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Abstract. Strategies to *improve* quality of gravity die casting for Sn-Pb alloy are outlined here by modifying the mould's gating system, i.e. mainly the down sprue and the sprue well. Analysis based on the experimental work of 27 casting products delivers a promising result for industrial application. Quantitative analysis of porosity defect in this work was based on density analysis. The investigation of the effect of down sprue design on the casting defects was worked out through the variation of tapered down sprue by one degree and two degrees. From the density analysis, the two degrees tapered down sprue results in then less porosity defect. Meanwhile, the highest density was identified at 50 mm, when radius of the down sprue was investigated at 0 mm, 5 mm and 100 mm. Finally, the investigation for sprue well radius of 0 mm, 50 mm, and 100 mm shows that the best sprue well radius related to the highest metal density occurs at a radius of 50 mm.

Keywords: vena contracta, Sn-Pb alloy, die casting, porosity, down sprue

1. Introduction

Casting is one of the oldest manufacturing processes. The casting process is used due to its several advantages, i.e. suitable for mass production which requires high productivity, less finishing process as well as less waste and energy consumption. Die casting is widely applied for metal with low pouring point to avoid soldering occurring between casted metal and its die [1-3]. The product of die casting however experiences challenge in its quality, e.g. porosity, missrun, shrinkage, etc. A sound design of gating system should be applied to minimize turbulence flow while keeping other restriction for gating system, e.g. minimizing heat loss and waste, preventing freezing of molten metal in the gating system. Additionally, turbulence of molten metal results in the entrapment of air inside the molten metal which results in porosity defect. This defect deteriorates mechanical properties of casting product. Many researches therefore worked out to improve casting quality particularly by optimizing the gating system [4,5].

The entrapped air reacts with molten metals mainly with metals having more negative Gibbs energy (see the Ellingham Diagram). This reaction then forms metal oxide and bifilm entrapped inside the casting product [6]. This circumstance then contributes to decreasing molten metal fluidity and lower mechanical properties of casting product. As fluidity decreases, molten metal experiences high thermal loss due to longer contact duration between the molten metal and the die. Die material was made off metal, e.g. steel, which have relatively high thermal conductivity compared. High heat loss in the gating system due to heat transfer from liquid metal to its die results in higher energy consumption due to higher pouring temperature, missrun defect, and shrinkage defect.

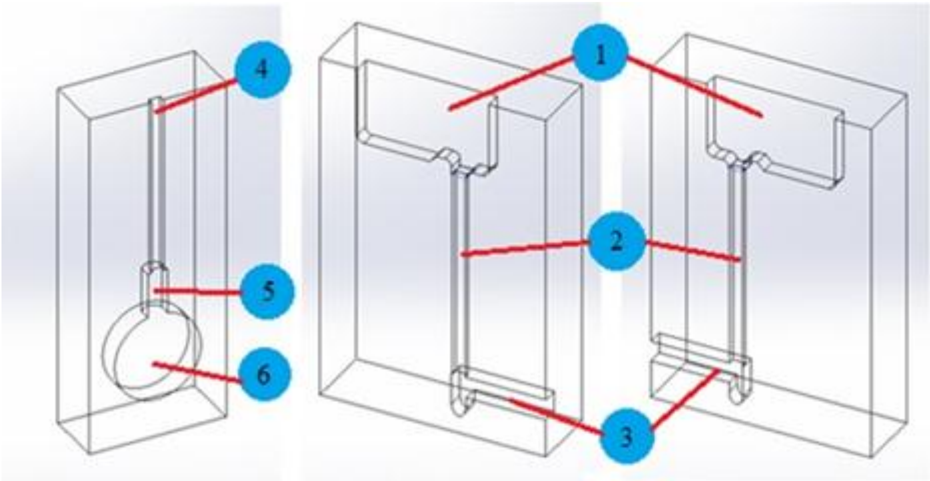
Previous result on down sprue research over the years shows the importance of well design of down sprue. Baghani *et al.* [7] reported that that surface turbulence resulting entrainment defect occurs due to high formation of vortex flow in the sprue base. Many research works, e.g. [7,8], reported that vena contracta, occuring when molten metals flow through a sharp change of direction in the end of down sprue, is believed to contribute to porosity defect. Compared to die casting, vena contracta causes more severe defect in sand casting since vena contracta in sand casting can suck air both inside the sand mold and the air atmosphere [8]. Elliot [9] also reported that the vena contracta occured in the down sprue and runner contributed to the porosity. This is due to more porosity and moist found in sand casting than in die casting.

