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ORIGINAL ARTICLE

A Preliminary Study of Fabrication Technology for Dynamic Compression Plates Using Centrifugal Casting Process

A.K. Nasution[1*], D. Gustiani[1], A. Handoko[1], Mukhtar[1], Zulkarnain[1], A. Arafat[2], M.H. Idris[3,4] and M.H. Ramlee[4,5]

[1]Department of Mechanical Engineering, Faculty of Engineering, Universitas Muhammadiyah Riau, Pekanbaru, Indonesia
Phone: +62761-35008; Fax: +62761-35008
[2]Department of Mechanical Engineering, Faculty of Engineering, Universitas Negeri Padang, Padang, 25131, Indonesia
[3]School of Mechanical Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia
[4]Medical Devices and Technology Centre (MEDiTEC), Institute of Human Centered Engineering (i-Humen), Universiti Teknologi Malaysia, 81310, Johor, Malaysia
[5]Bioinspired Devices and Tissue Engineering (BIOINSPIRA) Group, School of Biomedical Engineering and Health Sciences, Faculty of Engineering, Universiti Teknologi Malaysia, 81310, Johor, Malaysia

ABSTRACT – The high cost of health services in low-income countries has caused them to produce implants and medical devices at low cost. This research highlights a preliminary study of the design concept, mould design, and fabrication of horizontal type centrifugal casting machines for the manufacture of dynamic compression plates materials. Normally, dynamic compression plate is produced from materials such as 316L stainless steel, cobalt, and titanium alloys. In this work, aluminium-silicon alloy was used in this preliminary study. Aluminium-silicon alloy was melted at a temperature of 730 °C and poured into a mould with a rotational speed of 1500 rpm. Tensile, hardness and microstructure investigation were carried out to discern the mechanical properties of the cast product from the horizontal type centrifugal casting machine. Results showed the measured value of tensile strength is not significantly different in the two zones of cast pipe, the butt zone of fall of molten metal (specimen A) was 147 MPa, and the butt-end zone (specimen B) was 142 MPa. The hardness value for the as-cast pipe obtained from the outside, middle, and inside, was 104.0, 92.9, and 80.3 HV, respectively. Evaluation of microporosity in fractures (from tensile test) results from horizontal type centrifugal castings showed a small distribution. Meanwhile, the calculation of the contour hole processing time for DCP with eight holes is 38 minutes per implant.

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KEYWORDS
Centrifugal casting; Mould design; Microporosity; Dynamic compression plate; Low-cost

INTRODUCTION

Due to economic reasons coupled with rapid technological advancements, the government is pushing for innovation and promoting local products. This strategy is expected to promote self-sufficiency and reduce imports, thus will positively impact the economy. One of the identified sectors is health services, particularly in the manufacturing of biomedical devices. By locally producing medical devices, it is expected to lower the prices of the devices to reasonable levels and improves the community's well-being. The high demand for orthopaedics implants in Indonesia is not in line with the public purchasing power of implants available in the market [1]. The high cost is because the implants are still imported and are among the most valuable trade commodities [2]. Based on a survey from the Ministry of Health of the Republic of Indonesia, only 6% of medical devices were produced locally, and the remaining 94% were imported [2]. This number is far below neighbouring countries such as Malaysia (10%), Vietnam (13%), India (18%), and Thailand (33%). The data above shows Indonesia's high dependence on imported products [2]. To be able to serve the health sector faithfully, high technology demand has become an essential component in producing medical equipment for treating patients. Two main factors contribute to the high production cost of implants which are; imported raw materials [3] and the machining process [1].

There are many types of manufacturing to produce implants, including additive manufacturing, machining, investment casting technologies, and forgings. This type of manufacturing is the high cost at machine investment and very low productivity [1]. A study by Salim et al. [1] revealed that by considering manufacturing, the productivity of implant products could be increased with optimum production processes such as metal forming and casting. An alternative process was used in this research which was the centrifugal casting process. Based on research conducted by Dewo et al., Indonesian-made plates have lower mechanical properties compared to the European AO standard plates [4]. Therefore, it is a need for a production process that concurrently improves the mechanical properties of the plates.

Several studies have been carried out on the design and manufacturing process of centrifugal casting machines, such as a study by Tattimani and Agari [5]. They studied the effect of rotational speed in vertical centrifugal casting on the wear properties of produced aluminium tubes. The experiments were carried out using Al_2Si alloy material with a rotational speed of 1000 rpm; showed a uniform cylinder tube was formed. In another related work, Rao et al. [6]

