Performance Evaluation of Permanent Steel Mold for Temperature Monitoring During Squeeze Casting of Non-Ferrous Metals.

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ABSTRACT

Permanent steel mold was designed, machined and evaluated by monitoring the temperature of squeeze cast aluminum and brass rods on a Vega hydraulic press. The operation was performed with and without pressure on the cast specimen at pouring temperature of 700 ^{0}C and 980 ^{0}C for aluminum and brass metals, respectively. The solidification rate (temperature with time) was monitored with a three-channel digital temperature monitor data logger while the tensile strengths of both samples were also determined.

The results showed an increase in the solidification rate for both samples with increase in the applied pressure. The maximum solidification rate for aluminum was obtained at an applied pressure of 127 MPa and 95 MPa for brass. The tensile strength of both samples increased with increase in applied pressure. The maximum tensile strength of 34.38 MPa was obtained for aluminum at applied pressure of 127 MPa and 80.21 MPa for brass at an applied pressure of 95 MPa. Above these values there was no significant increase in the tensile strength with increase in applied pressure. The results obtained were similar to that already established in the literatures which make the machined permanent steel mold suitable for squeeze casting of non-ferrous metals.

(Keywords**:** permanent mold, squeeze casting, non-ferrous metal, solidification temperature, heat transfer)

INTRODUCTION

Metal casting is a process where large and intricate shapes which cannot be economically formed in one piece by either forging or welding are obtained. In sand casting processes, the molds used are usually destroyed in order to eject the product after solidification, as against permanent mold casting where the molds are used repeatedly without destruction during each casting operation.

Permanent mold casting is a modern casting method when compared with sand casting, in which casting is made by pouring liquid metal into re-usable mold (Kobryn and Semiatin, 2001 and Wallac et al 2009). The use of permanent mold in metal casting gives room for its automation and mass production within a short time cycle. The mold materials for permanent mold could be steel, wrought iron, graphite and zirconium, depending on the metal to be cast and the heating condition subjected to (Serope and Steven, 2006).

Permanent mold casting process can be referred to as metallic or die casting which includes gravity, slush, centrifugal and squeeze casting. Squeeze casting technique has been employed for making products with improved properties and near net shapes (Yanling et al, 2009). The method is defined as a casting technique, in which liquid metal is metered into a metallic mold under high pressure application for better filling and rapid solidification rate. This rapid solidification was as a result of the intimate contact area of steel mold wall and liquid melt interface due to pressure application leading to higher heat transfer coefficient and solidification rate (Xiao et al, 2010). This favors the formation of fine grains structure that is actually one of the factors responsible for the improvement of mechanical properties of the cast product.

Comparing effects of different casting methods on the grain sizes, solidification rate and mechanical properties of as- cast product, it was established that the grain size of the cast products increased for the squeeze casting method than other methods (Abdulkabir, 2010, and Eman, 2011). As a result of pressure application on the squeeze cast product, the mechanical property obtained was found superior to those obtained by sand or chill casting methods (Abdulkabir, 2010).

Squeeze casting method is frequently used for non-ferrous metals and its alloy of both monolithic alloys and metal – matrix composites parts. Parts that can be obtained by squeeze cast method include, vane, connecting rod joint of aerospace structure, rotary compressor vane, shock absorber cylinder, diesel engine piston, cylinder liner bearing materials among other components parts used as automobile, nuclear, aeronautical components, sports equipment, cooking utensil, and many other industrial equipment (Raji and Khan, 2006).

Non-ferrous metals have overwhelming characteristic features which have opened the way for their versatility in the field of engineering applications. The current global trends for more advanced technological products of lightweight and fuel economy (Kaczmar et al., 2010), improved mechanical properties such as strength and high surface integrity especially in the automotive industry and other engineering applications, makes squeeze casting technique more preferable than other convectional casting procedures. Most excitingly, a better and improved product can be obtained more favorably from squeeze casting process by controlling various casting parameters during casting, to obtain a suitable and desired engineering component. The flexibility of process control with squeeze casting has actually enhanced wide area of study of various metals and alloy composition for an improved performance.

