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Modeling and Experimental Study of Al-Cu Alloy Sand Casting for Circuit Breaker

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***Abstract*—Aluminum is a light metal with good electrical conductivity and widely applied for electrical devices. One of its application is the circuit breaker component. The 2xxx series of aluminum alloy has a copper alloying element which increases its mechanical properties and improves quality of electrical conductivity. This research aims to obtain the best gating system design of the circuit breaker mold by ANSYS modeling. This research also is subject to measure the influence of Cu alloying to the rate of electrical conductivity, strength, and hardness in aluminum alloys for circuit breaker application by experimental working. Aluminum is alloyed with variations of 1; 2; 3; 4; and 5% copper addition. Modeling of thermal analysis and structural analysis was calculated by ANSYS Mechanical APDL with a finite element method to find the best design for the sand casting experiments. Chemical composition, metallography, brinnel hardness, tensile, XRD, and electrical conductivity tests were conducted in this study. The highest strength is 59.50 MPa was acquired on Al - 3% Cu while the lowest strength is 37.43 MPa was on Al - 1% Cu alloy. The peak of hardness 48.70 HBN could be drawn at Al - 4% Cu. In the other hand, the dip of it was Al 1% Cu of 25.5 HBN. The last variable, conductivity, has the highest amount as of Al-5C, alloys with a value of 12.88 S / M, which is found on Al-1Cu with a value of 9.30 S/m.**

***Keywords*— aluminium; casting; modelling; copper; mechanical properties; conductivity.**

I. INTRODUCTION

In recent years, there has been an increasing interest in aluminum manufactures productions in various fields ranging from transportation, construction, packaging, electrical, and others. In electrical appliances aluminum used as a component in circuit breaker. Aluminum and its alloys have good properties such as good strength, high corrosion resistance, good machinability, easy casting, and economical price [1]. The commonly used alloying elements in aluminum alloys are copper, silicium, magnesium, manganese, nickel and others [2]. Electrical components must have properties appropriate to their use such as good mechanical properties and good electrical conductivity.

Before the experimental casting begins, simulation modeling using ANSYS Mechanical APDL was formulated to determine the best gating system design. ANSYS Mechanical APDL is a type of ANSYS parametric design language which can be used to develop the model in certain parameter. ANSYS user stimulates two or three-dimensional model, i.e. surface, shells, spring, beam, etc. [3].

In 2015, ANSYS simulation was conducted by Vinit Bijagare [4] to observe the effect of riser and runner toward temperature distribution. The result showed that riser addition reduced porosity effectively compared to only utilizing runner as a riser.

In 2016, Hemant [5] observed simulation and experiment of cooling rate and solidification in pure aluminum casting. The simulation result showed that metal temperature decreased meanwhile, mold temperature increased due to the heat transfer from molten metal to the mold. The conclusion from this study states that cooling rate can be plotted in ANSYS.

This research aims to analyze the effect of adding a copper element to mechanical properties value and electrical conductivity value of aluminum alloy through sand casting method. Such a method was chosen due toa simulation conducted by Bahtiyar, 2016 [6] which mentioned that thermal stress of metal mold was higher compared to the sand mold. Higher thermal stress is linear with higher shrinkage. Sand mold results on better cast product with smaller shrinkage than metal mold.

In 2017, Hardik Rathod researched predictions of shrinkage porosity defects in sand casting with ANSYS software. Micro porosity can occur in Al-Si caused by two factors, namely hydrogen rejection due to drastic reduction from the solidification process and due to volume contraction along with inter poor dendritic feeding during solidification. It can be concluded that thermal gradient, cooling time, solidification time, and the speed of solidification become parameters of the occurrence of porosity, but the position of porosity will depend on the geometry and parameter changes in temperature [7].

Setyawan, 2006 [8] researched the effect of copper variation addition and casting mold types toward the hardness of aluminum-silicon alloy. The conclusion of this research is higher Cu addition will increase the hardness of aluminum-silicon alloy (Al-Si); at Cu 8% addition would produce the average hardness of 100.57 HBN. The effect of temperature on the conductivity of Al-Cu alloy was observed by Aksoz et al. [9]. Conductivity decreased as long as the temperature increased. The highest conductivity value at Al-3wt% Cu was of 0.055×10^8 S/m, and the lowest aluminum with 52.50 wt% Cu was approximately 0.033×10^8 S/m — the research performed by Atmaja, 2011 [10] discussed copper addition to mechanical properties aluminum alloy. Tensile strength, hardness, fatigue resistance peaked up to its threshold approximately 4% Cu and gradually declined at 6% and 8% Cu. The declination at Al alloy was caused by $CuAl_2$ when the Cu addition was more than 4% Cu.

