precision engineering companies were successful in integrating AM into their production workflow, majority of the business stakeholders are still skeptical about the benefits AM can offer to the global supply chain. The lack of long-term awareness and fixation on traditional manufacturing is responsible for the limited adoption of AM in Asia. The benefits of AM have been well documented and publicised over the years, however, AM equipment manufacturers continue to struggle to convince traditional manufacturers to adopt these advanced technologies in their production workflow.

Injection molding is one of the most successful engineering technologies, with the ability to produce products within a short cycle time. Rapid, high-quality production was possible with the help of internal cooling channels that run through the pre-form, promoting efficient thermal cooling. The introduction of cooling channels using conventional machining methods generally consists of straight drill holes. Traditional fabrication methods such as Wire EDM or CNC milling may make navigating along complex channels difficult, eventually leading to non-uniform cooling and increased production cycle time.

AM overcomes these challenges and enables the production of molds with improved part functionality through design freedom. As such, subtractive manufacturing technologies no longer limit the incorporation of complex cooling channels in mold manufacturing. Recently, attention has also been drawn to the use of hybrid manufacturing to shorten the lead time for mold production via AM, a technique facilitated by precision alignment and laser referencing.

Univac Precision Engineering Pte Ltd (Univac), a company specialising in tooling and molding assemblies, values the potential opportunities that additive manufacturing could offer. Univac plans to expand its production capabilities by integrating AM into its manufacturing workflow to remain competitive in the industry. In the injection molding industry, tooling inserts were fabricated using maraging steel or heat-treated stainless steel with a hardness of approximately 50 HRC. High hardness is required to increase the durability of the inserts, while heat-treated stainless steel is preferred for products with medical applications. ASSAB Corrax had been Univac's preferred choice for heat-treated stainless steel due to its superior corrosion resistance and high hardness. Coincidentally, GF Machining Solutions Pte. Ltd (GFMS) – Singapore Institute of Manufacturing Technology (SIMTech) Joint Lab was developing the process parameters using ASSAB AM Corrax powders. This chain of events sparked the interest of Univac, GFMS and SIMTech to synergise their efforts for the industrial adoption of additive manufacturing technology for the injection molding industry.

This whitepaper aims to help companies understand how they can pivot towards AM to improve productivity and competitiveness. It also underlines how Univac seized the opportunity by collaborating with SIMTech (research institute of the Agency for Science, Technology and Research, A*STAR) and GFMS in its joint lab. Together, they worked on a solution that gels additive and traditional manufacturing technologies. This study presents case studies, parameter optimisation, material evaluation and performance evaluation of additive manufactured inserts with conformal cooling channels.

Figure 1 DMP Flex 350 and CUTAM 500 in GFMS-SIMTech joint lab

Design Freedom

Mold design with proper cooling channels improves cycle time and productivity in an injection molding process. Limited by the current state of subtractive manufacturing technologies, cooling channels created using straight drilled holes causes hotspots in the cavity region, leading to non-uniform cooling during injection molding. As a result, production costs increase as products produced often have a high volume of defects and rejection rates during quality inspection. The maturing of AM technologies could help to overcome these limitations. Leveraging design freedom in AM enables the fabrication of tooling inserts with conformal cooling channels. Mold designers are equipped with the correct tools to create cooling channels with equal distance from the surface of the cavity by tracing along the contour or shape, as seen in Figure 2. As such, cooling efficiency can be improved which reduces cycle time and rejection rates.

Another critical advantage of design freedom in AM lies in the flexibility of the shape of the channel. Dynamic cross-sectional shapes enable cooling lines to run along challenging regions in a tooling insert, which were once limited by subtractive manufacturing (circular shaped). Although the use of circular channels promotes design convenience, it results in irregular distances from the insert surface as seen in Figure 3. Designing optimised channels such as elongated channels supports better heat transfer. An elongated channel has a higher surface to cross-sectional area ratio than a circular channel for a constant cross-sectional area. The increase in the surface area further improves the heat exchange properties of the cooling channel. Here, mold designers from Univac took advantage of the design freedom in AM and redesigned the shape of a cooling channel to fit into a thin-walled region of a tooling insert, estimated to be 5 mm in wall thickness (Figure 4). The cross-sectional areas are kept constant to prevent flow braking effects.

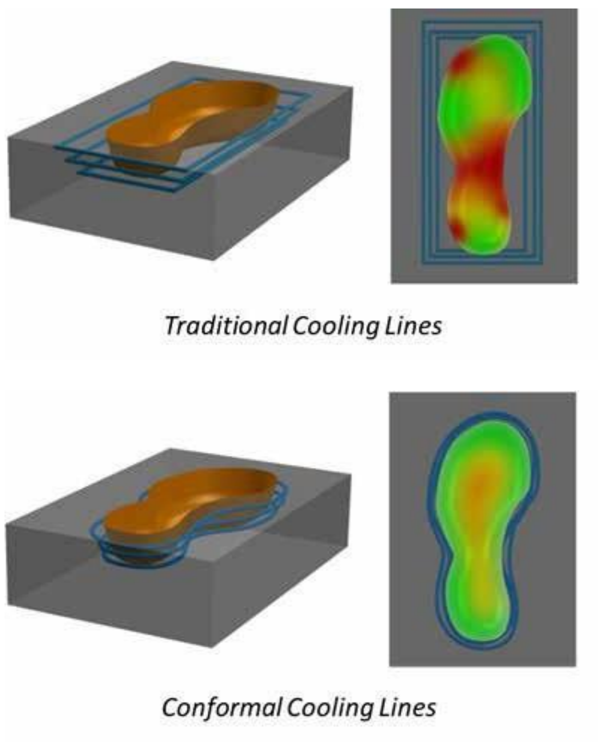


Figure 2 Illustration of traditional and conformal cooling channels[1].

