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EFFECT OF VORTEX RUNNER GATING SYSTEM ON THE MECHANICAL STRENGTH OF Al-12Si ALLOY CASTINGS

WPŁYW KANAŁU UKŁADU WLEWOWEGO NA WYTRZYMAŁOŚĆ MECHANICZNĄ ODLEWÓW ZE STOPU Al-12Si

Gating system design is an essential element in casting process which affects significantly the molten metal flow behavior, heat transfer and solidification of the melt. Optimum gating design will lead to a good quality of casting product. One of the major components in gating system is runner. This study was conducted to determine the effect of vortex runner diameter gating system on the mechanical strength of Al-12Si alloy casting. Simulation was conducted to study the behavior of the fluid flow and the results obtained showed close agreement with the results obtained from the experiment. Experimental results showed that the casting product with bigger vortex runner diameter gating system led to the improvement of average bending strength.

Keywords: gating system, sand casting, mechanical strength, weibull analysis

Układ wlewowy to podstawowy element w procesieodlewania, który znacząco wpływa na płynięcie ciekłego metalu, transport ciepła oraz krzepnięcie metalu. Optymalny układ wlewowy gwarantuje dobrą jakość odlanego produktu. Jednym z głównych elementów układu wlewowego jest kanał wlewowy. Celem pracy było zbadanie wpływu średnicy kanału układu wlewowego na wytrzymałość mechaniczną odlewów ze stopu Al-12Si. Celem zbadania zachowania przecieczy przeprowadzono symulacje i otrzymane wynikiwykazują dobrą zgodność z wynikami otrzymanymi doświadczalnie. Wyniki doświadczeń pokazały, że zastosowanie większej średnicy kanału układu wlewowego prowadzi do poprawy średniej wytrzymałości odlewów na zginanie.

1. Introduction

One of the important features of mould cavity is the gating system (Campbell, 2003 and Esparza et al., 2005). The gating system is composed of pouring basin, sprue, runner, gate and riser. The function of sprue and runner is to allow the molten metal to completely fill the cavity of casting component. Furthermore (Beeley, 2001), uniform flow of the molten metal is required to avoid entrapment of air, metal oxidation and mould erosion. In casting process, mould filling plays a significant role in ensuring the quality of casting component produced. This is evident through a number of extensive research effort have been made in studying the effect of gating design on the flow pattern of melt entering the mould cavity (Esparza et al., 2005, Masoumi et al., 2005, Babaei et. al, 2006). Esparza et al. (2005) performed the 3D gating design optimisation. Two design variables were runner depth and tail slope and a mathematical nonlinear optimisation model was developed with the aim of minimizing the aluminium velocity subject to constraints which ensure there was no trap air in the main runner when the metal entered the mould cavity via the ingate. Masoumi et al. (2005) studied the effect of gating design on mould filling, where direct observation was employed to experimentally observe the flow pattern. The results showed that an increase in the width of the gate with a constant thickness resulted in the variation of mould filling. A considerable effect of the geometry of a gate with a constant cross section area on flow pattern was observed, which primarily resulted from the change of the metal front pressure at the entrance. Babaei et al. (2006) improved advection algorithm of computational modeling of free surface flow using structured grids. A computer model was develop with the features with accurate convection of fluid in all directions in free surface and the mould filling was simulated in 3D. There was good correlation between the experimental and simulated results for gray iron samples. This was due to the higher momentum of the melt during filling of the mould and

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also lower effect of surface tension of the melt and mould wall.

It has been shown that an optimum gating system design could reduce the turbulent of the melt flow; minimize air entrapment, sand inclusion, oxide film and dross [Hu et al., 2000, Dai et al., 2003]. Hu et al. (2000) designed and optimized of runner and gating systems for the die casting of thin-wall magnesium telecommunication parts. They discovered that a proper runner and gating system is very important to secure good quality die castings through providing a homogeneous mould filling pattern. The preliminary design with a split gating system led to a swirling filling pattern and insufficient central flow, which prematurely closed the edges and left the last filled areas falling into the inner portion of the part. The preliminary design was improved by using a continuous gating system and a bigger runner size. The gate area was increased and the gating speed slightly reduced. Dai et al. (2003) studied the effects of runner system design (vortex, rectangular and triangular runner systems) on the mechanical strength of Al-7Si-Mg alloy castings. It was found that the use of vortex runner could effectively control the chaotic behaviour of liquid metal flow in the runner, assist in the reduction of ingate velocity, and the consequent reduction of casting defects.

