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Effect of multi-step slow shot speed on microstructure of vacuum die cast AZ91D magnesium alloy

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Abstract: Two multi-step (two-step and three-step) slow shot speeds were used in the vacuum die casting process of AZ91D magnesium alloy. The vacuum pressure variation in the die cavity before mold filling was monitored by using a pressure sensor. The microstructures of the produced castings were analyzed with optical microscope and image analysis software. The experimental results demonstrate that, the vacuum pressure in the die cavity at the beginning of mold filling is significantly reduced by using three-step slow shot speed, resulting in a low gas porosity level in the produced castings. At an appropriate multi-step slow shot speed, the dwell time of the liquid metal in the shot sleeve before mold filling can be reduced and the flow of the liquid metal in the shot sleeve at the later stage of the slow shot process can be restrained, which cause a low externally solidified crystal content in the produced castings.

Key words: magnesium alloy; vacuum die casting; slow shot speed; gas porosity; externally solidified crystal

1 Introduction

High-pressure die casting is currently the most common process for manufacturing near-net shape cast components of magnesium and aluminum alloys [1]. For die casting produced by a cold chamber die casting machine, molten metal is first poured into the shot sleeve, and then pushed by a plunger to flow in the shot sleeve, enter the runner and gating system, and inject into the die cavity. As the casting solidifies, the die opens and the casting is ejected from the die. In the injection process, the initial air in the shot sleeve and die cavity may be trapped in the molten metal as small air bubbles which will cause gas porosity when the metal is solidified [2]. The presence of gas porosity limits the integrity of the casting, generally produces low quality casting which is unsuitable for further heat treatment. The mechanical properties of the casting suffer from the gas porosity and lack of heat treatment [3].

Vacuum die casting process is an effective way in reducing the gas porosity level in castings and has been widely applied in the die casting industry [4,5]. The vacuum pressure in the die cavity at the beginning of mold filling has a great influence on the quality of vacuum die castings. In order to enhance the evacuating ability of the vacuum system, equipment techniques, such as the designing of vacuum valve [5] and the mold sealing technique [6], have achieved considerable attention. An ultra-high vacuum level of 5−10 kPa can now be achieved. The volume of gas porosity in castings can be significantly reduced while filling the die cavity with such high vacuum levels [7,8]. The vacuum die castings containing low volume of gas porosity are suitable for heat treatment, and thus the metallurgical characteristics and mechanical properties of the vacuum die castings can be further improved [9−12].

The designing of the slow shot speed is very important for the vacuum die casting process. Firstly, the vacuum pressure in the die cavity at the beginning of mold filling strongly depends on the slow shot speed as it determines the vacuum time before mold filling. Meanwhile, the designing of the slow shot speed can affect the flow behavior and solidification condition of molten metal in the shot sleeve before the high speed injection, and thus has great influence on the gas

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entrapment and formation of externally solidified crystals (ESCs) in the shot sleeve. Many numerical models have been developed and applied to investigating the flow behavior of molten metal in the shot sleeve [13−17]. Whereas, experimental study of the effects of the slow shot speed, especially on the formation of ESCs, has drawn little attention. In the present work, multi-step (two-step and three-step) slow shot speeds were used in the vacuum die casting of AZ91D alloy. The influence of the slow shot speed on the microstructure, especially on the ESC content, was studied by investigating the changes of microstructures at different slow shot speeds.

2 Experimental

The experiments were carried out on a TOYO BD−350V5 cold chamber die casting machine incorporated with a self-improved TOYO vacuum system. Table 1 shows the nominal composition of AZ91D magnesium alloy used in this work. The vacuum pressure variation in the die cavity before mold filling was monitored by a KEYENCE pressure sensor which was mounted on a vacuum pipe installed on the top of the vacuum valve half on the fixed die half. The accuracy of the pressure sensor is 0.1 kPa. Plate-shaped castings consisting of six plates with different thicknesses ranging from 1.25 to 7.5 mm were made on the machine.

Table 1 Nominal chemical composition of AZ91D magnesium alloy (mass fraction, %)

Al	Zn	Mn	Si	Fe
9.02	0.66	0.199	0.0311	0.0010

Cu	Ni	Be	Mg
0.0023	0.0007	0.0010	Bal.

