STATISTICAL DETERMINATION OF THE EFFECTS OF POURING TEMPERATURE ON MECHANICAL PROPERTIES OF ALUMINUM ALLOY CAST

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ABSTRACT

The determination of effects of pouring temperature on mechanical properties of aluminum alloy using statistical method was successfully investigated. The automotive industry faces failures and accidents due to inadequate mechanical properties of cast parts, particularly at higher temperatures. These inadequacies in mechanical properties are not unconnected with their pouring temperature during casting. This study aims to determine the optimal pouring temperature for aluminum alloy casting to achieve optimal mechanical properties. A total of thirty-two (32) casts, were produced via sand mould at four (4) different pouring temperatures namely 660°C, 690°C, 710°C and 740°C which were achieved with the aid of a thermocouple. The specimens were afterwards tested for quality of properties such as density, hardness, water retention capacity and tensile strength, and how these mechanical properties failed under different pouring temperatures. Samples were taken to an Atomic Absorption Spectrometer to test for their chemical composition. Data obtained were analyzed using ANOVA technique. Results showed percentage composition of Al (83%), Si (11%), Cu (3%) and others (3%). It was revealed that variation in the pouring temperature significantly affected the quality of density, tensile strength and hardness, whereas, it had no significant effect on the water retention capacity of the aluminum casts. The optimal pouring temperature is 690°C, with the optimal range being 690°C and 700°C, for producing high-quality casts.

Keywords: Aluminum alloy cast, ANOVA, Pouring temperature, Mechanical properties, Hardness

1 INTRODUCTION

It is expedient to determine the pouring temperature or range of temperatures for aluminum alloy casting that will yield the optimum mechanical properties mix such as greater density, excellent dimensional stability, surface hardness and wear resistant properties. Aluminum Alloy casts have found their usefulness in the automotive industry in the production of components such as pistons, cylinder blocks, cylinder heads, cylinder liners, bearings, connecting rods, turbo chargers, jet engine parts, impellers, metal composites, actuators, brake calipers and rotors. Increase in the performance, efficiency and reliability of these cast parts for service has been found to be proportional to the improvement in their mechanical properties. However, these mechanical properties are affected by the pouring temperature during casting [1], Analyzing the relationship to understand how the pouring temperature affects the mechanical properties of a cast using a very reliable statistical analytical technique like the Analysis of Variance (ANOVA) will be of best interest. According to [2], Aluminum-Silicon (Al-Si) alloys are most versatile materials, comprising 85% to 90% of the total aluminum cast parts produced for the automotive industry. However, most Al-Si alloys are not suitable for high temperature applications because tensile and fatigue strengths are not as high as desired in the temperature range of 500°F - 700°F.[3]revealed that Aluminum Alloy casting process involves so many parameters such as melting temperature of the charge, temperature of the mold, pouring speed, pouring temperature, composition, micro structure, size of casting, runner size, and solidification time. This paper focuses on a relatively high cooling strength and low compositional segregation Aluminum alloy that will yield more uniform properties, the green sand mold was used for the casting operation and aluminum was the base material. In the same vein, the focus of this statistical method using the ANOVA technique is based on the one-way ANOVA, which is used to analyze a single factor of interest for two or more groups [4]. Also, the mechanical properties analyzed were limited to the following: Hardness, Density, Water Retention Capacity, and Tensile strength. The general objective of this research work is to determine the effects of pouring temperature on mechanical properties of aluminum alloy using statistical method in order to improve the service performance and reliability of Aluminum alloy products. Pouring is a process by which molten metal is transferred to the cast for cooling and solidification and thus be converted into final product. Pouring temperature is the temperature to which the molten metal has to be raised [5]. Temperature must also take into account the heat loss due to the transfer of metal through ladles. Also, distance between the furnace and mold has to be considered as well as heat loss due to the heat absorbed by ladles. The casting process can usually be done in permanent metal casts [6]. However, due to repeated exposure to high temperature of molten metal, these casts have a limited life, or can be used for metals with low pouring temperature requirements. Therefore, one of the main requirements of the casting process is refractoriness or in other words, the capability of east to bear high temperatures of the molten metal without undergoing any changes in its physical properties. This is a very important requirement in alloys with high melting point such as steel. However, this issue may be taken secondary in alloys with lower melting points. Where alloys with high melting point are being used, the molds need to be lined with an insulation material with refractory properties so that the mold retains its shape and original characteristics. Sand and ceramic materials have very high ability to withstand high temperatures of molten metal without undergoing a change in their properties. Therefore, they are used as coating material for molds in which alloys with high temperatures have to be poured for cooling. Sand and ceramic can withstand temperatures as high as 165℃-1820°C [7]. Also, sand retains the shape given to it when it is put into a mold. It also permits various gases to escape through its structure. Sand casting can be used in processing of low-temperature metals, such as iron, copper, aluminum, magnesium, and nickel alloys and also for high temperature metals where other mold material cannot be used. Metal molds have a limited capacity to withstand high temperatures. Metal molds are used in processes like Die Casting (where molten metal is forced into steel molds under high pressure) and permanent molding. These molds may change their physical properties in case molten metal above 118°Cpouring temperature are processed in such molds. For any alloy with temperature above this temperature, metal molds are not suitable [8].

