THERMAL PROCESS AND NOVEL CONTROL METHODS FOR SPIN-CASTING

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ABSTRACT

The quality of spin casting products and mould life are critically dependent on thermal conditions they undergo. In order to improve the performance of production and to optimise the spin-casting process, characteristics of the thermal process was firstly identified by means of the measurement and simulation. Furthermore the investigation of the developed control methods, including the thermal property substitute method and mixture method of the metal powder, was kept on the effect of air-cooling induced automatically from the spinning of the mould on the thermal process.

The air cooling system was developed to optimise the thermal process during casting, utilising a theoretical analysis of the air-flow characteristics in a cooling tube submerged in a silicon mould and the characteristics of convection heat transfer associated with the mould and cast part. A numerical simulation of the casting process was also adopted in the analysis. The effect of the developed system on the thermal process was determined experimentally and it was found that a system of air-cooling, automatically induced from the spinning of the mould, is feasible in optimisation of the thermal process.

The developed control methods can be applied to the practice of spin casting individually or collectively according to the specific situations and requirements.

Keywords: Spin casting, mould cooling, thermal property substitute, mixture method, induced air-cooling.

1. INTRODUCTION

Spin casting uses centrifugal force to cause the melted casting material, such as zinc alloy or a plastic substance, to flow into the manufactured casting cavities. This force is created in a configuration where the casting mould rotates around the co-axis of the spin casting machine. Spin casting is used widely in the prototyping industry as a secondary process to convert a master model into a functional metal or plastic part. The main problem with this process is the poor thermal conductivity of silicon rubber as mould material.

Silicon rubber can withstand a temperature of 420ºC and, thus, allows the spin casting of low-melting alloys such as pewter and zinc. However, its low thermal conductivity - of approximately 0.2 $W/m{\cdot}^{o}C$ (Achmidt, Henderson, & Wolgemuth, 1993; Cengel, 1988) - leads to an increase of the mould temperature during the casting process, and thus a very low cooling rate of the cast parts. The repeated heating-up of the mould has a damaging effect on the mould surface and the cast part quality due to thermal stress, and the necessary long cooling times between casting spots decreases the production efficiency. Therefore, the heat transfer characteristics play an important part in the mould life and quality of the product during the casting process. It also influences the maximum temperature, temperature distribution and cooling time of the mould and casting.

To avoid such damage, it is necessary to cool down the mould between shots and to control the cooling process as well as the temperature distribution of the cast parts. In order to control and to optimise the cooling process of spin casting manufacturing, effective, simple and economic cooling methods need to be developed.

During the casting process, the silicon mould and the cast products rotate around a fixed axis and, hence, water-cooling - usually used in injection casting - cannot be used here (Rees, 1995). Furthermore, any method that has any fixed connection between mould and the surroundings cannot be used.

Natural cooling during spin casting is widely adopted by industry (Tehcast Industries Inc., 1991), but with the evident drawbacks, this slows the casting process down.

Forced convective heat transfer - whereby fans are used to cool down the mould - has been recommended, but it cannot effectively control the casting processes. A forced convective cooling method, utilising an air pump, was developed by Yong-Ak Song (2001). This system, using a modified spin-casting facility, has the ability to control the casting and cooling process effectively. The casting equipment facilitates high pressure airflow along the length of a shaft into the centre of the mould. This necessitates complex modifications to a standard spin-casting apparatus and is not really feasible.

Based on the investigation of thermal process of spin-casting, some novel control methods were developed in this article.

2. RESEARCH METHODOLOGIES

The combination of the experimental method (Huan & Jordaan, 2003) and numerical simulation (Huan & Jordaan, 2004) was adopted to study the characteristics of the spin-casting process and to develop the control methods.

The original experimental mould sketched in Figure 1, was designed to study the casting process and to compare it with the suggested design moulds demonstrated in sections below.

The experimental parameters were as follows:

Clamping pressure:	1.38×10^5 Pa (20 PSI)
Rotating speed:	500 RPM
Casting temperature of zinc:	400ºC
Casting temperature of pewter:	360ºC

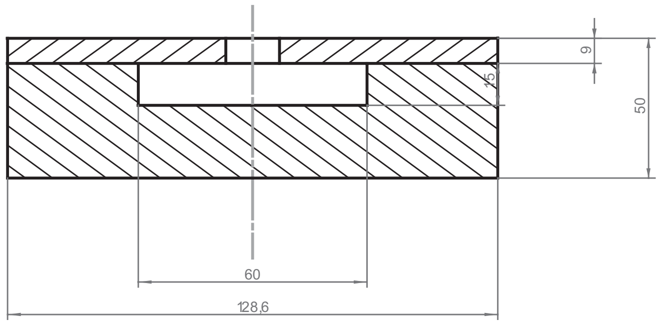


Figure 1: Schematic representation of original experimental mould

The developed 3-D transient numerical simulation software based on Galerkin finite element method (Huan & Jordaan, 2004), namely Spincool, was developed to assist the study due to the limitation of the measurement.

The 3-D temperature in the domain of mould and casting part with time can be obtained for any sophisticated geometry and conditions as long as the initial and boundary conditions are supplied.

3. THERMAL PROCESS OF SPIN-CASTING

The cooling curves after casting with pewter and zinc (Fig. 2) show that the natural cooling process is composed of three phases, viz. (1) liquid cooling, (2) solidification, and (3) solid subcooling.

During the liquid cooling process, the temperature decreases quickly to the melting temperature. In fact, the casting materials change phase at the temperature point that is a few degrees lower than the melting point. This temperature difference is called the sub-cooling degree. The sub-cooling degree, taking the above figure as the example, is 5-6°C for pewter and about 3°C for zinc alloy.

During the phase change, it takes a relatively long period of time to exit the melting point and to enter the solid sub-cooling condition.

