Study on Milling-combined Laser Consolidation System (Invited Paper) – For the Advanced Injection Mold by Additive Manufacturing –

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A multitasking machine, in which a metal powder is selectively heated and fused by laser beam irradiation and the edge of the consolidated structure is cut with an end mill, has been developed for the production of injection mold. This machine has an advantage that the molding die does not have to be separated for the cooling channels. However, it is difficult to finish the internal face of cooling channels which are complicatedly located inside the molding die. This study describes a finishing performance of cooling channel with a face protuberance inside a molding die with free abrasive grains. A fluid flow in the cooling channel is calculatedly simulated, and the effect of internal face protuberance which is spirally arranged on the finishing performance is experimentally investigated. The results showed the application of the face protuberance on the internal face was quite effective for the improvement of the face condition. The internal finishing of cooling channel was also effective for the improvement of the thermophysical properties.

***Key Words*:** Selective Laser Sintering, Selective Laser Melting, End mill Internal cooling channel, Monitoring

1. Introduction

Various types of layered manufacturing techniques have been proposed since Kodama first presented a new method for fabricating three-dimensional plastic models[1]. These layered manufacturing techniques were followed by the development of a three-dimensional CAD system and classified as being distinct from the forming and material-removal processes[2]. A variety of materials, such as polymers, ceramics, and metal powders, have been used to manufacture a range of prototypes, tools, and functional end-products[3]. Indeed, the use of metal powders in layered manufactured techniques is especially remarkable because the structures obtained are strong enough for practical use.

Recently, a multitasking machine, in which a metal powder is selectively heated and fused by laser beam irradiation and the edge of the consolidated structure cut with an end mill, and which results in improved cost performance and reduced production times, has recently been developed for the production of injection mold[4]. The injection mold produced by the layered manufacturing processes has the advantage that the cooling channel can be complicatedly located by using a designed CAD model. Additionally, the injection mold does not have to be partitioned into separate block to locate the cooling channels. However, the internal face of the cooling channels obtained by the layered manufacturing processes is not uniform due to the partially molten powder, the adhered powder and the pore[5]. It is difficult to finish the internal face of the cooling channel which is located inside the injection mold.

This paper deals with an internal finishing of a cooling channel located in an injection mold which is fabricated by the layered manufacturing. The free abrasive grains are used to finish the internal face of the cooling channels. A fluid flow in the cooling channel is calculatedly simulated, and the effect of internal face protuberance which is spirally arranged on the finishing performance is experimentally investigated. Additionally, the effect of internal face finishing on the thermophysical properties of the cooling channels is also evaluated.

2. Layered manufacturing equipment

2.1 Metal powder

The SEM image of metal powder is shown in Fig. 1, and its specifications are summarized in Table 1. The metal powder used in the experiment is a mixture of 70% alloy steel powder (ISO: 42CrMo4), 20% copper phosphorous alloy powder (ASTM: C52100) and 10% nickel powder in weight. Each powder was prepared by gas atomization method, so that its shapes are irregular. The average particle diameter of powder mixture used

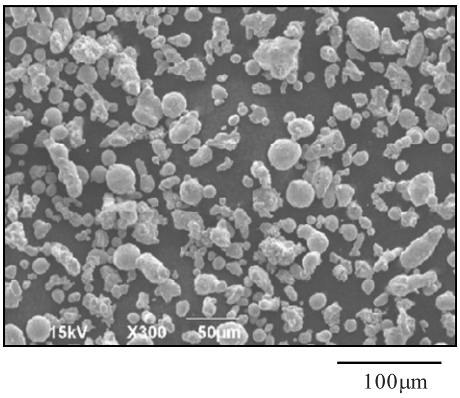


Fig. 1 SEM image of metal powder

Table 1 Specifications of metal powder

Material		Fe, Cu, Ni
Shape		Irregular
Particle mean diameter [μm]	d	25
Thermal conductivity [W/m·K]	T_k	0.14

Table 2 Specifications of metal powder

Laser type		Yb:fiber (CW)
Beam diameter [μm]	ϕ	100
Wavelength [nm]	λ	1070
Maximum power [W]	Q	200
Scanning speed [mm/s]	F	440
Layer thickness [μm]	t	50
Hatching pitch [μm]	H	50