This present work, machining of permanent steel mold for squeeze casting of non-ferrous metals was designed and machined using mild steel. The performance evaluation was carried out by monitoring solidification temperature of cast aluminum and brass metal rods at varying applied pressures and testing for the tensile strengths.

MATERIALS AND METHODS

Mild steel was used for the fabrication of the squeeze cast rig. It was used due to its good conductivity, availability, lower thermal expansion at elevated temperature and good machinability. The punch diameters of 20 mm and 30 mm were designed and machined to take up the operating load on the rig. The ultimate tensile strength of aluminum and mild steel used are 301$\times$ 10^6 N/m^2 and 310 $\times$ 10^6 N/m^2, respectively. The maximum load acting on the rig (p) can be expressed as;

$$p = \delta A \qquad (1)$$

Where,
δ –Ultimate tensile strength (N/mm^2),
A – Cross-sectional area (mm^2).

The safe load was confirmed by using Johnson's parabolic formula. Thus;

$$p = \delta_c \, A \, [1 - b \, (L_p / K)^2 \,)] \qquad (2)$$

Where,
δ_c -Elastic limiting stress,
L_p -Length of the punch required,
K -Least radius of gyration.
L/K -Slenderness ratio,
b -constant (3 x 10^{-5}) depending on the end factor,
A -cross- sectional area of the punch,

$$A = \frac{\pi D^2}{4} \qquad (3)$$

Where,
D –Diameter of the punch (mm).

The blank mild steel was machined and split into two equal halves on the convectional machine tools. All machining operations of the rig component parts were performed on the lathe machine with serial number 1019265, beaver vertical milling machine with serial number Vprb8825/2 and ARCHDALE sensitive drilling machine with serial number vdi0789. The rough and finish spindle speeds for all machining operations performed were kept within the range of 230rpm and 350rpm at varying feeds and depths of cut. The schematic diagram of the rig is as shown in Figure 1. The rig components, Figure 2 were later assembled, tested and evaluated with squeeze casting of aluminum and brass rods' specimens.

Machining Sequence of the Parts

The rig consists of the punch, rig cover, inner core, rig block, rig seat, cavity for the heater rods, flanges and the toggle bolts as shown in Figure 2. Each of these component parts were machined separately to make them fit into the mold assembly.

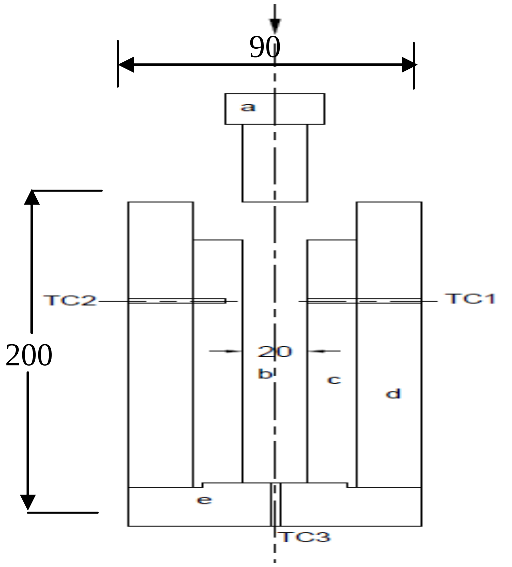

Figure 1: Schematic Diagram of Squeeze Casting Rig.

a – Punch, b – rig cavity, c – inner core, d – rig block, e – die seat, Tc1- Thermocouple position1, TC2 – Thermocouple position 2 and TC3 – Thermocouple position 3.

