Laminated Injection Mould with Conformal Cooling Channels:Optimization, Fabrication and Testing

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***Abstract*- Conformal cooling channels follow the cavity shape and can provide a better cooling performance in injection moulds. Laminated tooling is one of the techniques for manufacturing injection moulds with conformal cooling systems. A laminated tool is made by stacking metal sheets of varying thicknesses from which pre–calculated profiles have been cut. The stacked sheets result in a jagged die surface that has to be finished before use. Although larger number of small thickness sheets result in small irregularities that can be finished easily, it increases the cost of profile cutting process. Therefore, one of the issues in laminated tooling is determination of sheet thicknesses so that the laminated die can be made optimally. In this paper, an optimization method is presented to find the best size of the various laminas based on CAD model surface geometry such that the surface jaggedness and the number of slice is reduced at the same time. The final mould is fabricated based on suggested optimization method. It is then testedto show the improvement in cooling performance as compared to the same die with conventional cooling channels.**

Keywords*- *Laminated Tool; Injection Mould; Conformal Cooling System; Optimization

I. INTRODUCTION

Laminated tooling is one of the powerful technologies to create conformal cooling channels in injection mould tools. In this technique, tools are made by dividing them into individual slices and then making each slice separately. Then, the slices are joined together to form the final pre-machined tool. Then a post-processing - usually CNC machining - is needed to finish the tool and reach user specified tolerances. This post-processing is to remove the stair step effect as a result of joining of sheets of metals together. Therefore, having less stair case effect on pre-machine tool surface is desirable to minimize the cost of post processing.

From the beginning of the research in the field of laminated tooling, different methods have been suggested to improve the surface quality in the final product. Dickens [1] considered different slice thicknesses to minimize the amount of material removal in post processing. He also suggested the idea of having different slicing directions to have a better surface quality. However, he limited his study to only vertical and horizontal directions. Also, in his study, uniform slicing strategy is used with manually selected slice thicknesses. While some researchers such as Tata et al. [2] considered adaptive slicing for a better surface quality.

In adaptive slicing, CAD model surface geometry is taken into account to find the slice thicknesses suited for each region of CAD model surface. Whereas in uniform slicing the same thickness slices are used for the entire CAD model, Figure 1. Although a better surface quality can be achieved in adaptive slicing, to find the best arrangement of slices based on CAD model surface geometry, it requires more calculation time comparing to what uniform slicing needs.

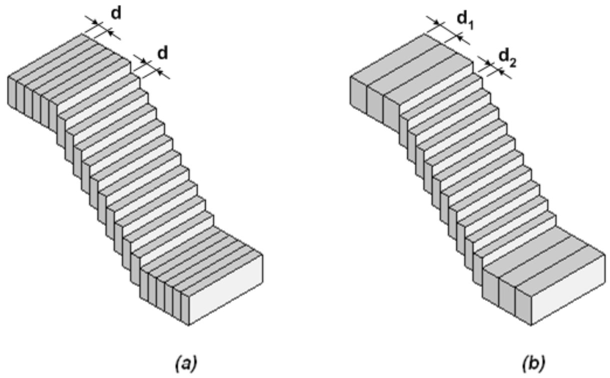

Fig. 1 Schematic of: (a) uniform and (b) adaptive slicing

In 2001, Paul [3] investigated the sources of surface roughness in laminated object manufacturing (LOM). He considered the effect of layer thickness and slicing direction to control the stair step effect. However, in his study there is no investigation, other than trial and error, on how the best slicing direction can be found.

Im and Walczyk [4] showed that surface quality improves if the slices are cut with a 5-axis laser cutting machine which can follow any optimized trajectory. They considered the surface geometry in the generation of optimized cutting trajectories. However, their method requires sloped laser cutting and this can be done only by a 5-axis laser cutting machine, which can be considered a manufacturing limitation since 5-axis machines are not always readily available.

Besides laser cutting, researchers also have used other technologies for creating individual slices. For example, Ahn et al. [5] considered hot wire cutting process in various cutting angles to reduce the surface jaggedness.

Yoon and Na [6] showed how, as a post processing tool, a laser beam melts material to fill the surface uncertainties created by stair case effect. They also showed that the surface hardness could be improved by impregnating hard particles in molten material.

