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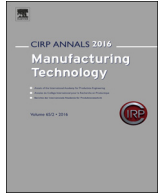
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Innovative grid molding and cooling using an additive and subtractive hybrid CNC machine tool



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ABSTRACT

An innovative injection mold making and cooling approach using a hybrid additive and subtractive machine tool is proposed in this paper. Approximated mold geometry is quickly formed using prefabricated blocks. Directed Energy Deposition (DED) followed by finish milling is then used to form the continuous free-form surface of the mold cavity. The innovative technique enables quick fabrication of a mold with a conformal cooling channel resulting in a dramatic improvement in cooling performance of the mold. A mold prototype was fabricated and the performance was evaluated compared to a mold fabricated by the traditional subtractive machining method.

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1. Introduction

Additive Manufacturing (AM) especially for metal applications such as Selective Laser Melting (SLM) and Directed Energy Deposition (DED) has gained a lot of attention recently in academia as well as industry. According to a CIRP keynote paper in 2016 [1], the AM market is worth more than \$4 billion and is expected to grow up to \$20 billion in 2020. Due to high expectations for AM technologies, substantial efforts have been made by many researchers. Kakinuma et al. studied the influence of powder characteristics on clad quality of Inconel 625 [2]. Paris et al. reported the environmental impacts of AM as compared to traditional machining processes [3]. Newman et al. introduced a new concept of process planning for additive and subtractive processes [4]. Choi and Chang studied characteristics of laser deposited H13 tool steel [5]. Choi et al. studied the effect of specific energy input on microstructure [6]. Moreover, Thompson et al. summarized recent trends, opportunities, considerations, and constraints with regards to AM design [1].

One potential application for AM technology is to manufacture plastic injection molds. An example is fabrication of so called conformal cooling channels in the mold using SLM, which can improve cooling efficiency [7,8]. Cooling is one of the most important design considerations for injection molding as it constitutes up to 75% of the shot cycle time for plastic part manufacturing [9]. Conformal cooling technology creates a complex cooling channel which cannot be made by traditional machining processes. However, there are some drawbacks in the SLM based manufacturing of a mold. Production time is one issue as it is necessary to build

the mold from scratch with a large number of layers each having a thickness of only a few microns. Adjustment after manufacturing is also impossible for SLM, so the mold must be fabricated from scratch to make changes, which is a time-consuming process.

While the AM process achieves near-net shape parts with minimal material waste, the parts typically require post-machining processes such as cutting and grinding to ensure accurate geometry and to produce a good surface finish. Multi-axis hybrid CNC machine tools that combine both additive and subtractive processes have emerged that can optimize the advantages and reduce or eliminate the disadvantages of each process. One of the most prominent advantages of such hybrid machines is the ability to switch between additive and subtractive operations at any time. However, very few studies have been reported to fully utilize the unique capabilities of the machine and develop novel applications due to the complexities of both the AM process and the machine itself.

This paper proposes an innovative grid based injection mold fabrication and cooling technique in order to study the great potential of a hybrid additive and subtractive CNC machine and to introduce a unique mold design methodology. The overall concept of the grid mold and cooling are discussed, and feasibility testing of the mold is performed by fabricating a prototype using a hybrid CNC machine tool and testing it compared to a traditional mold.

2. Grid molding and cooling

2.1. Overview of grid molding and cooling

Fig. 1 shows the overview of the grid mold concept. Instead of removing material from a block stock with milling or EDMing or building the mold up from powder stock using SLM, the mold cavity geometry is discretized into a grid and approximated by a collection of blocks. Each block has a cutaway as shown on the left

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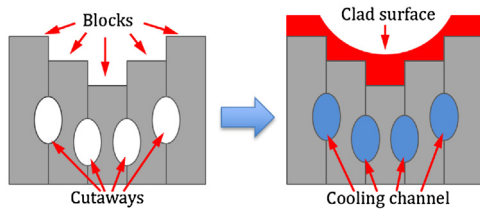


Fig. 1. Grid mold concept.

