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Experimental study of vortex flow induced by a vortex well in sand casting

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Key words:
Vortex flow; vortex well; Weibull analysis

Abstract – Fluid flow phenomena are very closely related to the casting quality and surface finish of the cast part. In addition, the good quality of the casting product can be achieved by using an optimum gating system design. In this work, a vortex well, which is one of the important components of gating system design, is utilized in order to demonstrate its effectiveness in improving the mechanical and microstructure properties of the cast part. An X-ray radiography test was performed in order to investigate the porosity distribution in castings with different vortex well dimensions. The scatter of flexure strength results was quantified by Weibull statistics. Microstructure analysis was conducted by using a scanning electron microscope (SEM) to examine the microstructure of selected casting specimens produced from the vortex well design. By optimizing the vortex well design, porosity inside the casting was significantly reduced, while the mechanical strength and reliability of aluminum casting were further enhanced.

Mots-clés :
Écoulement vortex ; canal de vortex ; statistique de Weibull

Résumé – Étude expérimentale de l'écoulement vortex induit par un canal de vortex dans le moule de sable. Les phénomènes d'écoulement du métal liquide exercent un impact direct sur la qualité et l'état de surface des pièces coulées en fonderie. De plus, une bonne qualité du produit coulé peut être obtenue par optimisation du design du système de coulée. Dans cette étude, on montre l'effet bénéfique d'un canal de vortex, qui est une partie importante du système de coulée, pour améliorer les propriétés mécaniques et la microstructure de la pièce coulée. Des examens par radiographie de rayons X ont été menés pour étudier la distribution de porosité dans la pièce coulée, en fonction des dimensions du canal de vortex. La dispersion des mesures de résistance à la flexion a été quantifiée au moyen d'une distribution statistique de Weibull. L'analyse microstructurale a été réalisée par microscopie électronique à balayage (MEB) ; on a examiné la microstructure de différents échantillons coulés, en fonction du design du canal de vortex. L'optimisation du design du canal de vortex a permis simultanément de réduire significativement la porosité interne des pièces d'aluminium coulées, et d'améliorer leur résistance mécanique et leur régularité.

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The gating system serves many purposes, the most important being conveying the liquid material to the mold, but also controlling shrinkage, the speed of the liquid and turbulence. Gating system design should aim at providing a defect-free casting. The metal should flow smoothly into the mold without turbulence.

The formation of various casting defects can be directly related to fluid phenomena involved in the stage of mold filling. For instance, rigorous streams can cause mold erosion, highly turbulent flows can result in air inclusion entrapments, and relatively slow filling might generate cold shuts. Porosity, which is a common defect in casting, could also result from improper design of the gating system. The existence of porosity defects could decrease the mechanical properties of the product. Typically, the greater the amount of porosity in a casting, the greater the deterioration in mechanical properties.

In sand casting, molten material is poured into a forming cavity, via a delivery system of ducts and channels, with the fluid displacing the air within [1]. The gating system may be designed to minimize turbulence, depending on the material being cast. Campbell [2] discovered that allowing the liquid metal out of the crucible or melting furnace and into the mold is a critical step when making a casting. It is likely that most casting scrap arises during these few seconds of pouring of the casting. During the filling process, the behavior of the liquid and its subsequent solidification and cooling determine whether the cast shape will be properly formed, internally sound and free of defects. Recent work observing the liquid metal as it traveled through the filling system found that most of the damage was done to castings by poor filling system design [3].

A vortex gate was explored for aluminum gravity casting by Hsu et al. [4]. In this work, the velocity of flow of the liquid metal was controlled below the critical velocity and, at the same time, a high flow rate was maintained. It was suggested that one of the most important requirements of a good running system was the limiting of the velocity in the ingate to below the critical velocity at which surface entrainment could occur. From the result, it was discovered that the vortex gate had the potential to reduce the large factor of the linear velocities into the molds. The centrifugal action forced the liquid metal against the sidewall of the filling cylinder, excluding air, dissipating the unwanted high energy of flow, and achieving a progressive and sequential filling geometry.

Campbell [5] highlighted the potential use of a vortex well. He suggested that the vortex well helps to solve the surface turbulence problem. The vortex well can probably be oriented either horizontally or vertically. Theoretically, the device works exactly opposite to the supposed action of a spinner designed to centrifuge buoyant inclusions from a melt. In the vortex well, the outlet to the rest of the filling system is the outlet that would normally be used to concentrate inclusions. Thus, the device certainly does not operate to reduce the inclusion content. However, it should be highly effective in reducing the generation of inclusions by surface turbulence at the sprue base of poorly designed systems. The vortex is extremely effective in absorbing the energy of the flow. In this respect, its action resembles that of a ceramic foam filter. To enable the device to be used in routine casting production, the energy-absorbing behavior would require quantification.

Besides, Dai et al. [6] studied the effects of runner system design on the mechanical strength of Al7SiMg alloy castings where the effects of using different runner systems (triangle runner, rectangle runner and vortex runner) on the mechanical strength of Al7SiMg alloy castings were investigated by both CFD modeling and experimental validations. All the castings were poured at a temperature of 735–740 °C. They found that the use of a vortex runner controls the chaotic behavior of liquid metal flow in the runner, and assists in the reduction of in-gate velocity, and the consequent reduction of casting defects.