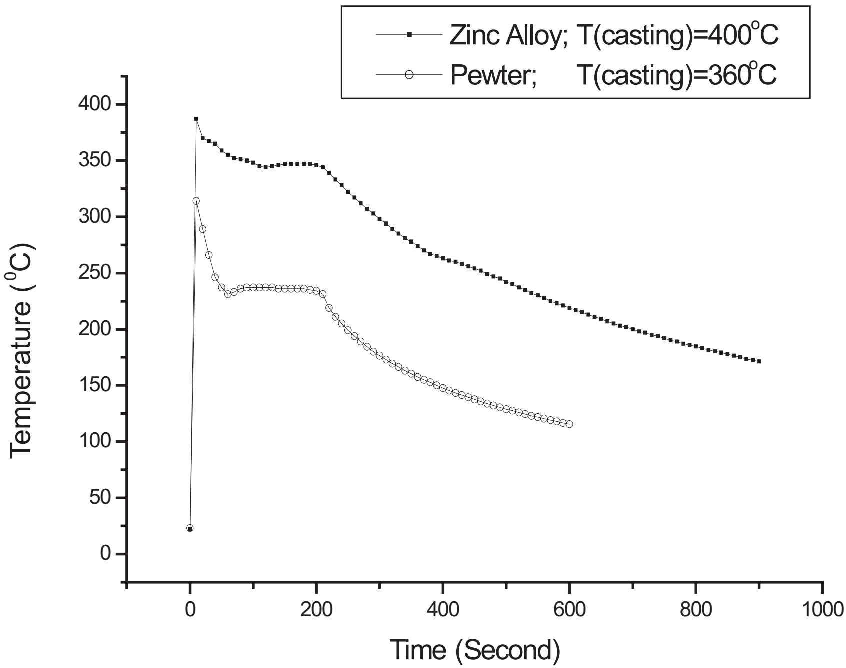


Figure 2: Casting process

3.1 Effect of clamping time on cooling process

During casting, the silicone mould is clamped by upper and lower clamp plates with a specified clamping pressure for a certain period of time. The clamping time plays an important part on the casting quality since insufficient clamping time will result in an incomplete distribution of the liquid casting material. Furthermore, the clamping time is also a key factor for the solidification process and the mould cooling process. The heat from the melted casting material should be transferred to the surrounding air via the silicone mould and the clamp plates - with the clamp plates having a higher coefficient of heat transfer than the surrounding air. Therefore, a longer clamping time will help to shorten the solidification time and mould cooling time (Fig. 3, 4).

The results show that the solidification time would be shortened to 10.7 minutes from 14.3 minutes if the clamping time is increased from 60 seconds to 90 seconds, the cooling process of the mould will be improved and the highest temperature will be decreased substantially.

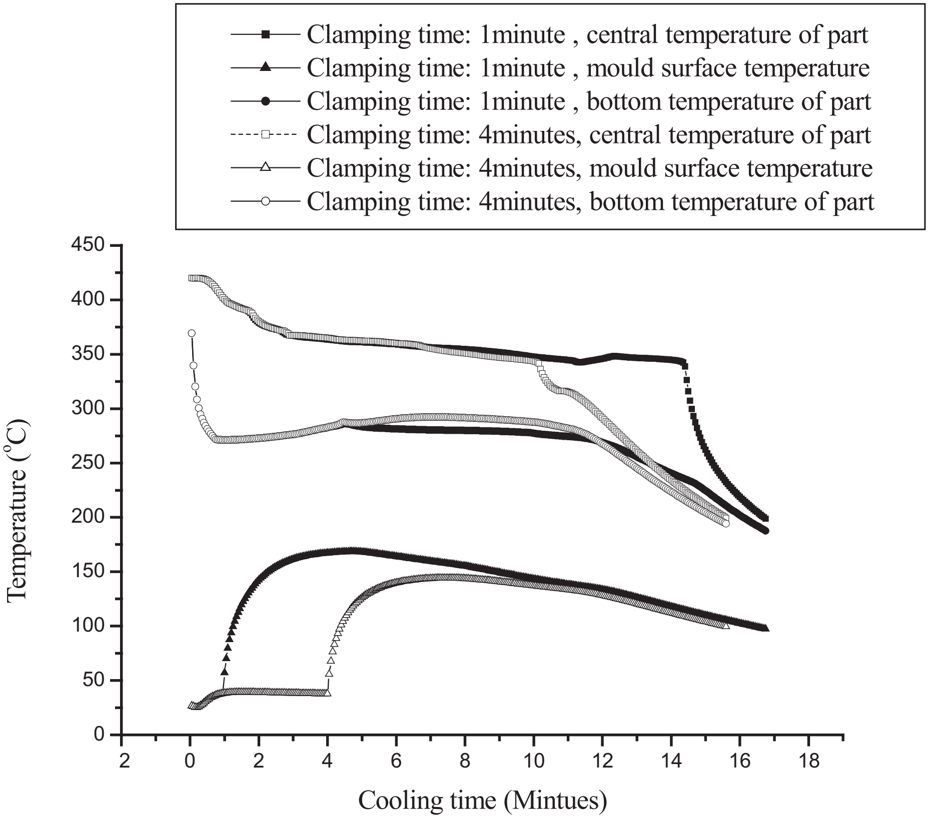


Figure 3: Cooling curves for different clamping times

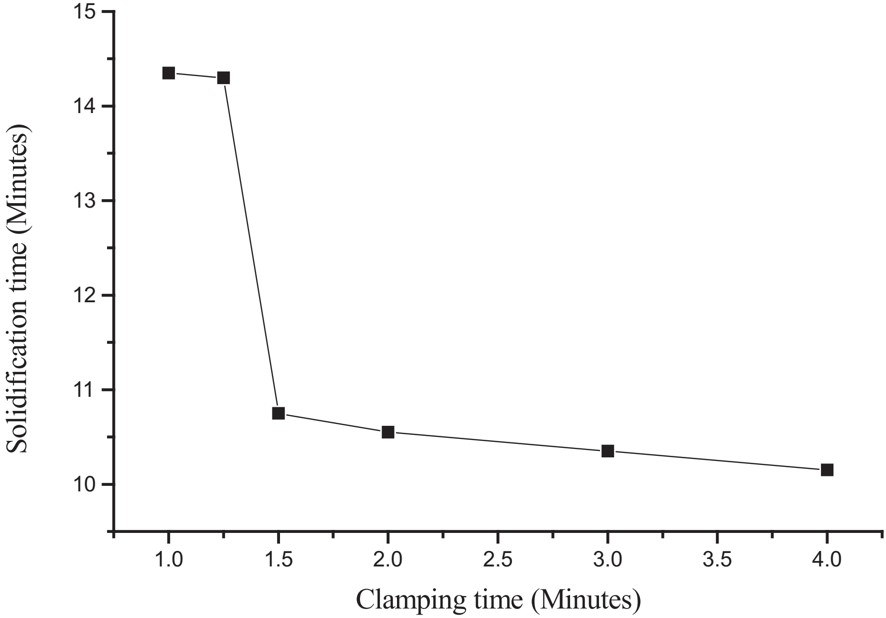


Figure 4: Relationship between clamping time and solidification time

3.2 Effect of convective heat transfer on the cooling process

After a certain period of clamping, the mould is taken out of the spin-casting machine. Normally natural cooling and/or a forced cooling process by means of fans are used. The effects of the coefficient of convective heat transfer on the mould cooling, solidification of the casting material and the mould surface temperature were simulated and shown in figures 5, 6, and 7.