Some of the techniques for volume deviation reduction in laminated tooling have roots in rapid prototyping (R.P.) where parts are usually produced by layered material deposition. In Dolenk and Makela's work [7], cusp height and stair case effect were introduced as two effective parameters to calculate the best slice thicknesses. Then in 2005, Kumar and Choudhury's [8] defined the cusp volume as the volume difference between two neighbouring slices. Then the thickness for each individual slice was found such that this cusp volume was always less than a user defined value.

All the R.P. based methods suffer from the same disadvantage that makes them unsuitable for laminated tooling application. In R.P. there is no limitation on the thicknesses that can be produced and presumably all the thicknesses coming from optimization process are accessible. While in laminated tooling, the thicknesses are limited to those that are commercially available.

An appropriate joining method is another important aspect of creating successful laminated tools. In some cases, such as injection moulds, it is crucial to join layers together such that no leakage happens either in cooling channels or inside the cavity. Nakagawa et al. [9] addressed this problem in 1985. Despite of using a strength bonding process to bond layers together, they faced leaking problems in the aluminium tool they manufactured using laminated tooling technique.

One of the first research groups to consider the joining issue in laminated tooling were Bryden et al. [10] in 1999. They suggested the brazing process for joining layers. They tested different thickness sheets to measure the strength of the joint based on the layer thickness when the same brazing conditions are used to form them. In 2003, Yoon and Na [11] showed that for laminated dies used in low temperature, dip soldering is also a suitable choice for the joining process. Despite of all the researches in improving joining strength, sealing the cooling channels is still an issue in the production of laminated tools.

Profile Edge Lamination (PEL), as another method for laminated tooling was first introduced by Walczyk et al. [12], [13], layers of sheet metals are stacked and clamped together in a frame. The holding forces provided in this method are suitable for using the laminated die for sheet metal forming. They are not suitable for injection moulding due to leakage problem may occur between clamped layers.

Recently, Ahari et al. [14] proposed a genetic algorithm based optimization method to find the best arrangement of commercially available gauges that minimizes the surface jaggedness in the final product, and consequently minimizes the post-processing cost. Their investigation is based on two most effective parameters in reducing laminated tooling costs: volume deviation between assembled slices and the actual CAD model, which minimizes CNC machining cost; and the number of slices which reduces the cost of laser cutting.

They also proposed a new optimization algorithm [15] that employs crowding method to inject diversity into the population and let the system find a more reliable solution for the best set of thicknesses to cover the entire model, thickness vector, before getting trapped in a local optimum.

In the current work, a laminated tool is taken from design to production and the process steps are followed from the beginning to the end. This tool is designed and built with conformal cooling system. All the processes followed to make this laminated tool are based on the methods explained in [14] and [15]. The same tool with conventional cooling channels is also tested to compare its performance with the laminated tool.

The thicknesses for the slices are found with the method explained in [15]. The designed tool is fabricated and the final tool is tested to show its improvement in production time and the cooling system performance.

In the following sections, the optimization procedure is briefly discussed first. Then the proposed method is applied to an injection mould for fabricating a new laminated die with conformal cooling channels. The results for conventional and laminated moulds are presented in the end.

II. OPTIMIZATION PROCEDURE

A laminated tool is an assembly of sheets of different thicknesses. The aim of laminated tooling optimization is to find a set of thicknesses that minimizes the surface jaggedness. This reduces the post-processing, usually CNC machining, cost. The part that the laminated die was designed for is shown in Figure 2. The conventional mould with straight cooling channels and the design of a mould with conformal cooling channels are shown in Figures 3 and 4, respectively.