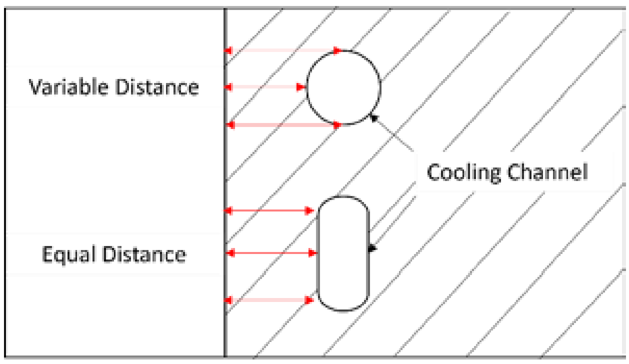


Figure 3 Illustration showing the distance from the insert surface for a circular and elongated cooling channel.

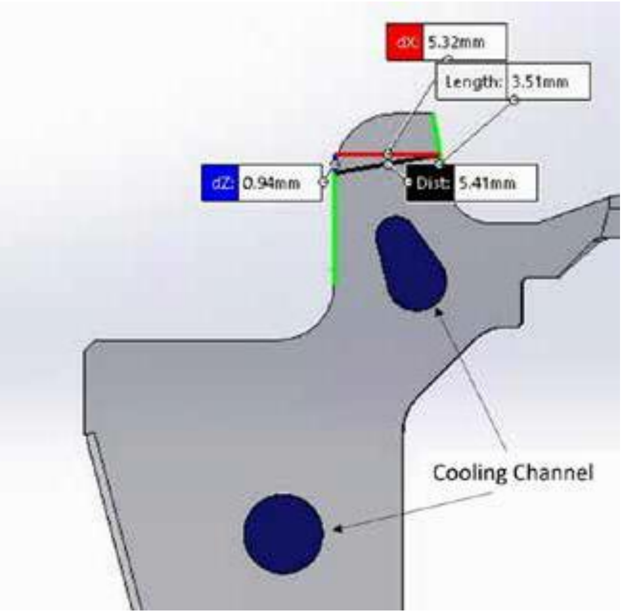


Figure 4 Application of design freedom in a thin-walled region.

A general practice in designing traditional cooling channels includes spacing a diameter's length between other channels and surfaces. However, such guidelines were applicable when channels were circular. We adapted the traditional approach to suit the ever-changing cross-sectional shapes for additively manufactured conformal cooling channels. In most applications, we tend to change shapes between circular and elongated channels, as illustrated in Figure 5. It is crucial to ensure that the cross-sectional area of the channels is consistent throughout the insert to prevent excessive build-up in resistance and void formation.

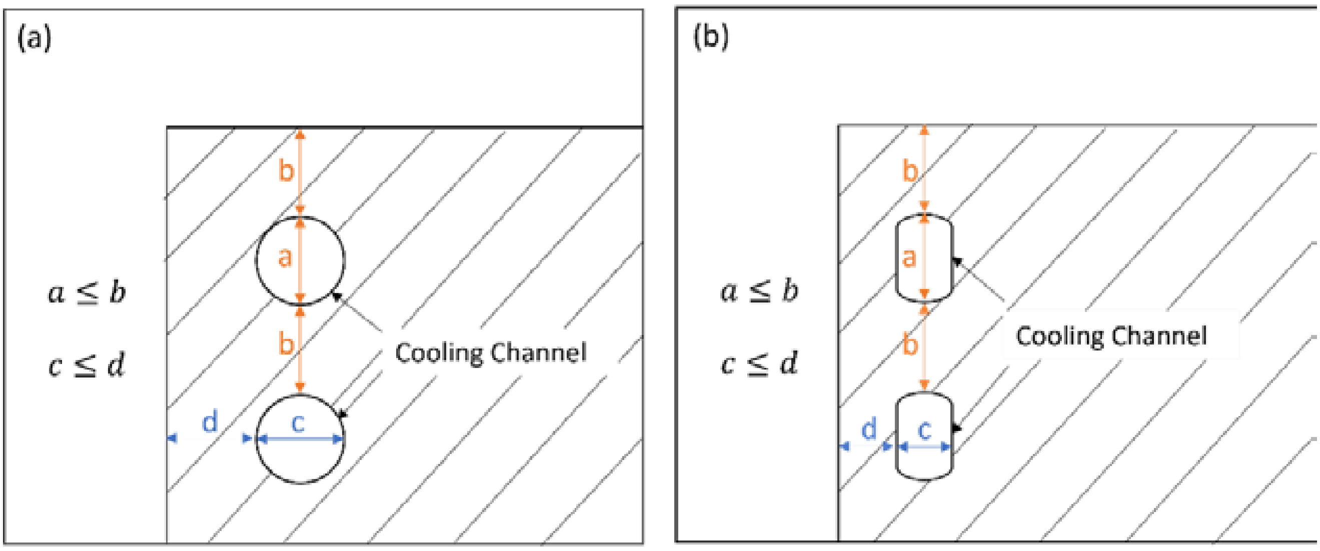


Figure 5 Illustration shows the general guidelines for designing circular and elongated channels.

Simulation

A critical part of the AM workflow, simulation helps address manufacturing problems before production. Designers use simulation software to evaluate and improve the cooling efficiency of the channels (Figure 6). The simulation software quickly identifies issues in the design, such as potential hotspots, shrinkage, warpage, or weld lines. Using simulation to evaluate the conformal channels minimised the need for reworking or modification at the later stages.

