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Design of conformal cooling layers with self-supporting lattices for additively manufactured tooling

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ABSTRACT

Additively manufactured (AM) conformal cooling channels are currently the state of the art for high performing tooling with reduced cycle times. This paper introduces the concept of conformal cooling layers which challenges the status quo in providing higher heat transfer rates that also provide less variation in tooling temperatures.

The cooling layers are filled with self-supporting repeatable unit cells that form a lattice throughout the cooling layers. The lattices increase fluid vorticity which improves convective heat transfer. Mechanical testing of the lattices shows that the design of the unit cell significantly varies the compression characteristics.

A virtual case study of the injection moulding of a plastic enclosure is used to compare the performance of conformal cooling layers with that of conventional (drilled) cooling channels and conformal (AM) cooling channels. The results show the conformal layers reduce cooling time by 26.34% over conventional cooling channels.

1. Introduction

Many manufacturing processes require the careful control of surface temperatures, and heat transfer rates, to increase production and improve product quality. Injection moulding, blow moulding, die casting and extrusion are all examples of manufacturing processes that can benefit from incorporating methods of increased and balanced heat transfer within the tooling.

For injection moulding, heat transfer is usually carried out using straight cooling channels drilled into the mould. Due to conventional manufacturing constraints it is often difficult, or impossible, to position these channels close to the surface of the cavity in a way that provides optimal heat transfer. Increasingly, additive manufacturing (AM) is being used to produce conformal cooling channels in moulds and mould inserts. Powder bed techniques that utilise binders, lasers or electron beams, known variously as 3D printing, Direct Metal Laser Sintering (DMLS), Selective Laser Melting (SLM), Laser Cusing, and Electron Beam Melting (EBM), have a proven ability to produce highly complex cooling channels capable of reducing cooling times. As cooling accounts for a large portion of the total cycle time, this can lead to significant cost savings. Schmidt et al. [1] showed in one case study that 3D printed conformal cooling tool inserts reduced cooling and cycle times by 19–20% over conventionally machined inserts.

Many other manufacturing processes may also benefit from advanced thermal management of the tooling. Shayfull et al. [2] concluded that rapid heat cycle moulding, in which the mould is heated and cooled for each cycle is also likely to benefit greatly from conformal cooling, however this is yet to be fully explored. Au and Yu carried out computer aided engineering simulations to demonstrate the benefits of conformal cooling over conventional cooling for blow moulding tooling [3]. Hölker et al. showed that conformal cooling of extrusion dies could reduce surface defects on the extruded material [4]. Armillotta et al. showed that conformal cooling improves the surface quality of die cast parts, reduces cycle time and reduces part porosity [5].

As additively manufactured tooling is becoming more mainstream, research has shifted from case studies which show the benefits of conformal cooling, to design automation and optimisation. The more design freedoms the manufacturing process allows, the larger the solution space and the more challenging it is to design an optimal solution. Typically, conformal cooling channels are designed iteratively, using simulation software to evaluate mould performance and provide information for the next iteration. While this method often leads to high performance it requires substantial design time and can result in extremely complicated cooling circuits. Wang et al. developed a method of automatically generating conformal cooling circuits based on Centroidal Voronoi Diagram meshes [6]. The tooling was not experimentally

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tested, however, simulations showed reduced cooling time and improved uniformity of temperature and volumetric shrinkage. Au et al. developed an automated design methodology using a line of sight based algorithm to generate preliminary cooling channel designs [7]. Again simulations showed the method to be promising. As with most conventionally designed cooling circuits, these design automation strategies adopt circular cooling channels. This is likely to be because the axis-symmetric cross-section reduces design complexity and manufacturing issues. However, circular cross-sections also restrict how close the channels can be to the mould surface as a certain minimum offset distance must be left to ensure uniform surface temperatures. The work of Altaf et al. [8] and Shayfull et al. [9] shows the benefit of using U shaped and square profiles respectively to provide more uniform heat transfer to the mould surface.

A recent development by Au and Yu was the introduction of a conformal layer consisting of interconnected scaffold or porous elements [10,11]. The scaffold elements provide structural support whilst helping to disperse coolant throughout the layer. Simulations showed the improved heat transfer and temperature uniformity, however no physical testing results were presented.

A critical issue often overlooked in literature on conformal cooling is the design for manufacture issues associated with metal AM methods. Most important of these is the need for support structures for overhangs, bridges and nested surfaces. With highly complex circular channels or interconnected scaffolds there is a need to ensure the features can be built successfully without the need for support structures, as they are extremely difficult to remove post build and restrict fluid flow [12].

The primary aim of this paper is to design and test conformal cooling layers with easy to build support lattices for efficient and balanced heat transfer. First the general design methodology for creating conformal layers is described. Then the experimental method is presented including the design and testing of simplified test pieces. Finally a virtual injection moulding case study is used to demonstrate the benefits of the method when applied to injection moulding.