Thin-wall castings are often advantageous because of their lightweight structure, which enables increased payload and reduced energy consumption in aerospace and automobile applications. There has been a growing demand to meet the stringent requirements of the design engineers for producing thinner section castings with good mechanical properties. Thin-wall castings of this material can pose manufacturing problems associated with mold filling. Rapid cooling of thin-wall sections of the casting reduces the fluidity of the molten metal, which could cause the molten metal to prematurely freeze before it can completely fill the mold cavity, resulting in an incomplete fill or cold shuts. Hence, one of the prime factors to be taken into account in foundry practices of thin-section castings is the fluidity, and thorough knowledge of the various factors influencing it is also essential [7].

In addition, Voigt [8] studied the fillability of thin-wall steel casting, and the wall thickness and pouring temperature had the greatest effect on casting fill. As wall thickness increased, the volume to surface area of the casting increased, which also increased the solidification time, allowing the metal to flow further in thicker sections. Besides, Yeung et al. [3] investigated the morphology of solidification of thin-section ductile iron castings and concluded that the length and the number of the dendrites depended on the solidification rate or wall thickness. As the solidification rate decreased or the wall thickness increased, the dendrites decreased in number and length.

There are several important requirements for casting aluminum alloys; good corrosion resistance, high level of mechanical properties, and finally, good castability. The last property is particularly important; it implies that solidifying metal is not prone to hot cracking, possesses excellent fluidity in the molten state and minimal porosity. It is because of excellent castability that Al-Si casting alloys have retained their leading role among all other casting alloy compositions for 60 years, even though the general level of all other properties is quite average [9].

An AlSi7Mg alloy is a good candidate material for application in cast components in the automotive industry because of its low density, good casting properties and treatability [10]. Jiang et al. found that in the die-cast material, oxide films are found to be significantly important in controlling fatigue life. Lewis et al. used AlSi7Mg to study a finite-element model of the squeeze casting process from which a mathematical model of the squeeze casting process was developed. The effectiveness of the developed FE programs was demonstrated by means of various numerical examples, where the model was capable of analyzing the complex phenomena of filling, solidification and stress development during the squeeze forming process [11].

Kocatepe investigated the effect of low-frequency mechanical vibration on the porosity of unmodified and metallic sodium-modified AlSi7Mg and AlSi12Mg alloys. The effect of low-frequency vibration on the porosity was analyzed using optic and quantitative metallographic techniques. The results indicated that the amount and size of pores were increased with increasing vibration intensity in unmodified AlSi7Mg and AlSi12Mg alloys. Vibration of sodium-modified AlSi7Mg and AlSi12Mg alloys increased the amount and size of the pores [12].

Besides, Rou et al. studied the microstructure and wear behavior of grain-refined and modified Al7Si0.3Mg (AlSi7Mg) alloy. Combined grain refinement and modification were achieved by inoculating AlSi7Mg melt with various inoculation levels (0.2, 0.5 and 1.0 wt%) of a novel Al base master alloy containing Ti, C and Sr (synthesized in the authors' laboratory) at 720 °C. The wear resistance of AlSi7Mg alloy improved with the addition of this master alloy up to 0.5 wt% [13]. Lewis et al. also used AlSi7Mg as the cast metal material. They explored two alternative techniques to overcome some of the limitations of traditional numerical simulation schemes for the casting process simulation. The first technique used a geometric transformation method known as medial axis transformation, predicting hot spots, whereas the second technique, based on meshless methods, was used for simulating the mold filling process [14].

From a literature review, it is understood that very few research works have been published so far on vortex gates and vortex wells and there is no reported research work on the effect of a vortex well on mechanical and microstructure properties of AlSi7Mg alloy. The purpose of this research is to determine the effect of vortex-well design on the mechanical properties, microstructure and porosity distribution patterns of AlSi7Mg alloy castings by using a sand casting process.

1 Experimental procedure

1.1 Geometry design

The geometry design consists of five separate parts which are the well, sprue, runner, ingate and plate. *Solidworks* software was used as a drawing tool to create the geometry design in a solid model. The 3D solid model files were then converted into stereolithography (STL) format before being transferred to a Rapid Prototyping MJM Machine for parts fabrication work. The geometry design is presented in Figure 1.

1.2 Pattern preparation

For the vortex well, sprue and runner parts, the pattern was fabricated using the Multi-Jet Modeling (MJM) machine in order to achieve accurate dimensional accuracy.

Multi-Jet Modeling, also known as *Thermojet*, is a quick rapid prototyping process

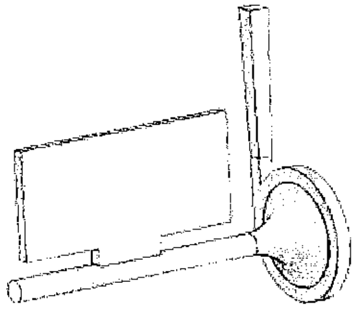


Fig. 1. Vortex well Design.
Fig. 1. Design du canal de vortex.

used for concept modeling. The system generates wax-like plastic models. The machine uses a wide-area head with multiple spray nozzles. These jet heads spray tiny droplets of melted liquid material which cool and harden on impact to form the solid object. The process is commonly used for creating casting patterns for the jewelry industry and other precision casting.