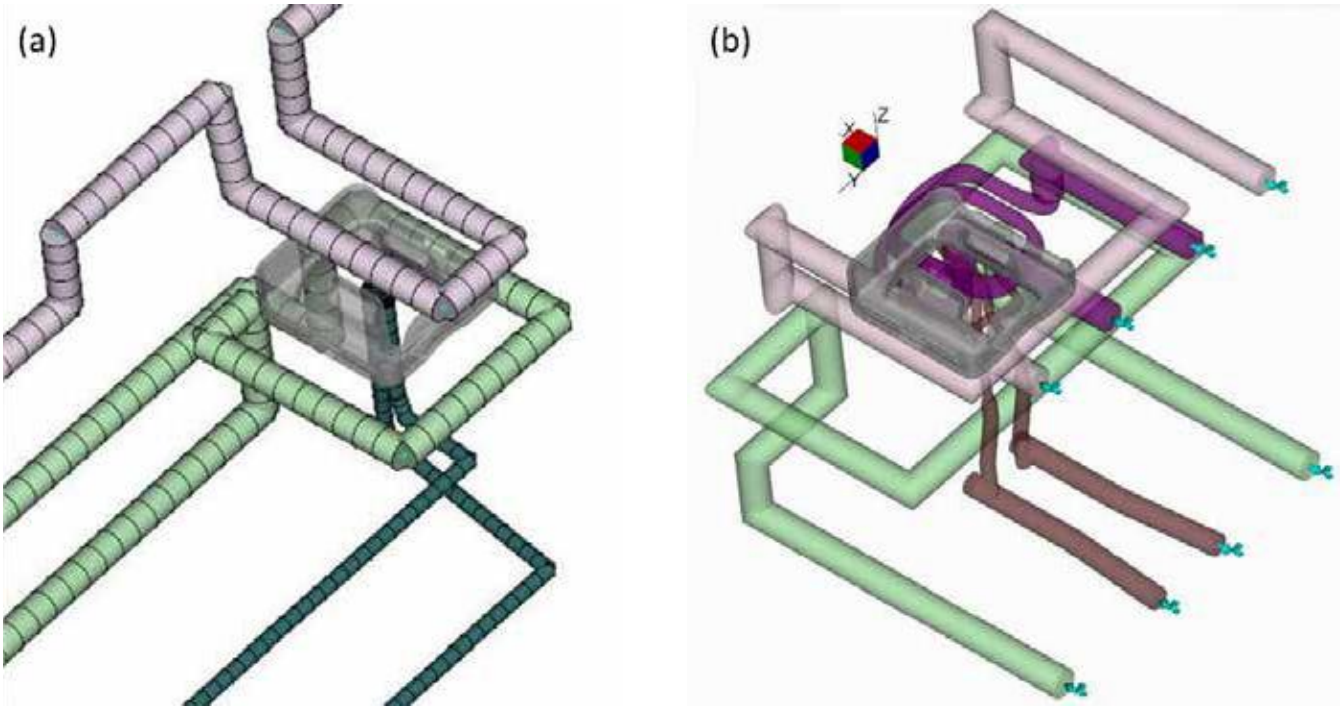


Figure 6 Layout of the cooling channels for (a) conventional and (b) conformal cooling systems in Moldflow simulation.

In this paper, we performed simulation work using Moldflow®simulation software to evaluate the performance of the tooling inserts. It accurately predicts the cooling efficiency, average product temperature, and potential hotspots that could cause defects. In Figure 7, we observed a hot spot region near the runner of the insert, with temperatures up to 94.56°C before the use of conformal cooling channels. The temperature was reduced to approximately 92.76 °C after using conformal cooling channels.