II. Materials and Methods

A. Modeling

The geometry of the circuit breaker component used in the modeling is displayed in Fig.1 below.

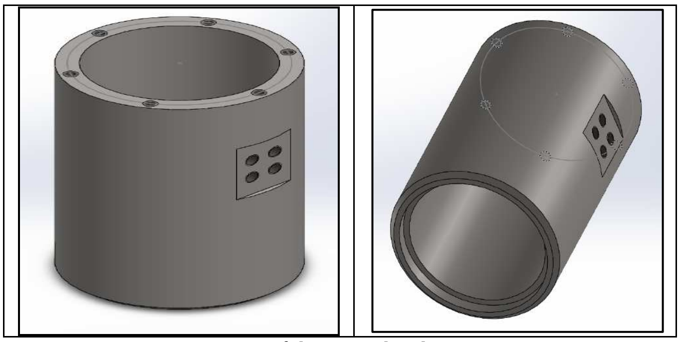


Fig 1. Casting geometry of the circuit breaker component in 3D

The element type used in this study is SOLID278 (brick 8node 278) for thermal analysis in 3D thermal conduction. Meshing used by cast bright has an elemental length of 0.008 m and 0.02 m for sand molds. Fig. 2 shows the geometry of castings and molds that have been done meshing. After performing these steps, the boundary condition is incorporated in the modeling that is adapted to the original condition of the casting experimentally. The heat transfer that occurs in the casting process is convection, which is placed on the outside of the mold, which will affect the temperature distribution. Then it is assumed that there is no inclusion of the foreign body in the molding cavity, the mold material and the material of castings are considered homogeneous, and the pouring speed is considered the same. Heat flux was applied in the mold geometry, convection was applied to the outside of the mold, and the initial temperature was applied to both castings and molds. There will be heat transfer from the casting material into the mold, causing the molten metal to lose heat when poured into the print cavity during the casting process. In contrast, mold will experience the increase of heat due to heat transfer from molten metal.

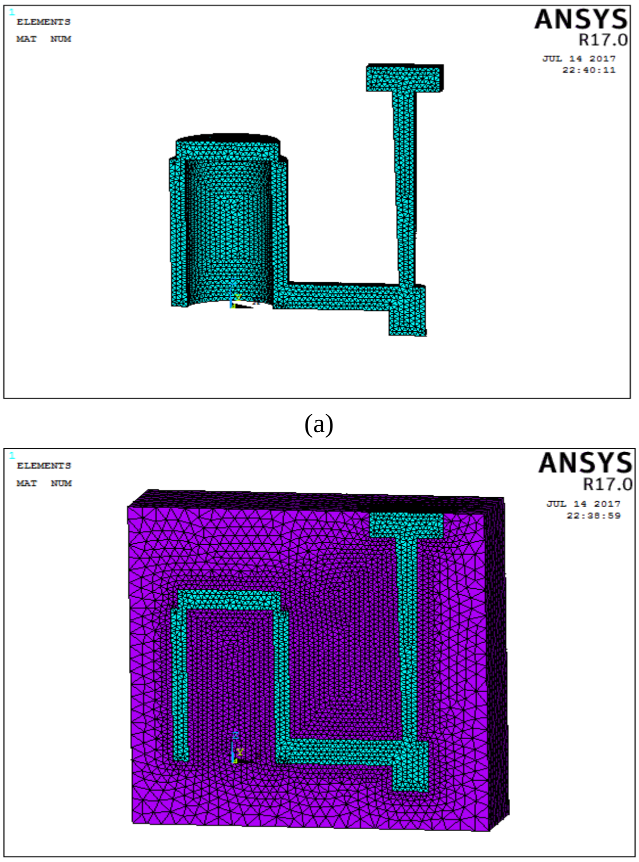


Fig 2. Meshing (a) casting and (b) mold

B. Experimental Casting

Materials used include aluminum with the composition of (wt%): 99.93% and 0.07% others and copper with composition of (wt%): 99.8% and 0.2% others. They are then cut to the appropriate weight to form aluminum with 1%, 2%, 3%, 4% and 5% copper alloys. Based on research by Sumaiya Shahria [2016] about the simulation of the composition of sand mold casting [11], Casting mold in this experiment is prepared using 91% the sand from Madura Island, 5% water and 4% *bentonite*. The research material was heated up to 1200^{o}C gradually for 45 minutes.