2 METHODOLOGY

2.1 Casting Method

As regards the casting methods utilized, it started with the making of patterns, bearing in mind the expected tests to be carried out at the testing machines, followed with the making of the mold. Next, scraps of neat aluminum ceilings, free of dust and contamination, were charged into a graphite crucible furnace.

The crucible, which uses combustion to melt the material, was powered by Automated Gas Oil (AGO) or diesel mixed with air from a blower. Furthermore, to minimize oxidation of aluminum, mixture of sodium chloride and potassium chloride powder known as halide salt was added to exclude oxygen and create a protective atmosphere inside the furnace. This will reduce the effect of oxidation. The resulting melt was thoroughly stirred intermittently to ensure uniformity of material, especially the times that the temperature of the molten metal was checked with the use of thermocouple by dipping the tip into the liquid. Finally, the molten metal was then skimmed to remove the oxides and impurities before pouring. The distance from the cope to the drag was measured to be 12cm (0.12m), while the average pouring duration was 5seconds which resulted in a pouring speed of 2.4cm/s (.024m/s). After the casting process, some of the samples were polished and taken to an Atomic Absorption Spectrometer to test for their chemical composition. After the test specimens (casts) were produced, they were taken to the mechanical testing laboratory to ascertain their mechanical properties. Thereafter, the mechanical testing results were put in ANOVA statistical form for analysis. The null hypothesis tested by one-way ANOVA and the Fisher's test (F-test) was employed for this study.

2.2 Density Values

In the first premise, all thirty-two (32) casts were weighed using a Loading Balance to ascertain their individual masses. In the same vein, an empty calibrated cylindrical flask was weighed to be 94g.Next, an empty weighing bowl and collector were obtained, and the bowl, filled with water to the brim, was placed in the collector. Next, the casts were immersed into the bowl, one at a time, to displace a certain quantity of water. For each of the immersions, the displaced water into the collector was transferred into the cylindrical flask and weighed. The difference in the masses of the cylindrical flask as a result of the displaced water were obtained, which is equivalent to the displaced volume. This is in accordance with Archimedes' principle that an object submerged in water will displace the volume of water equivalent to its mass/weight. For example, for the cast with known mass of 378g and submerged into the bowl of water.

$$\text{Mass of empty cylindrical flask} = 94\text{g} \tag{1}$$

$$\text{Mass of cylindrical flask containing water displaced by the 378g cast} = 288\text{g} \tag{2}$$

$$\text{mass equivalent of the water displaced} = 288\text{g} - 94\text{g} = 194\text{g} \tag{3}$$

$$\text{Density} = \frac{mass}{volume\ dispaced} \tag{4}$$

2.3 Water Retention Capacity

Here, the samples were simply submerged in water, after their original masses were noted, for duration of twenty (20) hours (almost 1day). Thereafter, they were removed from the water and re-weighed. All the samples recorded increase in mass showing they had absorbed some water. The difference in mass shows the water retention capacity of aluminum which forms the data. It is important to note that aluminum which absorbed water will not rust, but reduces in size and ages faster than the one that did not absorb water. Thus, mass after immersion minus mass before immersion gives the data values.