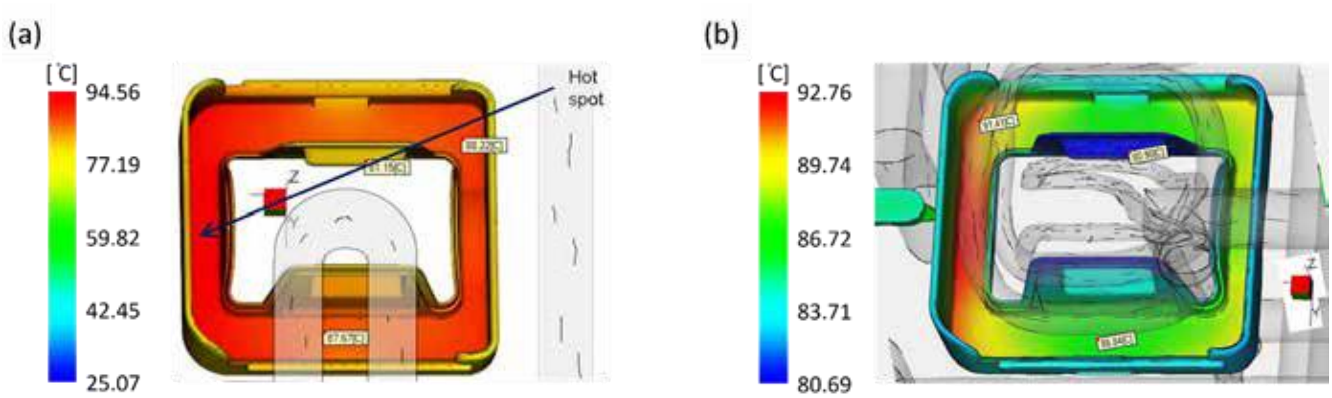
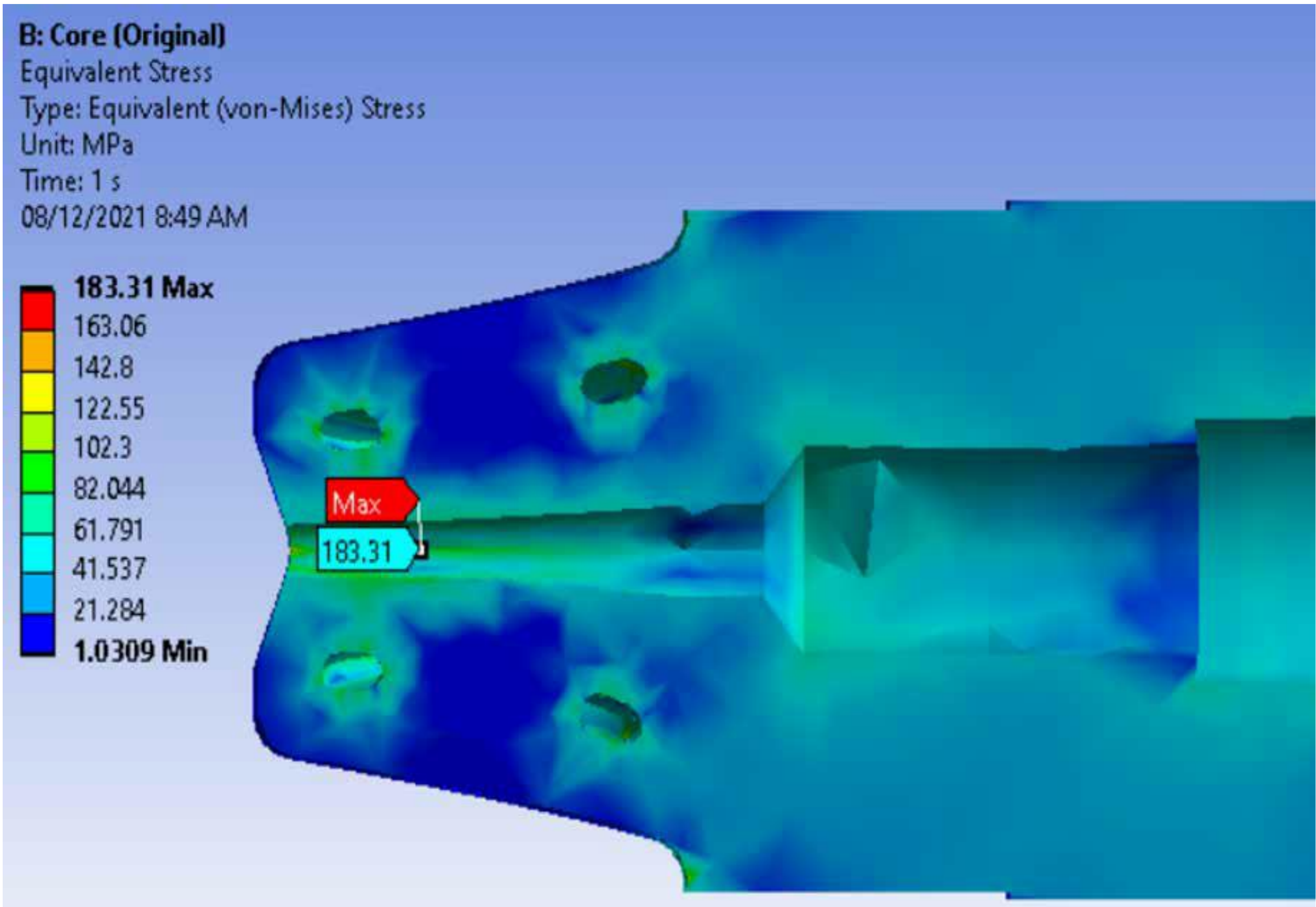


Figure 7 Temperature plot from the Moldflow simulation.

Further simulation analysis shows that the difference in the temperature gradient during the injection moulding process was significantly reduced from 69°C to 14°C with conformal cooling channels. The overall operating temperature of the mould was reduced with the use of inserts that has conformal cooling channels. It enabled the mould assembly to reach its overall equilibrium temperature faster, with improved product quality and a lower rejection rate.

To prolong and understand the lifetime of the tooling inserts, we also performed simulation work using Ansys to predict the mechanical stresses due to cyclic loading during its operation. It gives us confidence in the life cycle of the tooling inserts. For example, the maximum tensile strength of ASSAB AM Corrax is approximately 1600 MPa. For it to withstand a fatigue cycle of 1 Million cycles, the Von Mises stress should not exceed 40% (640 MPa for this case). In Figure 8, we observed that the simulated maximum stress was 183.3 MPa which falls well below the allowable stress.

Figure 8 Von Mises plot from Ansys simulation.



Process Development

A key objective of the SIMTech-GFMS partnership focused on the process development of new materials for its industrial AM equipment, DMP Flex 350. Univac's interest in ASSAB AM Corrax metal powder presents a fantastic opportunity for process development and ready end-user demonstrators. ASSAB AM Corrax is a grade of stainless-steel powder from ASSAB Singapore, a distribution network for Uddeholm, known to have superior corrosion resistance and high hardness. It is suitable for injection molds in demanding applications such as medical parts or corrosive plastics. The process development study consists of powder qualification, process window development and build validation.

Qualification of powders remains an integral part of AM process workflow. Leveraging on SIMTech's materials evaluation facilities in A*STAR's Additive Innovation Centre (AIC), the ASSAB AM Corrax powders received from ASSAB were evaluated following guidelines set by interna- tional standards. The results were benchmarked against ASSAB AM Corrax's material datasheet to ensure consisten- cy across various powders. Here, we observed that most data falls within the specifications in the material datasheet (Table 1). The powders were also examined under a scanning electron microscope (SEM) (Figure 9) to evaluate their shape and size.