Fluid flow phenomena involved in the stage of mould filling has a direct consequence to the formation of various casting defects.. For instance, rigorous streams and highly turbulent flows will cause mould erosion and air entrapment. On the other hand, relatively slow filling will lead to premature solidification and it will prevent the molten metal from being improperly distributed within the mould as studied in [Attar et al., 2005]. Attar et al. (2005) found that improper design of the gating system will lead to porosity defect in casting as evident in [Lee et al., 2001 and Katzarov, 2003]. Lee et al. (2001) studied experimentally mould filling process in vertical centrifugal casting. The results from the experiments showed that the bottom filling method was better than the top one, which could achieve stable filling, minimize turbulence and avoid drastic liquid collision. The existing of porosity defect will decrease the mechanical properties of the product. Generally, the greater the amount of porosity in the casting component, the greater it will be the deterioration in mechanical properties.

The pouring of molten metal into the mould is one of the critical steps in casting process. During filling process, the behavior of the liquid will determine whether the cast shape is properly formed, internally sound and free from defect. According to Campbell (2003), most of casting scrap arose during the few seconds of pouring of the casting. This was supported by Yang *et al.* (2004), where inappropriate filling of casting caused surface oxide films to be folded into the bulk liquid due to higher liquid metal kinematics energy, resulting "entrainment damage". It was found that the entrapped oxide films were frequently accompanied by different casting defect such as shrinkage pore, cracks and porosity.

Barkhudarov and Williams (1995) studied the significance of mould filling process to the mechanical properties of metal casting, especially for metals that exhibited a formation of strong oxide film such as aluminum alloy. They demonstrated that, it was possible using advanced numerical methods to accurately described three dimensional mould filling phenomena with large deformation of metal free surface. Such modeling was useful for designing runner and gating systems involving the formation of oxide films or containing other surface inclusions. Furthermore, Babaei *et al.* (2006) found that mould filling was a very important step in determining the quality of a casting. The fluid flow phenomena during the mould filling was very closely related to the casting quality, surface finish and macro segregation of the cast part and mould erosion. Dimensional accuracy of a casting and die life was also affected by the fluid flow in the mould cavity. In addition, the flow pattern of metal affected the temperature distribution in the mould cavity, which was the initial condition for solidification process to occur.

Other study related to the effect of gating design on the flow pattern was done by Masoumi et al. (2005) and Hu, et al. (2000). An experiment by pouring aluminum alloy into a sand mould was conducted to find various flow patterns, resulting from different gating designs. The results showed that the geometry and size of the gate; and the ratio of gating system had a significant influence on the pattern of mould filling. An increase in the width of the gate with a constant thickness led to the variation of mould filling. Three different patterns were observed, where the patterns were narrowing, expansion and deviation of molten metal fronts. For aluminum alloys casting, the decrease of its mechanical properties was closely related with the area fraction of defects, such as porosity and oxide films in the fracture surface of the casting sample [Dai 2003.]. Campbell (2003) also pointed out that the runner system design had an important influence on the tensile strength of aluminum cast alloy. While many works have been done on gating design optimization, there is little information available on the effect of runner diameter on the mechanical strength of casting component.

2. Experimental method

2.1. Geometry design

In this study, vortex flow runner system with 3 different diameters was used to produce plate casting. The geometry design consists of sprue, runner, ingate and plate. The 3D solid model was converted to stereo lithography (STL) format before transferred to Z406 3D Printer for fabrication. The geometry dimensions are presented in Table 1 and its isometric and front view are shown in Figure 1.