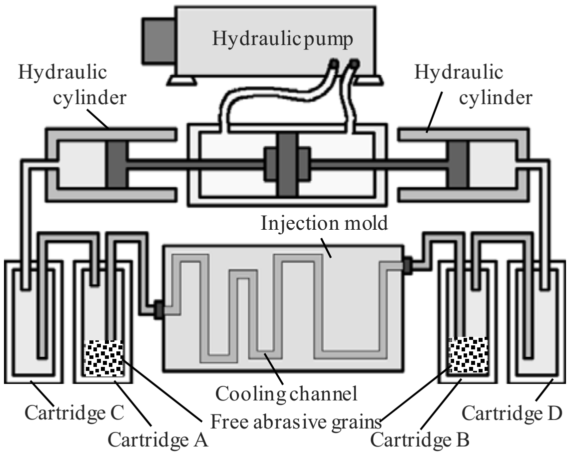
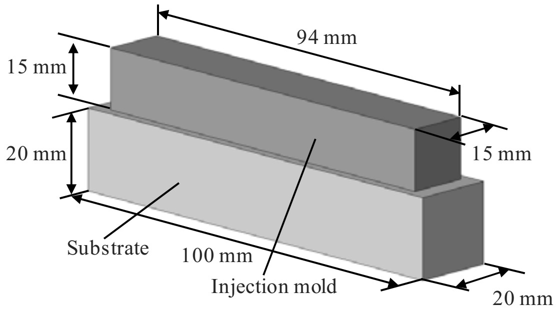


Fig. 2 Finishing equipment for internal face of cooling channel

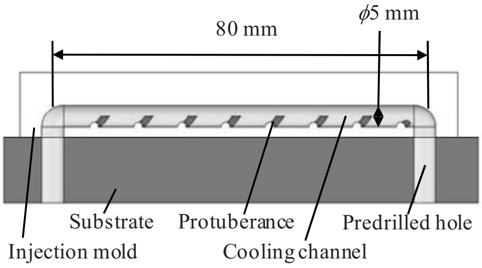
in the experiment is 25 μm. Structures produced by this powder mixture have sufficient strength and hardness for fabrication of the injection mold.

2.2 Layered manufacturing equipment

The fabrication of injection mold using the metal powder is performed with LUMEX25™ (Panasonic Electric Works Co., Ltd.), and its consolidation conditions are given in Table 2. The laser beam used in the equipment is a Yb:fiber laser (IPG Photonics Corp.: YLR-SM) with a wavelength of 1070 nm. The laser beam which is led to the powdered surface through a galvanometer mirror forms a Gaussian shape and the beam diameter at the focal spot is 100 μm. In brief, the metal powder is deposited on the substrate at a thickness of 50 μm using a leveling blade. A laser beam is then focused on the powdered surface through a galvanometer mirror, and scanned over it using programmed NC data. The hatching pitch of the laser beam is kept constant to 50 μm. After scanning a consolidation layer, laser irradiation is performed whilst varying the scan direction of the laser beam by 90° to prevent anisotropy of the consolidated structure. These processes are repeated until the injection mold is completely fabricated. The injection mold thus obtained is clarified into full melting, so that the inside of the injection mold is completely molten and uniformly alloyed. These processes are performed under a nitrogen atmosphere to prevent oxidization of the metal powder during laser irradiation. The substrate surface is sandblasted with the average grain size of 300 μm to improve the wetting property of the molten powder, and its surface roughness is kept constant of R_a=3.5 μm[6].



(a) Outside drawing



(b) Cross section

Fig. 3 Cooling channel with the face protuberance

3. Experimental setup and conditions

3.1 Finishing equipment for internal face of cooling channel

The experimental setup for finishing the internal face of the cooling channel which is located inside the injection mold is illustrated schematically in Fig. 2. This system consists of a hydraulic pump, a hydraulic cylinder, and four cartridges. The cooling channel inside the injection mold can be connected to this system as the connected channel builds a closed loop. The cartridge A and the cartridge B are filled with a fluid and free abrasive grains, respectively. The cartridge C and the cartridge D are filled with a fluid, and these cartridges are used as a buffer so as not to flow the free abrasive grains to the hydraulic cylinder. When internal pressure is applied in the closed loop, the fluid containing the free abrasive grains is passed through the cooling channel and the internal face of the cooling channel is then finished by these grains. The free abrasive grains that pass through the cooling channel can be re-used for internal face finishing of the cooling channel by reversing the flow direction of the fluid containing the free abrasive grains. This is achieved by switching the electromagnetic valve with a period of 1 second. The internal pressure and the velocity of the fluid are controlled using a hydraulic pump.