*CORRESPONDING AUTHOR | A.K. Nasution | ahmadkafrawi@umri.ac.id

investigated the effects of rotational speed on the cast tube during vertical centrifugal casting processes on the appearance, microstructure, and hardness behaviour of the Al_2Si alloy with rotational speeds between 600 and 1200 rpm. In this paper, the Al-2Si alloy centrifugal casting with vertical mould produces a uniform cylindrical tube at a rotating speed of 1000 rpm and has a finely structured grain size with high hardness values. The research and proposed design of a centrifugal casting machine for the manufacturing of turbine bearings was conducted by Desai and Sheth [7] using mould speeds before and after rotation of 10 rpm and 350 rpm, respectively. The paper concerns the study and proposed designs of horizontal centrifugal casting machines to produce the bearing of the steam turbine large dimensional with controlled metal pouring. In another related study, Oyewole and Sunday [8] researched the design and fabrication of a centrifugal casting machine. This paper successfully designs and fabricates a vertical centrifugal casting machine with a 600 rpm shaft rotation for aluminium alloys up to 6 kg. Seabra et al. [9] examined the design and development of a centrifugal casting machine for pistons production using functionally graded materials (FGMs) with rotational speeds between 300 rpm and 2000 rpm. This paper discusses the development of vertical axis centrifugal casting machine tools to produce pistons with a well-controlled sequential pouring technique for different materials. Research on the influence of rotational speed of the centrifugal casting process on the appearance, microstructure, and sliding wear behaviour of Al_2Si cast alloy was conducted by Mukunda et al. [10] with rotational speeds from 20 rpm to 2000 rpm.

In this paper, we discussed the effect of liquid metal flow for Al-2Si alloys with various rotational speeds. At an optimum speed of 800 rpm, a uniform cylinder was formed. Chirita et al. [11] researched the advantages of the centrifugal casting technique on the production of structural components with Al-Si alloys using a high-frequency induction centrifugal casting furnace for AS12UN aluminium alloy material. This work discusses the mechanical properties advantages of using the horizontal centrifugal casting technique as compared to traditional gravity casting. The results of the centrifugal casting process are much more effective in terms of obtained mechanical properties compared to gravity casting. Therefore, it is necessary to design and manufacture a horizontal type centrifugal casting machine for an initial study of producing DCP with large quantities and good mechanical properties. With this process, it is also expected to reduce production time, costs and scrubs waste from the machining process.

MATERIALS AND METHOD

Materials

The material used is an aluminium alloy from automotive waste (piston), which is processed into ingots. Furthermore, the ingot composition test was carried out using an X-Ray Fluorescence Analyzer (model: Vanta IP55-C series, Olympus, USA). The chemical composition of the Al-Si alloy from the ingot after examined are listed in Table 1.

Table 1. The chemical compositions of the Al-Si workpiece material alloy.

Element	Si	Fe	Zn	Mn	Cr	V	Pb	Ti	Al
wt.%	18.160	0.486	0.058	0.099	0.039	0.022	0.001	0.057	Balance

Fabrication Method

Ingots were prepared conventionally and processed in a 2HP/AC horizontal casting machine setting. A mould with a diameter of 116 mm and a length of 350 mm was used based on the consideration of making 42 DCP implants, as shown in Figure 1. Horizontal centrifugal casting parameters refer to previous research [12], which produced cast products with the best surface quality, the lowest shrinkage cavity defects, and the lowest porosity and maximum tensile strength. The horizontal centrifugal casting parameters for the mould rotation at 1500 rpm and a melting point of 720 °C, while the machines used are shown in Figure 2. The machining process for smoothing the outside and inside surfaces of cast pipes using a conventional lathe. Measurement of the thickness distribution of the cast pipe is done using a calliper with ± 0.02 mm accuracy and a distance of 30 mm for each measurement. Meanwhile, cutting of the cast pipe into the plate was using a cutting band saw.

Mechanical Testing

For the strength analysis, each specimen underwent five times tensile tests according to the ASTM E8 standard [13]. The specific schematic drawings with the dimensions of the specimens that have been used in this study are shown in Figure 3. It should be noted that the specimen size and dimension is for large-diameter tubular products. The tensile test was conducted by using an axial-torsion universal testing machine (Instron 8874, USA).

Meanwhile, the distribution of hardness was measured using a Vickers microhardness tester (Matsuzawa DVK II, Japan) according to the ASTM E384 standard [14]. The hardness readings were recorded at intervals of 1 mm using a 5 kg load for 15 seconds, and the test was repeated five times.

Microstructural Analysis

Microstructural analysis was carried out to examine the voids and porosity without being etched. Furthermore, the fracture microstructure was examined to observe the microporosity. This microstructure analysis using a scanning electron microscope coupled with an energy dispersive spectrophotometer (SEM/EDS; Hitachi TM3000, Japan).