Chemical composition, metallography, XRD, tensile, hardness, and electrical conductivity test were conducted in this experiment. The measurement of chemical composition was performed using Optical Emission Spectroscopy (OES). The purposes of the XRD test was to determine the phase transformation and compound which were formed during casting process elements by observing at compounds formed on the alloy of castings. Hardness Test is conducted to determine the hardness value of the castings. The preparation of specimens is done by cutting the castings until they have a flat surface. Testing was done with Wolpert UH-930 by taking three indentation points. The tensile test is performed to determine the maximum strength value of a material until it fails. ASTM E-8M performed the preparation of the test specimen with a thickness of 12.5mm.

Electrical conductivity test was accomplished to measure electrical conductivity value of Al-Cu alloy. Resistance value from the test used to acquire electrical conductivity.

III. Result and Discussion

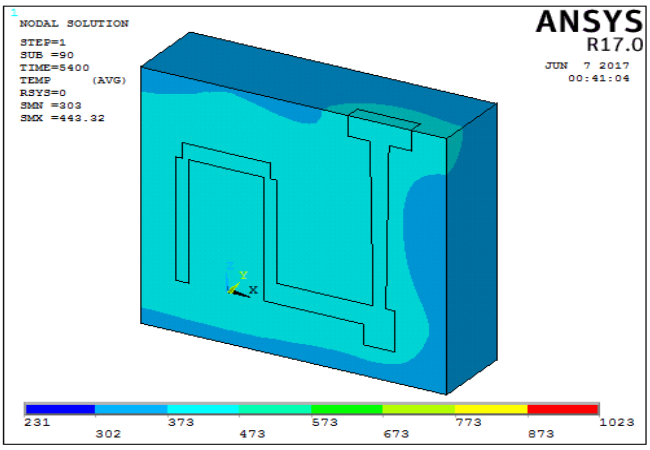
A. Modeling

In this research, the geometry form is made half; it is aimed to simplify the simulation of the casting process. The convection of boundary conditions was applied to the outer edge of the sand mold that was in direct contact with the atmosphere. In this limiting condition, the convection heat transfer coefficient is 11.45 W / m^2.K. The bulk temperature of sand mold is 303 K. For this thermal transient simulation, the initial temperature at the castings is 1023 K. This is because aluminum 2024 is already above the liquids temperature of 923 K. The Heat flux given on the front of the cast is 0 regarding of the half-geometric shape. Variation applied based on gating system shape are illustrated in Table 1.

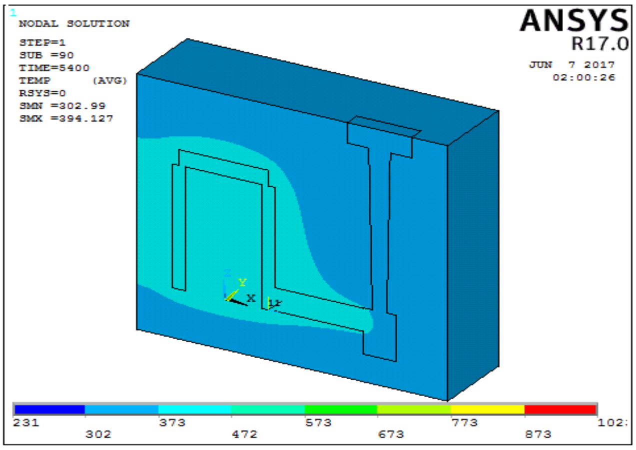
TABLE I
VARIATION OF CHANNEL SYSTEM

Model	Runner Position	Channel System Shape
1	Centre	Rectangular
2	Centre	Circular
3	Edge	Rectangular
4	Edge	Circular

Fig. 3 is the cooling distribution of casting material. At most, freezing starts from the metal part affected by the sand mold wall. At that moment, the heat starts to be absorbed by the sand mold so that the clotting process occurs. The geometry of the *sprue* is insignificant as the heat will soon be transferred to the sand. Smaller dimensions and the same temperature difference compared to other positions would result in the highest conduction. At the same time, its freezing process will flow to the pouring basin because of direct contact with the atmosphere; this explains massive convection occurred in the process. The cooling process will continue to the runner and eventually reach the casting material. At the 5400 seconds, the heat on the casting is slightly reduced as the heat flows from the mold to the atmosphere slows down; thus, it takes a longer time for the castings to have the same temperature as the atmosphere.