3.2 Analysis of fluid flow in cooling channel

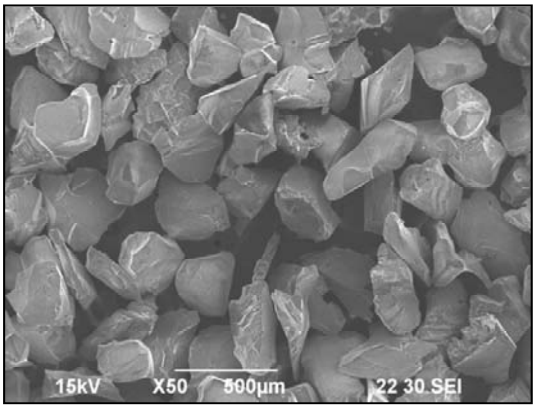
In order to evaluate a fluid flow in the cooling channel, a flow simulation with COSMOS Flo Works™ is performed. The model designed by 3D CAD system is shown in Fig. 3 and its analysis conditions are summarized in Table 3. The model size of injection mold is 15 × 94 × 15 mm and U-shaped cooling channel with a diameter of 5 mm and a length of 80 mm is located inside. A semicircle face protuberance with a height of 1 mm and a pitch

Table 3 Analysis conditions for internal flow

Cooling channel		
Form		U-shaped
Diameter [mm]	f	5
Length [mm]	L	80
Solution		
Fluid		Water
Flow rate [l/s]		0.3
Temperature [K]		293
Outlet pressure		Static
Boundary condition		Adiabatic wall

Table 4 Experimental conditions for internal finishing

Free abrasive grain		
Material		Al_2O_3
Diameter [μm]		60, 100, 300
Concentration [vol%]	C_v	4 - 8
Fluid		Water



1 mm

Fig. 4 SEM image of free abrasive grains
(Material: Al_2O_3, Grain size: 100 μm)

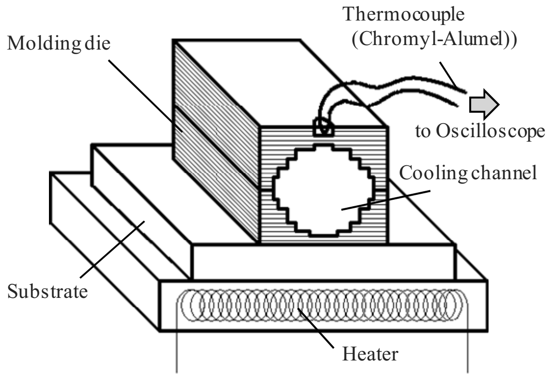


Fig. 5 Finishing equipment for internal face of cooling channel

Table 5 Conditions for investigation of thermophysical property

Thermocouple		
Type		Chromyl-Alumel
Diameter [mm]	ϕ_t	1.6
Distance from edge [mm]		1.0
Injection mold		
Initial temperature [K]	T_i	473
Solution		
Type		Water
Temperature [K]	T_s	273
Pressure [Mpa]	P	1.4

of 10 mm is spirally arranged only on the bottom face of the cooling channel due to the limitation of the layered manufacturing technique. The fluid in the analysis is water with a temperature of 293 K and its flow rate is 0.3 l/sec. An adiabatic wall is applied to the internal face of the cooling channel, and an outlet pressure is defined as a static condition. The cooling channel without the face protuberance is also evaluated for comparison.

