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THERMAL CONDUCTIVITY AUGMENTATION OF EPOXY INJECTION MOULDS FOR COOLING TIME REDUCTION

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ABSTRACT: Polymer injection moulds are generally manufactured with tool steels which give reliable functioning of moulds with long service life. Manufacturing of injection moulds in steel is a lengthy process due to the strength and hardness. If the injection mould is required quickly for a short prototype or production run, one of the good choices is to use Aluminum filled epoxy material, which can give a mould in a very short time using Rapid Tooling (RT) techniques, as compared to a machined tool. Aluminum-filled epoxy tools work best for relatively simple shapes. The benefits of fabricating injection moulds with epoxy resins includes time saving, ability to set at room temperature and ease of machining. But a major drawback of epoxy material is that the cooling time for epoxy injection moulds are still relatively long due to the poor thermal conductivity of epoxy. This paper reports investigation of an innovative idea for enhancing the thermal conductivity for epoxy moulds. The basic concept behind the idea was to embed high thermal conductive metal insert within the mould between the cavity and the cooling channel. This technique will increase the effective thermal conductivity of the epoxy mould, leading to reduction in cooling time for the injection moulded polymer part. By substituting part of the epoxy with low-cost aluminum, a cost advantage is also to be derived, besides increased mould strength. Experimental analysis done in the current study also verified that mould with embedded metal insert has considerable shorter cooling time.

INTRODUCTION

Injection Moulding (IM) is a common plastic processing technique and is used in the plastics industry worldwide (Rosato 2003). In the past decades, the existing market has grown exponentially resulting in fast production rates and less time for products to reach the market. But for the injection moulding industry, conventional mould manufacturing methods can take up to several weeks for a working mould. The slow and tedious steps involved in fabricating a mould includes designing the mould, the programming of Computerized Numerical Controlled (CNC) machines and the post processing and polishing of the mould.

In injection moulding, process cycle time is a crucial factor as it directly affects the efficiency of the process. The process cycle time in injection moulding depends significantly on the cooling time of the part, which is provided by the coolant flowing through the channels in the injection mould. Conventional fabrication techniques are used to drill straight holes in the mould which act as cooling channels which have limitations in terms of geometry and coolant mobility. To overcome these problems, the concept of conformal cooling was introduced as an effective alternate to conventional cooling. The emergence of Additive Manufacturing (AM) and Rapid Tooling (RT) techniques has offered new degrees of freedom to injection mould manufacturers. AM & RT processes not only decrease the mould development time considerably but also aid in the development of conformal cooling channel within the mould.

Cheah et al. (2002) experimented on the fabrication of injection moulding tool with aluminum-filled epoxy. In their study, a technique of using rapid soft-tooling known as aluminum filled epoxy resin tooling for injection mould fabrication, was successfully investigated. An epoxy resin mould was evaluated and the characteristics of the injection moulded end products were presented. In another study, Chua et al. (1999) described rapid tooling (RT) as the technology which adopts Additive Manufacturing (AM) techniques applied to tool fabrication. In the study, several popular RT methods were discussed and classified. A comparison was also made on these methods which are based on tool life, development time and cost of the fabricated tool.

The concept of conformal cooling in injection mould tools has been experimented and published by various researchers. One such experimental research was conducted by Sachs et al. (2000) on the fabrication of injection mould tooling by using the 3D printing RP technology. Conformal cooling channels (CCC) were incorporated both in core and cavity of the mold. The performance of this mould was compared against the performance of an injection mould with straight cooling channels. The mould with conformal channels also maintained a more uniform temperature distribution during a moulding cycle. Xu et al. (2001) did their study on the design of conformal cooling channels in Injection Moulding tools with AM technologies. They observed that tools with conformal cooling channels have demonstrated improvements in production rate and part quality as compared with conventional tools. Another study by Rannar et al. (2007) was on the fabrication of conformal cooling channels within tool inserts by Electron Beam Melting (EBM) process. Conventional injection mould cooling channel was fabricated with straight holes, and an AM tool was manufactured by EBM technique. Their main study was on the evaluation of cooling time and dimensional accuracy. Khurram et al. (2013) presented their study on an innovative concept of Profiled Conformal Cooling channels (PCCC) in an Aluminum filled epoxy mould using AM and RT techniques. They compared the cooling times for the moulds with circular and profiled channels experimentally. Cooling channels have a circular cross section whereas in PCCC, the cross sectional shape is so designed that the flat face surface of the channel facing the cavity follows the profile of the cavity. In their experimental analysis, it was indicated that PCCC mould has less cooling time than mould with circular channels. They also described that the concept of PCCC could be applied to metal moulds fabricated with RT and AM techniques. Ferreira and Mateus (2003) presented a study of rapid soft tooling technology for plastic injection mould tools. Main purpose of their work was to propose some original approaches to integrate RP and RT techniques with composite materials cooled by CCC to manufacture injection moulds. Their analysis pointed out that the properties of the parts injected in RT moulds, regarded as a soft tool, cannot sustain comparison with metallic production moulds. Hassan et al. (2009) described in their work that nearly 70% of the cycle time can be used up in cooling the melted polymer sufficiently so that the part can be ejected without any significant deformation. They described that an efficient cooling system design providing a uniform temperature distribution throughout the moulded part during the cooling process ensures the quality of the part by preventing differential shrinkage, internal stresses, and mould release issues. It also reduces cooling time for the part and accelerates the solidification process to enhance the productivity of the moulding process.