Sprue well decreases the porosity since it reduces the kinetic energy of fallen molten metal [10]. In addition to sound design of down sprue, the design of sprue well plays another important role in increasing casting quality. Elliot [9] noted that well deisgned sprue well decreases surface tubulence since well-designed sprue well can suppress formation of vena contracta. In agreement, Campbell [11] also found that sprue well decreases the speed of molten metal. This reduces air entrapped in the liquid metals as well as formation of metal oxide. Sprue well should however be carefully design since excessively low metal speed causes missrun defect since hot molten metal loses more temperature when its speed decreases.

2. Method and material

2.1 Casting procedure

The objective of this research is to investigate the shape of the down sprue, the shape of the end of down sprue, and sprue well. The investigation conducted with Sn-Pb alloy correlates those factors to casting defect particularly porosity, shrinkage and missrun. Gravity die casting was applied in this research due to its easy mold preparation and due to its process repeatability compared to sand casting. In this work, St-37 was used as die material (**Figure 1**) while casted metal was 70% Sn - 30% Pb alloy. At this composition, the liquidus temperature of this alloy is app. 195 ºC (**Figure 2**) [12]. Density determined by using Archimedes' principle density shoed that density of this alloy is 8523 kg m^{-3}. Although the liquidus temperature of this alloy is only 195 ºC, the suitable pouring temperature in this work was investigated through several attempts. It was found that suitable pouring temperature for this alloy is 450 ºC due to high heat transfer loss from liquid metal to die material. Pouring below this temperature was observed to result in missrun defect. After several attempts, it was also then decided that molten metal poured directly in the down sprue and not to pouring basin since pouring of molten metal on the pouring basin resulted in high thermal loss. To have constant die temperature before pouring of molten metal, die was left cooled after each trial for several hours until the die reached room temperature. The subsequent trial was performed only after the die material reached room temperature.



Note:
1. Pouring basin
2. Down sprue
3. Runner
4. Vent
5. Riser
6. Product mold

Figure 1. The sketch of die used in this work

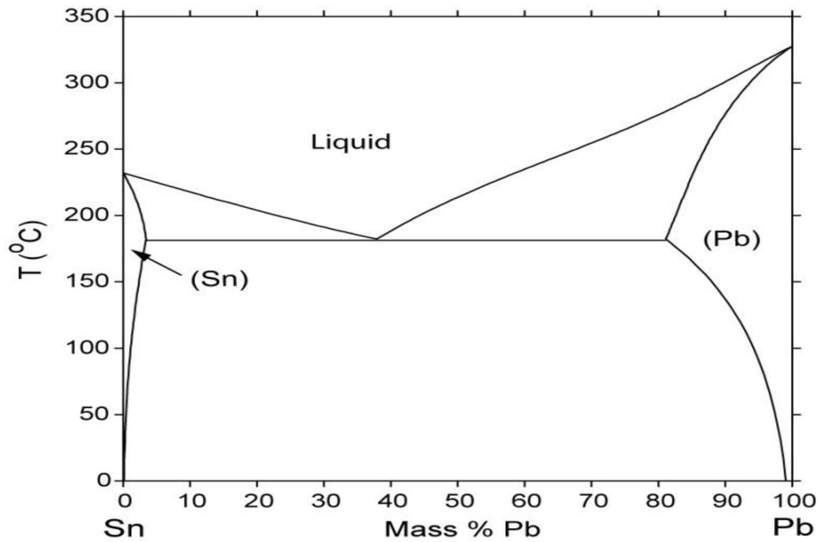


Figure 2. Sn-Pb phase diagram [12]