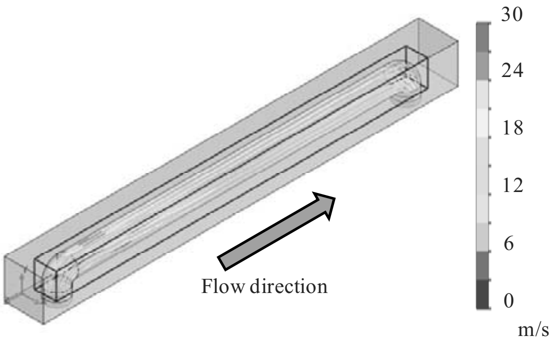
3.3 Experimental conditions for internal finishing

In order to investigate the internal face conditions in the cooling channel, the injection mold which was the same model as shown in Fig. 3 was fabricated using the above-mentioned layered manufacturing equipment. The substrate used is the carbon steel (AISI: 1049), and the hole with a diameter of 5 mm is predrilled in the substrate. After the fabrication of the injection mold, it was partitioned into two pieces at the center of the cooling channel to evaluate the internal face conditions. The cooling channel was then rebuilt by joining the two pieces of the injection mold with a packing.

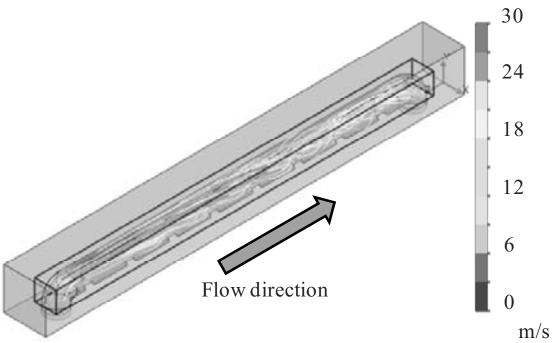
The experimental conditions for internal finishing are given in Table 4, and SEM image of the free abrasive grains is shown in Fig. 4. The free abrasive grains were made from Al_2O_3 and had an average diameter of 60, 100, and 300 μm. The internal pressure applied to the cooling channel ranged from 0.2 to 1.4 MPa. The maximum flow rate of the fluid containing the free abrasive grains is 0.3 l/sec and its value depends on the internal pressure loaded in the cooling channel by the hydraulic pump. After finishing with free abrasive grains, the upper face of cooling channels was measured with a three-dimensional surface profiling system (Tokyo Seimitsu Co., Ltd.: Surfcom). The cooling channel without the face protuberance was also fabricated using the above-mentioned layered manufacturing equipment to investigate the effect of the face protuberance on the finishing performance.

3.4 Effect of internal finishing on thermophysical property

In order to investigate the effect of internal face finishing on the thermophysical properties of the cooling channel, the temperature history inside the cooling channel was recorded. The experimental setup is illustrated in Fig. 5 and its conditions are summarized in Table 5. The thermocouple used in the experiment was a chromel-alumel thermocouple with a wire diameter of 1.6 mm. A pin hole with a diameter of 1.7 mm was fabricated on the surface of the molding die and the thermocouple fixed at a distance, *z*, of 2 mm from the internal face of the cooling channel. Cold water at T_s=273 K was passed through the cooling channel whilst the molding die containing the cooling channel was heated to T_i=473 K with a heater. The output signal obtained from the thermocouple was then recorded using an oscilloscope (Yokogawa Corp.: Scope Corder DL-750), and the time interval required by the measuring point to reach room temperature (300



(a) Without face protuberance



(b) With face protuberance
Fig. 6 Fluid flow in cooling channel

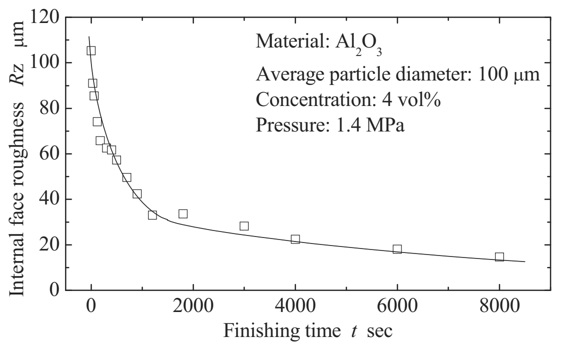


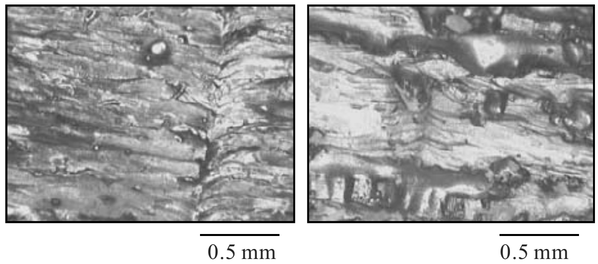
Fig. 7 Influence of finishing time on internal face roughness

K) was determined.

