Casting Quality Comparison: Vertical vs. Horizontal HPDC

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ABSTRACT

Castings made using conventional horizontal HPDC and vertical HPDC are characterized in terms of porosity formation using optical microscopy, X-ray, and T4 heat treatment. It has been found that much less porosity is formed in castings made using the vertical HPDC than that using conventional horizontal HPDC process. Numerical simulation has been performed to investigate the behavior of molten metal in the shot sleeve for both processes. The simulation results suggest that comparing with the conventional horizontal HPDC process, the vertical HPDC 1) eliminates wave formation in the shot sleeve and thus reduces entrapped air in the molten metal, 2) has a smaller surface area of molten metal in the shot sleeve and thus reduces oxide formation over the melt surface, and 3) has a smaller temperature gradient in the melt that reduces the formation of cold flakes and pre-solidified materials in the shot sleeve. It is expected that the use of the vertical HPDC process has the potential of improving the pressure tightness of die castings.

INTRODUCTION

Porosity is one of the die casting defects that reduce the leak-tightness and the mechanical properties, especially the elongation and fatigue life of the casting [1]. It is well known that porosity results from dissolved hydrogen in molten metal [2], entrapped air in the shot sleeve and in the gating systems, gases released in the die cavity, and oxides/cold flakes. Reducing entrapped air in the shot sleeve tends to reduce porosity level in a casting [3].

Most HPDC machines used in industry are horizontal ones. A horizontal die casting machine utilizes a horizontal shot sleeve to feed molten metal to the die [4-5]. As molten metal is poured into the shot sleeve, it stays at the bottom of the shot sleeve and only partially fills the shot sleeve. A ram is then used to pushed the molten metal in the shot sleeve into the die cavity. As the ram travels horizontally from the pouring end to the die end, the shot sleeve is gradually filled the totally before the molten metal enters into cavity in the die. In adequate shot profile leads to the formation of molten metal wave in the shot sleeve which entraps air into the molten metal and increases porosity in the casting. Care much be taken to avoid wave formation in the shot sleeve. Still, it is difficult to determine if wave formation is suppressed in the shot sleeve.

Vertical HPDC machines have not been widely used in the die casting industry. Gibbs Die Casting may be the only die casting company in the US using this process. Figure 1 illustrates the vertical HPDC process. The shot sleeve is placed vertical under the die. It sways out to receive molten metal and then swings back to its position under the bottom of the die. A ram travels upward to push the molten metal into die cavity. The vertical HPDC machine looks identical to an indirect squeeze casting machine, except that the ram can travel as fast as that in a horizontal HPDC machine. In fact, vertical HPDC machine evolves from the indirect squeeze casting machine. During the vertical HPDC process, the molten metal always
covers the entire top of the ram. Gravity prevents wave from formation in the shot sleeve. As a result, the ram can travel at high speeds without causing wave formation. This is equivalent to the total fill of a shot sleeve for a horizontal HPDC process. Still, little work in available in literature on the internal integrity of castings made using the vertical HPDC process.

The aim of this work is to investigate the quality of an engine cover castings made using both the conventional horizontal process and the vertical process. Optical microscopy is used to characterize the microstructure of the casting. X-ray inspection of the porosity is performed. Selected castings are CT scanned for detecting the morphology and size of the pores. T4 heat treatment is also performed to check blistering formation that is related to porosity in casting as well. Finally, mechanical properties of coupon taken at various locations on the castings are characterized. Our experimental finding suggests that the vertical HPDC process is capable of producing castings with improved internal integrity.