Fig.2 The part is produced by the conventional tool

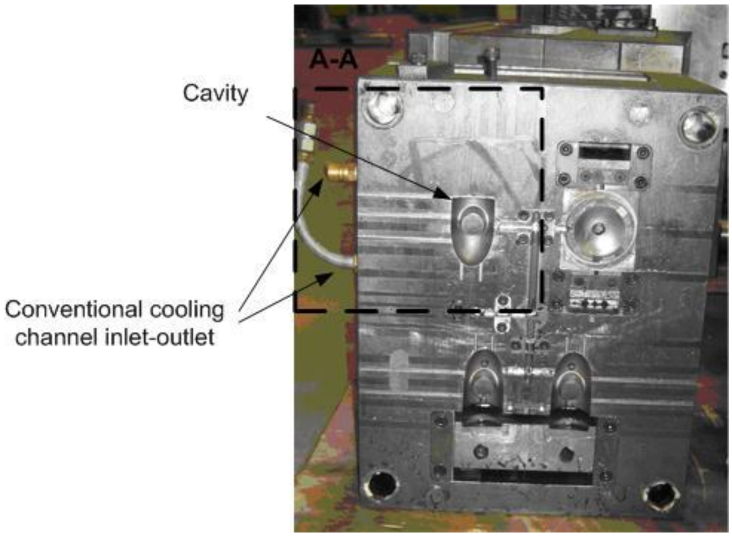

Fig.3 The original injection mould tool

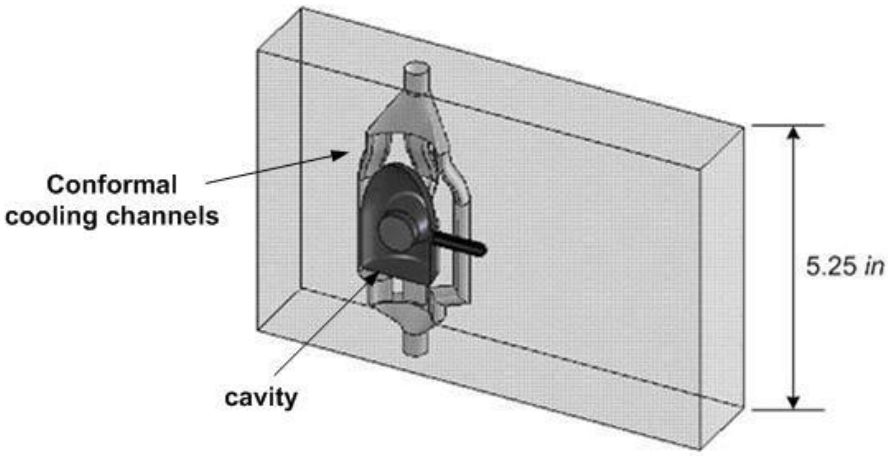

Fig.4 The main portion of CAD model used in optimization process

For the model shown in Figure 4, since the cavity and cooling channels are the features used in the optimization procedure, other features are omitted.

The first step in optimization process is to select the set of available sheet thicknesses that is used in manufacturing of this laminated tool. This set of thicknesses is called the *standard set*. For this example the standard set is selected based on the most commercially available sheets of metals:

$$\{1/2'', 7/16'', 3/8'', 5/16'', 1/4'', 3/16'', 5/32''\} \quad (1)$$

It should be mentioned that this set can be any combination of available sheet metals and there is no limitation on the value of thicknesses and the number of thicknesses being used in the standard set.

The final laminated tool is a combination of these thicknesses joined together through a brazing process. The aim of the optimization process is to minimize the weighted sum of the number of slices and volume deviation between assembled slices and the actual CAD model.

The optimization procedure consists of a volume deviation calculation module and genetic algorithm based optimization. Each portion is briefly discussed in the following sections. For more details please see [14].

III. OPTIMIZATION MODULE

The objective function used to minimize the volume deviation and the number of slices is:

$$\Theta(\Delta V, N) = \frac{1}{\alpha \times \Delta V + \beta \times N} \tag{2}$$

where ΔV and N are volume deviation and number of slices, respectively. The parameters α and β are weight factors which show the importance of each quantity during the optimization. These parameters are user defined. In this work more focus is on minimizing volume deviation, thus it is assumed that $\alpha = 3\beta$.

Any combination of the standard thicknesses specified in the standard set (1) which when stacked together covers the CAD model is called a thickness vector. For example a thickness vector for the model presented in Figure 4 can be:

$$\{7/16, 3/8, 5/16, 3/8, 1/4, 3/16, 5/16, 1/4, 3/16, 1/4, 3/16, 7/16, 3/16, 5/16, 3/8, 3/8, 7/16\} \tag{3}$$

As explained in [14], thickness vectors are created randomly via the first generation in genetic algorithms based optimization process. Therefore, each thickness vector is a potential solution. This makes the solution space very vast as multitude of thickness vectors can be created by different combination of standard thicknesses. It should be mentioned that there is no limitation on the number of times a specific standard thickness is repeated in a thickness vector. In this work genetic algorithm (G.A.) is used in optimization process.

Since G.A. is a population based optimization method, it is a good option for optimization in vast solution spaces such as what is needed in the application of this research. GA starts with a large population of potential solutions which are refined and filtered in each generation. G.A. is based on the biological evolution where strong members of the population of a kind can survive through generations. In G.A., objective function which consists of all characteristics of the kind, important in its survival is evaluated for all members of the population in each generation. Then by ignoring weaker members of the population and applying genetic operators such as crossover and mutation to the rest, a new generation is created. This loop is continued until a termination criterion is satisfied. Usually, convergence happens during generation evolution in genetic algorithm based optimization and the members of the final generation usually converge to a unique value which is the solution of the optimization process.