TABLE 1

Dimension of Casting Geometry

Geometry	Size (mm)			Diameter (mm)	
	Length	Height	Width	Top	Bottom
Sprue	–	190	–	15	10
Ingate	60	15	10	–	–
Plate	200	100	10	–	–
Runner	245	–	–	–	–
Runner Diameter	Runner 1 = 15mm, Runner 2 = 20mm, Runner 3 = 25mm				

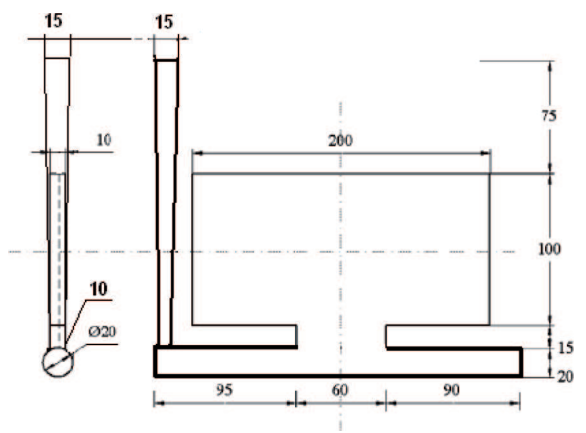


Fig. 1. Geometry of gating system and cast part

2.2. Materials selection

Material used in this research was Al-12Si or Aluminium LM6 alloy. The chemical composition of this alloy is shown in Table 2. Al-12Si alloy is widely used in the form of general purpose sand casting and die casting. The eutectic composition of Al-12Si giving these alloys low melting temperature, good fluidity and good cast ability characteristics. Due to the excellent fluidity characteristics, Al-12Si alloy is used to cast thinner and intricate sections compared to other casting alloys, which is useful for producing complex casting with large surface area and thin wall geometry. The alloy is used where rigidity, good corrosion resistance and high fluidity in casting are greater importance than strength [Askeland and Phule, 2003]. Furthermore, this alloy has high corrosion resistance which is applicable for marine work application. Al-12Si alloy is lighter than the aluminum copper alloys, which is suitable for aero and automobile construction [Higgins, 1993].

2.3. Finishing process

After molten metal was solidified and cooled at room temperature, casting product was removed from the mould. Casting product was machined to separate ingate and plate area. The plates then were machined vertically and horizontally using band saw machine for three points bending specimen preparation as indicated in Figure 2.

TABLE 2

Chemical Composition of Al-12Si Alloys

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	0.1	10.0 ~ 13.0	0.6	0.5	0.1	0.1	0.1	0.05	0.2	Remainder

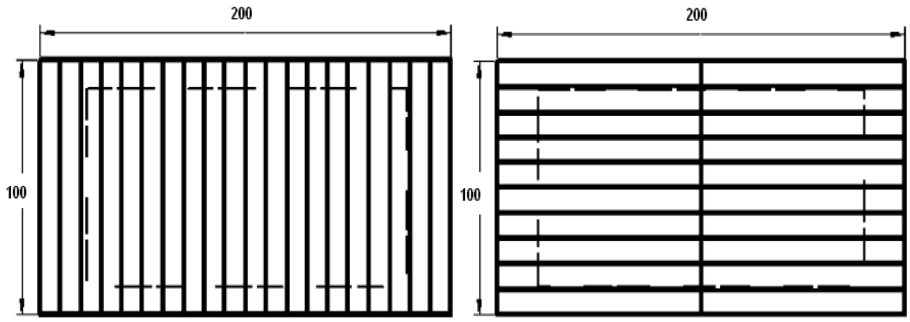


Fig. 2. Cutting Methods of Casting Samples for 3 Points Bending Test

2.4. Testing

2.4.1. Point Bending Test

3 Point Bending Test was carried out to obtain the mechanical strength of Al-12Si alloys casting. This test was selected due to brittle characteristic of casting specimens resulting from the silicon morphology which developed during eutectic solidification. The bending test was performed using AG-I SHIMADZU Universal Testing Machine at room temperature with reference of Standard Test Methods for Bending Test of Material for Ductility – ASTM E290-97a.

2.5. Results Analysis

2.5.1. Weibull Distribution Analysis

The Weibull distribution is an indicator of the variability of strength of materials resulting from a distribution of flaw sizes. This behavior results from critical sized flaws in materials with a distribution of flaw size. The term "flaw" refers to features as small pores (holes), inclusions or micro crack and it does not refer to atomic level defects such as vacancies or dislocation [Askeland, and Phule, 2003].