(a)



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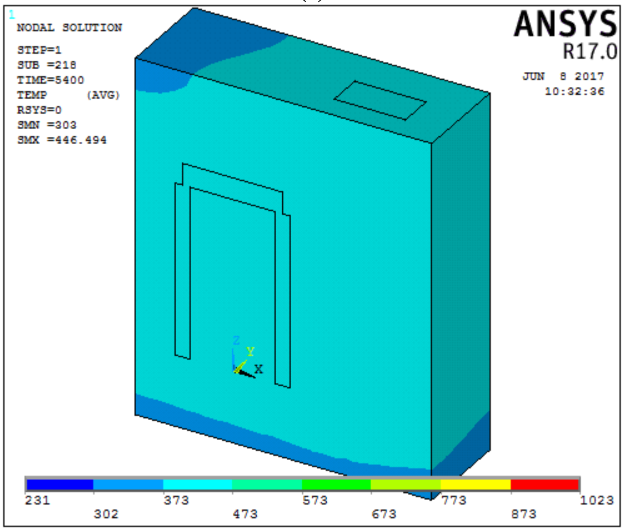

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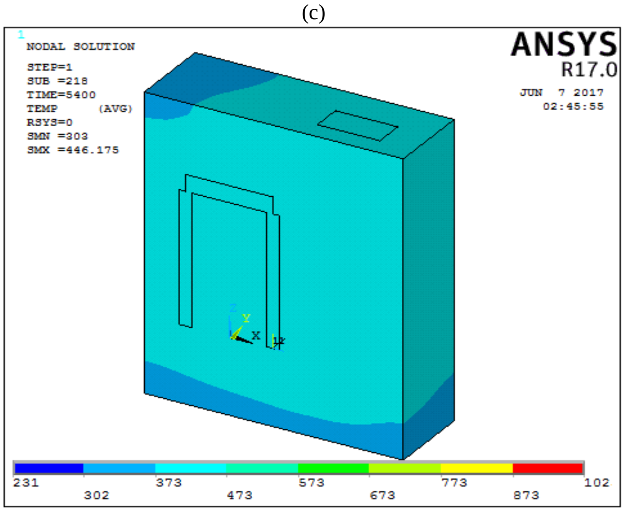


(d)

Fig 3. Shows the temperature distribution of the solidification process on the channel system at 5400 seconds: (a) model I, (b) model II, (c) model III, (d) model IV.

By the four models of the gating system, the shape with the runner position in the center of the printed material provides smaller thermal stress than that on the edge of the casting material. When the runner position is located in the middle of the printed material, the shape of the circular canal will result in a lower thermal voltage. The geometry shape will affect the thermal stress of the printed material.

The deformation occurring in model 4 has the highest value. While model 2 has the smallest ones. This phenomenon is closely related to the thermal stresses in metal castings. This proves that there is shrinkage in the castings due to thermal stress. The thermal stress will put pressure into the mold and cast [12]. The shrinkage can be seen in Table 2.

TABLE II
MAXIMUM SHRINKAGE OCCURS DURING THE CASTING PROCESS

Gating design	Shrinkage (mm^3)
Rectangular casting 1 (model 1)	72815.24
Circular casting 1 (model 2)	72259.08
Rectangular casting 2 (model 3)	74279.38
Circular casting 2 (model 4)	78595.24

To produce a good casting material requires good quality castings process. To obtain a good quality casting should have a final cast shape by the design that has been planned. Good castings can be identified from the riser's ability to fill the void in the castings due to the shrinkage process. Hence, it is necessary to calculate to acknowledge the quality of the casting process. Table 3 describes the formula to find the value of the quality of castings.

TABLE III
MOLD CASTING QUALITY FORMULA [13], [14]

Type	Formula
Quality	$\frac{\text{shrinkage free casting volume}}{\text{mold volume}}$
Feeding Efficiency	$\frac{\text{shrinkage volume}}{\text{riser volume}}$
Shrinkage	$\frac{\text{shrinkage volume}}{\text{mold volume}}$

According to the mold, the value resulted from the simulation is drawn in Table 4.