IV. VOLUME DEVIATION (VD) MODULE

The VD module begins the evaluation of the objective function by slicing the 3D model into thicknesses specified in each thickness vectors. The VD module first finds the 2D profile in each intersection of a slice plane and the actual CAD model. Thereafter, each slice has two 2D profiles one on either side. Then a unique profile which is the union of these 2D profiles is determined. The next step is multiplication of the area of this union profile and the thickness of the slice to obtain the volume of the individual slice. The volumes of all slices are added together to obtain the overall volume of assembled slices. The volume of the actual model is also calculated using a SolidWorks® Application Programming Interface (API) function. The volume deviation as well as the number of slices is known and used to calculate the objective function value. Figure 5 summarizes the slicing procedure for each individual thickness vector. Here:

P_i : The slice plane;

V_s : The total volume of assembled slices;

V_a : The volume of actual CAD model;

A_i : The area of i_{th} slice;

V_i : The volume of i_{th} slice.

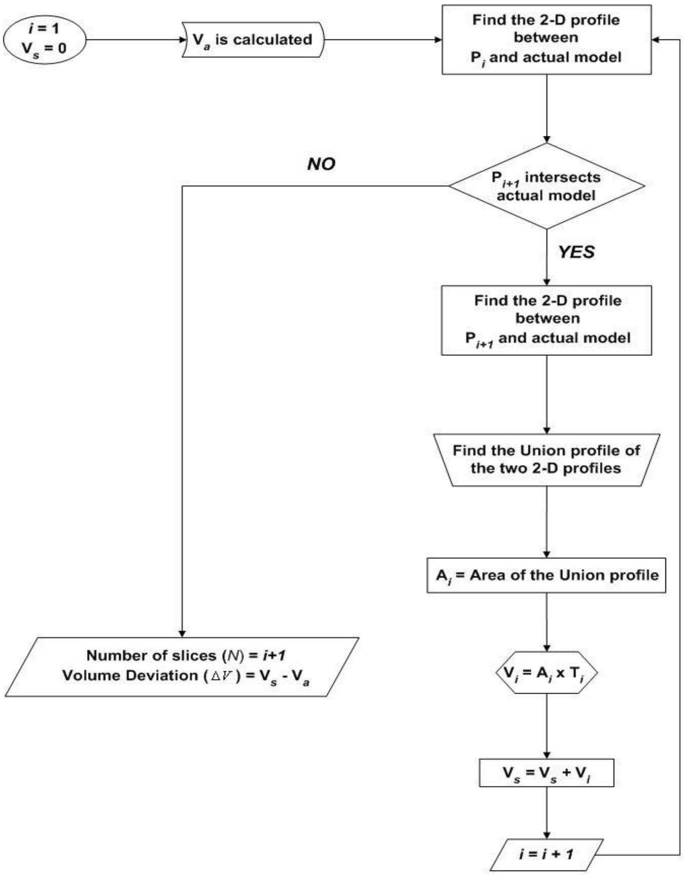

Fig. 5 VD module procedure

This procedure is conducted for all thickness vectors in the population. Then, all ΔV_m and N_m, where m is the population size, are sent to optimization module for objective function evaluation. The genetic algorithm based optimization process to reach the best thickness vector was explained briefly in Section 2, and also in [15] in more details.

V. RESULTS

The result of the optimization procedureisthe optimum thickness vector. This is done by relocating the slice planes such that the smaller thicknesses are inserted where cavity and/or cooling channels have abrupt angle with the slicing direction, and thicker thicknesses where cavity and/or cooling channels have flat angle with the slicing direction. This process is conducted during the GA generations. Figure 6 shows the optimum thickness vector for the part shown in Figure 4. After having the best thickness vector, the fabrication procedure is started.