of Fig. 1, which may vary between blocks. By aligning these cutaway sections of each block, a cooling channel can be generated through the grid as shown on the right of Fig. 1. After assembly of the blocks within a frame, DED processes are applied to cover the blocks and frame to form a continuous surface. Finally, the mold surface can be finished by machining operations to achieve a smooth surface. In addition to quick formation of rough mold geometry by blocks, another advantage of the grid molding technique is that it can easily form a complex cooling grid through the entire mold to effectively remove heat from the mold during injection operations. Another benefit is that bi-metallic molds can be formed by using different materials for the blocks and clad surface. Easy to machine materials can be used for the blocks and frame for quick preparations while harder material can be used for DED on the surface to give better wear resistance. There are several key aspects to be studied in the grid molding and cooling approach. They include:

- Block design and standardization for production.
- Automation for rapid assembly.
- Additive process strategy and optimization.
- Residual stress analysis and control.
- Software development for design and automation.

Although all of these considerations are important to make this grid molding technique practical, this paper focuses mainly on a feasibility study of the grid mold design and fabrication method. Therefore, the objective was to fabricate the grid mold prototype, and test the performance of the mold compared to an existing mold created by traditional manufacturing methods.

2.2. Target mold design for prototyping

In this study, the mold cavity shown in Fig. 2a was used for prototyping. This is a mold used to manufacture a small plastic case by injection molding, and although the geometry of this part is mostly flat, the grid mold method is not limited only to flat geometries. The overall size is $180 \times 150 \times 35$ mm. Fig. 2b is a transparent view of the mold showing the existing coolant channel. Traditional mold cooling channels are typically made by drilling, thus the channel geometry and route are often limited. In contrast, cooling channels of the grid mold run through the entire volume of the mold, as shown in Fig. 3, and have much greater surface area for heat transfer. Depending on the cavity geometry, the position and size of the cutaway on each block can be easily adjusted to maximize the cooling efficiency. In the prototype design, two inlets and outlets were used to ensure flow throughout the channel. Wetted surface area of the cooling channel in the grid mold is 2.44 times greater than that of the traditional drilled cooling channel.

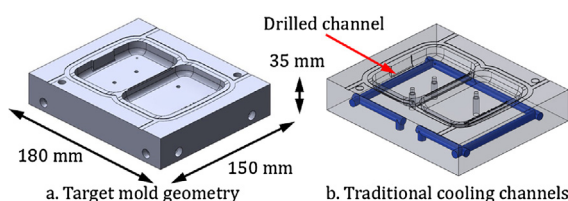


Fig. 2. Target mold geometry and drilled cooling channel.

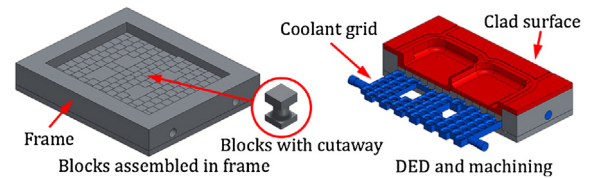


Fig. 3. Grid mold prototype design, partial section view.

2.3. Flow and cooling performance analysis

Simulations were used to qualitatively compare the cooling capacity of various cooling channel configurations. SOLIDWORKS Flow was used for this analysis. Steady state heat transfer simulations were run using a specified heat flux on the cavity surface. The heat flux was calculated as the amount of flux necessary to cool the part in the 32 s of cooling time from an injection temperature of 220°C to an ejection temperature of 60°C for polypropylene. Based on the mass of the part, this was calculated to be 213.28 W. Coolant inlets were given 0.35 MPa of pressure at 40°C , while the outlets were set to 0.26 MPa. The coolant conditions were selected to match parameters currently used with the traditional mold. Outer walls were considered adiabatic and drilled holes had a wall roughness of $1.5\ \mu\text{m}$. Material properties of P20 tool steel were used for the cavity. The final temperature contours of a cross section near the middle of the mold are shown in Fig. 4. It can be seen that the grid cooling channel has a much higher cooling capacity and more uniform mold temperature which should correlate with better part accuracy and uniformity. Simulation results are summarized in Table 1 showing the superior cooling performance of the proposed grid based mold.