One constant slow shot speed and two multi-step (two-step and three-step) slow shot speeds were used in the experiment. The variations of the three slow shot speeds used in the experiments with plunger position are shown in Fig. 1. For the constant one, the slow shot speed increases to 0.15 m/s after the plunger moves 40 mm, and then keeps constant until the high speed injection takes place. For multi-step slow shot speed, the slow shot speed is divided into multi steps. The two steps in the two-step slow shot speed are 0.4 and 0.15 m/s. The three steps in the three-step slow shot speed are 0.4, 0.15 and 0.05 m/s. For both multi-step slow shot speeds, the first step reaches 0.4 m/s after the plunger moves 40 mm and ends at the plunger position of 80 mm, and then the slow shot speed decreases to the second step of 0.15 m/s after the plunger moves 120 mm. For the three-step slow shot, the second step ends at the plunger position of 165 mm, and then the slow shot speed decreases to the third step of 0.05 m/s after the plunger moves 205 mm. Table 2 lists some other important process parameters used in the experiments. A total of 30 castings (10 for each condition) were produced. The plates with thickness of 3.75 mm in the castings produced were taken as specimens for further analysis.

Some specimens were sectioned at the middle for microstructural examination. The sections were polished by standard metallographic techniques and etched with an acetic nitric etch. Micrographs were taken at the

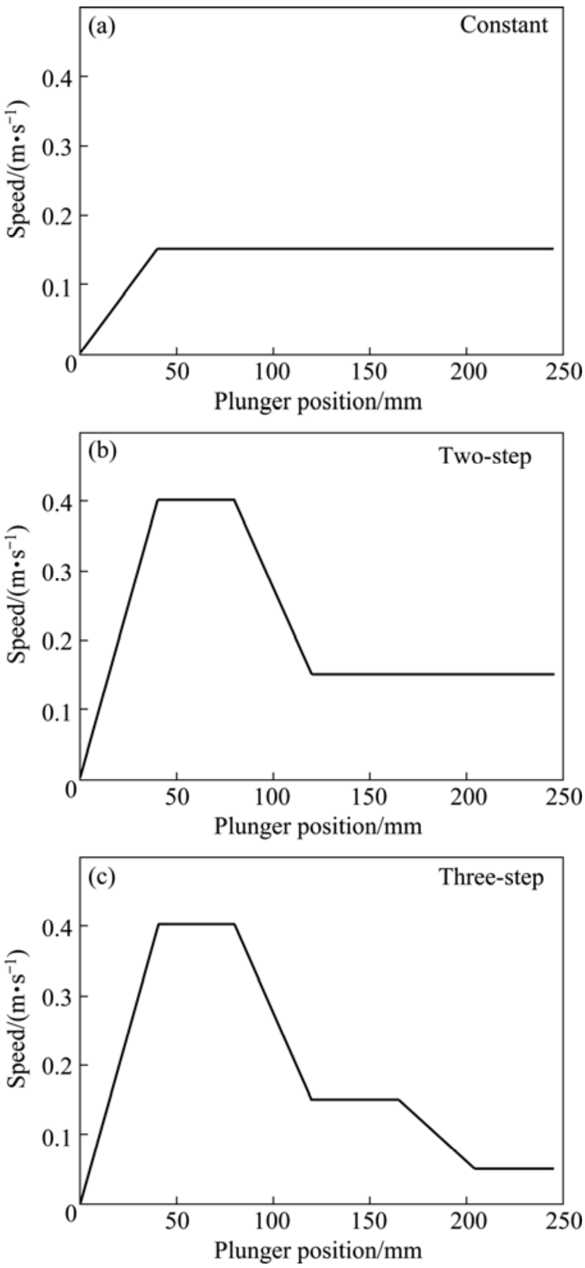

Fig. 1 Variations of slow shot speeds used in die casting with plunger position

Table 2 Process parameters used in die casting

Pouring temperature/°C	Die temperature/°C	Fast shot speed/($m \cdot s^{-1}$)	Intensification pressure/MPa
680	180	5.0	13.7

middle of the sections with a Zeiss microscope. The ESCs measurements were performed with the Micro-image Analysis & Process image analysis software at 100× magnification. At least three micrographs were analyzed for each measurement.

3 Results and discussion

3.1 Dwell time of liquid metal in shot sleeve before mold filling and vacuum pressure in die cavity at beginning of mold filling

The measured vacuum pressure and cylinder pressure during the vacuum die casting processes at different slow shot speeds are shown in Fig. 2, where t identifies the dwell time of the liquid metal in the shot sleeve before mold filling and p is the vacuum pressure in the die cavity at the beginning of mold filling. The subscripts 1, 2 and 3 indicate the constant, two-step and three-step slow shot speeds used in the vacuum die casting processes, respectively. As shown in Fig. 2, t and p will be effectively reduced at multi-step slow shot speeds. Such relation $t_1>t_3>t_2$ and $p_2>p_1>p_3$ can be observed in Fig. 2. The exact values of t and p at different slow shot speeds are given in Table 3.