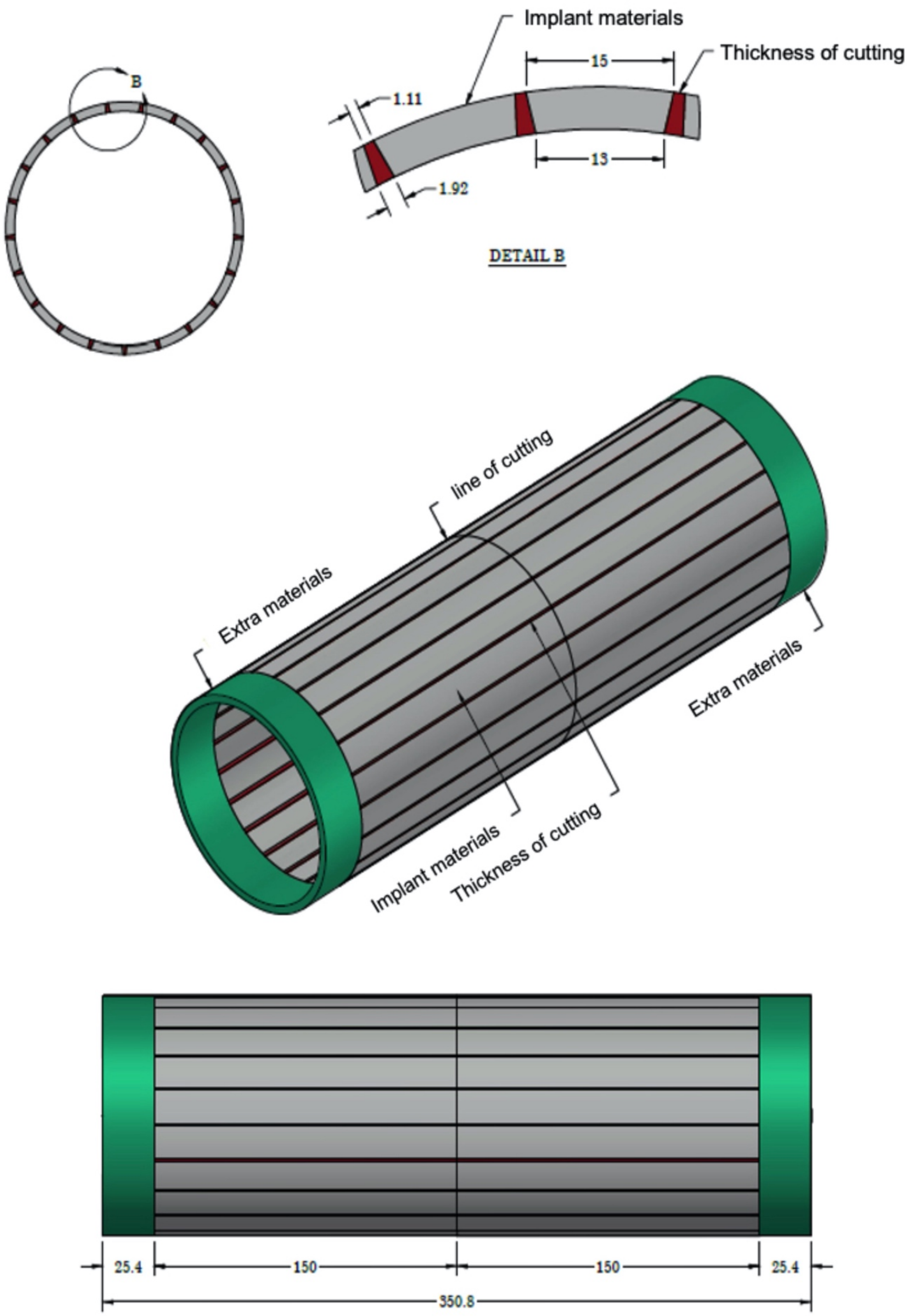


Figure 1. Mould dimension design for 42 dynamic compression plates.

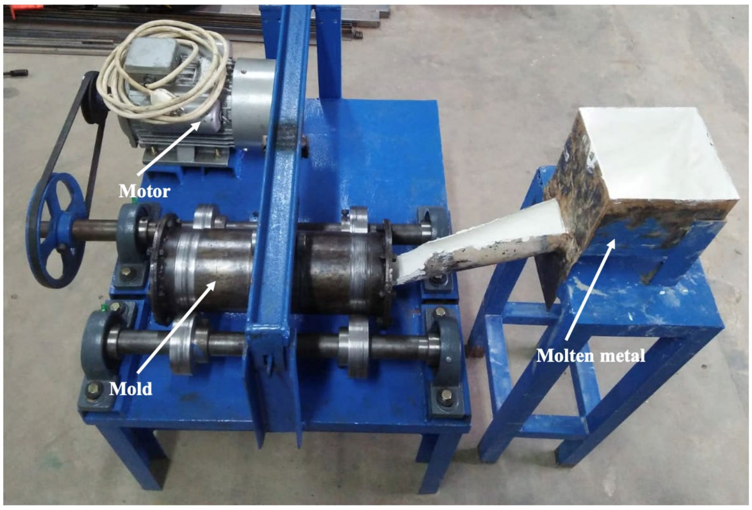


Figure 2. The horizontal centrifugal casting machine.