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 [Dai, 2003]. For aluminum castings, the two parameter form of Weibull distribution is widely adopted and it can be expressed as:

$$\boldsymbol{F}_p = 1 - \exp\left[-\left(\frac{\sigma}{\sigma_0}\right)^m\right] \tag{1}$$

where $\boldsymbol{F}_p$ 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 of the strength of the materials. For pressure die castings, a Weibull modulus is often between 1-10, whereas for many gravity filled casting it is between 10 and 30 [Campbell, 2003].

3. Experimental results and discussion

3.1. Point Bending Test results

Frequency histograms of a bending strength are plotted and presented in Figure 3.

The average bending strength values in descending order are as follows;

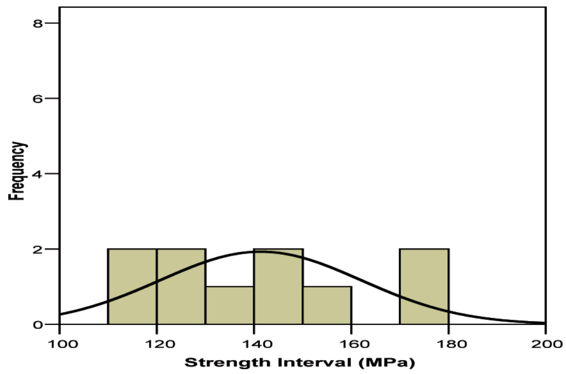
25 mm RD (**170.244**MPa) > 20 mm RD (**156.643**MPa) > 15 mm RD (**141.366**MPa)

for horizontal sampling method. (RD: Runner Diameter)

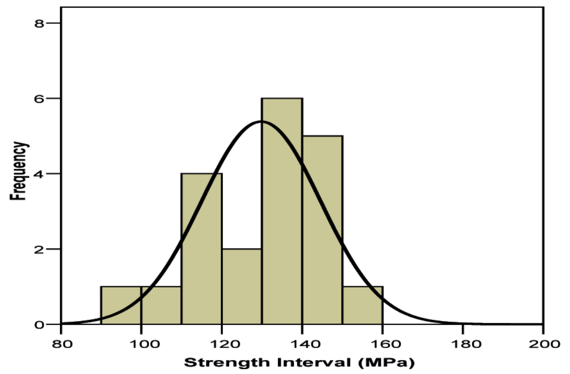
25 mm RD (**158.003**MPa) > 20 mm RD (**144.451**MPa) > 15 mm RD (**129.791**MPa)

for vertical sampling method. (RD: Runner Diameter)

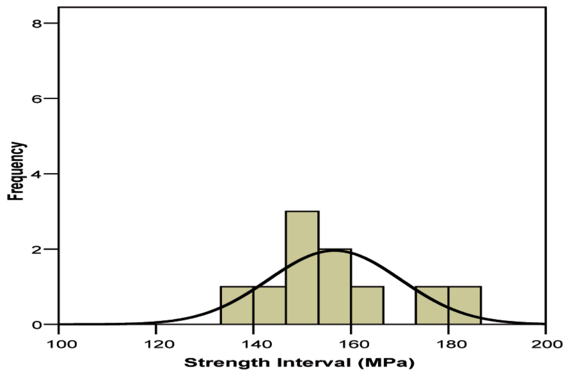
An average of bending strength values from both sampling method showed that when the diameter of runner increase, the average bending strength also increase. For horizontal sampling data, the higher flexure strength values was observed in specimen that was located far from ingate area. When the specimen used for 3 point bending test was located near the ingate, the bending strength values were declined gradually. On the other hand, for vertical sampling data, the trend of flexure strength values was higher at the beginning and ending area, whereas at the central area, the strength value was slightly reduced. These trends are recognized as "edge effect" where the outside surfaces of the plate casting have a higher mechanical strength than the central area. This was due to a higher cooling speed on the casting surface lead to a finer microstructure which increases the mechanical strength of the parts [Campbell, 2003].