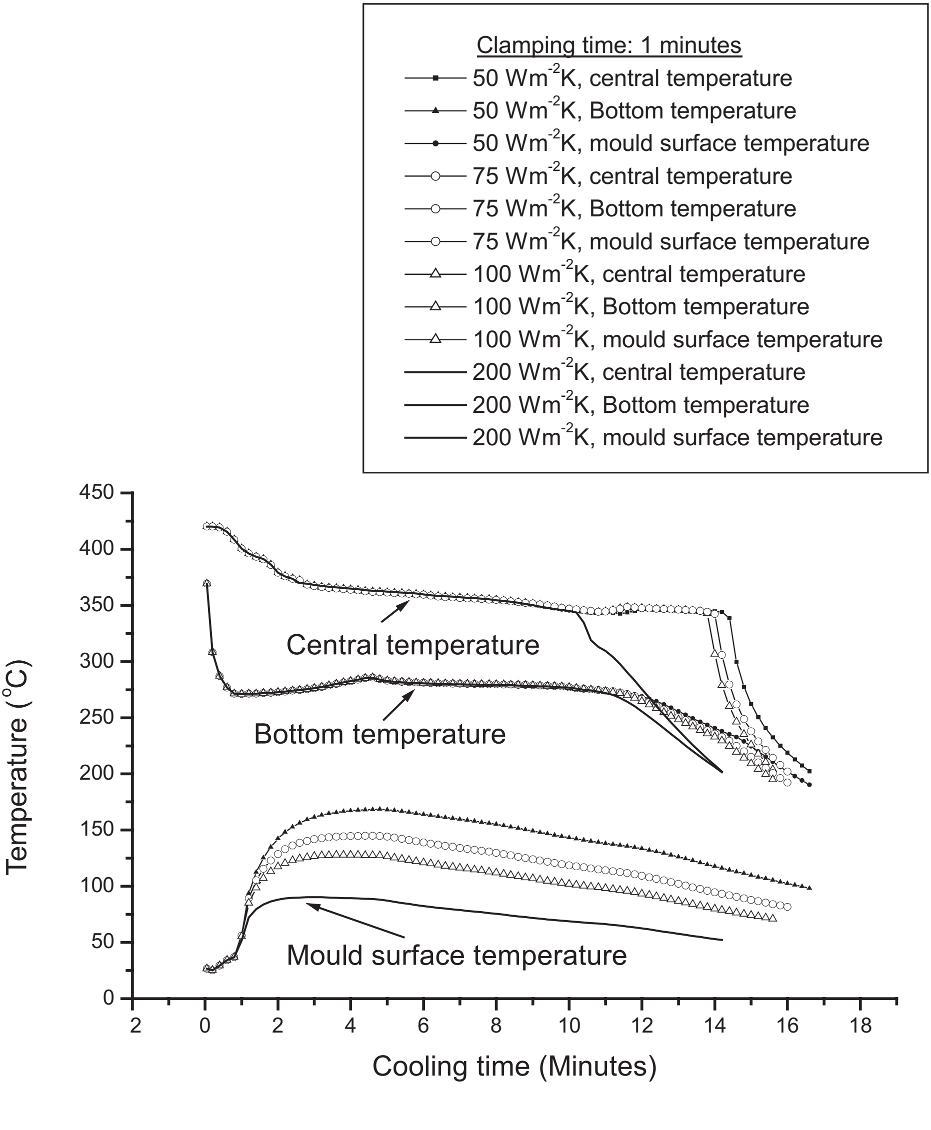


Figure 5: Cooling processes with different coefficient of convective heat transfer