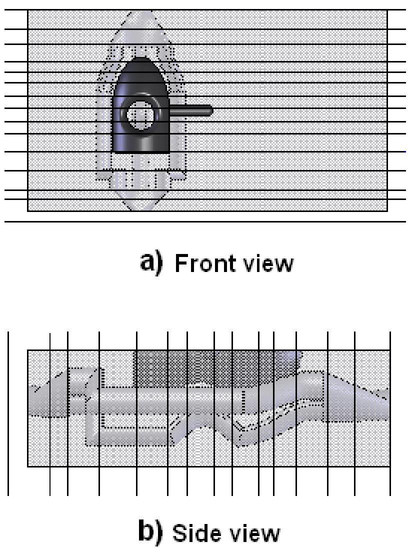

Fig. 6 Slice planes location at the end of optimization procedure

For the example considered in this work, the fabrication of the laminated tool began with laser cutting the lamina according to the best thickness vector.

Figure 7 depicts an individual slice after laser cutting process. As it can be seen in this figure, besides cavity and cooling channel profiles, each slice has three guide holes which assist in the assembling process to prevent any error.

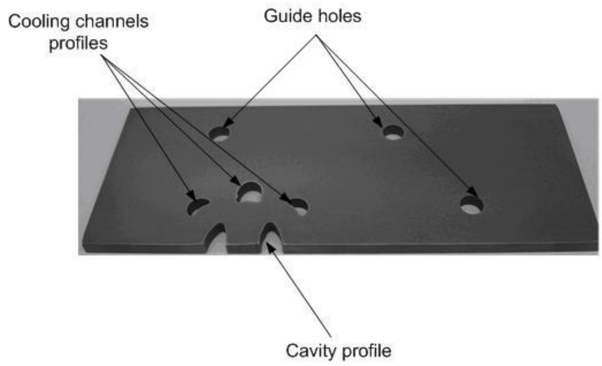

Fig. 7 One sample after laser cutting process

After cutting, the sheets are bonded and joined together using brazing process. Brazing was selected based on the suggestions already made in literature as it is the most trusted method to lower the risk of leakage between layers. Figure 8 shows the laminated tool after the brazing process. The portions of the rods outside of the assembled slices will be removed during CNC machining.

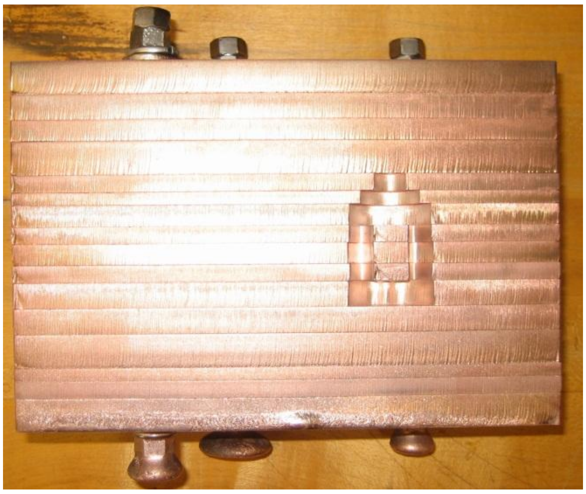

Fig. 8 The laminated tool after brazing process

The final step in laminated tooling process is post-processing step which is CNC machining. The machining step will remove stair case effect on the tool surface and bring it to near net shape. Here, as shown in Figure 9, the brazed assembly is machined based on the data from the CAD model presented in Figure 4. The CNC machining process was done on an OKK 3-axis CNC machine at CNC shop in University of Waterloo.

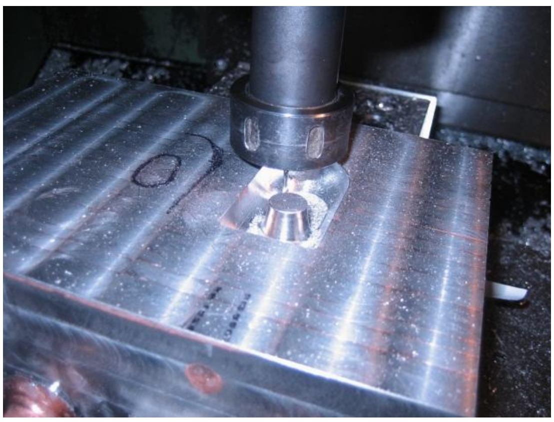

Fig. 9 The CNC machining process

The machining time to finish the sides of the laminated tool is almost equal to the time required for a traditional tool which is made from a block of material. However, as it can be seen in Figures 8 and 9, in the inside of the cavity, only the stair step effects need to be removed, and this results in a reduction in the machining time.