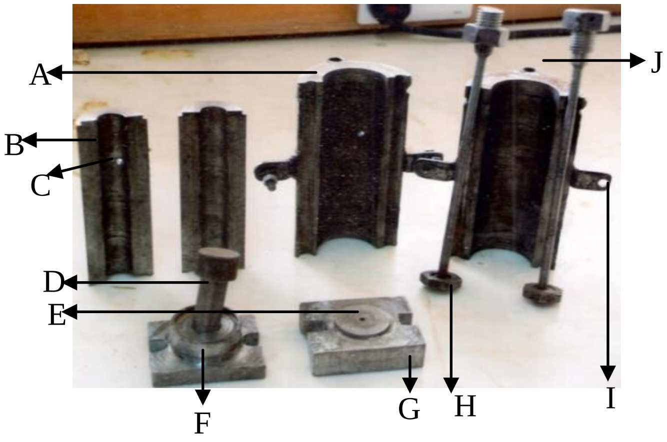

Figure 2: Pictorial View of the Rig Components Part.

A – Rig Block, B – Inner Core, C – Thermocouple position TC1 &2, D – Punch,
E - Thermocouple position TC3, F – Rig cover, G -Die Seat, H- Toggle-bolt, I - Flange,
J – Cavity for heater rod.

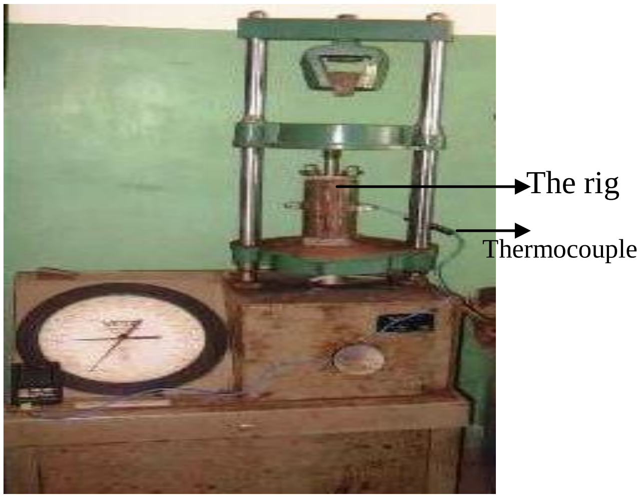

Figure 3: Experimental Setup for Squeeze Casting.

EXPERIMENTAL PROCEDURE

Aluminum and brass metals were samples of non-ferrous metals squeeze castint using the produced rig. The scraps of purity aluminum and brass were melted in an electric furnace contained in a steel crucible. A Vega hydraulic press, model number UTM3C and serial number 1061 with a maximum operating capacity of 89 kN was used for the application of predetermined load on the squeeze cast product as shown in Figure 3.

Metered quantity of molten aluminum and brass were carefully poured into the die at temperatures 700 ^{0}C and 980 ^{0}C, respectively. Six samples each of aluminum and brass specimens were squeeze cast with and without pressure application. The pressure applied ranged from 64 to 190 MPa, with a retention time of 50 s. The solidification rates of both samples were monitored using a digital temperature monitoring data logger through the cromel-alumel thermocouple inserted into the rig wall and cast metal. The graphs of temperature against time for the solidification of both specimens were plotted. The tensile strengths of both cast specimens were also examined at different applied loads on a Monsanto Universal Tensometer with serial number 10584.

Temperature versus Time Curves Determination

The mold was prepared to accommodate thermocouples to monitor the solidification temperatures at TC1 (1 mm into the cast metal), TC2 (4mm from the surface of the cast metal into the steel mold) and TC3 (1 mm into the cast metal from the bottom of the die seat) as shown in Figure 1.

During casting, the solidifying temperatures (TC1) at the cylindrical surface of the cast molten aluminum metal was monitored at a position of approximately 1 mm into the cast molten aluminum metal with time. The thermocouple was connected through a cold junction maintained at the temperature of melting ice, 0 ^{0}C to the read out device. The temperature with time readings with type K chromel-alumel thermocouple sensor were recorded and stored in the SD card of the digital data - logger.