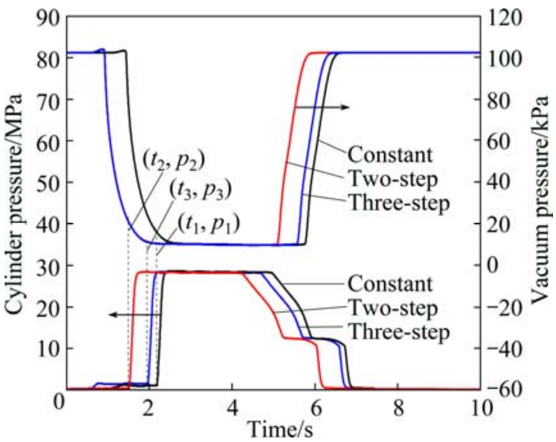

Fig. 2 Measured vacuum pressure and cylinder pressure variations against plunger moving time at different slow shot speeds

Table 3 Dwell time of liquid metal in shot sleeve before mold filling and vacuum pressure in die cavity at beginning of mold filling at different slow shot speeds

Slow shot speed	t/s	p/kPa
Constant	2.17	16.1
Two-step	1.50	20.9
Three-step	1.94	11.3

3.2 Gas porosity

Figure 3 shows the typical micrographs from the middle of the section in specimens produced at different

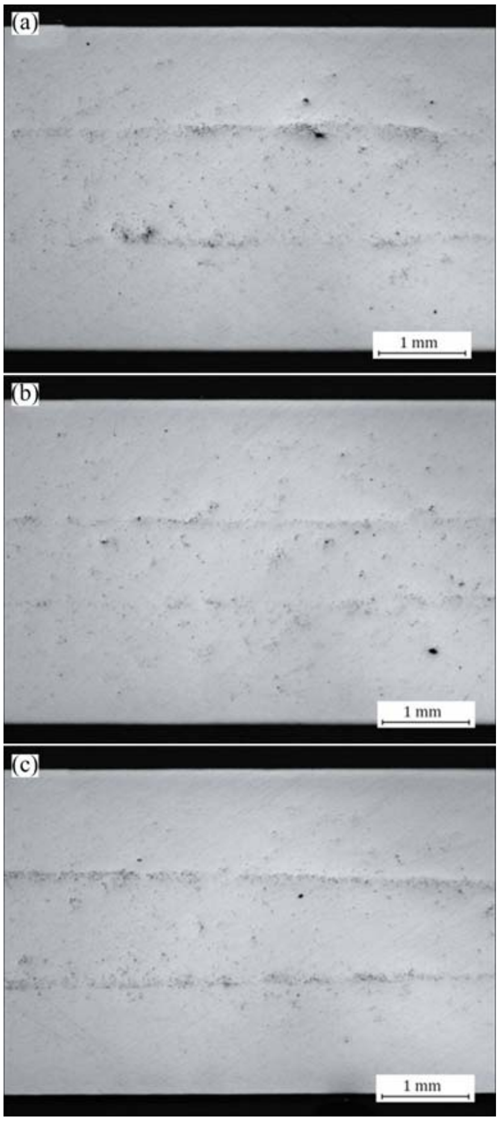

Fig. 3 Optical micrographs from middle of section in specimens produced at constant (a), two-step (b) and three-step (c) slow shot speeds

slow shot speeds. The black nearly spherical feature in the micrographs is the gas porosity. The bands located between the center and outer surfaces of the castings are defect bands. A region containing a defect band from Fig. 3(c) is shown in Fig. 4 at a higher magnification. This demonstrates clearly that the defect band contains a much higher fraction of shrinkage porosity when compared with the adjacent regions and the average size of the shrinkage porosity is much smaller than that of the gas porosity. It can be seen from Fig. 3 that all the three specimens are of low gas porosity level. This can be attributed to the low vacuum level achieved in the die cavity at the beginning of mold filling during the vacuum die casting processes. It is also seen that the gas porosity level in the specimens produced at the three-step slow shot speed is lower when compared with the specimens produced at the other two slow shot speeds. This is due to the fact that the vacuum pressure in the die cavity at the beginning of mold filling is the lowest at three-step slow shot speed, as shown in Table 3. This demonstrates that, by reducing the vacuum pressure in the die cavity at the beginning of mold filling through the multi-step slow shot speed, the gas porosity level in the produced specimens can be effectively reduced.