TABLE IV
MOLD CASTING QUALITY, FEEDING EFFICIENCY, AND SHRINKAGE

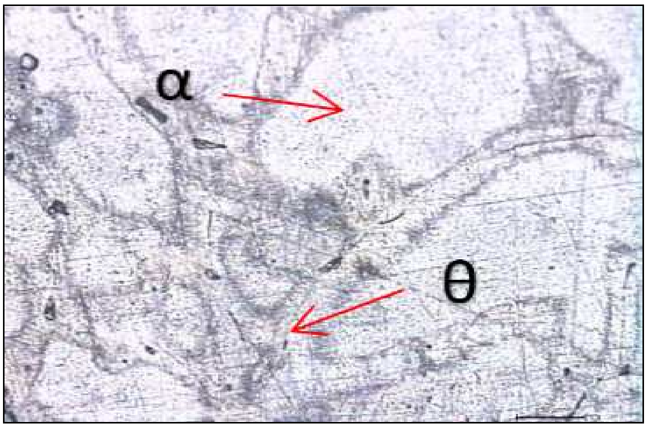
Variable (%)	Gating Design			
	Model I	Model II	Model III	Model IV
Quality	99.170	99.180	99.160	99.110
Feeding Efficiency	15.520	15.390	15.820	16.750
Shrinkage	0.830	0.820	0.840	0. 890

Table 4 describes mold casting quality, feeding efficiency, and shrinkage. Based on Table 4, in general, the quality of the castings based on these four models is first-rate. Shrinkage allowance appears below the maximum tolerance value of an aluminum alloy, from 1.3% to 1.6 %. However, its feeding efficiency of the four models in the sequence is still around 15%; indicating the less efficient role of the riser to fill the cast material.

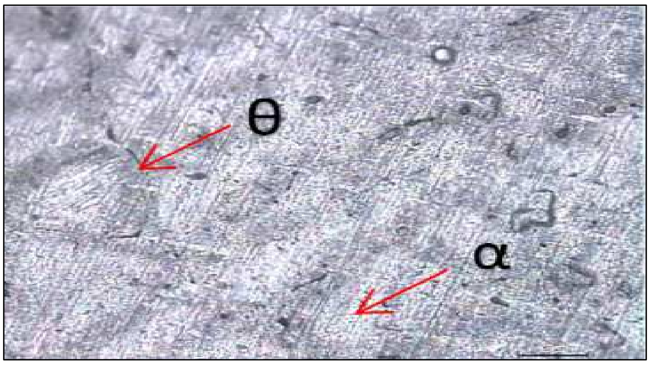
B. Experimental Casting

Figure 4 illustrates the metallographic results of castings with various percentages of alloy additions. Phases α and θ of the alloys were formed in the microstructure of casting material. Phase θ, Al_2Cu, is shown in the darker color section while the α phase is indicated on the white part. The percentage of copper in the alloy, the fraction of the area, and the roughness of the θ phase increase; while the grain size of the α phase decreases [15]. More dislocation causes high stress in the grain, which affects its higher yield strength.

1) Metallography and XRD Test: In Figure 4 the five metallographic variables indicate the presence of porosity in the castings through the black spot. The phenomenon occurs because of HNO_3 from Keller Etsa solution, which is a strong oxidizer and reacts with copper. The surface of θ phase would be corroded while that of the α phase would not; due to the latter's strong and hard passive oxidation layer. Several factors are causing the appearance of porosity in castings such as pouring temperature, type of furnace used, length of stirring of liquid metal, sand mold quality, and alloy type. The appearance of the axis in the castings results in discontinuity on the cast metal resulting in a decreasing tensile strength.



(a)



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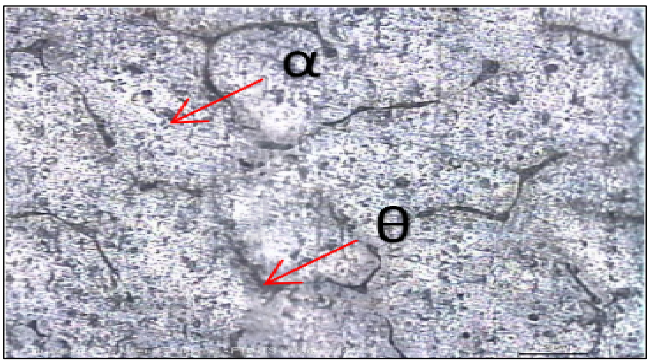

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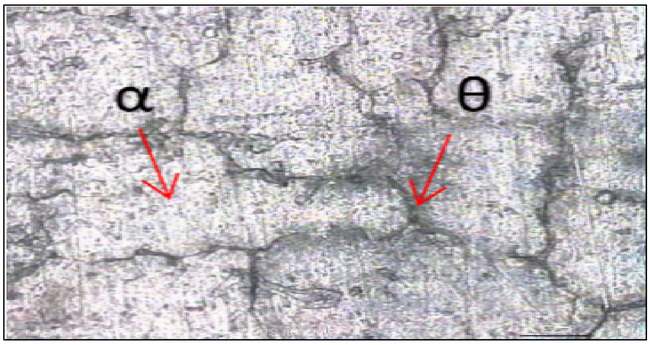