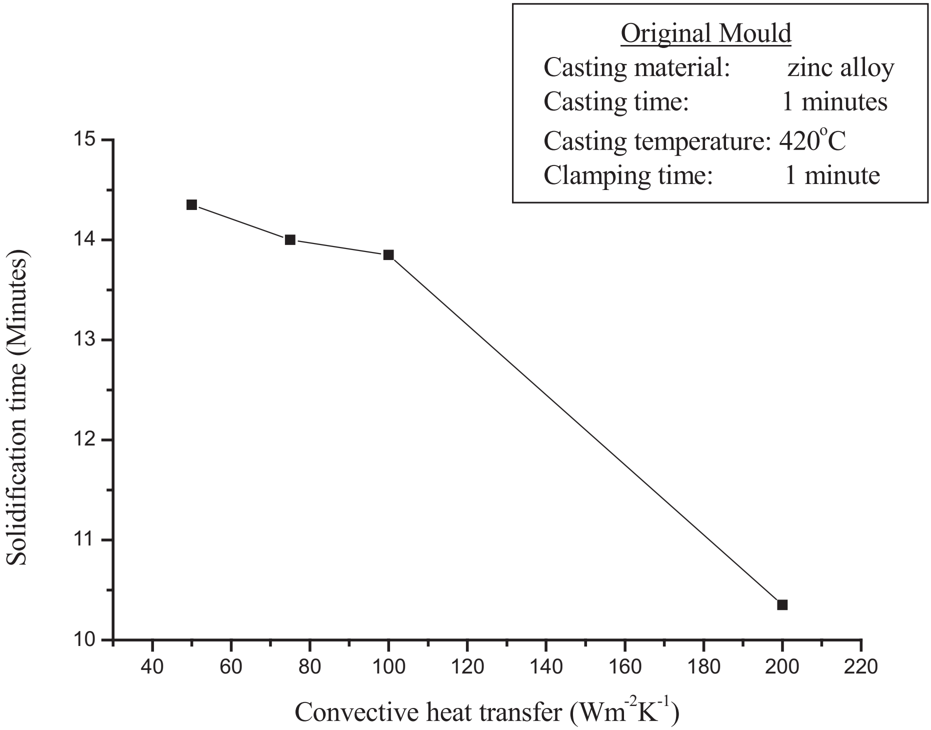


Figure 6: Solidification time with coefficient of convective heat transfer

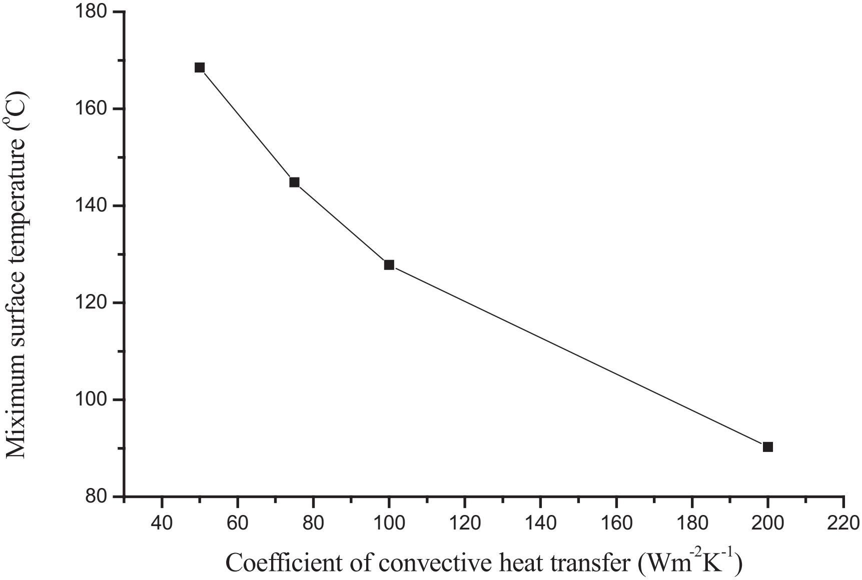


Figure 7: Maximum surface temperature with coefficient of convective heat transfer

Therefore, after the removal of the mould from the casting machine, continuous effective cooling is recommended. Circulating air at room temperature after placing the filled mould on a table with a metal surface is preferred.

4. CONTROL METHODS FOR THERMAL PROCESS

The developed thermal property substitute, the mixing method, and the induced air-cooling method were summarised below.

4.1 Thermal property substitute

Thermal property substitute is to replace the silicon material in the required area by the material with the higher thermal conductivity and/or heat capacity to improve the heat transfer. The substitute materials, like plain carbon steel and waxes, were investigated.

4.1.1. Cooling with different Cooling Materials (before removal of the cast part)

The experimental results for different casting materials and different cooling media including casting wax, beeswax, candle wax, and plain carbon steel are shown in figures 8 and 9.

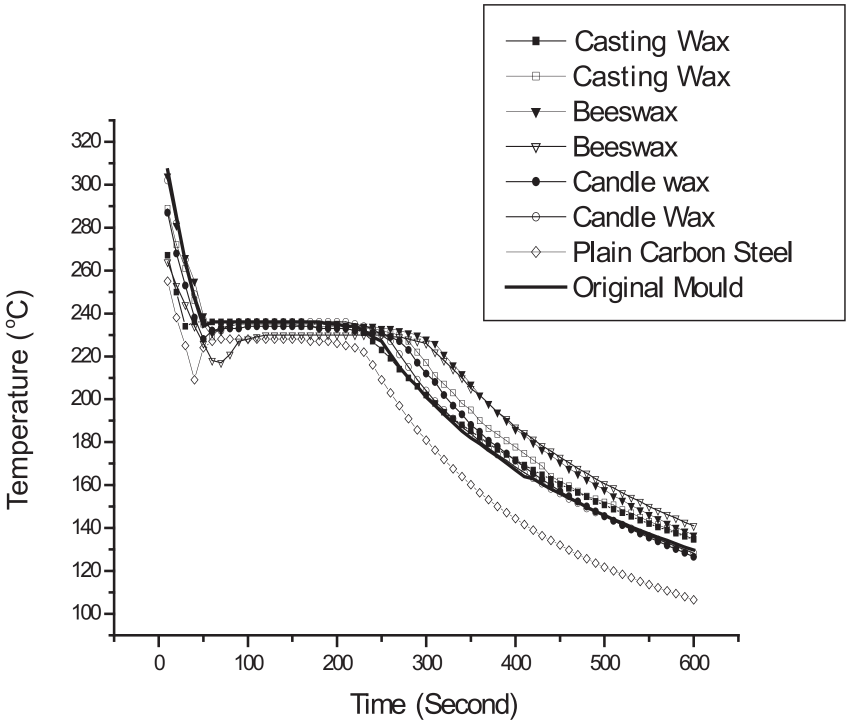


Figure 8: Cooling curve of a pewter part with different waxes and the plain carbon metal disc as cooling media

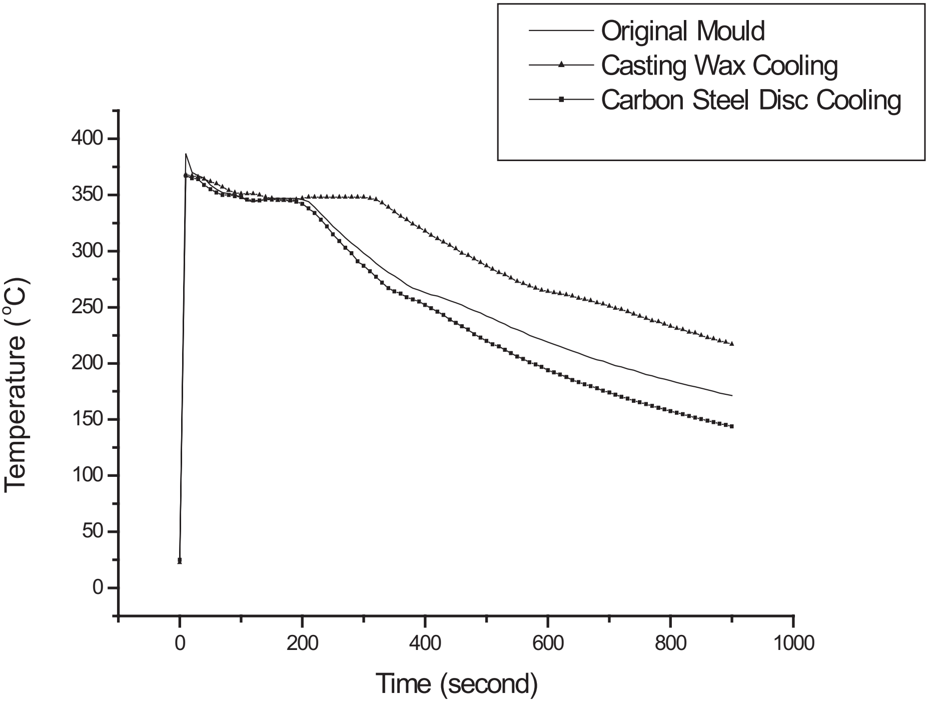


Figure 9: Cooling curve of a zinc alloy part with the casting wax and the plain carbon metal disc as cooling media

From the results it can be derived that:

(1) Plain carbon steel has the ability to substantially decrease the maximum temperature and shorten the cooling time. Taking the pewter casts in Figure 8 as an example, the maximum temperature measured was 307°C, whilst the temperature after 10 minutes was 130°C for the original mould. With a metallic disc as cooling material, the maximum temperature was 255°C with a final temperature after 10 minutes of 106°C. The time required to accomplish the phase change point was shortened from 2 minutes for the original mould to 1.5 minutes with a metal cooling disc.