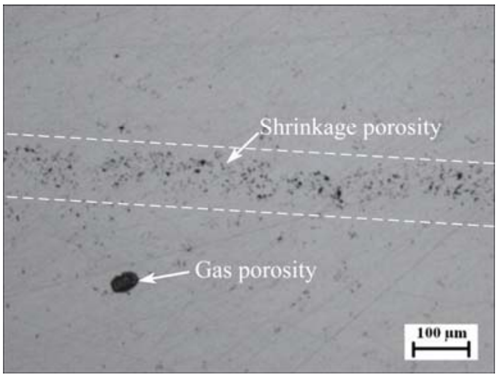

Fig. 4 Optical micrograph showing region containing defect band from Fig. 3(c) (Band edges are marked by dotted lines)

3.3 Externally solidified crystals

Figure 5 shows the typical etched micrographs from the middle of the section in specimens produced at different slow shot speeds. Figure 6 shows a higher magnified micrograph obtained from the specimens in vacuum die castings produced at the constant slow shot speed. The white or light gray phase in the micrograph is α-Mg containing ESCs and the α-Mg particles formed in the die cavity. Due to the high cooling rate of the molten metal after being transferred from the shot sleeve to the die cavity, the α-Mg particles formed in the die cavity are generally smaller in size when compared with the ESCs formed in the shot sleeve. In this work, the ones larger than 7 μm in diameter were taken as ESCs in the measurement. The measured average area fractions of ESCs in the specimens produced at the constant, two-step and three-step slow shot speeds are 14.08%, 8.83% and 5.83%, respectively.

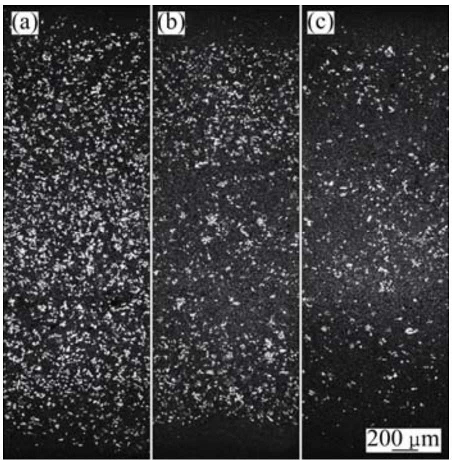

Fig. 5 Typical micrographs from middle of section in specimens produced at constant (a), two-step (b) and three-step (c) slow shot speeds

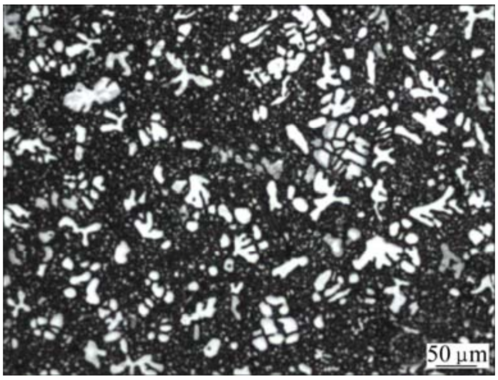

Fig. 6 Typical micrograph from specimens in vacuum die castings produced at constant slow shot speed

The ESCs in the castings originate from the floating crystals in a mixture of floating crystals and liquid forced from the shot sleeve into the die cavity during the fast shot process [18,19]. After the liquid metal is poured into the shot sleeve, it starts to solidify at the wall as a result of the heat extraction through the sleeve interface. A constitutionally undercooled zone can be established adjacent to the growing interface during the growth of the solid. Some equiaxed crystals can be formed in the zone. With the flowing of the liquid metal in the shot sleeve some growing dendrites at the wall are fragmented. The fragmented dendrites and the generated equiaxed crystals are transported from the sleeve wall into the bulk of the liquid metal. A mixture of floating crystals and liquid is thus formed in the shot sleeve. Whereas, as the temperature of the liquid metal is higher than the melting point, the remelting of the floating crystals would take place in the mixture. The transportation of floating crystals into the bulk of the liquid metal and the remelting of the floating crystals take place concurrently. When the transportation rate of the floating crystals surpasses the remelting rate, the content of floating crystals in the mixture would increase.