EXPERIMENTAL CONDITIONS

THE CASTING

The casting used for this research is an engine cover with integrated pump body shown in Figure 2(a). The engine cover and pump box are integrated into one part. It is a component currently in production using conventional horizontal HPDC processes. The alloy for this part is A380. Issues with this casting are porosity and pressure-tightness. Castings have to be scrapped if they fail the required X-ray inspection or the required leak testing after the part is machined. Vertical HPDC process was used to compare with the horizontal HPDC process in term of porosity level in castings.
CASTING CONDITIONS
For the vertical HPDC process, the casting is gated from the bottom shown in Figure 2(b). Table 1 lists the parameters for the casting processes. The maximum plunger velocity for both processes was around 3.5 m/s. The pouring temperature was 680-700 °C (1256-1292°F) for the horizontal HPDC process and was 635-640 °C (1175-1184°F) for the vertical HPDC process. The die temperature was 180-220 °C (356-428°F) for both processes. Degassing was performed before the molten metal was transferred from a ladle to the holding furnace for the horizontal HPDC. The metal for the vertical HPDC was not degassed.

Table 1 - The parameters for the casting processes

<table>
<thead>
<tr>
<th>Process</th>
<th>Pouring Temperature</th>
<th>Die Temperature</th>
<th>Slow Shot Velocity</th>
<th>Fast Shot Velocity</th>
<th>Cycle Time</th>
<th>Diameter of Tip</th>
<th>Length of Shot Sleeve</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal HPDC</td>
<td>680°C -700°C (1256°F -1292°F)</td>
<td>180°C -220°C (356°F -428°F)</td>
<td>0.2m/s</td>
<td>3.5m/s</td>
<td>80s</td>
<td>100mm</td>
<td>610 mm</td>
</tr>
<tr>
<td>Vertical HPDC</td>
<td>635°C -640°C (1175°F -1184°C)</td>
<td>180°C -220°C (356°F -428°F)</td>
<td>0.2m/s</td>
<td>3.3m/s</td>
<td>85s</td>
<td>110mm</td>
<td>280 mm</td>
</tr>
</tbody>
</table>

X-RAY INSPECTION
Selected castings were X-ray inspected using an X-ray machine (Model XG-1604L/C) made by Shanghai None-Destructive Equipment Ltd. An entire casting was scanned to search for porosity. Images of porosity were taken. The resolution of the X-ray machine is 0.5mm. Under as-cast conditions, porosity usually found at locations marked with P1 to P8 on Figure 2(a).

BLUSTERING FORMATION
Selected castings were T4 heat treated in order to induce blustering formation. The castings were heated up to 530 °C at a rate of 20 °C/min., held at 530 °C for 2 hours and then were quenched in water. Photographs of blustering at the casting surfaces were taken. X-ray inspection was also performed on castings T4 heat treated.

CASTING CHARACTERIZATION
Morphology of pores in castings was observed using optical microscopy on as-polished samples. 15 to 30 images were taken in each location. Pore sizes were measured.

Tensile coupons were taken from the region A shown in Figure 2. This location was chosen based on results obtained by X-ray inspection. Region A is located near the gates. Less porosity has been found both under as-cast conditions and at T-4 conditions in Region A. Tensile strength and elongation were measured on the coupons cut at regions A.

RESULTS AND DISCUSSION
Results on X-Ray inspection of the casting are shown in Figure 4. Figure 4(a) shows X-ray images taken from a casting made using the horizontal PHDC process, and Figure 4(b) shows that using the vertical HPDC process. Porosity has been found at all 8 locations marked on Figure 2(a) for castings made using the horizontal HPDC process. However, for the casting made using the horizontal HPDC process, porosity has been found only at location 8. Indeed, much less porosity has been detected in castings made using the vertical HPDC than that using the horizontal HPDC process. This result can be translated into reduced scrap rate for castings made using the vertical HPDC process.

It has to be noted that the resolution of X-ray inspection is limited. Pores or voids smaller than a millimeter cannot be observed. Thus T4 heat treatment was performed to evaluate blustering formation in castings. Figure 4 (a) and Figure 4(b) illustrate blustering on the surfaces of a vertical HPDC casting and a horizontal HPDC casting respectively. More blusters are found at the surfaces of the horizontal HPDC casting than that on the vertical HPDC casting.
Figure 3- X-Ray images taken at locations of P2, P3, P4, and P8 on (a) a horizontal HPDC casting, and (b) a vertical HPDC casting HPDC process. Red circles mark the pores found on the X-Ray image.
Figure 4- Blusters in castings subjected to T4 heat treatment. The casting is made by (a) Vertical HPDC, and (b) Horizontal HPDC.