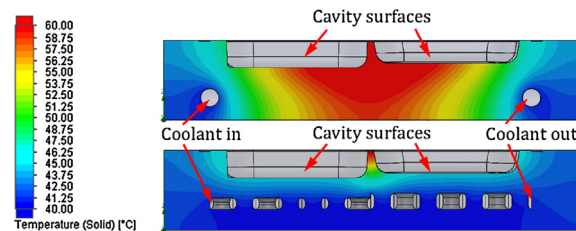


Fig. 4. Steady state cooling comparison of traditional (top) and grid (bottom) cooling channels, section view.

Table 1
Simulated steady state temperatures.

	Traditional	Grid mold
Thermocouple 1 avg. surface temp. [$^\circ\text{C}$]	57.6	44.1
Thermocouple 2 avg. surface temp. [$^\circ\text{C}$]	56.8	43.7
Cavity avg. volume temp. [$^\circ\text{C}$]	46.0	41.7

3. Grid mold manufacturing using hybrid machine tool

3.1. Additive and subtractive hybrid CNC machine tool

Since the grid molding technique requires deposition of metal layers on a pre-defined three-dimensional array of blocks, SLM or similar powder bed methods are not well suited to the application. In this study, a DMG Mori LASERTEC 65 3D was used for fabricating prototypes. The machine setup is shown in Fig. 5. This machine is a 5-axis hybrid CNC machine tool which enables both DED and traditional subtractive cutting to create complex metal geometry with a single machine setup. A laser head can be automatically exchanged as a tool in the spindle. Therefore, design changes and adjustments can be easily done at any time. This is a great advantage over SLM as SLM physically cannot add materials later to change and modify an already produced part.

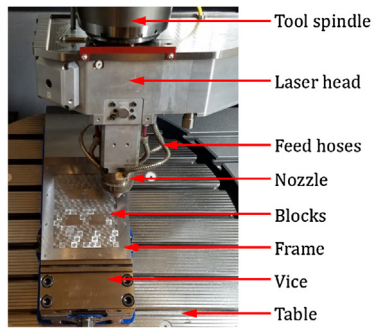


Fig. 5. Machine setup.

A disc type powder feeder system delivers metal powder from a storage hopper using argon as an inert carrier and shield gas. The powder stream is directed by means of an annular nozzle concentric with the laser into a conical formation around the laser, with the powder converging at a point 13 mm from the end of the nozzle. The laser creates a melt-pool on the substrate where the incident powder melts and builds up the surface.

3.2. Mold materials

Materials were chosen to achieve both good manufacturability and mold performance. Pre-hardened NAK55 tool steel was used for the blocks and frame of the mold. The material has a hardness of 40 HRC, but is easy to machine due to sulfite additive. H13 tool steel was selected as the clad material for superior performance as the mold surface. The H13 powder size ranged from 53 to 150 μm . Both NAK55 and H13 are commonly used to manufacture plastic injection molds.

3.3. Block discretization and assembly

A block discretization size of 10 mm square was used based on the geometry of the target mold. Cutaway portions of each block were turned down to a diameter of 7 mm in order to generate the cooling channel. Because the mold experiences over 50 MPa of pressure during injection, a static analysis was conducted to ensure adequate strength of the mold. In order to accommodate plastic injection gates and thermocouple instrumentation, several clusters of blocks were replaced with larger single blocks to prevent holes at those locations from intersecting with the cooling channel. In total, 145 blocks were assembled within the outer frame as shown in Fig. 6.

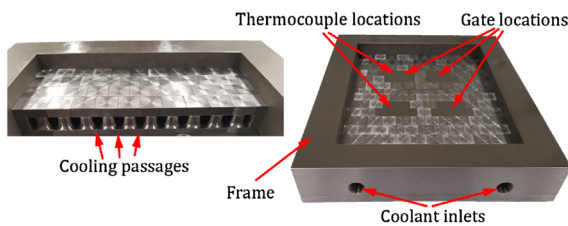


Fig. 6. Grid mold assembly before cladding.