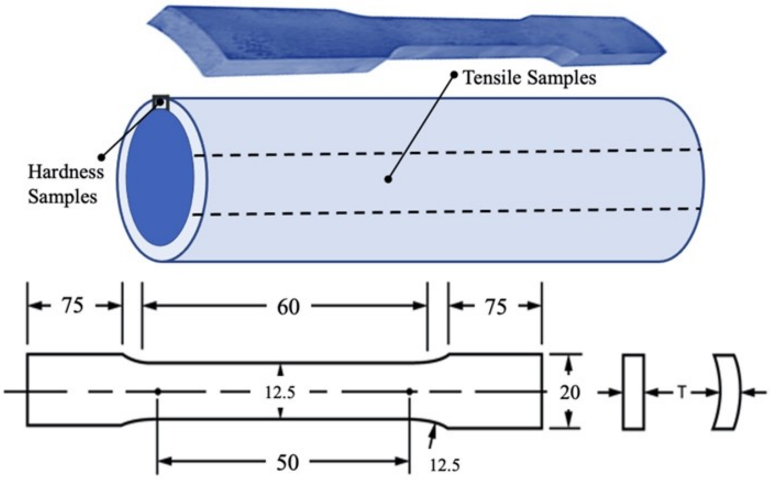


Figure 3. Locations of the sample cut and tensile test specimen dimensions. Adapted from ASTM E8 [13].

The Geometry of the Plates

The DCP was made using a computer numerical control (CNC) machine Emco Concept Mill 55, Austria. Parameters for making holes with a spindle speed of 1500 rpm, feed rate of 200 mm/min, and cutting depth of 0.5 mm. The dimensions of the plates were measured using a digital calliper for the length, upper width, lower width, thickness, and diameter of the hole.

RESULTS AND DISCUSSION

Casting

Cast pipe produced from horizontal centrifugal casting was successfully produced with a rotating speed of 1500 rpm, as in Figure 4(a). Furthermore, the cast pipe was modified for smooth outside and inside surfaces, where a cutting depth of ±1 mm was used for cutting. Figure 4(b) shows a cast pipe with a thickness of 4 mm after going through the machining process. In order to get the 15×150 mm dimension of the DCP plate material shown in Figure 4(c), cutting process has been conducted again using the same machine. The results of the measurement of the thickness distribution of cast pipes are shown in Figure 5.

Horizontal centrifugal cast pipe was produced with a rotating speed of 1500 rpm. To produce a uniform cast pipe thickness, a high rotational speed of the mould is required [5, 10, 12], as demonstrated by Rao et al. [6] and Ali [12]. It should be noticed that if the rotational speed of the mould is too low during the manufacturing process, a 'rain phenomenon' appears in horizontal centrifugal casting. In this situation, the molten metal tends to fall from the top to the bottom of the mould where it can produce a non-uniform microstructure of plate [15]. The melted metal has a low viscosity, as viscosity plays an essential role in inflowing the melt along with the mould on the inside ring [5, 10]. Therefore, in this study, we used high speed of 1500 rpm as suggested by previous scholars in their works [5, 10, 12].

The surface roughness of the mould is essential to produce excellent product surface. It is to be noted that the rougher the surface of the mould, the surface of the product in the casting process is coarser. Mirbagheri et al. [16] mentioned that there is an effect of the roughness of the mould wall on the melting flow in the continuous casting process. Mirbagheri et al. [16] mentioned there was a formation of the vortex which affected the wall boundary, which was the interface between the mould wall and molten metal during casting. Rao et al. [6] reported that mould roughness has a greater influence on the lift of molten metal by minimizing the slip between the mould and molten metal to form a uniform cylinder.

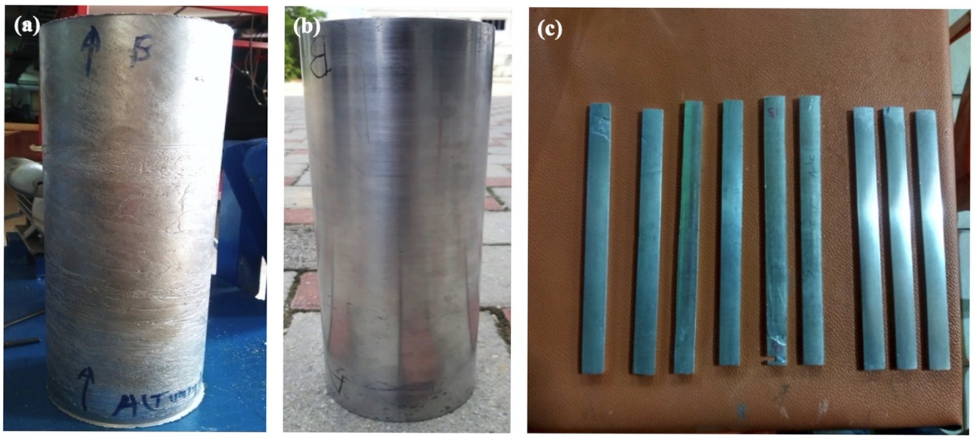


Figure 4. The fabricated casting pipe AlSi alloy using the horizontal centrifugal casting with (a) 6 mm thick AlSi alloy rotated at 1500 rpm, (b) 4 mm thick after the machining process, and (c) dynamic compression plate implant samples.