Microstructure characterization was performed. Table 3 lists the average number of pores, average pore size in area, maximum pore size in area, and average pore percentage location 5. It is clear that pores exist in castings made using both processes because the molten aluminum is not degassed. However, the maximum pore size in the casting made by using the horizontal HPDC process is at least two times larger than that using the vertical HPDC process. It is the large pores and the connectivity of the pores that are detrimental to the pressure tightness of the casting. In addition, large pores can be detected using X-ray and lead to rejection of the part as scrap. Blustering is also more sensitive to the size of the pores.

Table 3- Pores number and sizes at location P5 in castings made using the horizontal HPDC and the vertical HPDC process.

<table>
<thead>
<tr>
<th></th>
<th>Average Number of Pores</th>
<th>Average pore Size (pixels)</th>
<th>Maximum Pore Size (pixels)</th>
<th>Average Pore Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal HPDC</td>
<td>69</td>
<td>92</td>
<td>10723</td>
<td>0.358%</td>
</tr>
<tr>
<td>Vertical HPDC</td>
<td>96</td>
<td>74</td>
<td>4812</td>
<td>0.338%</td>
</tr>
</tbody>
</table>

Mechanical properties were measured using coupons cut from the regions marked with A shown on Figure 2(a). The flat locations were chosen because porosity has not been found using X-ray and were large enough for cutting tensile coupons. Table 4 lists the mechanical properties. The average tensile strength and the elongation of the vertical HPDC part is 3.6% and 25% higher than that of the horizontal PHDC part. Of the mechanical properties listed in Table 4, tensile strength is slightly affected by the presence of defects but elongation is affected significantly. The higher elongation of the casting made using the vertical HPDC over that made using the horizontal HPDC is an indication that the vertical HPDC process produces castings of higher internal quality than that of the horizontal HPDC process. Since no porosity has been detected in the regions where the tensile coupons were cut, it is believed that the elongation is affected by oxide films and cold flakes in the casting. The mechanical property data suggest that less oxide and cold flakes are formed in castings made using the vertical horizontal HPDC process than that using the conventional horizontal HPDC process.
Table 4: Mechanical properties of the castings made using horizontal HODC and vertical HPDC process.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Horizontal HPDC</th>
<th>Vertical HPDC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tensile Strength (MPa)</td>
<td>Elongation (%)</td>
</tr>
<tr>
<td>1</td>
<td>187.0</td>
<td>0.8</td>
</tr>
<tr>
<td>2</td>
<td>190.7</td>
<td>1.1</td>
</tr>
<tr>
<td>3</td>
<td>183.7</td>
<td>1.3</td>
</tr>
<tr>
<td>4</td>
<td>271.3</td>
<td>2.7</td>
</tr>
<tr>
<td>5</td>
<td>214.7</td>
<td>0.8</td>
</tr>
<tr>
<td>6</td>
<td>274.9</td>
<td>2.4</td>
</tr>
<tr>
<td>Average</td>
<td>222.40</td>
<td>1.52</td>
</tr>
</tbody>
</table>

The internal quality of a casting can also be evaluated using a quality index, \( Q \), proposed by Drouzy, Jacob, and Richard using the follow equation [6]:

\[
Q = UTS + 150 \log_{10} e_f
\]  

where \( UTS \) is the tensile strength in MPa and \( e_f \) is elongation to fracture. Substituting the average property data for both processes listed in Table 4, we obtain \( Q = 270.3 \) MPa for the vertical HPDC process and \( Q = 247.7 \) for the horizontal HPDC process. The quality index of the castings made using vertical HPDC is 9% higher than that made using the horizontal HPDC process. It is well known that defects such as oxides, and cold flakes affect the quality index of a casting, as well as porosity [7].