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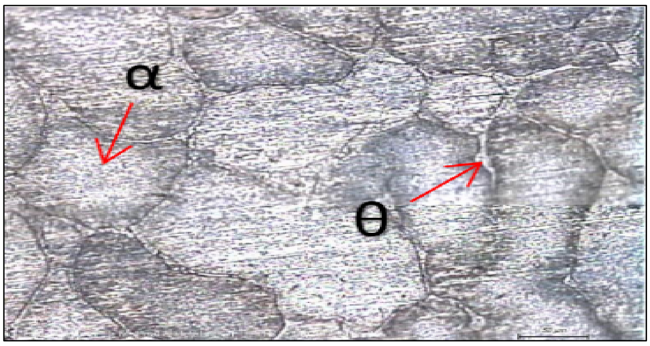


(e)

Fig 4. Microstructure of castings with 200x magnification of (a) Al-1Cu (b) Al-2Cu (c) Al-3Cu (d) Al-4Cu (e) Al-5Cu

The casting temperature was set to be 1200°C which had a significant range with the melting point of aluminum so that molten metal reacted with hydrogen in the air and trapped it inside while the molten metal was being solidified; thus this formed porosity.

Porosity process could also be conducted because molten metal experienced 10-minute stirring while adding the Cu to aluminum alloy. The other cause is about small size permeability of the sand grain. Later, copper addition would increase microporosity spread and form Al_2Cu within the aluminum alloy. The XRD pattern of Al-Cu alloy castings is depicted in Fig. 5. The XRD pattern in each variation of copper addition does not have much difference at 2θ each peak, but the peak intensity has little difference. These five XRD patterns show that the Al-Cu compound proves that the θ phase is formed during the cooling process.

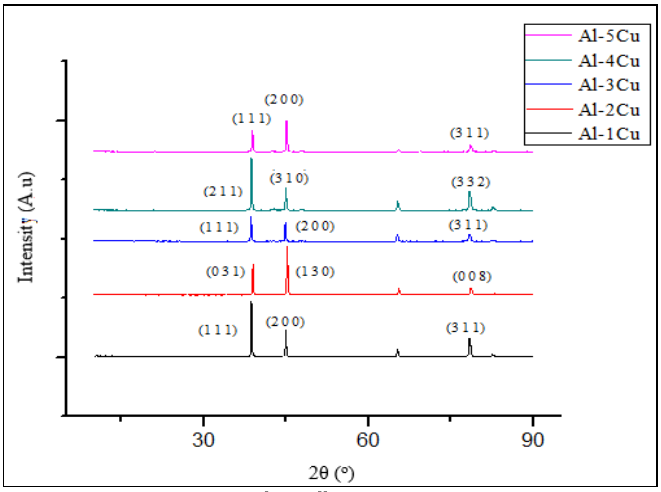


Fig. 5 Al-Cu alloy XRD pattern

2) Hardness test result: Fig. 6 describe the effect of adding copper elements to the hardness of the alloy. The hardness value of castings object tends to align with the increasing percentage of copper alloys [16]. The addition of copper to aluminum allows the formation of solid-solution α and Al_2Cu compounds (θ) during slow cooling [17]. Phase θ appears in precipitation form in the natural aging process. This precipitation acts as a barrier to the movement of the dislocations so that more force is required to move the dislocations to pass the distributed precipitates. The more copper percentage means the more θ phases that are formed on the alloy formulated in Brinell hardness value. It produces more grain boundary that emerges dislocations and increases the strength as well as the hardness of material as a consequence of dislocations themselves [18].

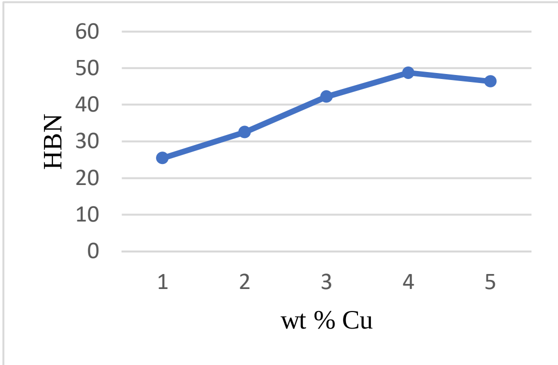


Fig.6 Brinell hardness value of Al-Cu alloy.