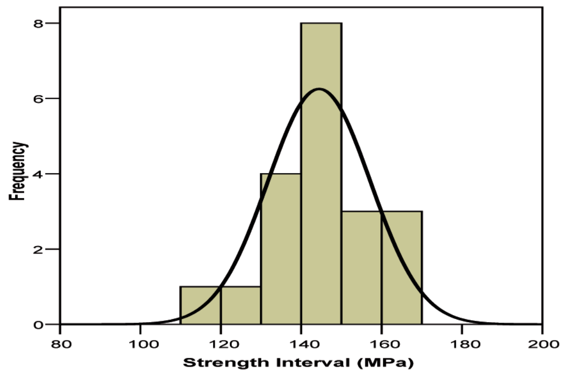
(a) Horizontal Sampling Using
15mm Runner Diameter



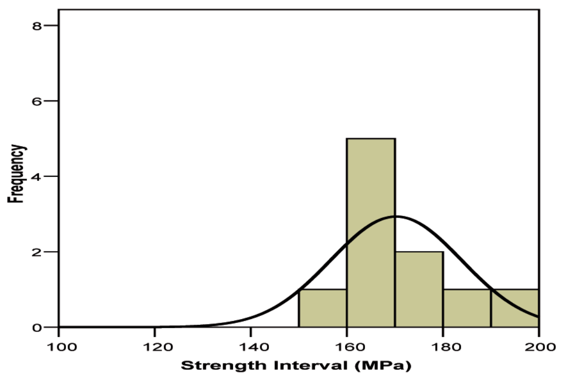
(d) Vertical Sampling Using
15mm Runner Diameter



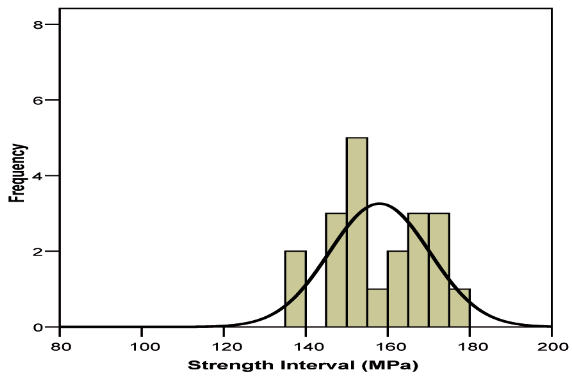
(b) Horizontal Sampling Using
20mm Runner Diameter



(e) Vertical Sampling Using
20mm Runner Diameter



(c) Horizontal Sampling Using
25mm Runner Diameter



(f) Vertical Sampling Using
25mm Runner Diameter

Fig. 3. Frequency Histogram Plots of Bending Strength for Horizontal and Vertical Sampling Method

3.2. Weibull Distribution Analysis

Table 3 and Table 4 show samples of Weibull distribution calculation for horizontal and vertical sampling method using 15 mm runner diameter. The sampling data was restructured to ascending orders. The Failure Probability, $F_p$is the numerical rank divided by n+1, where n is totals number of specimens. In this case, total number of specimen is 10 for horizontal samples and 20 for vertical samples.

TABLE 3
Calculation of Weibull Distribution for Horizontal Sampling Method
(Runner Diameter 15 mm)

Max. Force F (kN)	Stress σMpa)	Failure Probability F_P	ln [ln(1 / 1-F_P)]	ln σ
1.953	117.180	0.091	-2.351	4.764
1.988	119.280	0.182	-1.606	4.781
2.062	123.720	0.273	-1.144	4.818
2.137	128.220	0.364	-0.794	4.854
2.275	136.500	0.455	-0.501	4.916
2.388	143.280	0.545	-0.238	4.965
2.431	145.856	0.636	0.012	4.983
2.523	151.387	0.727	0.262	5.020
2.879	172.762	0.818	0.533	5.152
2.925	175.472	0.909	0.875	5.167

TABLE 4
Calculation of Weibull Distribution for Vertical Sampling Method
(Runner Diameter 15 mm)