	Test Method	Measured	Reference
Apparent Density (g/ cm³)	ASTM B212	3.9306	4.3
Tapped Density (g/ cm³)	ASTM B527	4.505	4.7
Flow-ability (s/ 50g)	ASTM B213	19.81	N/A
Particle Size Distribution (µm)			
D10	ASTM B822	24.468	25
D50		33.858	38
D90		48.083	53

Table 1 Characterisation data of ASSAB AM Corrax powders.

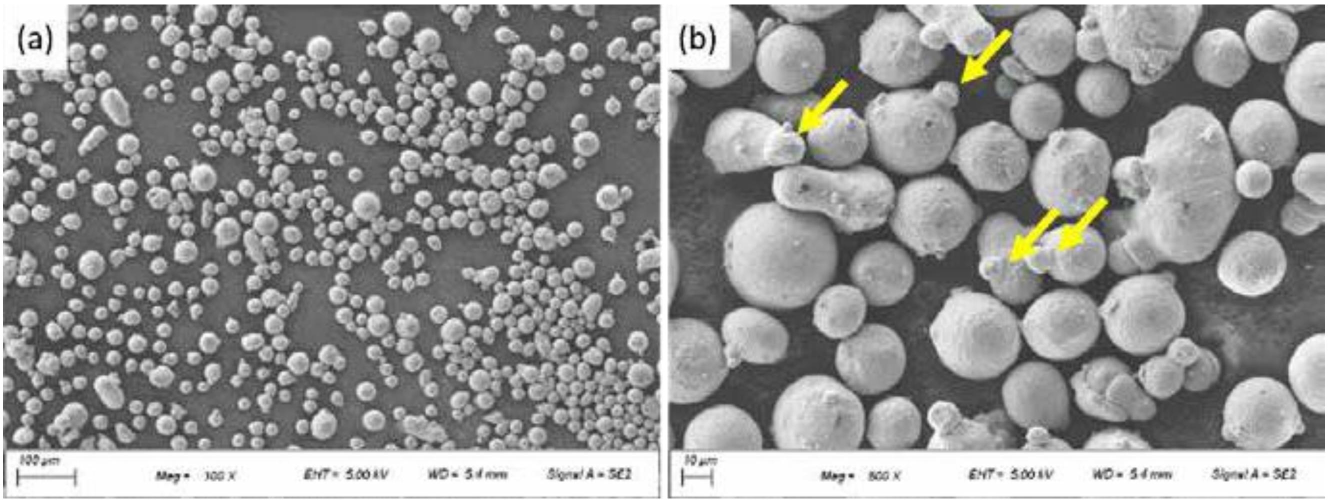


Figure 9 SEM image at (a) 100x and (b) 500x, showing the excellent distribution of spherical particles with a small number of satellites (indicated with arrows).

In the second part of AM process development, the aim is to identify a suitable process parameter. The combination of four critical parameters determines if the process parameter is suitable: (1) laser power, (2) scan speed, (3) hatch spacing and (4) layer thickness (LT), as shown in Figure 10. Density cubes, each with a unique process combination, are printed, and cross-sectionally examined using an optical microscope. Such an examination method is the most straightforward approach commonly practiced in the AM industry. 3DXpert has streamlined the process development stage with the laser and build style function to cater for research and development. This additional feature allows the process parameters to be populated automatically, reducing the risks of human errors.

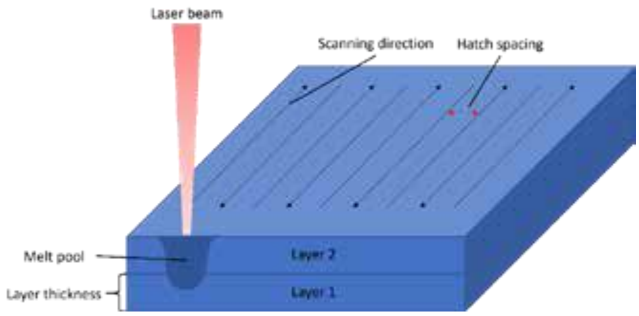


Figure 10 Schematic diagram illustrating the laser scanning process.

This study developed parameters for test cubes with 30 µm (LT30) and 60 µm (LT60) layer thickness while having a constant hatch spacing of 100 µm (Figure 11). The laser power and scanning speed were varied for the array of test cubes.

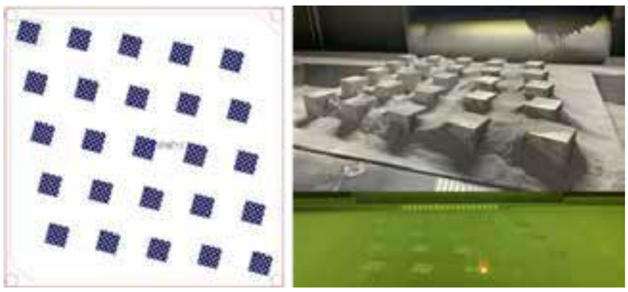


Figure 10 Schematic diagram illustrating the laser scanning process.

Process windows with up to 99.99% density can be observed at 30 µm (LT30) and 60 µm (LT60) layer thicknesses. A closer examination of the microstructure shows that most of the pores are spherical and small, with a low number of larger pores that can be identified as either hydrogen-induced or keyhole pores (Figure 12 and Figure 13). In this study, the optimised parameters can build parts with 99.9% density with pores not measuring more than 14 µm. Most importantly, no lack of fusion pores was detected, which often arise from insufficient energy input.