Prepared Samples of Brass and Aluminum Specimen for Tensile Testing

The specimens of aluminum and brass rods obtained through squeeze casting with and without pressure were prepared for tensile tests as in Figures 4a and 4b. The tensile test was carried out on universal tensiometer machine with serial number UTM 10584. The specimens were gradually loaded until they fractured and the measurements of ultimate tensile stress taken.

RESULTS AND DISCUSSION

Permanent Steel Mold

The designed and machined split mold was used for squeeze casting of aluminum and brass rods at varying applied loads. Thermocouples insertion probe points that were incorporated in the mold were used for monitoring the solidifying temperature of the cast metal. The split feature of the mold allowed for easy removal of cast piece after solidification, hence the mold constructed saved time with a reduction in the cost of operation that aided mass production of cast parts.

(a)

(b)

Figure 4: Specimen Prepared for Tensile Testing, (a – aluminum, b – brass).

Effect of Applied Pressure on Solidification of Aluminum Metal

Typical experimental result of solidification temperature with time of aluminum metal with and without pressure is as shown on figure 5. Without pressure application, the solidification of aluminum commenced immediately after pouring which followed the same pattern with pressure application. There was a rise in the solidification temperature of the cast metal as could be observed in Figure 5 when pressure was applied. At applied pressure of 190 MPa, there was temperature increase of about 17 ^{o}C after 5 s of pouring.

The rise in temperature may be as a result of the increase in the kinetic energy of the molecule and the internally generated heat due to a reduced volume of the melt brought about by pressure application that tends to increase the collision rate. This result was similar to that obtained during the squeeze casting of AA7010 alloy, in which a rise in the temperature was observed as pressure was applied during solidification (Yanling et al 2009).

A similar result was obtained by Aweda and Adeyemi (2009) in which they attributed the temperature rise to the increase in the internal energy generated within the cast – metal interface at the application of pressure.

Without pressure application, the solidification time of aluminum metal was within 8s, and 18.5s at applied pressure of 190 MPa. The pressure applied during solidification eliminated or reduced inclusion and gas porosity which consequently lead to a volume reduction of the solidifying metal.

The reduction of volume leads to increase in density of cast metal and the cast-mold contact interface which was responsible for the temperature rise and good heat transfer at the contact surfaces, hence higher solidification rate with applied pressure. This result was in agreement with that obtained earlier (Aweda and Adeyemi, 2009) where there was an increase in solidification rate with pressure application in squeeze casting products.

The solidification profile as shown in Figure 5 shows a sharp fall in temperature and then gradual decline. This behavior indicated a change of state of solidified metal. As the temperature falls, the metal loses heat through the inner mold surface where the heat lost gradually heat up the mold (mold wall temperature), thus increasing mold temperature and losing it to the ambient. There was rapid rise in mold wall temperature within the first 25 s of pouring with corresponding decrease in solidified metal temperature. After this, the temperature became almost steady owing to the decrease in temperature gradients brought about by the transfer of high energized molecules.

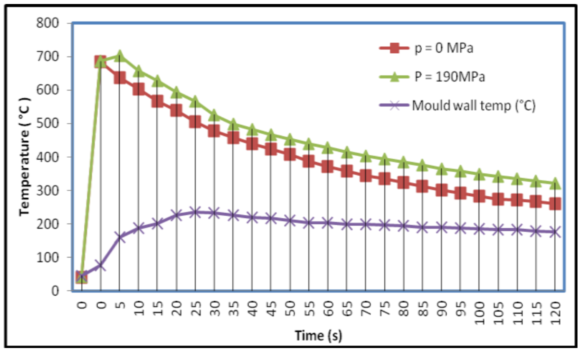

Figure 5: Graph of Solidifying Temperature against Time for the Squeeze Casting of Aluminum with and without Pressure Applications.