3.4. Direct energy deposition

After the mold geometry is approximated with the blocks, DED processes are used to form a continuous surface with a near-net shape of the mold geometry. Deposition conditions were selected based on a preliminary study of a range of laser fluence values from 2 kJ/cm^2 to 13.3 kJ/cm^2 based on results from literature on laser deposition of H13 [5]. Laser fluence was calculated using Eq. (1), where F is fluence in kJ/cm^2 , P is power in kW, D is laser spot diameter in cm, and V is feed rate in cm/s .

$$F = \frac{P}{D \times V} \quad (1)$$

Tests were conducted for 3 different powder flow levels: 10 g/min, 15 g/min, and 20 g/min. Single line cladding tests were

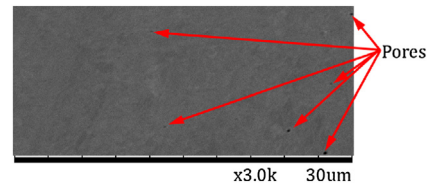


Fig. 7. SEM image of deposited H13 for selected cladding conditions.

performed then samples were sectioned and mounted for SEM examination for porosity and clad adherence. Conditions for selected samples were then used for surface clad tests, which were then also sectioned and mounted for SEM examination. The deposition conditions that were deemed to have produced the best clad in terms of porosity and layer height were chosen for use in the fabrication process. Fig. 7 shows a representative sample of the deposited H13 for laser power of 2000 W with feed rate of 550 mm/min, 10 g/min powder flow rate and 6 l/min carrier gas flow. A small number of micro pores were observed with an average size of approximately 0.4 μm and average porosity was calculated to be 0.3% by image processing.

Material was deposited on the mold substrate in a layer-wise fashion at a height of 1 mm per layer, with the orientation of each layer rotated 90° relative to the previous layer. A step over of 60% was used, corresponding to 1.8 mm based on a laser spot size of 3 mm. A deposition height of 16 mm from the lowest area of the mold substrate was desired for the top surface of the mold; however, an additional 2 layers were deposited in order to overbuild the part and ensure sufficient material for subtractive operations to be performed over the entire surface. The bottom side of the grid mold assembly required 8 clad layers. Fig. 8 shows the mold cavity after DED processes. Hardness of the H13 clad surface was found to be 57 HRC, which is equivalent to the hardness of heat treated H13.



Fig. 8. Grid mold after cladding.

3.5. Machining

Subtractive machining was conducted in several stages to maintain accurate part positioning throughout the material deposition process. After cladding of the top side of the mold, outer wall machining and top surface facing were performed to create flat surfaces for clamping and alignment during bottom cladding. After cladding the bottom side of the mold, outer wall machining and bottom surface facing were similarly conducted to create flat surfaces for clamping and alignment for finish machining of the top side of the mold. The completed mold cavity is shown in Fig. 9. Surface grinding operations were conducted

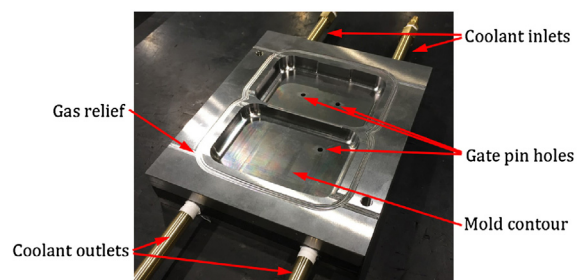


Fig. 9. Finished mold after machining.

prior to final assembly in the molding machine in order to produce flat and accurate faces for alignment of mating surfaces.

4. Plastic injection testing

4.1. Plastic injection and setup

Injection testing was conducted using the grid mold in order to assess the cooling performance as compared to the traditional mold. The injection test setup and plastic part produced by the mold are shown in Fig. 10. The plastic for this test was J-3021GA polypropylene, with an injection temperature of 225 °C at 52.5 MPa pressure and ejection temperature of 60 °C, with a total cycle time of 42 s. The core side of the mold used in this test had a traditional cooling channel created by drilling.