For this test piece, the time spent for finishing the cavity in the laminated tool was almost 15 minutes while the estimated time to make the same cavity from a block of material in traditional CNC based process is almost 15% higher. The approximated time for traditional CNC machining of the entire cavity can be easily found by using and CAM software such Master CAM. After all, as explained earlier in this section, it is predictable that machining inside the cavity to remove the stair case effect needs less time than machining the entire cavity as in the first case, only finishing cycles are needed.It should be added that more machining time reduction is expected while creating a larger tool.

On the other hand, one of the crucial issues in laminated tools manufacturing is to provide a reasonable surface quality of the cavity. This is more important especially in injection mould or hydroforming tools where a high surface quality for the part produced by the tool is needed. As Figure 10 shows, CNC machining can provide an acceptable surface quality for the cavity in this test tool.

To investigate the performance of the laminated mould with conformal cooling channels, and also to make sure there is no leakage through the cooling system or the cavity, the tool undergoes the production tests.

Fig. 10 Inside of the cavity and joined layers

Figure 11 shows the laminated injection mould tool during the production tests. The tests were conducted on an 83 ton Battenfeld 750, toggle machine. It has a 9oz. or 257 gram shot capacity and the screw diameter is 40mm.

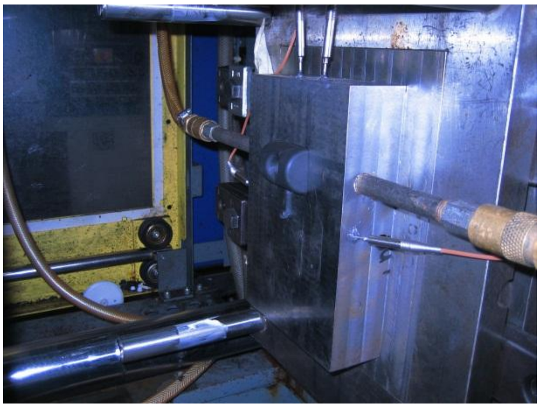

Fig. 11 The laminated injection mould tool during the operation withthe sensors installed to investigate the cooling channels performance

Firstly, no leakage was reported during the tests either from inside the cavity or along the cooling channels. As depicted in Figure 11, the cavity is properly filled during the injection process. Figure 12 shows the final product of injection moulding which is a plastic part used in the furniture industry. As depicted in this figure, the final part has an excellent surface quality, which means not only the surface of the cavity has been finished properly during CNC post processing, but also there is no leakage inside the cavity. This implies that in this laminated tool, the brazing process can provide enough strength to hold the sheets.

Fig. 12 The final product

Table 1 compares the performance of the proposed conformal cooling channel with the convectional one. An injection moulding process consists of boosting, holding, cooling, and ejection. As depicted in Table 1, with the conventional cooling channels, the time for cooling the injected mould is 50 seconds. This time then reduced to 25 seconds in the tool with conformal cooling system. This means almost a 50% reduction in the cooling time, without any negative effect on the quality of the product. This reduction is due to the ability of conformal cooling channels to follow the cavity. Moreover, considering the whole injection moulding process, the 50% reduction in cooling time means a 25% reduction in overall cycle time.

TABLE I FONT SIZES FOR PAPERS

Process	**Time required (Sec.) (Conventional cooling system)**	**Time required (Sec.) (Conformal cooling system)**
Boost	2	2
Hold	16	16
Cool	**50**	**25**
Ejection	22	22
Total	**90**	**65**

VI. CONCLUSION

To create a laminated tool with conformal cooling channels with minimum manufacturing costs, an optimization problem was defined. An adaptation of genetic algorithm was developed to solve this optimization problem. Slicing process was conducted in SolidWorks® to find the volume deviation and the number of slices, and then use those values in the optimization process.

A mould already in production line with conventional cooling channels, was reproduced by the laminated tooling technique with conformal cooling channels based on the proposed optimization method.

Results clearly indicated that using the optimized set of available sheets can reduce the post-processing cost. Also, conformal cooling channels created for the tool by the proposed optimization method could provide better cooling performance than conventional cooling channels.

As one of the future steps, slicing direction is considered in optimization procedure. Less machining cost is anticipated when slicing direction can be adapted to the surface geometry of a CAD model.

ACKNOWLEDGMENT

This work has been supported by the Natural Sciences and Engineering Research Council of Canada. The authors would also like to acknowledge WebPlas Inc. (http://www.webplas.ca) for technical support. Also all helps provided by CNC machine shop in University of Waterloo is kindly appreciated.

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