Effect of Applied Pressure on Tensile Strength of Squeeze Cast Aluminum Metal

Figure 6 is the graph of ultimate tensile strength with applied pressure of purity aluminum. Without pressure application, the ultimate tensile strength was 11.46 MPa, and 20.37 MPa at an applied pressure of 64 MPa. When the applied pressure was further increased to 95 MPa the value rose to 32.47 MPa, while further increase in the applied pressure does not lead to significant increase in the tensile strength of aluminum.

At an applied pressure of 127 MPa, the tensile strength obtained was 34.38 MPa. Above this pressure, the tensile strength decreases as seen in Figure 6. The increase in ultimate tensile strength may be as a result of the increase in melt temperature brought about by the applied pressure, which leads to a higher degree of undercooling that favored higher solidification rate. This leads to grain refinement by reducing the grain sizes which eventually lead to increase in the number of grains. Applied pressure tends to eliminate gas porosity and compensate for solidification shrinkage during casting.

The decrease in the tensile strength at applied pressure above 127 MPa may best be explained on the presumption that at such higher applied pressure, the aluminum molecules (grains) can no longer withstand such pressure thereby causing cracks which subsequently lead to a decrease in the tensile strength. From the result obtained, it can be observed that the maximum pressure to be applied to optimum tensile strength of pure aluminum metal can be approximated to 120 MPa.

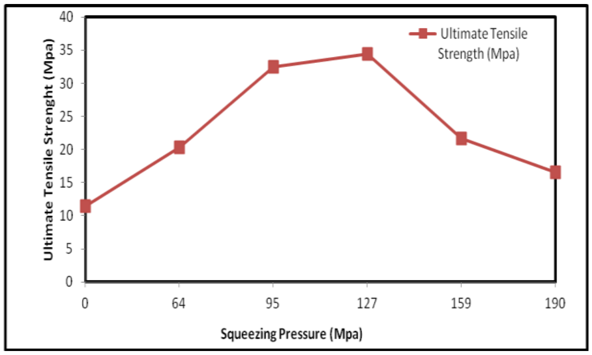

Figure 6: Effect of Squeeze Cast Pressure on the Tensile Property of Aluminum.

This result corroborated with that obtained on the effect of specific pressure on the mechanical properties of ZA27 alloy in which the ultimate tensile strength increases with applied pressure (Chen and San, 2005). The result of the study of the effect of squeeze cast of Al-8%Si alloy was in agreement with the present study where an increase in ultimate tensile strength was obtained at a maximum applied pressure of 125 Mpa after which it remained almost constant at any further increase in applied pressure (Abdulkabir, 2010).

Effect of Applied Pressure on the Solidification Time of Squeezed Cast Brass Metal

Figure 8 is the graph of temperature with time for the squeeze cast of brass metal under varying applied pressures. The solidification time gradually increases with increase in applied pressure. It was noticed during casting that, the melt solidified within 30 seconds with or without pressure application. This was likened to non–preheating of the mold that led to increase in the temperature gradient which shortened solidification time.

With pressure application, there was an increase in the temperature of the solidifying brass which led to higher degree of undercooling due to rapid solidification rate that took place. Cast brass metal without pressure took 17 s to solidify and 28 s at a pressure application of 190 MPa. Thus, increase in solidification rate with increase in applied pressure.

The increase in the solidification rate experienced was as a result of pressure application that tends to increase contact surface of the solidifying metal with that of the mold surface. The increase in contact surface enhanced conduction of heat away from the solidifying metal and hence higher solidification rate. It was also observed in Figure 8 that, the mold wall temperature gradually increased with the release of heat from the solidifying brass. This is because, as metal solidifies, heat is abstracted from it, making the mold wall temperature to increase within 50 s of pouring and becomes almost constant afterwards. Similar result was reported in the literature where it was observed that, the liquidus temperature increased with the increase in applied pressure (Yanling et al 2009 and Abdulkabir, 2010). They also opined that, 5 s was enough for the solidification of an alloy when a pressures of between 0 Mpa and 190 Mpa were applied.