3) Tensile test result: The yield strength and UTS values of the castings object increased in addition to 1 to 4 percent of copper, then decreased by 4 to 5 percent. Al_2Cu appears in the form of precipitate in the natural aging process. This precipitate acts as a barrier to the movement of the dislocations so that more force is needed to move the dislocations to pass the distributed precipitates. More force is required, which causes increased strength and hardness of castings. Fig. 7 shows the strength values of Al-Cu alloys.

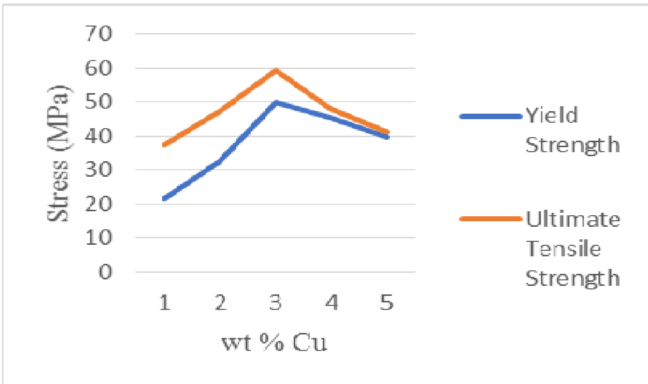


Fig. 7 Al-Cu alloy strength value

4) Electrical conductivity test result: In the electrical conductivity test, it is found that the more copper element added to the alloy, the conductivity value increases. This is due to the movement of electrically charged particles presence between aluminum and copper. Aluminum and copper each have three, and two valence electrons forming has a metallic bond where all the valence electrons of both elements can move freely and easily drain the electric current. Copper valence electrons are less than aluminum, which means the electrons of copper are freer to move and result in larger reaction forces than other electrons. As a result, the addition of copper elements to the Aluminum alloys will increase the electrical conductivity. Test results are presented in the form of resistance (R). The value of electrical conductivity is then calculated using the equation.

$$\sigma c = 1/(RA) \tag{1}$$

Where σc is the electrical conductivity, l is the distance between current sources, R is the resistance of the LCR meter measurement, and A is the area of the surface perpendicular to the current source. The value of the sample resistance and the electrical conductivity value of the calculation are presented in Table 5.

TABLE V
ELECTRICAL CONDUCTIVITY TEST RESULTS OF AL-CU ALLOY

No	Alloy	R (Ω)	Σc (S/m)
1	Al 1% Cu	0.11E+01	643.96E+01
2	Al 2% Cu	0.10E+01	688.39E+01
3	Al 3% Cu	0.08E+01	969.69E+01
4	Al 4% Cu	0.08E+01	867.25E+01
5	Al 5% Cu	0.08E+01	993.33E+01

The electrical conductivity values of all variations are compared in the graphic form shown in Fig. 8.

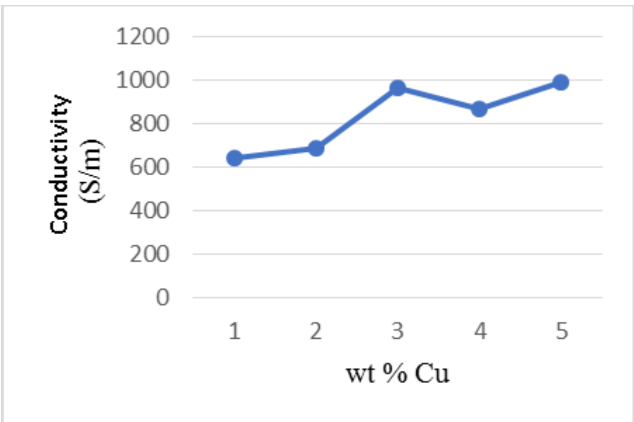
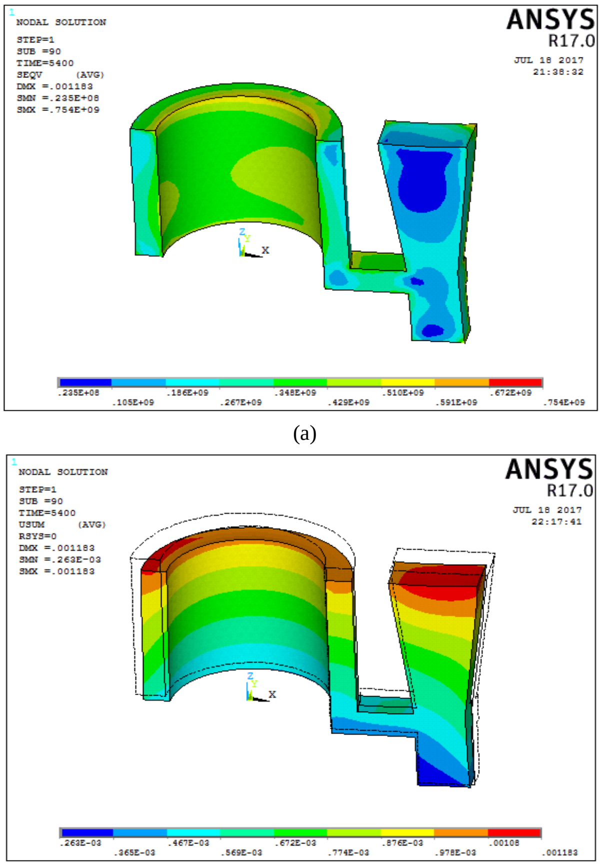