Mould Thermal Management is a critical issue in injection moulding method and also has key effects on production cycle times, which directly links with cost and part quality. Due to these reasons, cooling system design has great implications for plastic product industries involving injection moulding techniques. Thermal management of injection mould tools is very much enhanced with the application of conformal cooling channels as compared with conventional

method of cooling with straight drilled holes. The concept of conformal cooling channels is shown in Figure 1.

Figure 1. Conformal Cooling Passages. [Sachs et al., 2000]

Rees (2005) indicated some of the most important factors that influence the cooling of a mould. These include the flow of coolant, temperature increase (ΔT) of the coolant, chemical composition of the coolant, cooling channels (layout, size) and thermal conductivity of mould parts. The heat contained in the molten polymer is transferred to the mould cavity, and has to be removed so that the plastic can return to its solid form before ejection. The heat removal takes place mostly through the cooling medium after travelling through the mould material. The thermal conductivity of the mould material is an important factor in the overall injection moulding process. The thermal conductivity of the material directly relates to the cooling of the mould and hence to the productivity of the IM process.

Epoxy used for the current work has a major drawback of low thermal conductivity which generally ranges from 0.6 – 0.7 W/mK. Aluminum particles are mixed with epoxy to increase thermal conductivity. But even in the case of aluminum filled epoxy, the thermal conductivity is very low as compared to metal moulds. This low thermal conductivity can be an issue in the moulds fabricated with epoxy as the cooling time is pretty high as compared to metallic moulds. The typical injection moulding cycle times are indicated in Figure 2.

Figure 2. Cycle time in injection moulding [Dimla et al., 2005]

If the thermal conductivity of epoxy could be enhanced, we can get the maximum advantages of RT techniques for injection moulding process. Hence, another novel idea was envisaged of embedding high thermally conducting metal inserts within the epoxy moulds to enhance the thermal conductivity of moulds made with epoxy in order to reduce the cooling time for the polymer part.

A study on the tribological behavior of aluminum filled epoxy based materials was performed by Vasconcelos et al. (2006). Their study was focused on the role of the particles and fibres in the friction and wear at room temperature and at a typical plastic injection temperature of 160°C. They

explained that thermal conductivity and wear resistance are critical parameters for a good service performance and durability of the mould.

METHODOLOGY

Design and Modeling of Patterns

Solid models of Rapid Prototype patterns for the channel and moulded part were generated as exact counterparts of the mould, in terms of dimensions, location with respect to the cavity and position with respect to the base as designed earlier. The wax patterns were produced with Thermojet 3D printer. The computer aided design model for mould pattern with conformal channel is shown in Figure 3.

Figure 3. Mould Pattern with Conformal Cooling Channel. [Khurram et al. 2013]

Embedding Conducting Metal Inserts in the Epoxy Moulds

The heat from the melted plastic is transferred to the mould cavity, and is removed mostly through the cooling medium. The heat travels from the heated plastic part into the mould material towards the cooling channel where it is taken away by the cooling fluid. The travel of heat in the epoxy will be slow due to the low thermal conductivity. If a high conducting metal medium is placed within the heat flow lines, the heat will travel faster through the metal and reach the channel in a shorter time. This was the basic idea for the current research. Metal inserts made with aluminum alloy were embedded between the mould cavity and the cooling channel for the epoxy mould.

The insert for epoxy mould is ring shaped. The insert is so designed that it seats on the cavity pattern exactly at the center line of the cavity and cooling channel. The inserts were fabricated using 10 mm thick aluminum alloy plate. The inserts were cut according to the designed size with the electric discharge machining (EDM) wire cut process. The inserts were placed for the mould on the cavity pattern as shown in Figure 4 and Figure 5.

Figure 4. Epoxy mould pattern with Conducting Insert

Figure 5. Insert Placement for the mould

Fabrication of Epoxy Moulds with embedded Conducting Thermal Inserts and Thermocouples

The ready mould frame with patterns and aluminum insert is shown in Figure 7. For the measurement of moulded part temperature, thermocouples needed to be placed within the mould cavities with circular channels. The technique used for doing that was to embed the thermocouple inside the mould cavity during the epoxy casting process. Two thermocouples each were embedded in such a way that the thermocouple bead was at the center plane of the mould cavity. The positions for the center plane on the part pattern were measured and marked. The thermocouples were passed through the thermocouple holder fabricated with Thermojet 3D printing process as shown in Figure 6.