2. Design methodology

The design methodology is similar to that outlined by Au and Yu [10]. The mould wall is first created by offsetting from the cavity surface (or part model). A second larger offset is used to define the depth of the cooling layer, as shown in Fig. 1. From the second surface the outside of the mould is defined.

A lattice structure is then created by patterning unit cells to fill the overall conformal layer dimensions. The two models are then superimposed and any redundant lattice structure may be removed. Other features such as inlet and outlet ports, guide vanes and alignment features are added last.

The design of the lattice structure will vary from case to case however the main considerations are that all struts are (ideally) over 45° from the horizontal to prevent build errors, and with low enough aspect ratios to prevent buckling [12]. The length of unsupported overhang on the upper surface of the cooling layers should be as small as possible while not impeding flow. This is to ensure the upper cavity surface has sufficient support. The unit cells also need a base level of symmetry to ensure successful patterning.

In practice it may be that only the convex side of the mould requires a conformal cooling layer. As the polymer on the concave side of the part usually cools more slowly it is this area that will often benefit the most from conformal cooling layers. By being selective with the placement of the conformal layers (by using tooling inserts) the overall tooling costs can be mitigated.

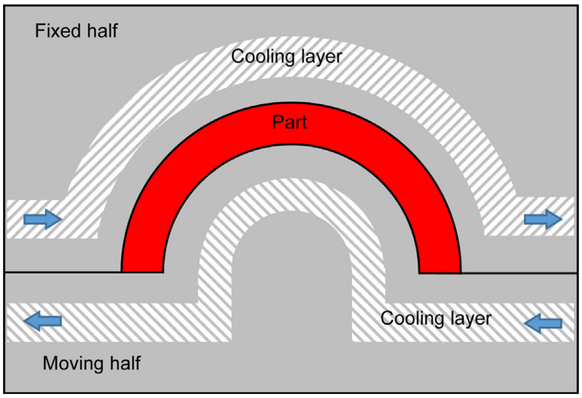

Fig. 1. Schematic injection moulding tooling with conformal cooling layers.

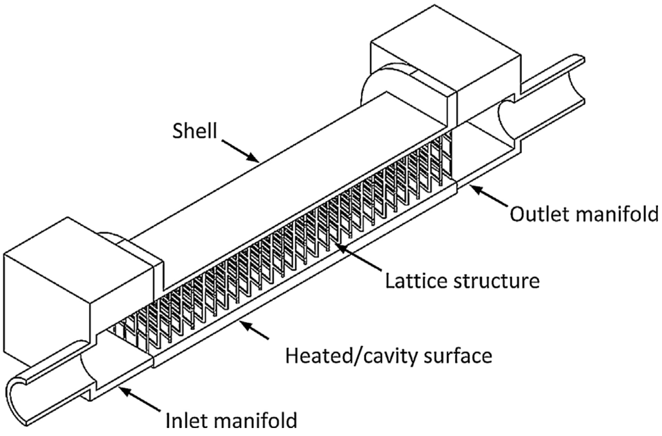

Fig. 2. Sectioned thermal transfer test piece showing internal lattice structure.

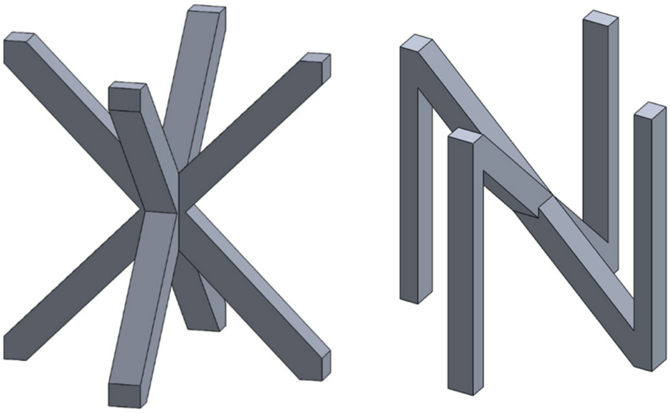

Fig. 3. Unit cells: cross (left) and N (right).

2.1. Design of thermal transfer test pieces

In order to test the heat transfer characteristics of conformal cooling layers three test pieces were manufactured on a Renishaw AM250 with Al10SiMg powder. The choice of material was based on what the machine was loaded with at the time. The test pieces were designed to represent one half of a small injection moulding tool, with a flat cavity surface, in order to simplify the application of a thermal load (Fig. 2). The lattice dimensions are 95 × 35 × 15 mm and the mould wall is 3 mm thick. The manifolds were fabricated from plain carbon steel.

Fig. 3 shows the unit cell geometries used in the test pieces. The struts were chosen to be 0.5 mm thick and the cells fit within a 5 mm