The same conclusion can be drawn with zinc alloy as casting material (Figure 9). In the original mould, the maximum temperature measured during the cooling process was 387°C, with a temperature of 171°C after 15 minutes. The same values with a metallic cooling disc were 367°C and 144°C respectively.

(2) Use of cooling materials with melting temperatures lower than the casting temperature (e.g. casting wax) in a mould causes a decrease in the maximum

temperature to some degree, but does not shorten the total cooling time. In some cases it can even result in increased cooling and phase change times. For instance, casting wax can decrease the highest temperature for pewter as casting material from 344°C to 333°C with a casting temperature of 360°C, but the cooling time is not shortened.

4.1.2. Cooling of mould after removal of the cast part

Figure 10 shows the cooling process of the mould after removal of the cast part. The initial mould temperature was 110°C .

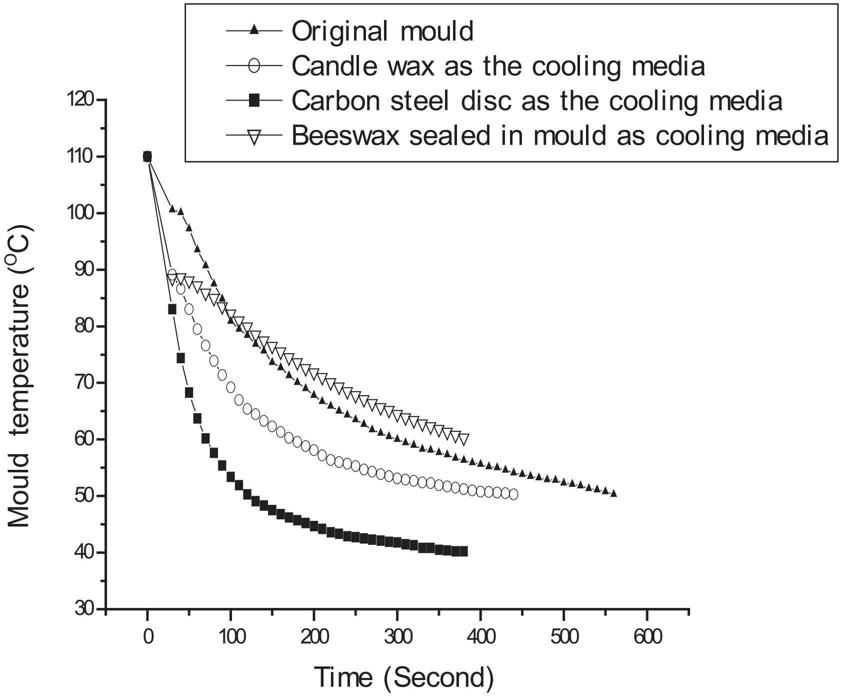


Figure 10: Mould-cooling curve after removal of part

It proves that carbon steel cooled mould cools down much faster after removal of the product than an un-cooled mould, or a cooled mould from which the cooling material has been removed. This is an important consequence of mould cooling since it shortens the overall production cycle - and hence increases the manufacturing efficiency. Waxes do not have the obvious effects on the casting process.

4.1.3. The Effect of Cooling on mould temperature for different shots

Figure 11 shows the mould temperature after different shots. The measurement position is on the mould surface, 1cm from the sprue of the mould. The casting time was 1 minute and measurements were carried out upon removal of the cast part – after an additional 30 seconds.

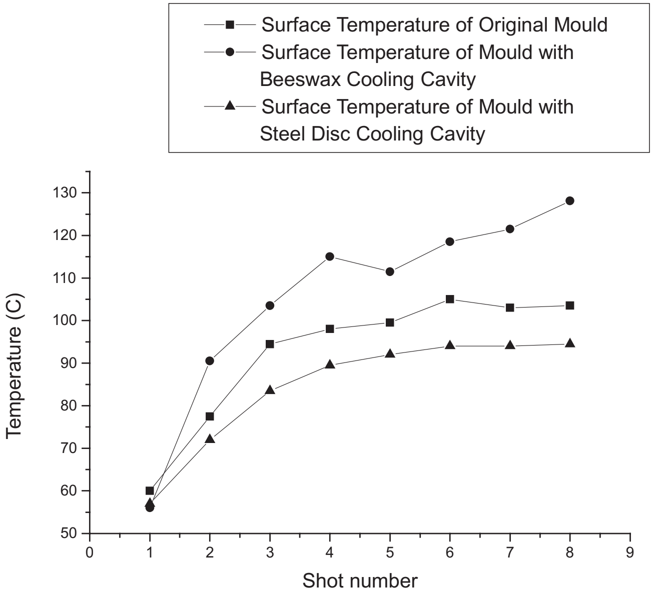


Figure11: Temperature of mould t op surface with multiple shots

From the results, it is evident that plain carbon steel limits the mould surface temperature best of the different cooling materials tested for this characteristic - which is useful for continuous manufacture. In the experimental case, the plain carbon steel cooled mould was stabilised at 85 ~90 after about ten shots. This was about 15~20 lower than for the original mould, whereas with wax as cooling medium, the mould temperature was about 20 higher than the original mould.

4.2 Mixture method

The mixture method is of copper powder or other metals with a higher thermal conductivity and heat capacity, with the silicone rubber material evenly in the appropriate composition before vulcanising.

The effects of a metal powder with the higher thermal conductivity and higher thermal storage ability, mixed with the silicone rubber in different compositions before vulcanising on the cooling process and the cooling time are shown in Figures 12 and 13. It is obvious that the copper powder has a large potential to improve the cooling process and decrease the solidification time of the cast part. It promises to be an effective approach for all shapes of cast parts, and warrants experimental evaluation.