Figure 3. Exemplary die casting products in this work

2.2 Determination of density

In many works, porosity was observed through X-ray analysis or density determination. Many attempts had been made in this work to observe porosity through X-Ray analysis but it did not deliver any result. In this work density measurement was therefore implemented. Determination density supported by application of the Archimedes' principle is generaly used to qualitatively represents porosity in casting product, e.g. [13-15]. After gasting system and casting product is expelled from the mold, casting product is truncatted from the gating system and frozen riser above the casting product (**Figure 3**). After that, mass of the casting product (m) was determined by weighing it [kg]. Volume of casting product (V) [m^3] was determined by using Archimedes' principle so that the density [$kg\ m^{-3}$]was calculated by using equation 1.

$$\text{Density} = m / V \quad (1)$$

3. Result and discussion

3.1 Influence of tilt angle of down sprue

Down sprue variation was conducted by varying the tilt angle of down sprue (**Figure 4a**). Vena contracta takes place for non-tapered down sprue. Although the possibility of vena contracta for non-tapered down sprue is documented, e.g. [16], there is no information concerning the best tilt angle for Sn-Pb alloy casting. Flow in gravity die casting depends on the properties particular poured metal and at particular temperature as well. Analysis in this work was therefore done to compare the density of casting product for non-tapered down sprue, 1 degree and 2 degrees tilt angle (**Figure 4b**). For each variation of down sprue tilt angle, 3 samples were collected. Thus there are 9 samples in this analysis. The density of 2 degrees tilt angle shows the highest density (**Table 1**) which correlates with assumed less vena contracta. Compared to non-tapered and 1 degree tapered down sprue, the density of 2 degrees tilt angle is the highest. Future work is however important to further increase the tilt angle until the maximum angle for casting, mainly Sn-Pb alloy, can be discovered.

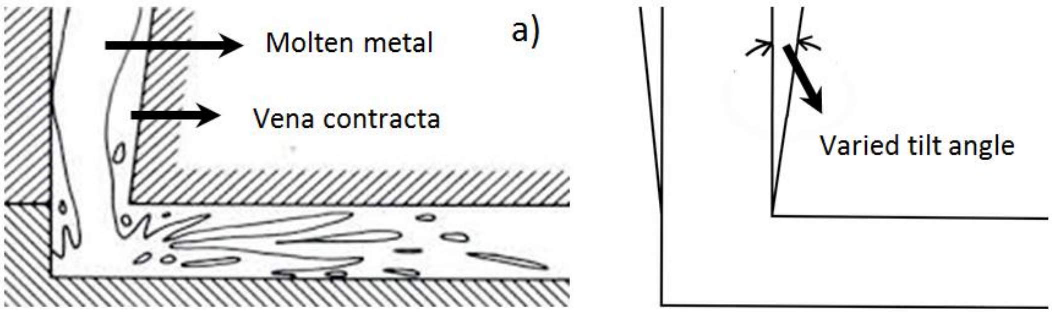


Figure 4. a) Vena contracta in the non-tappered down sprue [16], b) Varied tilt angle in this work

Table 1. Density for 3 varied tilt angles of down sprue

Down sprue tilt angle	Density [$kg\ m^{-3}$]	
	Average	St. Dev.
Non-tappered	8360	43
1 degree tilt angle	8410	26
2 degrees tilt angle	8424	33

3.2 Influence of the radius at the end of down sprue

Another strategy to eliminate vena contracta was worked out in this research by curving the end of down sprue (**Figure 5**). The vena contracta occurs in the case for no radius at the end of down sprue. Therefore this work investigated the optimum radius at the end of down sprue. The end of down sprue was curved at radius of 50 mm and 100 mm. Density of casting product was compared for the cases of no radius, 50 mm radius and 100 mm radius. The best tilting angle of down sprue from the previous trials, i.e. at 2 degrees, was continually used. Therefore, the lowest density occurring at no/ radius (**Table 2**) is similar for the last variation in **Table 1**. For each variation of radius, 3 samples were made. Thus there were 9 samples in this analysis. The result showed that the best radius at the end of down sprue occurs at 50 mm radius and not at 100 mm radius. Bigger vena contracta in this work is predicted to occur at 100 mm radius (**Figure 6**). However, this prediction needs to be reconfirmed by the next research, e.g. by computational simulation. This result is in contradiction with Campbell [16] as he suggested that larger radius is better to supress formation of vena contracta. On the other hand, Kannan [14] suggests that the shape of mold should be as close as possible to the shape of molten liquid flow. This is important to suppress the formation of vena contracta.