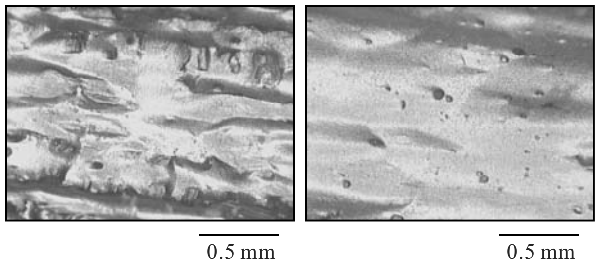
4. Results and discussions

4.1 Analysis of fluid flow in cooling channel

Fig. 6 shows the influence of the face protuberance on flow profiles in cooling channel[7]. As shown in Fig. 6(a), the fluid flow without the face protuberance is externally thrust depending on the centrifugal force which is generated at the entrance region. Therefore, the velocity distribution is occurring in the cooling channel, that is, the fluid flow at the external position is faster than that at the inner position. The velocity of fluid flow then becomes slow gradually due to the internal face roughness in the cooling channel. On the other hand, as shown in Fig. 6(b), the fluid flow with the face protuberance is flowing spirally according to the face protuberance on the internal face. There is almost no velocity distribution at the position of the cooling channel.



(a) Before finishing (b) After 500 sec



(c) After 4000 sec (d) After 8000 sec
Fig. 8 Images of internal face in cooling channel

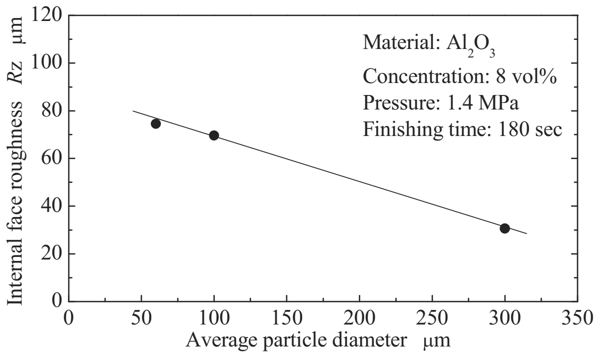


Fig. 9 Influence of grain size on internal face roughness

4.2 Influence of finishing time on internal face roughness

Fig. 7 shows the variation of the internal face roughness with finishing time without the face protuberance; photo images of the internal face after different finishing times are provided in Fig. 8[8]. The internal face roughness of the cooling channel improved significantly during the first 1000 seconds of finishing, after which it improved at a constant rate up to a finishing time of 8000 seconds. As shown in Fig. 8(a), stain, partially melted powder, and adhered powder can clearly be seen on the internal face prior to internal finishing. However, as shown in Fig. 8(b), these unstable layers are removed upon introducing the free abrasive grains into the cooling channel, which results in an alloyed face inside the injection mold. After removal of these unstable layers, the condition of the internal face improved slightly with finishing time, as shown in Fig. 8(c), to finally give the smooth internal face shown in Fig. 8(d). These results confirm that the significant improvement achieved during the initial stages of finishing is due to the removal of the aforementioned unstable powders.

4.3 Influence of grain size on finishing performances

Fig. 9 shows the variation of the internal face roughness with different average particle diameter of the abrasive grain without