2.4 Tensile Strength Testing

The castings were taken to the grinder to remove the excess flakes bringing the shape to be properly locked into a bolted socket provided. Next, they were taken to the equipment used for ultimate tensile test which is Avery - Denison Universal Testing Machine with a capacity of 600KN and an analog scaling system. The machine is hydraulically operated. The test specimens, having been locked in the bolted socket were then fed into a locking socket which provided the grip of specimen at the base and at the top. Thus, the test specimen was held at both ends and made to be slightly tensioned, with the scale meter and load meter set at zero and the pump handle in the down position and locked. The pump handle was then operated to apply the load. The load was increased uniformly and the corresponding extension was noted. This process was repeated for other specimens.

2.5 Hardness Values

In continuation with the values got from the tensile strength test, Meyer's law was applied which reveals that there exists a relationship between ultimate tensile strength (UTS) and Brinell Hardness Number (BHN) which is given as:

$$UTS = 3.4(BHN) \quad (5)$$

Where 3.4 represents Meyer's index for materials like aluminum cast.

2.6 Statistical Approach

To ensure a good sample size for the experiment, care was taken to avoid bias by applying randomized block design approach during collection of data, and to ensure precision, eight (8) levels (replicates), four easts per casting operation, for each pouring temperature were obtained. Choosing a balanced design has two important advantages. First, the ANOVA is relatively insensitive to small departures from the assumption of equality of variances if the sample sizes are equal. Second, the power of the test is maximized if the samples are of equal size [9]. In addition, the casts were of uniform material. Thus, a total of 32 samples were obtained in all. ANOVA technique is to be used to determine whether there are significant differences among the means of four pouring temperature groups of aluminum cast (650°C, 690°C, 710°C, and 740°C) in relation to mechanical properties (density, water retention capacity, tensile strength and hardness).In the typical application of ANOVA, the null hypothesis says that all groups are simply random samples of the same population. This means that all treatments have the same effect (perhaps none). Rejecting the null hypothesis implies that different treatments result in altered effects. By construction, hypothesis testing limits the rate of Type I errors (false positives leading to false scientific claims) to a significance level. Experimenters also wish to limit Type II errors (false negatives resulting in missed scientific discoveries). In this case, the null hypothesis is accepted when it is false. The Type II error rate is a function of several things including sample size (positively correlated with experiment cost), significance level (when the standard of proof is high; the chances of overlooking a discovery are also high), and effect size (when the effect is obvious to the casual observer, Type II error rates are low) [10].

Decision Rules

If $Fcal > Ftab$, reject null hypothesis, H_0 (6)

If $Fcal < Ftah$, accept null hypothesis, H_0 (7)

I. For Water Retention Analysis

Since $Fcal = 1.716 < Ftah = 2.946$, Accept H_0 (8)

II. For Density Analysis

Since $Fcal = 3.198 > Ftah = 2.946$, Reject H_0 (9)

III. For Tensile Strength Analysis

Since $Fcal = 19.585 > Ftah = 2.946$, Reject H_0 (10)

IV. For Hardness Analysis

Since $Fcal = 19.91603 > Ftab = 2.946$, Reject H_0 (11)

3 RESULTSAND DISCUSSION

3.1 Pouring Temperature of Aluminum Alloy Cast

The Aluminum Alloy Cast specimen results data are presented below. The data in Table 1 were analyzed and it showed that mass of aluminum alloy cast produced increases at lower pouring temperature