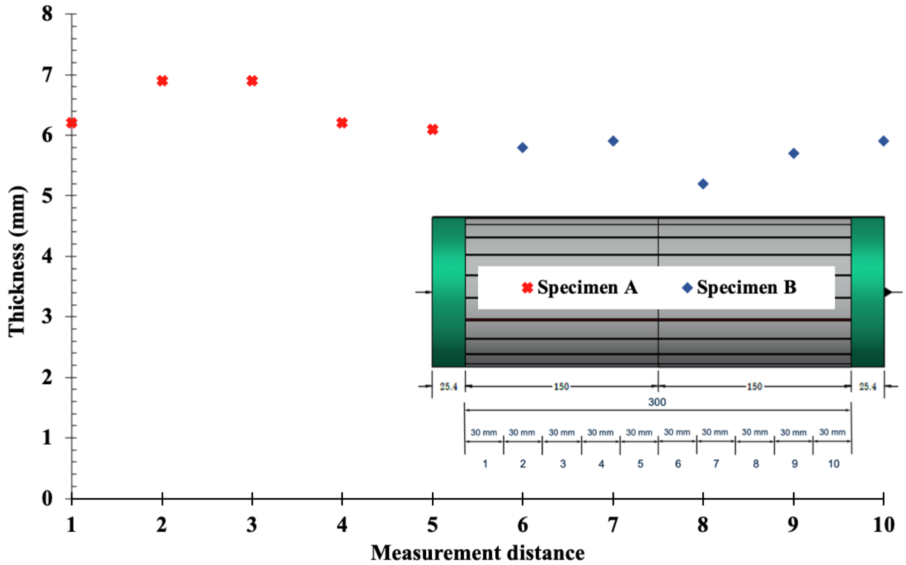


Figure 5. Thickness distribution from centrifugal casting rotated at 1500 rpm.

Mechanical Properties

Figure 6(a) shows the variation in tensile strength values for the cast pipe specimens in various zones with a thickness of 4 mm. The cast pipe zone was divided into two; specimen A is the butt zone of the fall of molten metal and specimen B is the butt-end zone. The maximum tensile strength value for specimen A showed an average strength of 147 MPa, while specimen B showed an average strength of 142 MPa. The yield strength for specimen A showed an average strength of 72 MPa, while specimen B showed an average strength of 65 MPa. When the results were viewed based on statistical analysis, the strength values of the cast pipe specimens were insignificantly different, and this is supported by the Young's Modulus value which is 25 GPa. The same result was explained by Ali [12] who carried out a study for the variation of the mould rotating speed from 600 rpm to 1240 rpm to obtain the maximum tensile strength when using a higher speed corresponding to G factor values. The use of a low G factor values on the liquid metal could not produce enough centrifugal forces against the mould wall [12].