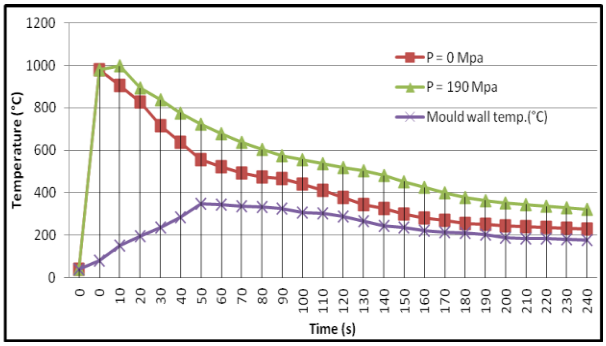

Figure 8: Graph of Solidifying Temperature against Time for the Squeeze Cast of Brass.

Effect of Applied Pressure on Tensile Strength of Squeezed Cast Brass Metal

Figure 9 illustrates the relationship between applied pressures and ultimate tensile strength as obtained for the squeeze cast of brass metal. The figure shows an increase in tensile strength with increase in applied pressure from 0 MPa to a pressure level of 95 MPa after which there was a drop in the tensile strength.

Without pressure application, the tensile strength was 49.66 MPa. When the applied pressure was increased to 64 MPa, the tensile strength increased to 56.66 MPa. Further increase of applied pressure to 95 MPa increased the tensile strength to 80.21 MPa which was the maximum tensile strength obtained in this present work.

A decrease in tensile strength of brass metal was observed on pressure application above 95 MPa which tend to remain almost constant with further increase in pressure. The reduction in strength of brass as obtained with increase in pressure as the 95 MPa was presumed to have been that, the brass molecules could no longer withstand high applied pressure and may have caused cracking in the metal and thereby reducing its strength. Therefore, it was opined that the optimum applied pressure required to obtain a good tensile strength of brass during squeeze casting was at 95 Mpa. This result obtained corroborated the already established literatures as reported in various studies (Aweda and Adeyemi, 2008, Regular et al, 2004 and Raji and Khan, 2006).

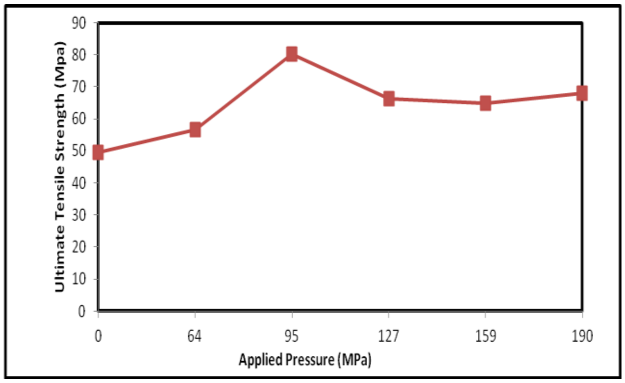

Figure 9: Effect of Squeeze Cast Pressure on the Tensile Property of Brass.

CONCLUSION

The following outcomes of the present work hereby submit that;

1. A permanent steel mold with cavity ranging between 10mm and 30mm was manufactured which incorporated heater rods and thermocouples for die preheating and temperature monitoring, respectively.

2. The results obtained from the mold suggested that it can withstand squeeze cast pressure and can be applied to non-ferrous metals,

3. The solidification rate of aluminum and brass metals increases with increase in applied pressure

4. The tensile strength increases for aluminum from 11.46 MPa at 0 MPa squeeze pressure to 34.38 MPa at 120 MPa squeeze pressure while for brass, its tensile strength increases from 50 MPa at 0 MPa squeeze pressure to 80.20 MPa at 95 MPa .

5. The optimum required squeeze pressure to obtain the optimum tensile strength for aluminum and brass metals was 120 MPa and 90 MPa, respectively, which can be adopted for the squeeze casting of 20mm rod as examined in this present study.