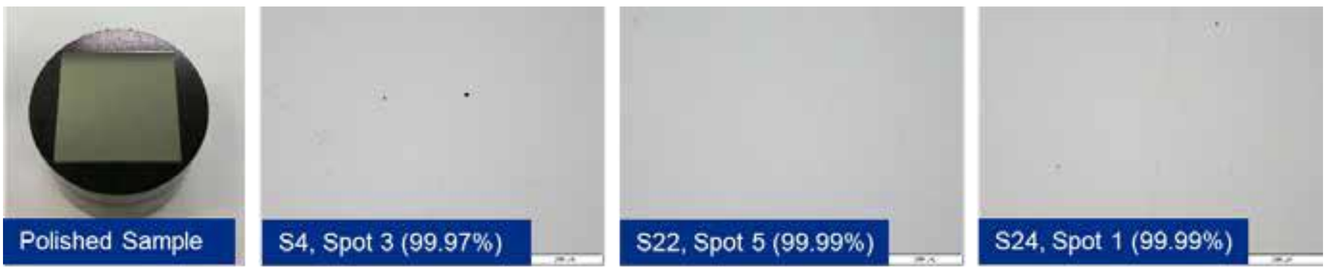


Figure 12 Optical microscope images of an LT30 polished sample at 100x magnification.

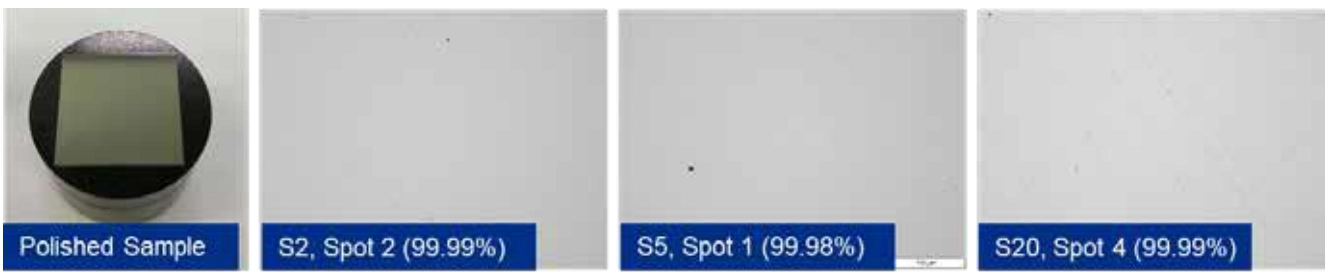


Figure 13 Optical microscope images of an LT60 polished sample at 100x magnification.

The final phase of process development covers the build validation step using the process parameter identified in the earlier part for LT30 and LT60 (Figure 14). The build configuration follows the guidelines recommended by GFMS. It helped to ensure printing consistency across the entire build plate, reducing the chances of failure or defective parts. In a typical build validation, these are the physical properties evaluated: (1) density, (2) hardness, (3) tensile strength, and (4) surface roughness. In addition to as-build properties, thermal-treated properties were also evaluated. It is an essential data set as tooling manufacturers may require additional thermal treatment processes to achieve improved tensile strength and optimised hardness for specific applications. A summary of the physical properties is shown in Table 2.

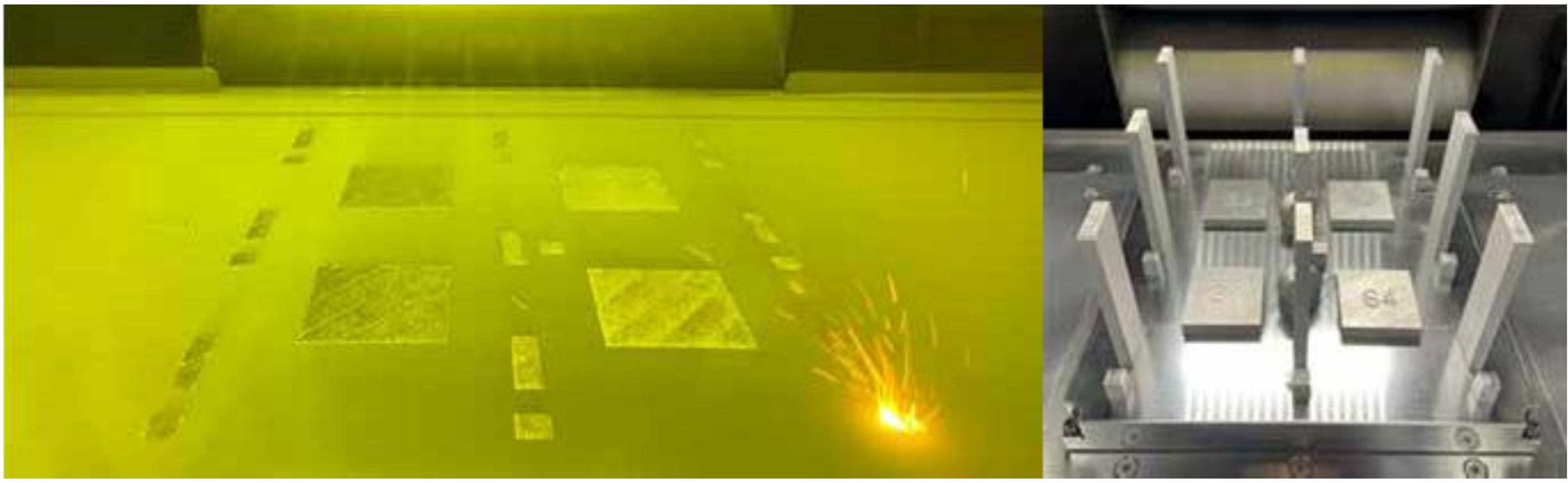


Figure 14 Build validation during printing in DMP 350 (left) and after powder removal (right).