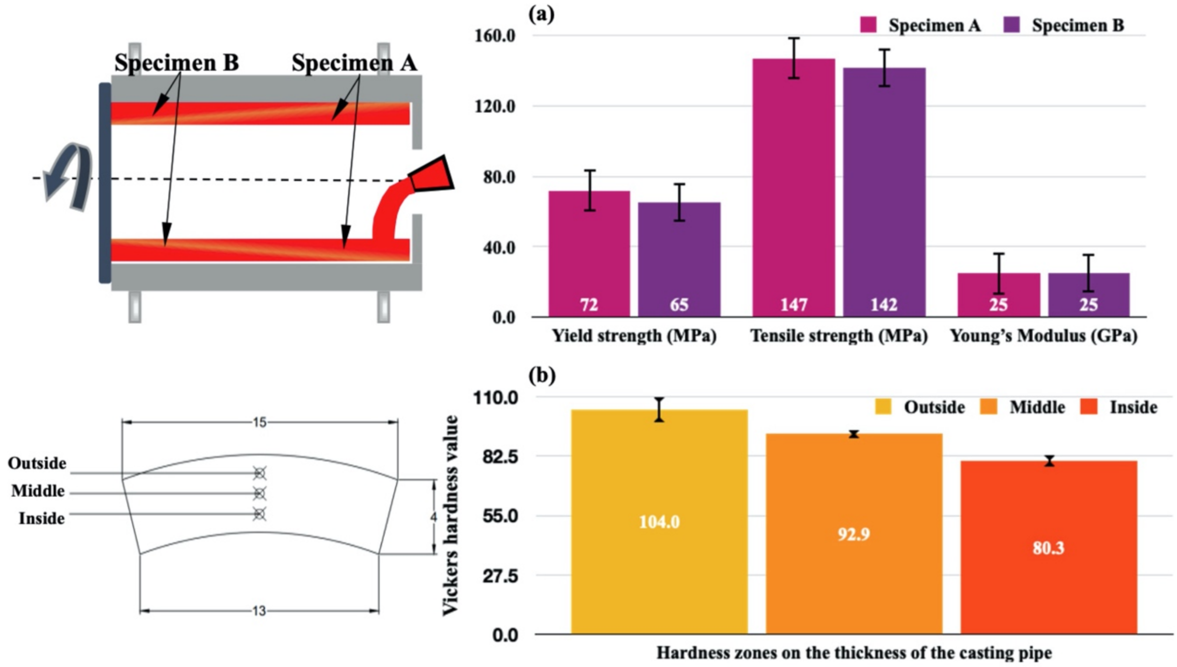


Figure 6. (a) Mechanical properties of different zones and, (b) Vickers hardness value for casting pipes from outside to inside surface.

The hardness values for the cast pipes determined using a Vickers microhardness tester is shown in Figure 6(b). The Vickers hardness test was divided into three regions, namely; outside, middle, and inside. The hardness test was carried out in a circular for all regions with a same distance of 1 mm. It was observed that high hardness value of 104.0 HV was in the outside zone, followed by 92.9 HV in the middle zone, and the lowest value of 80.3 HV for the inside zone, as shown in Figure 6(b). Likewise, from the research of El-Galy et al. [17], the hardness value of the outside zone was high. The results slightly decreased towards the middle zone, meanwhile the lowest value was shown in the inside zone. The maximum hardness of the outside zone was due to the direct contact between the molten metal and the mould, known as the cold zone. The hardness decreased slightly towards the middle zone; this zone in some literature is called the transition zone [18]. The lowest hardness is shown by the inside zone [17, 18], where the slow cooling zone is. The hardness value obtained from this experiment is higher than in the previous studies. In Mukunda et al. research results [10], Al-2Si hardness is 96 HV at mould rotation of 800 rpm and 85 HV at 1600 rpm. In comparison to El-Galy et al. [17] results on composite metal material (functionally graded Al-SiCp), which is 55 BHN (72 HV equivalent) at 1000 rpm mould rotation.

Microstructure Evaluation

Fine surface quality achieved in the cast pipe resulted from the horizontal centrifugal casting process as shown in Figure 4(b), after machining the outside and inside surfaces. The evaluation continued on the quality of the inside (cross-section) by cutting the cast pipe for each zone. Two different zones in specimens A and B were identified to show microstructure without etching. Figures 7(a) and 7(b) show the SEM results of specimen A taken randomly, while Figure 7(c) and 7(d) are for specimen B. In general, there is no visible porosity in all images, and no bubbles were formed during the curing process.

Figure 8 shows the microporosity of the fracture in the tensile specimens A and B. Based on the evaluation carried out on specimen B in Figure 8(c) and 8(d), there was less microporosity distribution compared to specimen A in Figure 8(a) and 8(b). Microporosity evaluation was carried out to identify defect formation during the solidification process, where it is well known that the aluminium alloys have a high affinity for oxygen. The formation of microporosity depends on many factors [19]. At the same time, Lewia [20] mentioned that three factors contribute to the development of microporosity in metals, namely shrinkage of the metal, gas evolution, and composition. Li et al. [21] revealed that the mechanism of microporosity defect formation involves heat flow, mass flow, and interactions between liquid, solid, and gas [22]. Whereas microporosity usually occurs during solidification casting [22]. After testing the composition in areas that have microporosity, there is an increase in oxygen gas in the area (shown in Figure 8). The formation of porosity in castings is an essential concern to predict the degradation of mechanical properties [19]. Microporosity is very dangerous and can propagate along grain boundaries, and is usually in the centre of porosity filled with oxides [23]. Li et al. [22] also said that increasing the amount of microporosity would reduce the nominal yield strength and tensile strength of the WE54 alloy exponentially.