REFERENCES

1. Abdulkabir, R. 2010. “A Comparative Analysis of Grain Size and Mechanical Properties of AL-Si Alloy Component Produced by Different Casting Methods”. *Journal of Technology*. 13(3):158-164.

2. Aweda, J.O. 2008. “Improving the Electrical Properties of Aluminum Metal through Squeeze Casting Process”. *NSE Technical Transaction.* 43(4):1 – 17. http//:Unilorin.edu.ng/publication/ Accessed on 24th of June 2012.

3. Aweda, J.O. and M.B. Adeyemi. 2009. “Determination of Temperature in Squeeze Cast Aluminum using the Semi-Empirical Equations Method,” *Journal of Material Processing Technology*. 209:5751-5759.

4. Chen–Xi, L.I. and San Jin-Chao. 2005. “Research on the Squeeze Cast Technology of the Casting with Large Ratio of Height to Thickness”. *Academic Journal of Electronic Publishing House, China Foundry*. 2(4):264-267.

5. Eman J. Abed. 2011. “The Influence of Different Casting Method on Solidification Time and Mechanical Properties of Al–Sn Castings”. *International Journal of Engineering and Technology*. 11(06):34 – 43.

6. Kaczmar, J.W., K. Granat, K. Pietrzak, K. Naplocha, and E. Grodzka. 2010. “Manufacturing of MMC based on CuZn38Al2Mn1Fe Brass Strengthened with δ – Alumina Fibres”. *Journals of Foundry Engineering*. 10:411 – 414.

7. Kobryn, P.A. and S.L. Semiatin. 2001. “Determination of Interface Heat- Transfer Coefficients for Permanent Mold Casting of Ti-6AL-4V”. *Metallurgical and Material Transaction*. 32B:685 -689.

8. Nakata. K., Y.G. Kim, H. Fujii, and T. Tsumura. 2006. “Improvement of Mechanical Properties of Aluminum Die Casting Alloy Multi-Pass Friction Stir Processing”. *Material Science and Engineering*. A437:274-280.

9. Raji, A. and R.H. Khan. 2006. "Effect of Pouring Temperature and Squeeze Pressure on Al-8% Si Alloy Squeeze Cast Parts". *Journal of Technology, Federal University of Technology, Adamawa, Nigeria*. 9(4):229-237.

10. Regular T., J.J. Sobezak, A. Fajkiel, and K. Dudek. 2004. "Effect of Applied Pressure on the Quality of Squeeze Cast Parts made from Al Si9Mg Alloy". *Journal of foundry Engineering*. 11:55 – 60.

11. Serope, K. and R.S. Steven. 2006. *Manufacturing Engineering and Technology. 5th Edition.* Prentice Hall: New York, NY. 207-273.

12. Wallac, J. D. Schwan, and Q. Zhou. 2009. "Die Material for Critical Applications and Increase in Production Rate. Diecasting.org: Wheeling, IL. http:// www.diecasting.org., Acessed on 04/05/2012.

13. Xiao – Hui C., Xu Huang and R. Xue – Ping. 2010. "Densification Mechanism of Squeeze Casting". School of Material Science and Engineering, University of Science and Technology Beijing: Beijing, China. 124- 136.

14. Yanling Y., P. Liming, F. Penghuai, H Bin, D. Wenjiang, and Y. Baozhang. 2009, "Effect of Process Parameter on the Microstructure of a Squeeze – Cast Mg2.5mass%Nd Alloy". *Materials Transactions.* 50(12):2820 – 2825.

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SUGGESTED CITATION

Aweda, J.O. and M.Y. Kolawole. 2014. **"**Performance Evaluation of Permanent Steel Mold for Temperature Monitoring During Squeeze Casting of Non-Ferrous Metals". *Pacific Journal of Science and Technology.* 15(1):24-31.

Pacific Journal of Science and Technology