The MJM process parts are also dimensionally stable enough to use for limited fit-check analysis applications. The wax makeup of the build material makes it applicable as investment and sand casting pattern material. The glossy surface finish and easy melt-out provide for clean, crisp metal castings [15].

1.3 Experimental testing

Two types of testing were conducted: X-ray radiography and three-point bending tests.

1.4 X-Ray radiography test

The X-ray radiography test was performed in investigating the porosity distribution in plate casting. The part was exposed to X-ray for a few minutes, and the result was obtained on a radiographic film.

1.5 Three-point bending test

The three-point bending test was carried out to obtain the mechanical strength of AlSi7Mg alloy castings. This test was selected due to the brittle characteristics of casting specimens resulting from the silicon morphology, which developed during eutectic solidification. The cutting methods of casting samples and the produced specimens are shown in Figure 2. The bending test was performed using an AG-I SHIMADZU Universal Testing machine at room temperature with reference to Standard Test Methods for Bending Test of Material for Ductility-ASTM E290-97a.

1.6 Weibull distribution analysis

Weibull distribution is a continuous probability distribution. The Weibull distribution, as a statistical description of metal strength properties, was originally used to analyze the yield strength and fatigue behavior of steel alloys [6]. For aluminum castings, the two-parameter form of Weibull distribution is widely adopted and it can be expressed as:

$$F_p = 1 - \exp\left[-\left(\frac{\sigma}{\sigma_0}\right)^m\right]$$

where F_p is probability of specimen failures (in the bending test); σ is the variable being measured; σ_0 is the characteristic stress (often assumed to be equal to the average stress) and m is the Weibull modulus. The Weibull modulus, m, is a measure of the variability in the strength of the materials [6].

1.7 Microstructure analysis

Microstructure analysis was conducted in examining the microstructure of selected casting specimens produced from vortex well design. The Energy Dispersive X-Ray Spectrometer model EX-23000BU was used for microstructure analysis. For specimen preparation work, the selected samples were mounted, then ground using silica carbide (SiC) paper. The specimens were polished using silica carbide (0.02 micron) before using the scanning electron microscope.

2 Result & discussion

2.1 Introduction

An X-ray radiography test was conducted to observe the porosity distribution in the plate

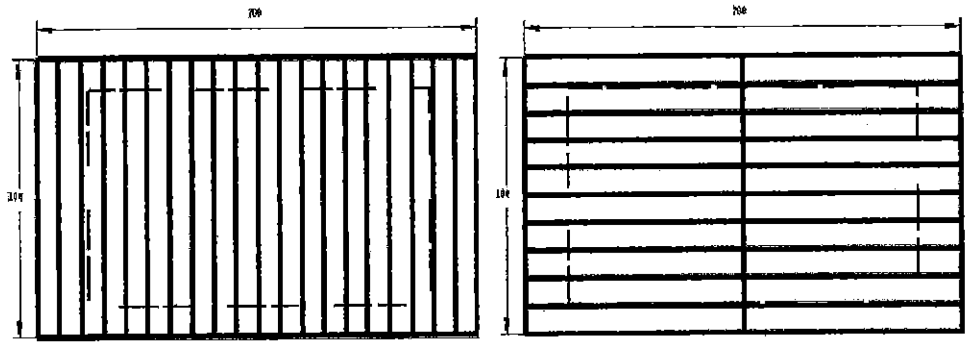


Fig. 2. The cutting methods of casting samples and the produced specimens will subject to three-point bend test ("edge effect" exists in the specimens out of the dash line).

Fig. 2. Méthode de découpe (verticale et horizontale) des échantillons pour préparation des éprouvettes des essais de flexion 3 points (des effets de bord existent au delà de la ligne pointillée).

castings. The results from the 3-point bending test were analyzed by using Weibull distribution analysis to measure the strength variability in the material. The microstructure of the cross-section area observed by scanning electron microscope was also analyzed and discussed.

2.2 Test results

Testing was conducted to investigate the porosity distribution in the plate castings and to obtain the mechanical strength of AlSi7Mg alloy castings. The results are discussed in the following section.

2.3 X-ray radiography test

Porosity sources are typically caused due to bubbles being trapped during solidification, entrapped air during filling, centerline shrinkage that occurs during the final solidification, blowholes from unvented cores, reactions at the mold wall, dissolved gases from melting, and dross or slag containing gas porosity. Figure 3 shows the result of the X-ray radiography test. In Figures 3a and 3b, a porosity defect was found in the plate casting. The detected area of porosity in Figure 3a was bigger than in Figure 3b. Moreover, in Figure 3c, there were no dark-colored marks found in the plate casting. Thus, no porosity was detected in the plate casting and the porosity distribution was increased when the diameter of the vortex well decreased.