	Test Method	ASSAB AM Corrax		LT30		LT60	
		As-Built	HT[1]	As-Built	HT[1]	As-Built	HT[1]
Ultimate Tensile Strength (MPa) **Vertical direction – Z**	ASTM E8M	1150	1700	1150	1700	1150	1700
Yield Strength (MPa) **Vertical direction – Z**	ASTM E8M	760	1600	760	1600	760	1600
Plastic Elongation (%) **Vertical direction – Z**	ASTM E8M	16	10	16	10	16	10
Vickers Hardness (HV)	ISO6507-1	320	505	320	505	320	505
Surface Roughness (Ra | µm)	ISO4288	-	-	-	-	-	-
Density (%)	-	-	-	-	-	-	-

[1] HT: Heat-treated condition recommended by ASSAB.

Table 2 Physical properties of as-build and HT ASSAB AM Corrax.

Based on the results, we could obtain build parts with mechanical properties close to the material database provided by ASSAB. The as-built LT60 has a slightly higher yield strength than the LT30. It is possibly due to the difference in energy density for both layer thicknesses. A change in the energy density could slightly influence the metallurgical microstructures and mechanical strength. It is worth noting that the mechanical strength for LT 30 and LT60 was similar after the heat treatment process to increase their mechanical strength and hardness.

Process Innovation in an AM Workflow

Convincing potential end users to adopt AM is no longer about technology validation or verifying printing feasibility. More often than so, business leaders search for suitable business models in this capital-intensive process. The focus has shifted to adopting AM, considering pilot production of additive manufactured components. Companies are re-evaluating the benefits of AM on the printing process and a broad range of other competencies along the entire end-to-end AM process chain. Unlike traditional mold production methods, which at times may take up to weeks, AM provides the ability to turn around a tooling component quickly in response to an urgent shortage of material or late change in mold design. Here, Univac demonstrates the ability and adopts the AM workflow in its manufacturing process with two ready case studies on mold production: (1) Full-built (FB) and (2) Hybrid-built (HB) manufacturing.

The full-built inserts shown in Figure 15 are additively manufactured using GFMS's direct metal printer, DMP Flex 350. Oxygen content must be controlled during process printing in most industrial AM components to ensure excellent and consistent part quality. Most commercial metal 3D printers introduce argon gas into the process chamber to reduce the oxygen level down to 1000 ppm. DMP Flex 350 redefines oxygen control in AM by delivering an oxygen environment of fewer than 25ppm (as low as 5ppm). An engineering feat featuring a combination of the full-piece metal casting of the chamber and advanced process control.

Once the printing process was completed, instead of using conventional separation methods such as band saw, the full-built inserts were removed using GFMS's AgieCharmilles CUT AM 500. The latest Electric Discharge Machining (EDM) innovation is a game changer compared to other separation techniques, offering three to four times faster cutting rates and requiring smaller cutting width (less material wastage) while retaining part integrity. The CUT AM 500 is essential to the manufacturing process and complements the technologies in the end-to-end AM workflow.

Figure 15 Ready demonstrator of a cavity and insert build in DMP Flex 350 in full-built.

Process Innovation using Hybrid Manufacturing

Additive manufacturing enables design freedom and optimisation of conformal cooling channels, offering companies a competitive advantage as it improves cycle time through thermal cooling efficiency. It holds another critical advantage in hybrid manufacturing, combining additive and subtractive manufacturing to improve the manufacturing process. Hybrid manufacturing synergies the advantage of additive and subtractive manufacturing to reduce production costs and lead time.

There are two main segments in hybrid manufacturing; it starts with machining a steel block to produce a pre-formed insert with through holes, as seen in Figure 16. The pre-formed insert was designed with an external fixture secured to the build platform, preventing it from shifting during printing. The subsequent process creates a new set of challenges. The difficulty in hybrid manufacturing was to ensure precise alignment of the pre-formed insert to the build coordinates in the metal printer. A minor shift in the alignment may cause the metal printing to fail abruptly, possibly due to localised stresses and, most importantly, causing the cooling channels to be out of alignment.

To overcome this challenge, GFMS has developed a highly reliable laser referencing system for this purpose. It was achieved by calibrating the laser output to the referencing holes introduced earlier, as seen in Figure 16. An advanced photoelectric technology compared the contrast in light reflection along the contour of the holes; DMP calibration software precisely locates the position of these referencing holes and determines the offset required. The accuracy of the alignment can be further improved by setting an offset threshold. In addition, hybrid manufacturing enables ease of part removal from the metal printer for post-processing, reducing the overall production lead time (Figure 17). An as-built insert will require 32 hours of printing and 4 hours to remove the part from the platform. In comparison, an insert fabricated using the hybrid method required 4 hours of machining and 14 hours of printing (Figure 18). Overall, the hybrid method reduced the lead time, from raw to rough finish, by approximately 50%. A closer look at the interface of the pre-formed and 3D printed part showed no visible delamination or defects (Figure 19). Good interfacial bonding between the pre-formed and the 3D printed part is crucial to ensure the performance of the insert. It could only be possible with precise control of the chamber environment and process parameters during fabrication.

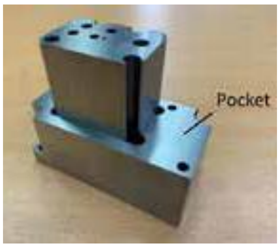


Figure 16 Tooling pre-formed with precision through holes for alignment.