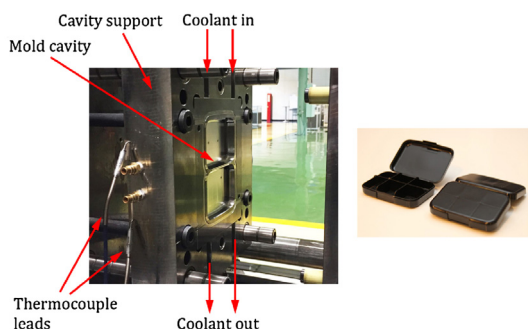


Fig. 10. Injection molding setup (left) and molded part (right).

4.2. Cooling performance

Temperature data was collected using 2 K type thermocouples placed 4.5 mm below the surface near the center of each pocket in the mold cavity. Readings were taken every 0.5 s while 100 shot cycles were run. Coolant at 40 °C was run with an inlet pressure of 0.35 MPa and outlet pressure of 0.26 MPa. Fig. 11 shows the thermocouple temperatures of the traditional and grid mold as 100 parts were produced, demonstrating a substantial reduction of both maximum temperature and temperature variation in the grid mold as compared to the traditional mold. As it can be seen, the temperature for the grid mold remained nearly constant throughout the test. Fig. 12 shows the thermocouple temperatures of each mold for a single injection cycle. Data used in Figs. 11 and 12 was taken only from one of the thermocouples, as the other thermocouple measured temperatures consistently 2 °C cooler in the traditional mold and 1 °C cooler in the grid mold, which indicates a more uniform temperature distribution in the grid

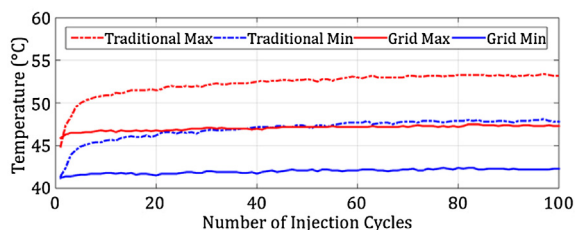


Fig. 11. Mold temperature for 100 cycles from cold start.

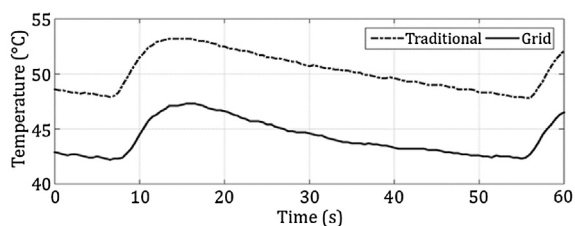


Fig. 12. Single shot temperature profile at steady state.

Table 2

Measured temperatures during injection test.

	Traditional	Grid mold
Max temp. [°C]	53.3	47.3
Min temp. [°C]	47.9	42.2
Max coolant delta temp. [°C]	13.3	7.3
% Reduction	–	45.1

mold. Table 2 summarizes the experimental data with temperatures reported as an average after steady state was achieved. The experimental results clearly show a remarkable cooling performance of the grid mold, which achieved a 45.1% reduction in temperature delta between the mold and coolant as compared to the traditional mold.

5. Conclusion and future work

The innovative grid molding and cooling method was proposed utilizing a hybrid additive and subtractive CNC machine tool. The grid mold prototype has been successfully fabricated and tested by comparing cooling performance with a mold made by traditional fabrication methods. Conclusions are as follows:

- DED and subtractive machining hybrid process can successfully produce functional molds using a framed grid of individual blocks as substrate.
- Simulation results showed very uniform cooling performance over the traditional mold.
- Grid cooling channels demonstrate significant improvement in cooling efficiency over traditional channels, with 45% lower delta from coolant to mold temperature, and result in more steady temperature during injection cycles.
- Shorter shot cycle time can be achieved with the grid mold and cooling approach due to improved cooling efficiency.

Future work on this topic includes fatigue study of DED fabricated mold components, further optimization of cladding parameters to control residual stress effects, software automation of grid discretization and block arrangement, and automation for rapid assembly of the discretized grid.

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