2.4 Three-point bending test

Histograms showing the scatter of strengths are given in Figure 4. It is clear that the means of the scatter were improved in the order of increasing vortex well diameter. The conventional design also represents lower bending strength than the vortex well diameter.

The average bending strength values for horizontal and vertical sampling methods are shown in Tables 2 and 3, respectively.

From both sampling methods, the average bending stress was increased as the diameter of the vortex well increased. Therefore, the increase in vortex well diameter led to an increment in the mechanical strength of casting alloys.

For horizontal sampling data, the highest flexure strength value was observed in specimens that were located far from the ingate area, as shown in Table 4. Besides, it also depended on the porosity distribution. These castings tend to have poor strength at the location of porosity distribution.

Moreover, for vertical sampling data, the trend of flexure strength values was higher at the beginning and ending areas. The strength value was slightly reduced at the central area. These trends are recognized as an "edge effect" where the outside surfaces of the plate casting have a higher mechanical

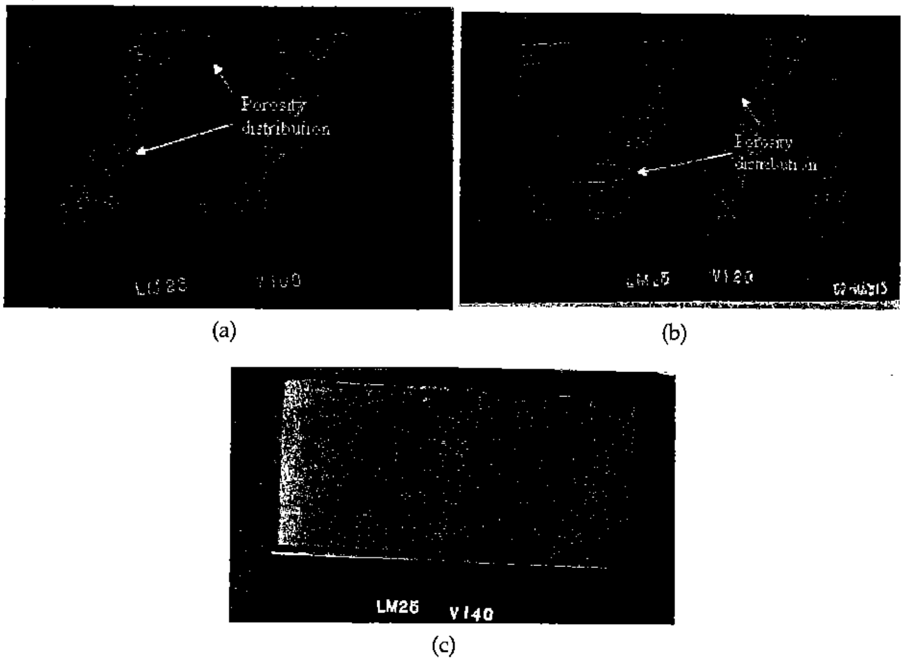


Fig. 3. Porosity distribution in casting plate by using X-ray radiography test. (a) 100 mm vortex well diameter. (b) 120 mm vortex well diameter. (c) 140 mm vortex well diameter.

Fig. 3. Distribution de porosité dans la plaque coulée, par radiographie X. (a) Diamètre du canal de vortex 100 mm. (b) Diamètre du canal de vortex 120 mm. (c) Diamètre du canal de vortex 140 mm.

Table 1. Chemical composition of Al-7Si-Mg alloys.

Tableau 1. Analyse chimique des alliages Al-7Si-Mg.

Comp.	Copper (Cu)	Magnesium (Mg)	Silicon (Si)	Iron (Fe)	Manganese (Mn)	Nickel (Ni)	Zinc (Zn)	Lead (Pb)	Tin (Sn)	Titanium (Ti)	Aluminum (Al)
(%)	0.1	02–0.6	6.5–7.5	0.5	0.3	0.1	0.1	0.1	0.05	0.2	Remainder

Table 2. The average bending strength values for the Horizontal sampling method.

Tableau 2. Valeurs de la résistance à la flexion, dans le cas d'un échantillonnage horizontal.

Vortex Well (VW) Design	140 VW	120 VW	100 VW	Conventional
Average bending strength (MPa)	337.9	279.3	234.6	223.7

strength than the central area. It is because of a higher cooling speed on the casting surface due to a sharp temperature gradient at the casting mold interface, which leads to a finer microstructure and therefore increases the mechanical strength of the parts [6].

2.5 Weibull distribution analysis

Weibull distribution is a continuous probability distribution. It is implicit in the Weibull distribution that the failure strength of material is determined by the distribution of defects resulting from its manufacturing [2].

From Weibull Analysis, the Failure Probability, F_p, is the numerical rank divided by $n+1$, where n is the total number of specimens. The Weibull distribution is given by the expression:

$$F_p = 1 - \exp\left[-\left(\frac{\sigma}{\sigma_0}\right)^m\right]$$

The minus sign in the exponential term was eliminated, and taking natural logarithms

Table 3. The average bending strength values for the vertical sampling method.
Tableau 3. Valeurs de la résistance à la flexion, dans le cas d'un échantillonnage vertical.