Max. Force F (kN)	Stress σ (Mpa)	Failure Probability F_P	ln [ln(1 / 1-F_P)]	ln σ
1.659	99.540	0.048	-3.020	4.601
1.769	106.140	0.095	-2.302	4.665
1.856	111.360	0.143	-1.870	4.713
1.873	112.380	0.190	-1.554	4.722
1.927	115.620	0.238	-1.302	4.750
1.958	117.480	0.286	-1.089	4.766
2.068	124.080	0.333	-0.903	4.821
2.135	128.100	0.381	-0.735	4.853
2.196	131.760	0.429	-0.581	4.881
2.227	133.620	0.476	-0.436	4.895
2.228	133.678	0.524	-0.298	4.895
2.254	135.244	0.571	-0.166	4.907
2.291	137.485	0.619	-0.036	4.924
2.315	138.919	0.667	0.094	4.934
2.343	140.586	0.714	0.225	4.946
2.371	142.285	0.762	0.361	4.958
2.414	144.815	0.810	0.506	4.975
2.417	145.031	0.857	0.666	4.977
2.450	146.981	0.905	0.855	4.990
2.512	150.720	0.952	1.113	5.015

Further calculation was made base on Equation 1. By eliminating the minus sign and taking natural logarithm twice, Equation 1 becomes;

$$\ln\left[\ln\left(\frac{1}{1-Fp}\right)\right] = m\ln(\sigma) - m\ln(\sigma_0) \qquad (2)$$

where m represent the Weibull modulus. When the value of Weibull modulus, m is getting bigger, it indicates that the range of mechanical strength becomes smaller. Figure 4 and Figure 5 depict the Weibull plots of horizontal and vertical casting specimens sampling.

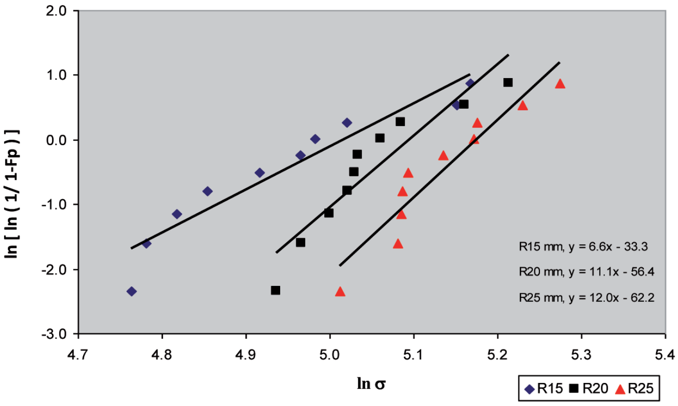


Fig. 4. Weibull Plots of All Casting Specimens for Horizontal Sampling

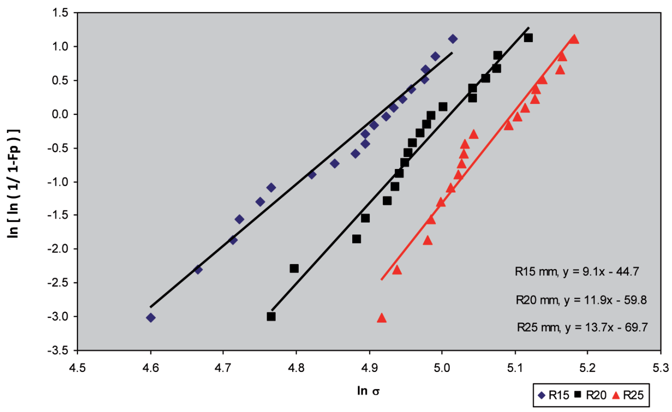


Fig. 5. Weibull Plots of All Casting Specimens for Vertical Sampling

The Weibull modulus of each runner diameter in horizontal and vertical sampling are shown as follow;
Horizontal samples; 15 mm : 20 mm : 25 mm = 6.6 : 11.1 : 12.0
Vertical samples; 15 mm : 20 mm : 25 mm = 9.1 : 11.9 : 13.7

The Weibull modulus values for both sampling method show that when the runner diameter increased, the m value also increased. This indicates that, strength variability of specimens produced by bigger vortex runner diameter gating system was smaller compared to specimens produced by smaller vortex runner diameter gating system.

4. Conclusions

This research was attempted to determine the correlation of vortex runner diameter size gating sytem on the mechanical strength of Al-12Si alloy castings. The size of vortex runner gating system was found to have an effect on the flexure strength of Al-12Si alloy castings. The results showed that the increment of mechanical strength of Al-12Si alloy castings was directly proportional with increment of runner diameter size.

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