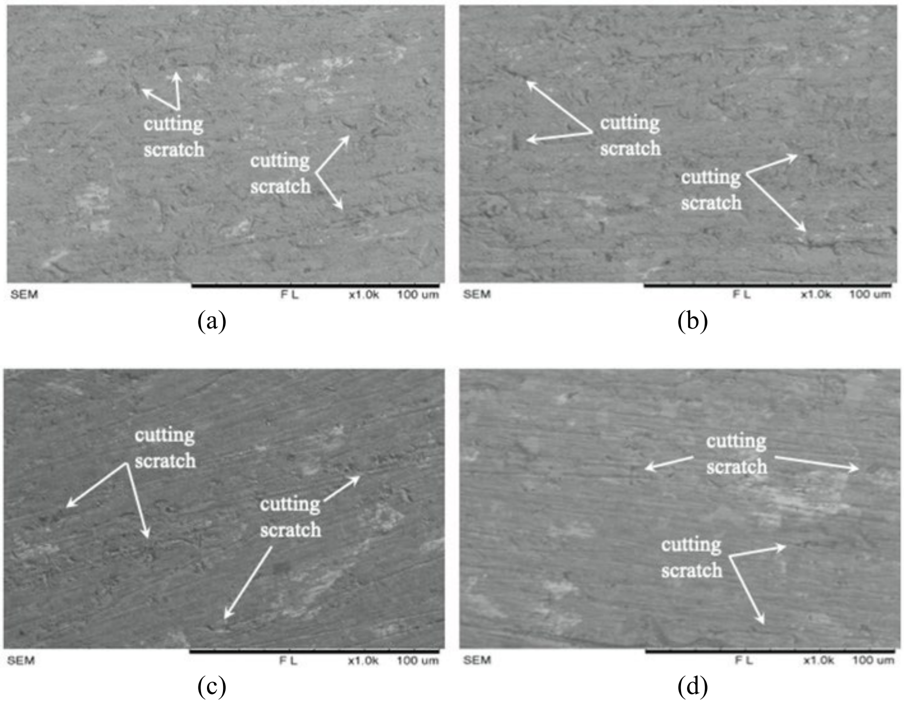


Figure 7. SEM images of cross-sections (without etching) of (a), (b) specimen A, and (c), (d) specimen B.

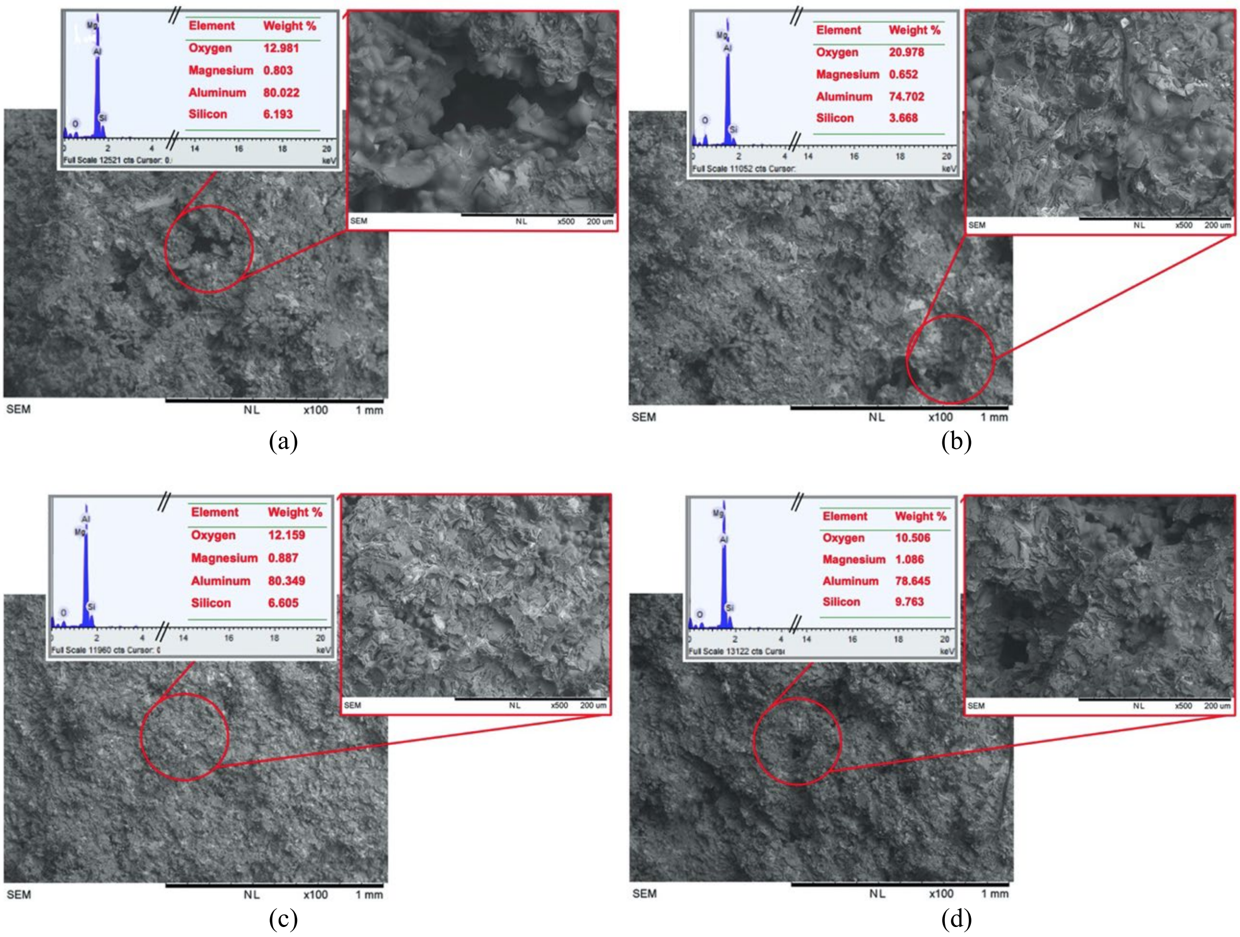
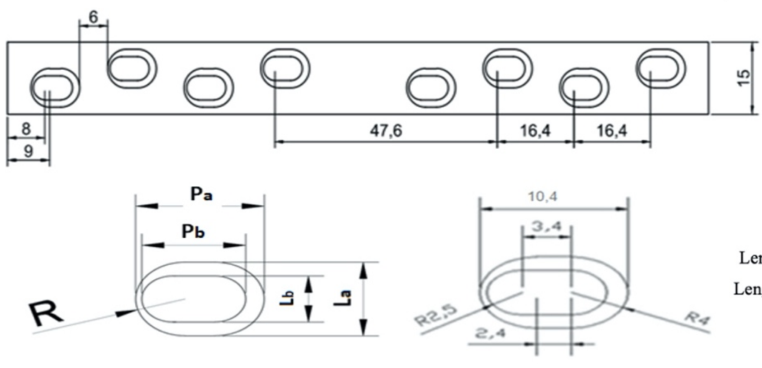