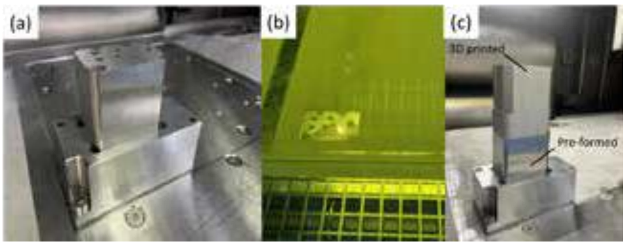
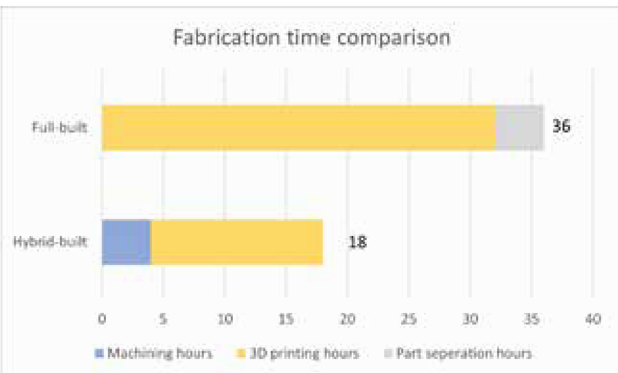


Figure 17 Images of the tooling at various stages of hybrid printing (a) mounting of the pre-formed, (b) 3D printing of the part on top of the pre-formed, and (c) the completed part.

Figure 18 Fabrication time comparison between full-built and hybrid built.



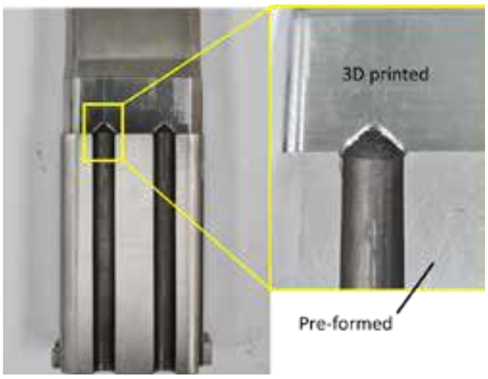


Figure 19 Image of hybrid-built insert after rough machining with an enlarged interface region.

Post Processing

The surface profile of the 3D printed tooling insert is uneven. The rough surfaces on the internal walls of the cooling channels could potentially encourage improved heat exchange. On top of a larger contact area, having a rough surface could also create turbulent flow in the channels2. Such turbulent flow also increases the heat exchange and cooling efficiency while providing3,4 better mixing of the fluids in channel5.

The external surfaces of the tooling insert required machining and polishing to size. The machining operation is performed in two stages. A rough finishing was performed for higher material removal rate before trimming it down with high accuracy to its final dimensions. In this case study, the insert was machined using the Mikron MILL HSM 500 model with an accuracy of ± 5µm. Highly polished mirror finishes were required in injection moulding inserts. Any defect or porosity in the insert becomes highly visible at this stage, affecting the part quality. The polished tooling inserts were defect-free, demonstrating the reliability of the developed process parameters.

Test Bed

The inserts were machined, polished, assembled, and tested using DOE methods. Actual test data such as the cycle time and cooling time was collected and shown in Table 3. Significant reductions in both the cooling time (approx. 40%) and cycle time (approx. 25%) were observed. Based on the cycle time, the insert with conformal cooling channels could save 142 days for a production run that required 1 million cycles. It is an enormous cost and time saving for the operations. The use of conformal cooling channels has proven to eliminate hot spots and thermal non-homogeneity.

The ability to improve tooling insert performance using additive manufacturing has been repeatedly proven as an effective way to fabricate conformal cooling channels. It could reduce fabrication lead time, cooling time and part rejection rates.

	Cycle time (s)	% change	Cooling time (s)	% change
Traditional cooling channel	49.8	~25%	25	~40%
Conformal cooling channel	37.50	~25%	15	~40%

Table 3 Compares cycle time and cooling time for traditional and conformal cooling channels.

Conclusion and Future work

Solving the challenges faced by the injection moulding industry cannot be done by a single manufacturing process. Evaluating the complete workflow, from design to end product, is crucial to optimise the process. Fabricating tooling inserts with conformal cooling requires careful design to ensure a smooth fabrication process from design, simulation, build, machining, and polishing. Thanks to the many experts in multiple fields and processes, GF Machining Solutions were able to offer solutions to solve challenging issues in the industries. The use of conformal cooling channels has improved cooling efficiency and thermal uniformity. Furthermore, it has successfully reduced the cycle time and improved the part quality.

Applying additive manufacturing to the mould-making process is not without its challenges. There are still other areas where the companies can investigate to improve the workflow or provide a holistic and synergistic approach. There is a lack of guidelines regarding when a part should be printed in whole or via hybrid processes. Several factors affect the decision process, such as cost, residual stresses, and fabrication lead-time. Companies could also look at ways to improve efficiency in the alignment of printing and post-process machining to optimise the supply chain from printing to machining and assembling the injection moulds.

Reference

1. GPI Prototype & Manufacturing Services. Whitepaper: Conformal Cooling Using DMLS. (2012).
2. Valizadeh, K. et al. A parametric study to simulate the non-Newtonian turbulent flow in spiral tubes. Energy Science & Engineering 8, 134–149 (2020).
3. Xu, Y., Islam, M. D. & Kharoua, N. Numerical study of winglets vortex generator effects on thermal performance in a circular pipe. International Journal of Thermal Sciences 112, 304–317 (2017).
4. Fiebig, M. Vortices, Generators and Heat Transfer. Chemical Engineering Research and Design 76, 108–123 (1998).
5. Everts, M. et al. The Influence of Surface Roughness on Heat Transfer in the Transitional Flow Regime. in International Heat Transfer Conference Digital Library (Begel House Inc., 2014). doi:10.1615/IHTC15.cnv.008338.

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