The transportation rate of the floating crystals is strongly dependent on the flow behavior of the liquid metal in the shot sleeve. More floating crystals would be transported from the sleeve wall into the bulk of the liquid metal if the flow of the liquid metal was enhanced. The remelting rate of the floating crystals is determined by the degree of superheat of the liquid metal in the mixture which is strongly dependent on the dwell time of the liquid metal in the shot sleeve. Due to the high degree of superheat of the liquid metal, the floating crystals transported into the liquid metal at the early stage of the slow shot process dissolve quickly. The ones in the mixture pushed into the die cavity during the mold filling process are mainly those entering into the liquid metal at the later stage of the slow shot process. It thus can be concluded that the floating crystals content in the mixture at the beginning of mold filling is determined by the dwell time of the liquid metal in the shot sleeve before mold filling and the flow behavior of the liquid metal in the shot sleeve at the later stage of the slow shot process.

Based on the analyses mentioned above, the difference of the ESC contents in the specimens produced at different slow shot speeds can be explained as follows. Firstly, for the constant and two-step slow shot speeds, as shown in Fig. 1, the slow shot speeds are same at the later stage of the slow shot process. The higher ESC content in the specimens produced at the constant slow shot speed is due to the longer dwell time of the liquid metal in the shot sleeve before mold filling. Secondly, for the constant and three-step slow shot speeds, the dwell time of the liquid metal in the shot sleeve before mold filling is little higher for the constant slow shot speed. As shown in Fig. 1, the slow shot speeds at the later stage of the slow shot process for the constant and three-step slow shot speeds are 0.15 m/s and 0.05 m/s, respectively. The higher slow shot speed causes a more violent flow of the liquid metal in the shot sleeve before mold filling. Both of two factors cause a higher ESC content in the specimens for the constant slow shot speed. Finally, compared with the three-step slow shot speed, the two-step slow shot speed has a higher slow shot speed at the later stage of the slow shot process and a shorter dwell time of the liquid metal in the shot sleeve before mold filling. The higher slow shot speed at the later stage of the slow shot process has a promoting effect on the ESC content in the produced specimens, while the shorter dwell time of the liquid metal in the shot sleeve before mold filling has a restraining effect on the ESC content. The higher ESC content in the specimens for the two-step slow shot speed demonstrates that the influence of the slow shot speed at the later stage of the slow shot process is dominant.

The experimental results demonstrate that it is an effective way in reducing the ESC content in high-pressure die castings by using the multi-step slow shot speed. At the early stage of the slow shot process the slow shot speed should be set at a relative high value to reduce the dwell time of the liquid metal in the shot sleeve. The slow shot speed at the latter stage of the slow shot process should be set at a relative low value to restrain the flow of the liquid metal in the shot sleeve.

4 Conclusions

1) The dwell time of the liquid metal in the shot sleeve before mold filling and the vacuum pressure in the die cavity at the beginning of mold filling can be effectively reduced by using the multi-step slow shot speed.

2) The gas porosity level in the vacuum die castings can be effectively reduced by reducing the vacuum pressure in the die cavity at the beginning of mold filling through using the multi-step slow shot speed.

3) It is an effective way in reducing the ESC content in high-pressure die castings by using the multi-step slow shot speed. The slow shot speed at the early stage of the slow shot process should be set at a relative high value to reduce the dwell time of the liquid metal in the shot sleeve before mold filling. The slow shot speed at the latter stage should be set at a relative low value to restrain the flow of the liquid metal in the shot sleeve. Less dwell time of the liquid metal in the shot sleeve before mold filling and weaker flow of the liquid metal in the shot sleeve at the later stage of the slow shot process would reduce the content of floating crystals in the mixture at the beginning of mold filling.

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分段慢压射速度对 AZ91D 镁合金真空压铸件组织的影响

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摘　要：在 AZ91D 镁合金真空压铸过程中使用 2 种分段慢压射速度(两段和三段)。在充型之前型腔内真空压力变化情况通过真空传感器进行监测。压铸件组织通过光学显微镜和图像分析软件进行分析。结果表明，采用三段慢压射速度时充型时刻型腔真空压力明显降低，导致所得压铸件中气孔含量很低。通过恰当选用分段慢压射速度，在充型之前金属液在压室中的停留时间可缩短，在慢压射过程后期阶段金属液在压室中的流动也将受到抑制，这些因素可导致所得压铸件中压室预结晶组织含量较低。

关键词：镁合金；真空压铸；慢压射速度；气孔；压室预结晶组织

(Edited by Xiang-qun LI)