Numerical modeling has been carried out using FLOW3D CAST to understand the benefit of using the vertical HPDC for making high internal quality castings. Conditions listed in Table 1 are used for the simulation. The transition from slow shot profile to high shot profile was assumed to be at the point when the liquid metal reaches the in-gate for the horizontal HPDC process and was at the point when the liquid metal passes the in-gate by 10mm for the vertical HPDC process. Since the geometry of the casting and the gating system is similar for both processes, the simulation is focused on the flow of liquid metal in the shot sleeve.

When liquid metal is poured through the pouring hole into a shot sleeve, the metal fills the bottom part of the shot sleeve. As the plunger move towards to die, the liquid metal is pushed towards the die and eventually fills the die cavity. Figure 5 illustrates the free surface of the liquid metal in a shot sleeve before liquid metal reaches the in-gate in the mold. The horizontal purple line at the bottom of Figure 5 is the free surface area curve for the vertical HPDC process where the free surface is the top surface of the molten metal. When the plunger pushes the metal upwards to the die, this surface area doesn’t change due to gravity. As a result, the line is a straight horizontal line until the top surface of the molten metal reaches the runner. The free-surface area is then reduced to that in the runner system.

For the horizontal HPDC process, the length of the liquid metal in the shot sleeve reduces as the plunger travels if the shot sleeve is initially filled for over 50%. Assuming that the slow profile is so perfect that no wave forms, the free surface area of the molten metal is a smooth linear line (blue line on Figure 5). Any disturbance such as wave formation on the free surface of the molten metal is going to increase the free surface area. As a result, the free surface area curve for any shot profile should fall above the theoretical curve on Figure 5.

Using the casting conditions listed in Table 1, waves do form in the shot sleeve. The calculated free surface area as a function of times is plotted as the red dash curve on Figure 5 above the blue line. The curve is no longer smooth. The zigzag nature of the curve reflects wave formation from time to time.
Figure 5 - Relationship between free surface area and time when a plunger starts to push molten metal towards die cavity for HPDC processes. The vertical dash lines indicate the moment when the liquid metal reaches the runner in the shot sleeve.

Figure 6 depicts the height of the wave in shot sleeve as the plunger moves towards the die for the horizontal HPDC process. As soon as the plunger starts to move, a wave is formed ahead of the plunger. The height of the wave, defined as the height of the wave from its peak to its valley, is quite stable at about 2 cm (or 0.8 in.). When the liquid metal reaches the entrance to the runner at about 900 ms, the liquid metal starts to jump up and down at the entrance to the runner, causing unstable waves up to about 10 cm (or 4 in.) tall. This is similar to what we usually see in a lake. As small waves reach the shore, they crash, forming much larger splashing waves. Such turbulent motion of the liquid front ought to cause issues with oxide formation and the entrapment of both air bubbles and oxides.

Simulation results shown in Figures 5 and 6 have demonstrated two important features of the vertical HPDC process in comparison with the horizontal HPDC process. One of the features is oxide formation and the other is entrapment of gases. Less oxide is entrapped and fewer amounts of gases are entrapped in a vertical HPDC process than that in a horizontal HPDC process.
OXIDE FORMATION AND ENTRAPMENT
The free surface area of molten metal in shot sleeve of a horizontal HPDC is 6 times higher than that of the vertical HPDC process when the molten metal is initially poured into the shot sleeve. 600 cm² of oxides is formed in a horizontal shot sleeve whereas only 100 cm² of oxides is formed in a vertical shot sleeve.