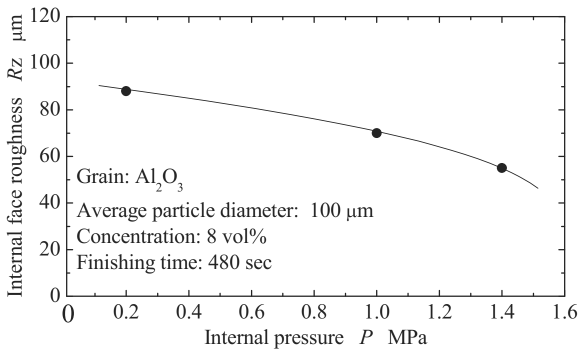


Fig. 10 Influence of internal pressure on finishing performance

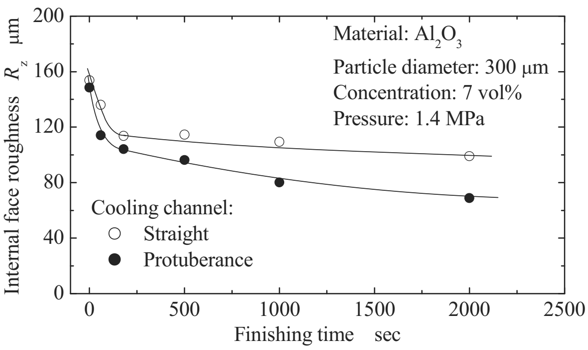


Fig. 11 Influence of face protuberance on internal finishing

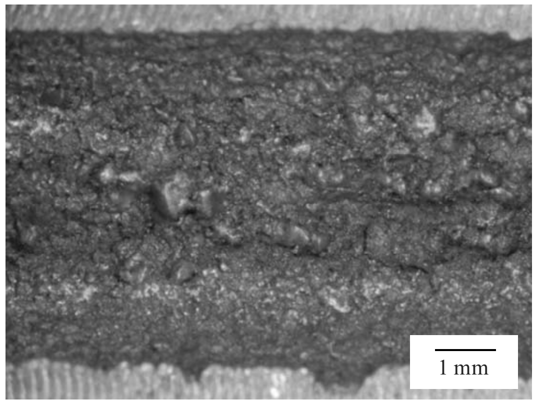
the face protuberance. The finishing time for the internal face was fixed at 180 sec. Abrasive grains with an average particle diameter of 300 μm improved the internal face roughness in the cooling channel to Rz =30 μm after 180 sec, although it should be noted that the finishing time for particles with an average diameter of 100 μm was over 1000 sec, as shown in Fig. 7. The use of large grain is therefore better suited for effective improvement of the internal face. Additionally, the internal face roughness improved with an increase in the average particle diameter, whereas smaller grains were more effective for polishing the internal face. This is due to the fact that free abrasive grains are employed to remove the unstable powder on the internal face rather than to polish the alloyed face. The use of small abrasive grains is more effective in improving the internal face roughness after initial removal of the unstable layers.

4.4 Influence of internal pressure on finishing performances

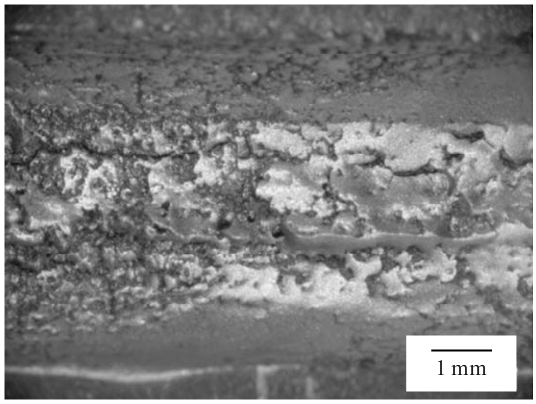
Fig. 10 shows the variation of the internal face roughness of the cooling channel with the internal pressure applied by the hydraulic pump. The finishing time was fixed at 480 sec, and the upper face of the cooling channel is summarized. It can clearly be seen from this figure that internal face finishing at a high internal pressure is better than at a low internal pressure. The high-speed flow of the free abrasive grains results in an increase in their kinetic energy, thereby increasing the force with which they collide with the internal face and resulting in an improvement of the surface roughness.

4.5 Effect of face protuberance on finishing performance

Fig. 11 shows the influence of face protuberance in the cooling channel on the finishing performance. In the case of the cooling channel with the face protuberance, it was same that the internal face roughness improved significantly during the first 180 seconds of finishing. However, after the significant improvement up to the finishing time of 180 seconds, the further improvement of the internal face roughness is obtained. The internal face roughness at the finishing time of 2000 seconds is 30% improved compared with that of 180 seconds.



(a) Without face protuberance (Rz=109 mm)



(b) With face protuberance(Rz=80 mm)
Fig. 12 Images of internal face in cooling channel

Fig. 12 compares the photo images of the upper face in the cooling channel in the finishing time of 1000 seconds. The stein on the upper face was almost removed and the application of the face protuberance in the cooling channel made it possible to finish the upper face effectively. The surface roughness on the internal face with the face protuberance was improved to R_z=80 μm.