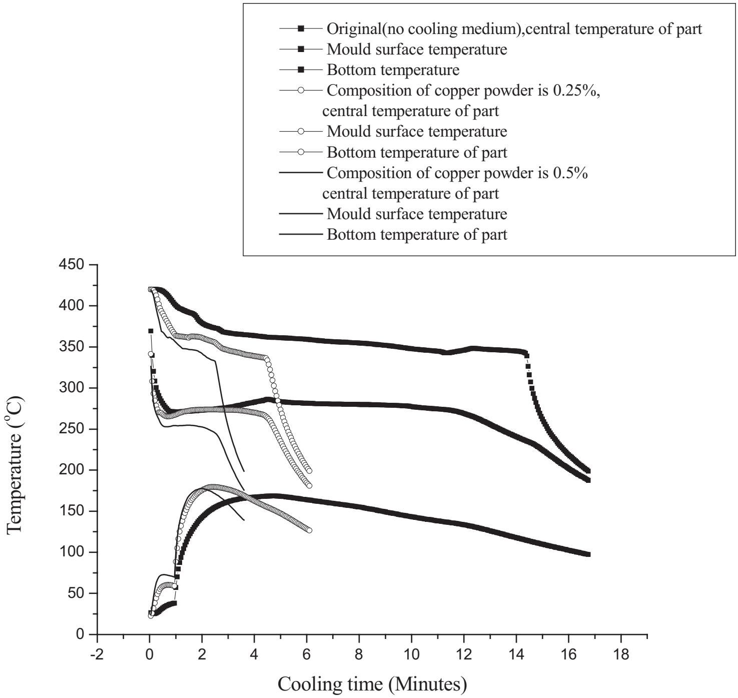


Figure 12: Composition of copper powder on cooling process

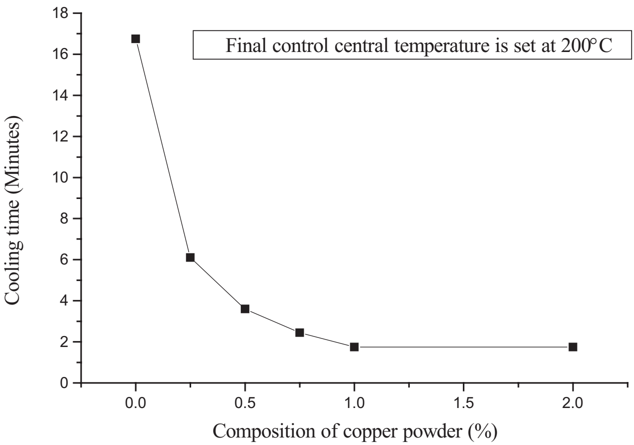


Figure 13: Composition of powder on cooling time

The combined effect of the operation condition at the clamping time of 90 seconds, coefficient of heat transfer of 200 $Wm^{2}K^{1}$ with a metal-topped cooling table and the metal plate covering the mould, and the silicone mould including 0.75% copper powder in mass is shown in Figure 14.

The results show that the methods suggested above should improve the casting process substantially. The par ameters can also be varied individually or collectively according to the specific application.

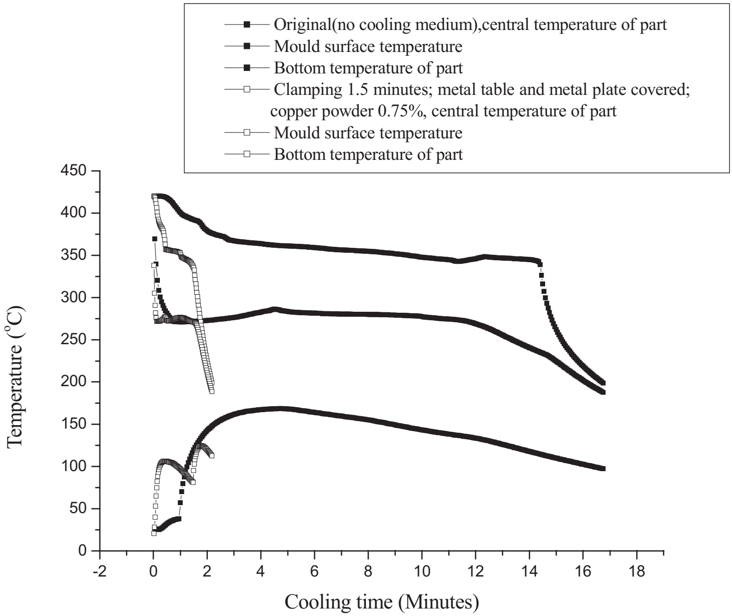


Figure 14: Total effect of the cooling approaches

4.3 Forced air-cooling induced from the spinning of the moulds

When the mould rotates around a fixed axis, it equates to a situation where the surrounding air circulates around the fixed mould's perimeter. If an air channel is made through the spinning mould (Fig. 15), a pressure difference will be established between the inlet and outlet whilst the spin-casting machine is in operation. Consequently, air at room

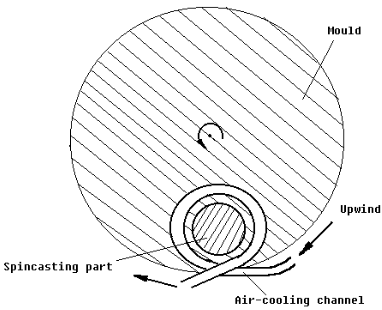


Figure15: Scheme of the air-cooling principle

temperature will flow through the air channel, which is next to the cavity of a mould. When the molten metal at high temperature is poured into the cavity, heat from the casting material will be transferred through the channel and to the ambient air by forced convection.

The relationship between the coefficient of heat transfer (Nusselt Number) and the pressure difference can be derived from the fundamental of thermal science (Sherwin, Horseley, 1996; Matworthy, 1997; Haberman, John, 1992; and Streeter, Wylie, & Bedford, 1998):

$$Nu \quad 703.94\left(\frac{D^4}{L^2}\right)^{1/3} \quad P^{1/3}$$ (For laminar flow) (1)

$$Nu \quad 1126.26\left(\frac{D^3}{L}\right)^{0\ 457} \quad P^{0\ 457}$$ (For turbulent flow) (2)

where D is diameter, L is length of tube, Nu is Nusselt number, and ΔP is pressure difference.

It can be concluded that heat transfer will result between air at room temperature and the mould when a pressure difference between the inlet and outlet of the air-cooling channel is established - and the heat transfer will be influenced obviously by the pressure difference. The potential of controlling the thermal process will be determined by the size of the pipe and the pressure difference between the inlet and outlet. In practice, the pipe size - which is limited by the practical situation - cannot be changed easily. Therefore, increasing the pressure difference will be the focus in trying to improve the thermal process. It is also of importance that the pressure difference is influenced by the shape and the size of the inlet and outlet.