Furthermore, as the plunger starts to push liquid metal forward, the free surface area of the molten metal creases linearly, indicating that the oxide film on the molten metal has to be broken up. As a result, new oxides are formed instantaneously at the locations where old oxides are fractured. The fragments of the oxide can be entrapped by the waves formed in the shot sleeve. Oxide entrapment is unlikely to occur in a vertical shot sleeve because the oxide film, after it has been formed, is not likely to be broken up because the free surface area doesn’t change after the plunger starts to move. In fact, the oxide film, undisturbed, should be useful in preventing further oxidation of the molten metal and in protecting the molten metal from absorbing hydrogen from moisture or gases in the shot sleeve.

To conclude, much less oxide is formed in a vertical shot sleeve than that in a horizontal shot sleeve. This accounts for the fact that the quality index defined by the mechanical properties is higher for castings made using the vertical HPDC process than that made using the horizontal HPDC process. Note that the tensile coupons were cut in regions where no porosity was detected using X-ray inspection. Oxides play an important role in affecting the mechanical properties, and thus the quality index of diecasting.

ENTRAPMENT OF GASES
Wave formation and oxide break up account for the entrapment of gases and absorption of hydrogen from environment. Porosity levels can be increased by wave formation in the shot sleeve formed during the slow shot profile and the formation of large unstable waves at the entrance to the runner when liquid metal reaches there. Wave formation doesn’t occur in a vertical shot sleeve. Furthermore, oxides that are entrapped in the molten tend to nucleate bubbles during the solidification process of the alloy. Reduced entrapped air and oxides during the vertical HPDC process account for the fact that less porosity is detected in the casting made using the vertical HPDC process than that using the horizontal HPDC process.

HEAT LOSS OF THE MOLTEN METAL IN SHOT SLEEVE
Another unique feature for the vertical HPDC is a smaller amount of heat loss of molten metal than that of the horizontal HPDC process. When molten metal is poured into a shot sleeve, the heat loss is controlled by the ratio, \( M \), of the volume to the total surface area of the molten metal. \( M \) is the modulus of the molten metal in the shot sleeve and is defined as:

\[
M = \frac{V}{S}
\]  

(2)

where \( V \) is the volume and \( S \) is the total surface area of the molten metal. The larger the \( M \) value of this ratio, the longer the molten metal to be able to held at liquidus temperature of the alloy.

Figure 7 shows the relationship between \( M \) and the times in a shot sleeve for these two HPDC processes using data listed in Table 1. The \( M \) value for the vertical HPDC process is much larger than that of the horizontal HPDC process. The benefits of having a larger \( M \) for the vertical HPDC process include 1) lower pouring temperature which is beneficial to the service life of shot tooling and dies, and 2) fewer cold flakes and less pre-solidified metals in the shot sleeve. Clod flakes and presolidified solids are detrimental to the mechanical properties because of larger dendritic length scanes and oxide formation at the surfaces of the cold flakes.
CONCLUSIONS

X-ray inspection and mechanical property testing indicate that castings made using a vertical high-pressure diecasting process contain less porosity and are of higher mechanical properties, especially elongation. The quality index of the castings made using the vertical HPDC process is 9% higher than that made using the conventional horizontal HPDC process.

Numerical simulation using FLOW3D CAST suggest that the free surface area of molten metal in shot sleeve is much smaller for the vertical HPDC process than that of the conventional horizontal HPDC process. Waves are formed in the shot sleeve of the horizontal shot sleeve. The formation of waves causes entrapment of gases and oxides that increases the porosity level and reduces the elongation of the castings made using the conventional horizontal HPDC process. For the vertical HPDC process, the shot sleeve is completely filled and the flow in the molten metal is less turbulent. As a result, less oxide and mold gases are entrapped in the shot sleeve of a vertical HPDC machine.

Numerical simulation results also suggest that the modulus of the molten metal in shot sleeve is higher for the vertical HPDC process than that for the horizontal HPDC process. As a result, liquid metal can be poured into the shot sleeve at low temperature for the vertical HPDC process than that of the horizontal HPDC process. Less pre-solidified material and cold flakes will be formed in the shot sleeve of a vertical HPDC machine that that in a horizontal HPDC machine.

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