4.6 Effect of internal finishing on thermophysical property

Fig. 13 shows the temperature history obtained from the thermocouple before and after finishing of the cooling channel. When cold water starts to flow into the cooling channel, the temperature of the consolidated structure gradually decreases with an increase in cooling time. The cooling rate of the consolidated structure increases with the degree of finishing of the internal face.

Fig. 14 shows a comparison of the thermophysical properties in the cooling channel before and after internal face finishing. Here, the time interval required for the consolidated structure to reach room temperature (300 K) is evaluated. The measurements

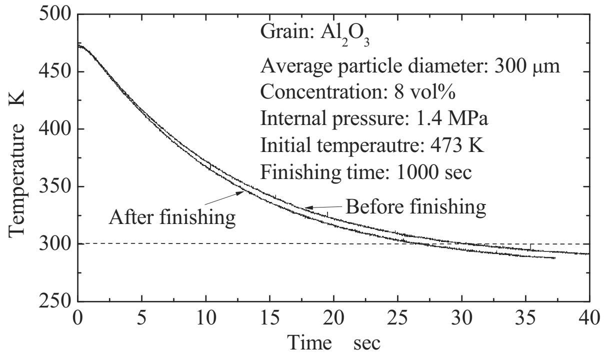


Fig. 13 Temperature history of the consolidated structure

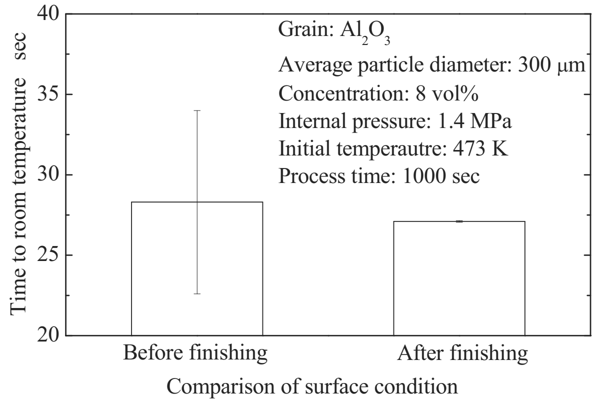


Fig. 14 Comparison of thermophysical property

of the time interval were repeated five times, respectively. It was found that the cooling time decreased slightly by approximately 4% as a result of finishing the internal face. This slightly decrease can be explained on the basis of the structure of the cooling channel. Thus, the thermal conductivity of the unstable layer containing the partially melted and adhered powders is lower than that of the inner block of the consolidated structure. The improvement in the thermophysical properties observed after finishing the internal face is therefore due to the removal of this unstable layer. Additionally, it was found that there was almost no scatter of the time interval required for the consolidated structure to reach room temperature after the finishing of cooling channel. This result suggests that it is possible to control the temperature of the injection mold easily by finishing the internal face of the cooling channel. These results clearly show that internal face finishing of the cooling channel with free abrasive grains is effective for improving its thermophysical properties.

5. Conclusions

In this paper, the finishing method for the internal face of a cooling channel located in the injection mold with free abrasive grains was proposed. The fluid flow in the cooling channel was simulated, and the effect of internal face protuberance which was arranged spirally on the finishing performance was investigated. The main results obtained are as follows.

1) The fluid flow with the face protuberance was flowing spirally according to the face protuberance on the internal face, and the velocity distribution inside the molding die was quite small although the fluid flow without the protuberance was externally thrust depending on the centrifugal force.
2) The internal face roughness of the cooling channel improved significantly during the first 1000 seconds of finishing, after which it improved at a constant rate up to a finishing time of 8000 seconds. The significant improvement achieved during the initial stages of finishing is due to the removal of the aforementioned unstable powders.
3) The application of the face protuberance was quite effective for the improvement of the face condition in the cooling channel.
4) The use of large grain is better suited for effective improvement of the internal face. Free abrasive grains are employed to remove the unstable powder on the internal face rather than to polish the alloyed face.
5) The cooling time of the consolidated structure decreased slightly by approximately 4% as a result of finishing the internal face. Additionally, there was almost no scatter of the time interval required for the consolidated structure to reach room temperature after the finishing of cooling channel. The internal face finishing was effective for the improvement of the thermophysical properties in the cooling channel.

Acknowledgement

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