Vortex Well (VW) Design	140 VW	120 VW	100 VW	Conventional
Average bending strength (MPa)	315.1	290.9	257.5	216

Table 4. Calculation of weibull distribution for the horizontal sampling method (vortex well diameter 120 mm).
Tableau 4. Calcul de la distribution de Weibull dans le cas d'un échantillonnage horizontal (diamètre du canal de vortex : 120 mm).

Max Force $F(N)$	Stress, σ (Mpa)	Failure Probability, Fp	$\ln(1/1-Fp)$	$\ln[\ln(1/1-Fp)]$	$\ln\sigma$
3241.56	235.617	0.091	0.095	–2.351	5.462
3381.41	258.605	0.095	0.100	–2.302	5.555
3672.5	275.438	0.143	0.154	–1.870	5.618
3712.66	278.449	0.190	0.211	–1.554	5.629
3761.25	282.094	0.238	0.272	–1.302	5.642
3765.16	282.387	0.286	0.336	–1.089	5.643
3769.69	282.727	0.333	0.405	–0.903	5.644
3864.38	289.828	0.381	0.480	–0.735	5.669
3910.47	293.285	0.429	0.560	–0.581	5.681
4204.69	314.852	0.476	0.647	–0.436	5.752

Table 5. The weibull Modulus for the horizontal sampling method.
Tableau 5. Module de Weibull dans le cas d'un échantillonnage horizontal.

Vortex well design	Conventional	100 VW	120 VW	140 VW
Weibull Modulus	12.1	10.4	12.4	13.9

twice gives;

$$\ln\left[\ln\left(\frac{1}{1-Fp}\right)\right] = m\ln(\sigma) - m\ln(\sigma_0)$$

where m represents the Weibull modulus. The slope of the graph is referred to as the Weibull modulus and it is helpful as a quantitative parameter that measures the reliability of the castings.

Figures 5 and 6 represent the Weibull plots of horizontal and vertical casting specimen samplings. The Weibull modulus values for the vortex well and conventional design for horizontal and vertical sampling methods are shown in Tables 5 and 6, respectively.

From the Weibull modulus values for both sampling methods, as the vortex well diameter increased, the m value was also increased. Besides, it was observed that the m value for the conventional design was smaller than the m value for the biggest vortex well diameter. So, the biggest vortex well diameter has the highest value of slope. This indicates that the higher the value of m, the narrower the range of strengths [2]. It was discovered that the oxide films are closely related to surface turbulence, as discussed by Dai et al. [6]. Thus, a reduction in surface turbulence will reduce the possibilities of free surface break-up and the entrapment of surface oxide films. Thus, by optimizing the runner system design through the use of a vortex well, the flow behavior during the filling is improved and the production of oxide films can be significantly reduced so that the mechanical strength and reliability of aluminum alloy castings can be enhanced.

2.6 Microstructure analysis

In this section, the microstructure of polished casting specimens, which was taken using a scanning electron microscope, is discussed.