Fig. 8 The value of Al-Cu alloy electrical conductivity.

C. Comparison of simulation of shrinkage castings with experiment

To validate, thermal stress and shrinkage on castings simulated by ANSYS with the experiment were compared. The shape of the geometry of casting material is made up of half of its original geometry. The patterns of thermal stress and shrinkage that occur during the simulation and deformation process in the experiment are displayed in Fig. 9 and Fig. 10 below.



(a)

(b)

Fig. 9 Simulation result of thermal stress (a) and deformation (b) casting at 5400 seconds.

Fig. 10 Casting experiment result at 5400 seconds

From the ANSYS simulation, the maximum thermal stress is taken from the center to the left-hand casting of the mold core at 5400 seconds in Table 6.

TABLE VI
MAXIMUM THERMAL STRESS VALUE ON CAST OBJECT

Distance from core mold (cm)	Maximum Thermal Stress (Pa)
0	4.40E+08
0.63	3.69E+08
1.15	3.26E+08
1.68	2.93E+08
2.10	2.71E+08

According to table 6, the maximum thermal stress on the cast decreased as the distance from the mold core increased. The cast object will experience cracks in the direct contact with the sand mold core up to a distance of 1.15 cm from the core and maximum thermal stress 3.26E+08. This can be proved by the experimental results that are displayed in Fig. 10 below.

Fig.10 Cracks that occur in the cast part with direct contact with the mold core

The results of the calculation of depreciation between simulations and experiments are illustrated in Table 5.

TABLE V
THE VALUE OF SHRINKAGE CASTINGS BETWEEN SIMULATIONS AND EXPERIMENTS

Method	**Shrinkage (mm^3)**	**Shrinkage %**
Simulation	75906	1.71
Experiment	133745	2.60

Based on table 5, the value of shrinkage between simulation and experimental work has a huge gap of approximately 0.9%. The simulation results have smaller shrinkage values compared to the experiment because the simulation has an almost ideal condition. The simulation of thermal and structural analysis cannot predict the magnitude of porosity shrinkage resulting in smaller depreciation values.

IV. CONCLUSION

The variation of the gating system shape has no significant impact on the temperature change of all four models in the heating and cooling process. The cast will experience a rapid temperature drop from 1023 K to 512 K from the initial second to the 300th. Maximum thermal stress 3.58E+07 Pa occurs in a circular gating system inlet with the position of a runner on the edge of a cast object. Whereas the lowest thermal stress in the circular gating system with the runner position in the center of the casting material is 2.61E + 07 Pa. Cast objects will not experience cracks as they have values below the ultimate tensile strength of the material. Thermal stress will affect the shrinkage that occurs, higher thermal stress in line with a higher value of shrinkage. The shrinkage values of models 1 to 4 are respectively: 72815.24 mm3, 72259.08 mm3, 74279.38 mm3, and 78595.24 mm3. The addition of a copper element to the aluminum alloy can increase strength value. The highest strength value is on Al - 3% Cu of 59.50 MPa and the lowest is on Al-1% Cu 37.43 MPa.

Furthermore, the addition of a copper element to the aluminum alloy can increase the hardness value. The highest hardness value is on Al-4% Cu that is equal to 48.7 HBN, and the lowest one is on Al-1% Cu equals to 25.5 HBN. The addition of copper elements to aluminum alloys can increase the value of electrical conductivity. The highest conductivity value at Al - 5% Cu was 993.33 S / m, and the lowest at Al - 1% Cu was 643.96 S / m. For future research, the topic of degasification technique in the casting process could be observed to reduce the porosity. Also, sand mold should be in solid and dry condition with good permeability to ensure that there is no gas trapped during the casting process.

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