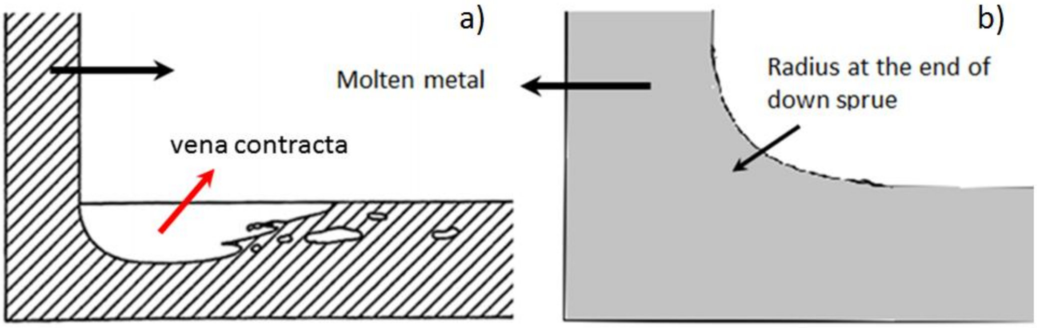


Figure 5. a) Vena contracta occurs when the end of down sprue has no radius [16], b) Variation of the radius of down sprue in this work

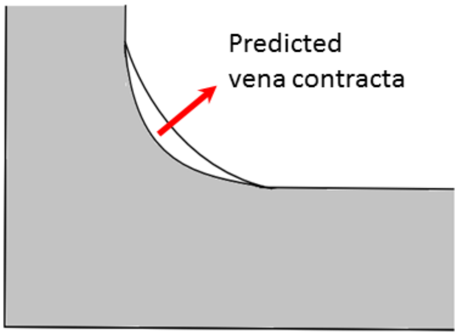
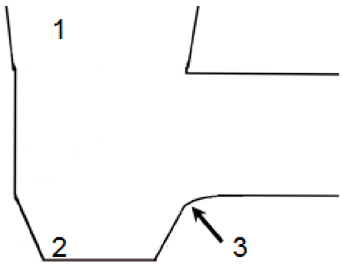


Figure 6. Estimated bigger vena contracta due to higher radius at the end of down sprue

Table 2. Density for 3 varied radius at the end of down sprue

Radius at the end of down sprue	Density [kg m^{-3}]	
	Average	St. Dev.
No radius	8424	24
50 mm radius	8461	51
100 mm radius	8433	47

3.3 Influence of sprue well radius



Note:
1: Tappered down sprue
2: Sprue well
3: Radius of sprue well

Figure 7. Varied sprue well radius (R) in this work

Sprue well is suggested in casting process to avoid initial splash and its bigger size is predicted to prevent formation of vena contracta [16,17]. However there is limited information on the effect of sprue well shape on the formation of vena contracta, mainly for casting of Sn-Pb alloy. This work therefore investigated the influence of sprue well radius on porosity of this alloy casting. The radius of sprue well in this work (Figure 7) was investigated for 3 variations, i.e. no radius, radius of 50 mm, and radius of 100 mm. For each radius variation, 3 casting products were made. Thus there were 9 samples in this analysis. As shown by the density analysis, the best radius to minimize porosity was 50 mm (**Table 3**). Surprisingly, 100 mm radius shows the lowest density and even lower than in the case of without radius. Further investigation is however required to understand the behaviour of molten metal when it passes the sprue well.

Table 3. Density for 3 sprue well radius

Radius at the sprue well	Density [kg m^{-3}]	
	Average	St. Dev.
No radius	8461	44
50 mm radius	8481	41
100 mm radius	8471	26

4. Conclusion

Modification of down sprue and sprue well shows promising result for industrial application. Investigation of down sprue shows that the 2 degrees tilt angle of downsprue results in less casting defect. Meanwhile, the best radius of the down sprue for die casting of Sn-Pb alloy was identified at 50 mm. Finally, the investigation of sprue well radius for 0 mm, 50 mm, and 100 mm shows that the best sprue well radius occurs at 50 mm. Suppression of possibly formation of vena contracta in this work shows it can increase quality of casting product. The result of this work however needs to be continued through subsequent investigation, e.g. computational simulation.

5. References

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