2.7 Scanning electron microscope

Some defects were observed when polished casting specimens were examined under a

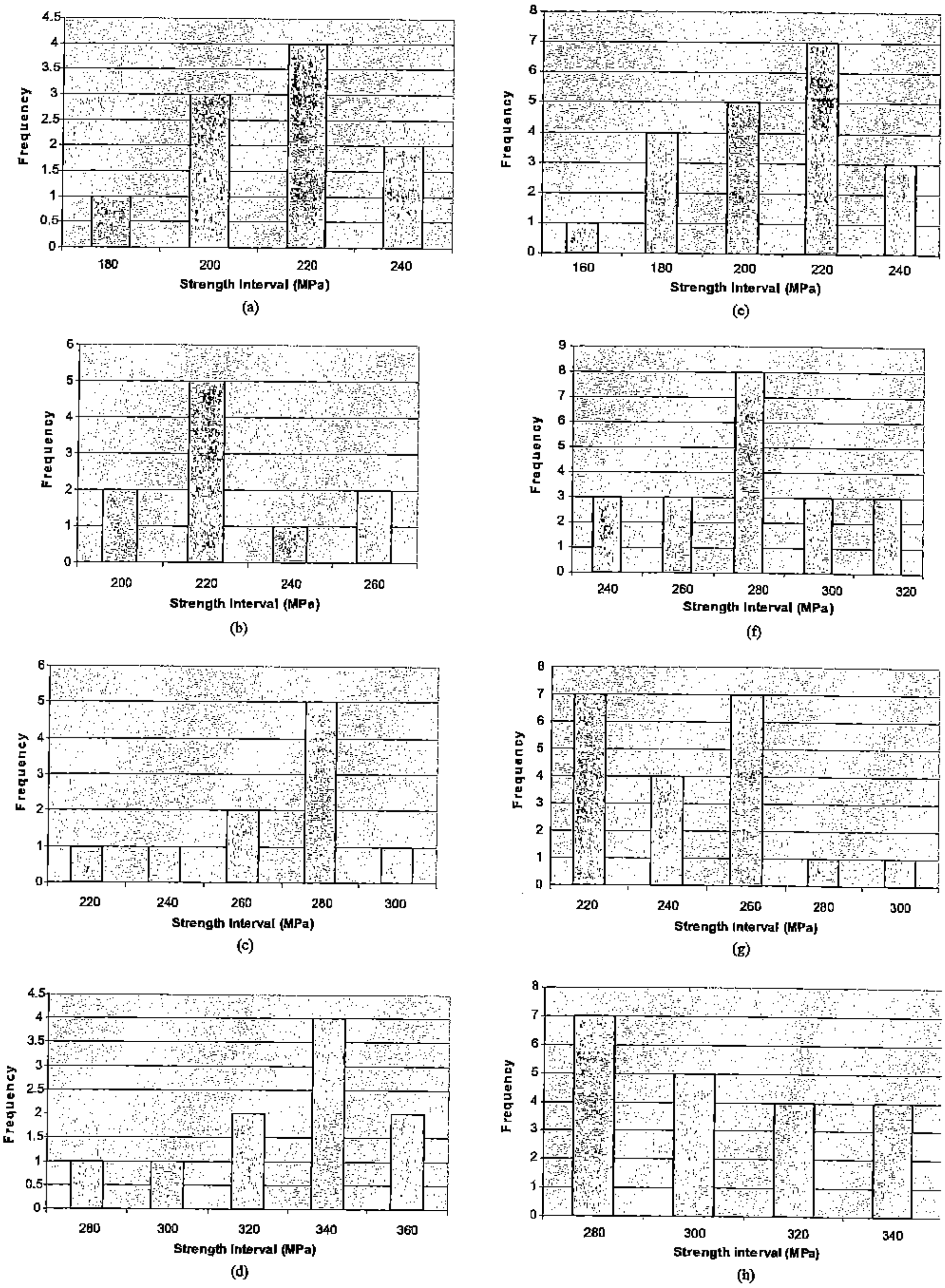


Fig. 4. Frequency histogram plots of bending strength for horizontal and vertical sampling methods. (a) Horizontal sampling using conventional design. (b) Horizontal sampling using 100 mm vortex well diameter. (c) Horizontal sampling using 120 mm vortex well diameter. (d) Horizontal sampling using 140 mm vortex well diameter. (e) Vertical sampling using conventional design. (f) Vertical sampling using 100 mm vortex well diameter. (g) Vertical sampling using 120 mm vortex well diameter. (h) Vertical sampling using 140 mm vortex well diameter.

Fig. 4. Histogrammes de fréquences des valeurs de résistance en flexion 3 points, dans le cas d'un échantillonnage horizontal et vertical. (a) Échantillonnage horizontal et design conventionnel. (b) Échantillonnage horizontal et diamètre du canal de vortex 100 mm. (c) Échantillonnage horizontal et diamètre du canal de vortex 120 mm. (d) Échantillonnage horizontal et diamètre du canal de vortex 140 mm. (e) Échantillonnage vertical et design conventionnel. (f) Échantillonnage vertical et diamètre du canal de vortex 100 mm. (g) Échantillonnage vertical et diamètre du canal de vortex 120 mm. (h) Échantillonnage vertical et diamètre du canal de vortex 140 mm.

Table 6. The weibull Modulus for the vertical sampling method.
Tableau 6. Module de Weibull dans le cas d'un échantillonnage vertical.

Vortex Well Design	Conventional	100 VW	120 VW	140 VW
Weibull Modulus	9.8	11.2	12.7	14.1

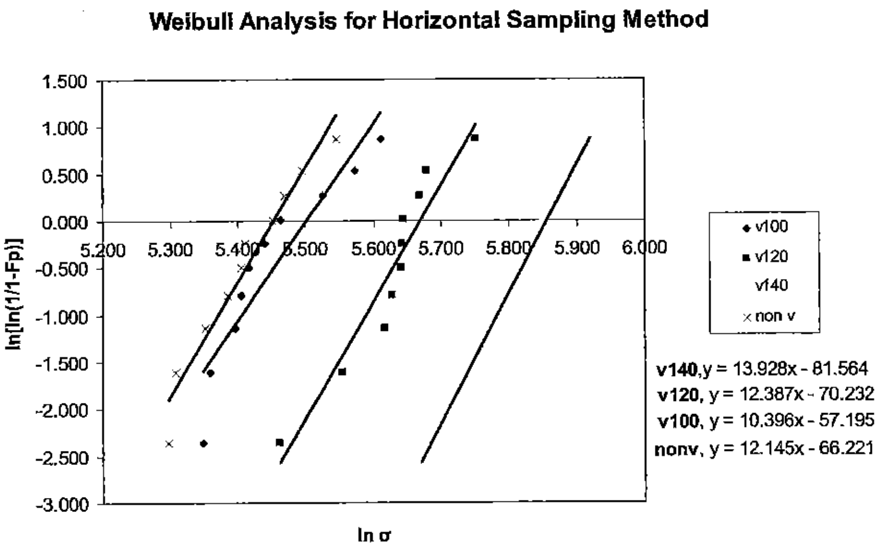


Fig. 5. Weibull plots of all casting specimens for horizontal sampling.
Fig. 5. Diagramme de Weibull pour tous les échantillons coulés, dans le cas de l'échantillonnage horizontal.