Figure 6. Thermocouple Placement CCC Mould with Insert

Epoxy resin was used for making injection mould cavities with aluminum inserts. Epoxy was poured in a bucket and weighed according to the volume. Then epoxy-hardener mixture was prepared inside the bucket with a steel mixer and de-gassed inside a vacuum chamber for 12 – 15 minutes. After de-gassing, the epoxy was poured onto the pattern inside the aluminum frame to cover the pattern assembly. During the cure cycle, the wax pattern was melted out from epoxy leaving the cavity, cooling channels, thermocouples and thermal insert embedded within the mould.

Epoxy Casting of Mould Core

The fabrication of the core for the cavity was also done with Thermojet wax. The wax mould was designed and Rapid Prototype pattern was produced as shown in Figure 7. Epoxy was poured in the pattern and after curing, the mould core was formed.

Figure 7. CAD model and wax Pattern with casted Mould Core. [Khurram et al. 2013]

Figure 8 shown below is the complete mould assembly used for the injection moulding experiments. Mould cavity and core were placed in the aluminum frame to be fitted in the vertical injection moulding machine. The mould assembly connected with cooling pipes and data logger is shown in Figure 9.

Figure 8. Complete Epoxy Mould Assembly

Figure 9. Experimental setup

Injection Moulding Experiments Procedure

For Injection Moulding experiments, a vertical injection moulding machine was used. Injection moulding experiments were done with moulds without and with the thermal conducting insert. Starting reference temperature for injection of material was taken as 31°C. Through trial moulding runs, the ejection temperature was determined as 35°C. Temperatures were recorded at the cavity wall, coolant inlet-outlet and ambient. Measurements were taken from mould temperature of 31°C taken as the reference injection temperature to the ejection temperature of 35°C. The data was converted in graphical form.

RESULTS & DISCUSSION

Temperature Graphs

The recorded temperatures were converted into graphical form given below.

Figure 10 indicates the temperature versus time curves for the mould without conducting insert.

Figure 11 indicates the temperature versus time curves for the mould with conducting insert.

Figure 12 shows the comparison of cooling times between the two types of moulds.

Figure 10. Temperature versus time graph for Mould with Insert

Figure 11 Temperature versus time graph for Mould without Insert

Figure 12. Cooling time comparison, Moulds without and with Insert

It is seen from the injection moulding experiments that the thermal conductivity of aluminum filled epoxy material is enhanced remarkably with the embedding of a thermally conducting insert within the mould. The cooling time for injection moulding process for the mould without the conducting insert was about 1000 seconds. This cooling time was reduced in the mould with the conducting insert to 440 seconds.

The heat flow from the melted polymer flows slowly in the mould without insert due to the low thermal conductivity of the material. When a material of high thermal conductivity like aluminum metal is embedded with epoxy material, the heat flows quickly in the high thermal conductivity material towards the cooling channel where it is taken away by the flow of cooling fluid.

The temperature rose to 80°C for the mould without insert as seen in Figures 10 and 12. For the mould with metal insert, it was seen that the temperature has risen to about 69°C (Figure 11 and 12). This is due to the high thermal conductivity of the aluminum insert as the insert is dissipating heat from the melted polymer quickly in case of the mould with insert as compared to the mould without insert. It was due to this reason that the temperature peak for the mould with insert is lower than that of the mould without insert.

The small difference in the temperature peaks in the two cavity thermocouples is due to minor uncertainties in the positioning and placement of the two thermocouples. Lines for water temperature at inlet and outlet shown in the graphs are overlapping because the difference in their temperatures is very small and the two lines are viewable separately at enlarged view of the temperature trace.

CONCLUSION

The benefits of fabricating injection moulds with epoxy resins includes time saving, ability to set at room temperature and ease of machining. The low thermal conductivity of the epoxy could be a problem as this would lead to longer cooling times of the injection moulded part. The embedding of a high thermal conductive material in the epoxy mould is an innovative idea for the enhancement of effective thermal conductivity of the mould.

The time taken for the part to reach ejection temperature of 35°C taken from the cavity of epoxy moulds for the moulds without and with thermally conducting inserts is given below.

- Time for mould without insert to reach ejection temperature 1000 sec
- Time for mould with insert to reach ejection temperature 440 sec

The cooling time for the mould with insert to reach the ejection temperature of 35°C is 560 seconds less than the time for the mould without insert, which implies a reduction of about 56% in cooling time. This indicates that the mould with insert is dissipating heat much faster as compared to mould without insert. The embedding of aluminum insert in the epoxy moulds is a novel concept which will be beneficial for the injection moulding process for the overall reduction in the process cycle time which could result cost saving for the process.

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