The potential for heat transfer between the induced air and the mould will be much different for laminar flow and turbulent flow. Turbulent flow will be preferable for thermal process control in a situation as described.

4.3.1 Influence of induced air on casting process

Simulation results on the thermal process for air velocities in the cooling channel of between 3 m/s and 10 m/s, are shown in Fig.16. The following parameters were assumed for the simulation:

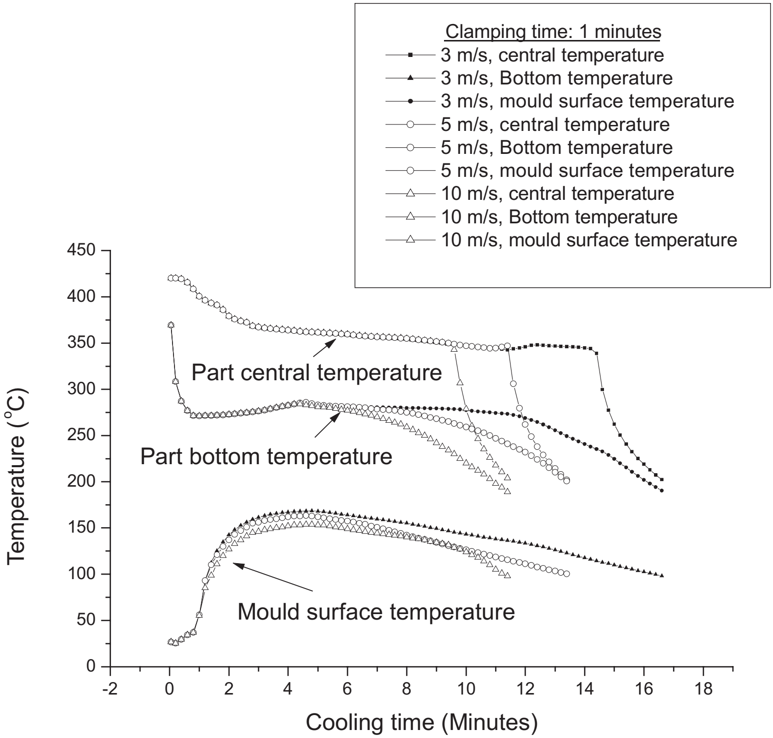


Figure 16: Simulated temperature variations at different airflow velocities and at different positions in the mould

(1) A 229-mm silicon mould with a thickness of 55 mm,

(2) A 16 mm cooling pipe, with its inner surface 5 mm from the outer surface of the casting cavity,

(3) A round casting cavity of 60 mm in diameter and a height of 15 mm.

The results of temperature variation with time at typical points on the cast part and mould showed that:

(1) The temperature distribution in the mould and the casting part should be improved significantly. For example, with an increase in the simulated airflow velocity from 3 m/s to 10 m/s, the highest mould surface temperature was decreased by about 20°C and the cast part's cooling was improved to an acceptable level, irrespective of the relative position on the cast part.

(2) The influence of a cooling channel on the thermal process is different from thermal property substitute method and the mixture method. These methods all improve the thermal process by modifying the equivalent thermal properties whilst all the heat released from the cast part is transferred to the surface through the mould material. The cooling method utilising induced-air directly removes the released heat from the area adjacent next to the cast part.

The solidification time for cast parts (Fig. 17) is also shortened significantly. With an increase in the average air flow velocity in the cooling channel from 0 m/s (no cooling channel) to 10 m/s, the solidification time is shortened from 14.3 minutes to about 9.7 minutes, thus by about 32%. Similarly the production rate (with a number of sequential shots) should be increased substantially.

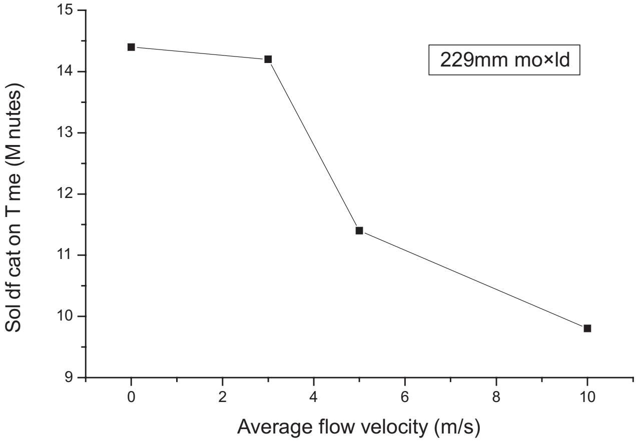


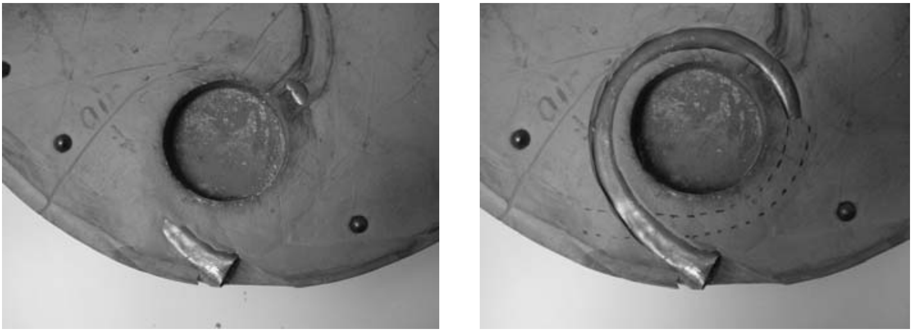
Figure 17: Solidification time with airflow velocity in cooling channel

4.3.2. Experimental Study and Results

The experimental procedures were conducted with a mould diameter of 381mm (15 inch) and a thickness of 55 mm, whilst a cooling pipe with a diameter of 16 mm and a length of 300 mm, 5 mm from the inner surface of the pipe to the outer surface of the casting cavity, was used. The circular casting cavity was 60 mm in diameter and 15 mm in thickness.

For all measurements, the casting time was 1 minute with a clamping pressure of 5.86×10^5 Pa (85Psi) with a rotational speed of 550 RPM, the interval between shots was 6 minutes.