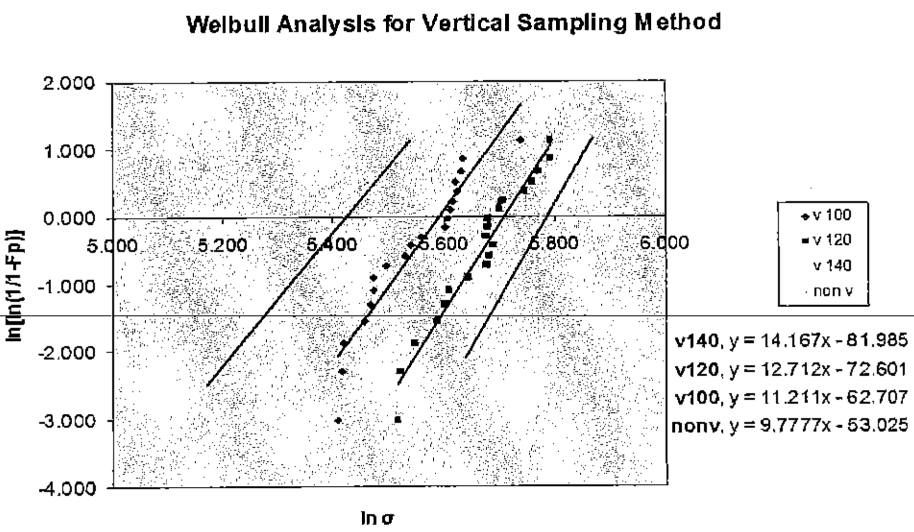
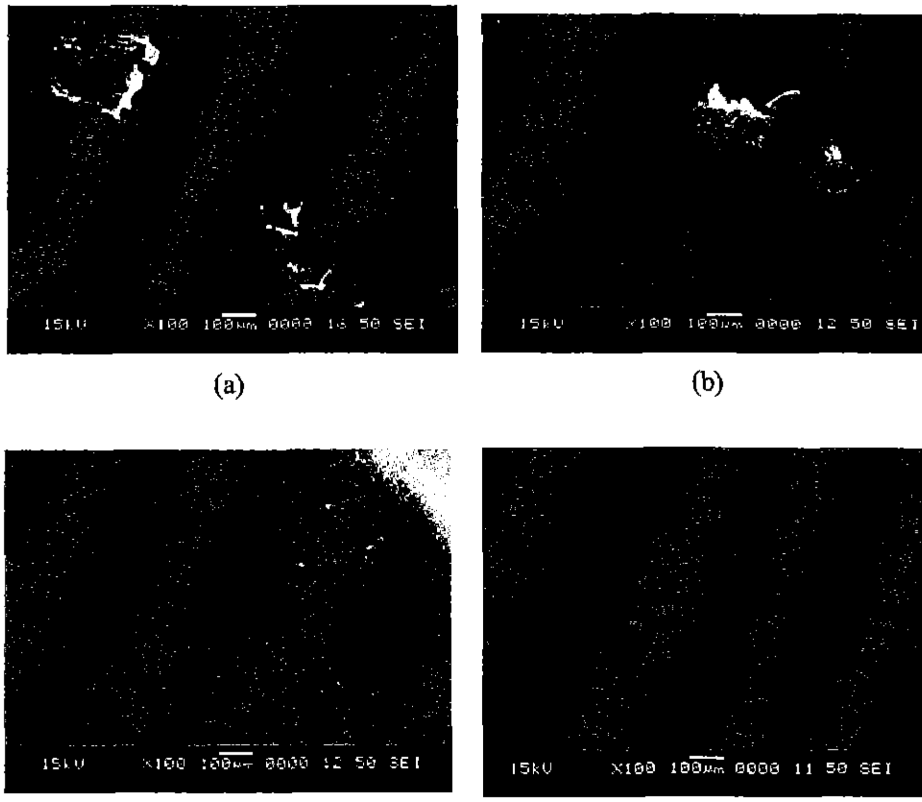


Fig. 6. Weibull plots of all casting specimens for vertical sampling.
Fig. 6. Diagramme de Weibull pour tous les échantillons coulés, dans le cas de l'échantillonnage vertical.



(a) (b) (c) (d)

Fig. 7. Defects in casting specimens by Scanning Electron Machine. (a) Conventional. (b) 100 mm vortex well diameter. (c) 120 mm vortex well diameter. (d) 140 mm vortex well diameter.

Fig. 7. Images MEB des défauts des pièces coulées. (a) Conventionnel. (b) Diamètre du canal de vortex 100 mm. (c) Diamètre du canal de vortex 120 mm. (d) Diamètre du canal de vortex 140 mm.

scanning electron microscope at 100 X magnification. The defects are recognized as pin holes, shrinkage and gas porosity.

Figure 7a shows pin hole defects found in a casting specimen using conventional design. As the molten metal solidified, the temperature fell, which decreased the solubility of gases, thereby expelling the dissolved gases. The hydrogen which was picked up by the molten metal either in the furnace or by the dissociation of water inside the mold cavity may escape the solidifying metal, leaving behind a very small diameter and long pin hole showing the path of escape.