Figure 8. SEM/EDS images show the microporosity of different locations on the fracture of the tensile test in (a), (b) specimen A and, (c), (d) specimen B.

Geometry of Implant Plates

Orthopaedic implants DCP with eight holes were successfully manufactured, as shown in Figure 9. The contour hole work was divided into four working stages; first stage is implant material setup, the second stage is the working of hole contours 1 to 4, the third stage is material position change, and the fourth stage is hole contours working 5 to 8. From the four stages of processing, it can be calculated that the plate hole working time was 38 minutes per implant. The difficulty of making holes, as mentioned by Salim et al. for DCP implant products which resulted in high production costs [1] could get better by using CNC milling and adjusting the processing stage. In the previous DCP implant plate production process, the forming process from conventional methods could take a longer time [1, 4]. This problem can be defeated with an alternative to the centrifugal casting process that can produce 42 plates in one production, as shown in this study. The fabrication technology for the manufacture of dynamic compression plates using the horizontal centrifugal casting process in this study is considered successful in reducing the stages of the manufacturing process. Whereas Dewo et al. and Aluede et al. suggest that locally produced low-cost dynamic compression plates must pay attention to mechanical strength [4], and the balance between strength and stiffness [24] is also fulfilled.



Geometric	Dimension
Number of Holes	8
Length, L (mm)	150
Upper width (mm)	15
Lower width (mm)	13
Thickness, T (mm)	4
Hole spacing, HS (mm)	6
Taper diameter, La (mm)	8
Hole diameter, Lb (mm)	5
Length of the upper hole, Pa (mm)	10.4
Length of the bottom hole, Pb (mm)	8.4
Upper radius, Ra (mm)	4
Lower radius, Rb (mm)	2.5

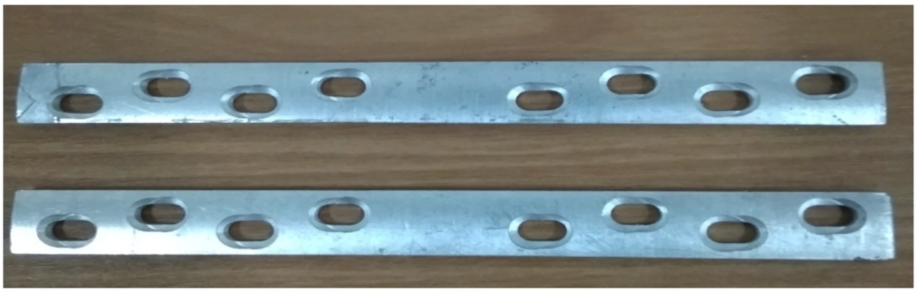


Figure 9. Geometry of the plate and photographs of manufacturing product from dynamics compression plate using Al-Si alloys.

CONCLUSION

This work succeeded in designing and manufacturing a horizontal type centrifugal casting machine with 2HP/AC specifications and a rotating speed of 1500 rpm. The casting process, which was carried out using Al-Si alloy as a preliminary study, was successful in producing a large amount of DCP plate material for a one-time production. The measured tensile strength is not significantly different in the two zones of cast pipe; 147 MPa for specimen A and 142 MPa for specimen B. The hardness value for cast pipe obtained from this work is higher than previous research with 104.0 HV for the outside zone, 92.9 HV for middle zone, and 80.3 HV for inside zone. Evaluation of microporosity in tensile fractures resulted from horizontal type centrifugal castings showed a small distribution. Meanwhile, the calculation of processing time for contour holes of DCP with eight holes was 38 minutes per implant. This work suggests that there is potential applicability of using horizontal type centrifugal castings to produce large quantities of DCP plate material and good mechanical properties within a short time duration.

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