The mould with a cooling channel as described is shown in Fig .18, Fig. 18(a) is the photo of the practical mould with the cooling channel emerged in the mould, whilst Fig. 18(b) is the photo for the same mould but the silicon cover layer was cut off to demonstrate the inner structure. The measured results are shown in Fig.19. It is important to note that, contrary to expectations, the relative temperature of the modified mould was higher than that of the unmodified mould. The reason is that the basic design of the improved mould could not ensure the required airflow in the cooling channel. The airflow with a low velocity has a low convection heat transfer coefficient. Therefore, the total effect is slowing down the heat transfer process and the solidification rate - with a corresponding increase in the mould surface temperature.



(a) (b)

Figure 18: Experimental mould with air-cooling channel

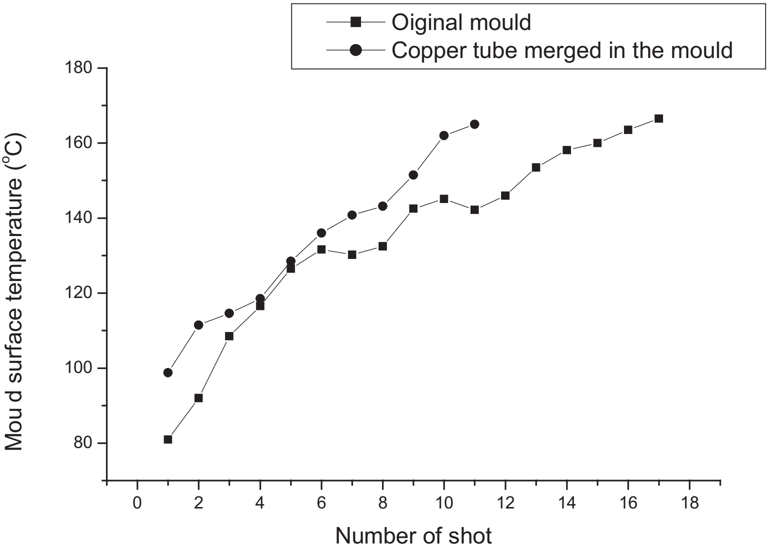


Figure 19: Comparison between original mould and improved air-cooling channel

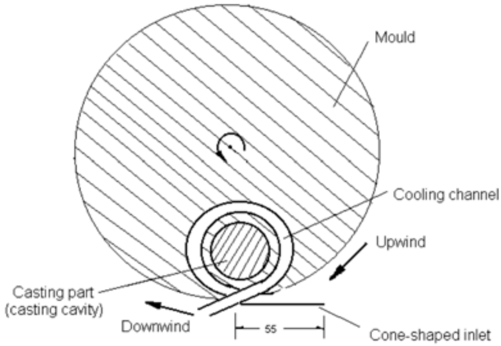


Figure 20: Scheme of the improved air-cooling channel

In order to improve the airflow in the cooling channel, the structure of the inlet had to be redesigned. The reason for the low airflow velocity inside the channel is the low pressure difference between inlet and outlet. If more air can be accumulated in front of the inlet of the channel, the required pressure difference will be increased. Therefore, a specially designed, cone-shaped inlet (Fig. 20) was developed, manufactured and mounted on the spinning mould. The experimental mould with the cooling channel and the cone-shaped inlet is shown in Fig. 21.

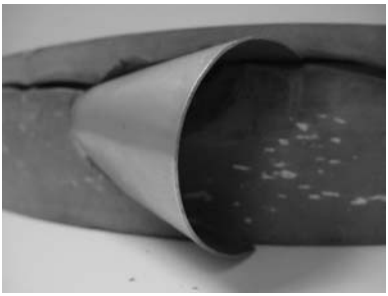


Figure 21: The improved mould with the cone-shaped inlet

The corresponding experimental results are shown in Fig. 22. The result was a decrease in mould surface temperature by an average of approximately 20°C compared to the original design. Thus, the thermal process was improved appreciably by the modified inlet opening. For example, the mould temperature for the 10th shot was 145.1°C for the original mould, 162°C for the preliminary mould with the air-cooling channel, and only 119.3°C for the mould with the cone-shaped inlet.

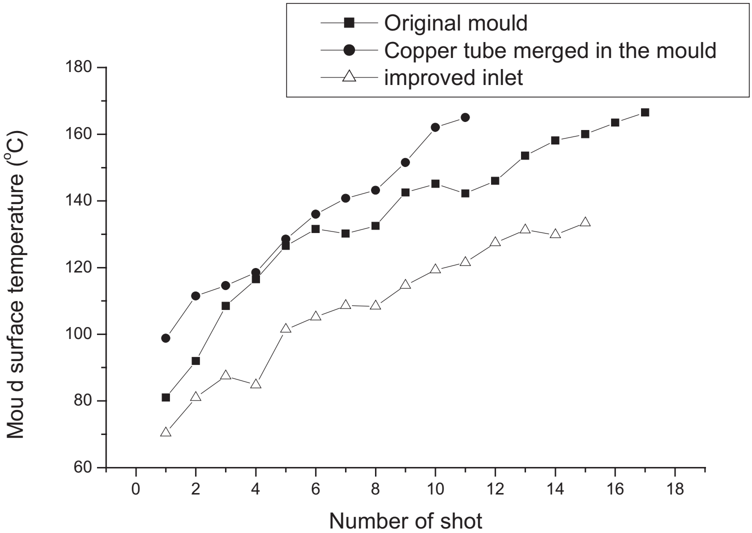


Figure 22: Comparison between original mould and improved air-cooling channel

5. CONCLUSION

The investigation of the thermal process of spin-casting and the developed control methods carried out by the experiments and simulation showed the characteristics of the casting process and testified the effectiveness of the thermal controlling ways, such as the thermal property substitute by the metal disc, the mixture method, and the automatically induced air-cooling method.

The casting process can be influenced by the operation factors, like the clamping casting time etc. the phase change in the casting is time-consuming, the thermal property substitute by the metal, the mixture with the copper powder at the composition of 0.75%, as well as the induced air-cooling method configured with the cone-shaped inlet of the channel have the potential to optimize the process with respect to the solidification rate, the maximum mould temperature, the mould temperature distribution, and the mould cooling speed.

The details was emphasized on the system of the induced automatically air cooling method. The results indicate that the inlet shape of the cooling channel is a critical factor in ensuring proper operation of the process. A cone-shaped inlet was proposed and consequently a decrease in mould temperature of 20°C was measured - relative to the original mould design. Thus, air-cooling induced from the spinning of a spin-casting mould is a feasible method to control the cooling process of the spin casting.

The developed control methods can be applied to the practice independently or collectively according to the specific situations and requirements.

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