While, in Figure 7b for a 100-mm vortex well diameter, the defects found in the specimen are shrinkage and pin holes. Solidification shrinkage occurs because metals are less dense as a liquid than a solid, so during solidification, the metal density dramatically increases, which leads to small pockets of liquid trapped throughout and ultimately porosity.

In Figure 7c for a 120-mm vortex well diameter, there were just small defects of gas porosity in the specimen. Gas porosity is the formation of bubbles within the casting after it is cooled. This occurs because most liquid materials can hold a large amount of dissolved gas, but the solid form of the same material cannot hold it, so the gas forms bubbles within the material as it cools. Gas porosity trapped inside the metal leads to an increased risk of breaking or stress corrosion. In Figure 7d for a 140-mm vortex well diameter, there are no defects found in the casting specimen. It is evident from Figure 7 that as the diameter of the vortex well is increased, there is a significant reduction in terms of shrinkage and gas porosities inside the cast part. Thus, the defects are reduced as the diameter of the vortex well is increased, as observed from a diameter of 140 mm, where less defects are found in the cast part.

For conventional casting, a lower mean bending stress is observed with a higher Weibull Modulus value, which means that there is very little scatter of fracture strength data and thus, a stress can safely be applied only slightly below the average bending stress. This is because the conventional casting design with a vortex runner has been shown to have good control of the chaotic behavior of liquid metal flow in the runner and the consequent reduction of casting defects, as discussed by Dai et al. [6]. For a vortex well diameter with a Weibull Modulus value below the conventional design value, this indicates that the scatter of fracture strength data is large and the stress in service must be kept far below the mean bending stress.

This can be explained because of the high pouring temperature applied, 735–740 °C, and this led to high fluidity of the molten metal. Thus, turbulent flow may happen when using a vortex well with a small diameter.

From the specimen observed, this indicates that when the bigger vortex well diameter was applied, the defect quantities in specimens became less. Besides, by using a bigger vortex, it decreased the turbulent flow of molten metal into the runner part. This minimizes the possibility of shrinkage porosity inside the plate area. The presence of these defects, as well as gas or shrinkage porosity, can make properties unpredictable and significantly affect the mechanical properties of aluminum castings.

3 Conclusions

The size of the vortex well diameter was found to have a significant effect on the flexure strength of AlSi7Mg aluminum alloy casting. The increment in mechanical strength of AlSi7Mg aluminum alloy casting was directly proportional to the increment in vortex well diameter. Besides, the conventional design also shows the lowest mechanical strength when compared with the vortex well design. Furthermore, from the X-ray radiography test, the porosity distribution in the casting plate was decreased by increasing the vortex well diameter. This also applies to the microstructure analysis, where defects such as porosity and shrinkage were minimized by increasing the vortex well diameter. By optimizing the vortex well design, defects can significantly be reduced and the mechanical strength and reliability of aluminum alloy casting can be further enhanced.

References

[1] R.M. Mcdavid, J.A. Dantzig, *Metall. Mater. Trans.* 29 (1997) 679-690

[2] J. Campbell, Castings, Elsevier Butterworth-Heinemann, UK, 2003

[3] C.F. Yeung, H. Zhao, W.B. Lee, *Materials Characterization* **40** (1998) 201-208

[4] F.Y. Hsu, M.R. Jolly, J. Campbell, *Int. J. Cast. Metal. Res.* **19** (2006) 38-44

[5] J. Campbell, Castings Practice: The 10 Rules of Castings, Elsevier Butterworth-Heinemann, UK, 2004

[6] X. Dai, X. Yang, J. Campbell, J. Wood, *Mater. Sci. Eng. A* **354** (2003) 315-325

[7] K.R. Ravi, R.M. Pillai, K.R. Amaranathan, B.C. Pai, M. Chakraborty, *J. Alloys Compo.* **456** (2008) 201-210

[8] R.C. Voigt, Fillability of thin-wall steel casting, Final Report, The Pennsylvania State University, 2002

[9] V.S. Zolotorevsky, N.A. Belov, M.V. Glazoff, Casting Aluminium Alloys, Elsevier, UK, 2007

[10] H. Jiang, J. Bowen, F. Knott, *J. Mater. Sci.* **34** (1999) 719-725

[11] R.W. Lewis, E.W. Postek, Z. Han, D.T. Gethin, *Int. J. Numer. Methods for Heat & Fluid Flow* **16** (2005) 539-572

[12] K. Kocatepe, *Mater. Design* 28 (2007) 1767-1775

[13] A.K.P. Rao, K. Dasa, B.S. Murty, M. Chakraborty, *Wear* **261** (2006) 133-139

[14] R.W. Lewis, R.S. Ransing, W.K.S. Pao, K. Kulasegaram, J. Bonet, *Int. J. Numerical Methods for Heat & Fluid Flow* **14** (2004) 145-166

[15] G.K. Cooper, Rapid Prototyping Technology: Selection and Application, Marcell Dekker, Inc., USA, 2001