Table 1. Masses of the Casts and Their Pouring Temperatures

Pouring	660°C	690°C	710°C	740°C
Masses (g)	400	403	378	383
	402	414	390	399
	409	409	366	358
	411	393	373	364
	420	417	350	348
	417	390	377	374
	398	401	387	349
	399	384	370	345

3.2 Density of Aluminum Alloy Cast and its Analysis of Variance

From Table 2a, the values of density were calculated using equations 3 and 4 This implies between 660°C and 690°C, as well as 690°C and 740°C pouring temperatures produced different densities, the remaining pouring temperature level produced approximately same density. This clearly concludes that the 690°C produces the maximum density and is thus the optimum temperature for density. Since F_{cal}=3.198 >F_{lah} = 2.946 as seen in Table 2b, we have a paucity of evidence to accept the null hypothesis, H_0. Therefore, we reject the null hypothesis and state that the pouring temperature significantly affects the density of aluminum cast. In other words, there is differential treatment among the different pouring temperatures on the density of aluminum. If the expected value of F is 1, it means no treatment effect. As values of F increase above 1, the evidence is increasingly inconsistent with the null hypothesis. To test the hypothesis that all treatments have exactly the same effect, the F-test's p-values closely approximate the permutation test's p-values: The approximation is particularly close when the design is balanced [11].

Table 2a. Values of Densities at different pouring temperatures

Temperatures	600°C	690°C	710°C	740°C
Density (g/cm3)	2.1	2.1	1.9	2
	1.9	3	2.8	2
	2.2	3.2	2.7	1.9
	2.3	2.7	2.2	1:08
	1.7	2.1	1.9	1.9
	1.8	'2	2	1.7
	1.9	1.8	1.9	1.9
	2	2.8	2.7	2.6
Total	15.9	19.7	18.1	15.8
Average	3.533333	4.377778	4.022222	3.511111
Variance	0.04125	0.274107	0.162679	0.073571

Table 2b. ANOVA Result for Density

Source of Variation	Degree of Freedom	Sum of Square (SS)	Mean of Square	F(cal)	F (tab)
Among Means (Pouring Temperature)	3	SSA=1.3234375	MSA=0.4414458	MSA/MSE== 3.198	2.946
Error	28	SSE= 3.86125	MSE=0.1379017		
Total	31	SST=5.1846875			

3.3 Water Retention Capacity

Water retention capacity was computed using procedures explained in section 2.3 as seen in Table 3a. Since Fcal= 1.716 <F_{lah} = 2.946, as can be seen from Table 3b, our data does not provide sufficient evidence to reject the null hypothesis (H_0). So, we accept the null hypothesis and therefore conclude that there appears to be no significant difference among the means of the test samples for water retention capacity. In other words, the temperature at which you do the pouring during casting does not significantly affect the water retention capacity of aluminum cast. This is in line with the report posited by [12] when he characterized the nomenclature and composition of aluminum cast alloys.

Table 3a. ANOVA Data for Water Retention Capacity

Temperatures	660℃	690℃	710℃	740℃
MASS (g)	2	2	3	2
Water Retention capacities (g)	2	2	4	3
	1	2	2	1
	3	5	3	2
	[illegible]	[illegible]	[illegible]	[illegible]
	2	3	2	3
	1	3	3	2
	2	1	2	3
Total	15	21	23	20
Average	1.875	2.625	2.875	2.5
Variance	0.410714	1.410714	0.696429	0.857143

Table 3b. ANOVA Result for Water Retention Capacity

Source of Variation	Degree of Freedom	Sum of Square (SS)	Mean of Square	F(cal)	F (tab)
Among Means (Pouring Temperature)	3	SSA=4.34375	MSA=1.4479	MSA/MSE== 1.716	2.946
Error	28	SSE=23.625	MSE=0.8437		
Total	31	SST=27.96875			

3.4 Tensile Strength

Results of tensile test was recorded in Table 4a. The pouring temperature of 690°C experienced the highest average tensile strength 155.2625N/mm^2. we see that there are significant differences between all pairs of means except for pouring temperature of 690°C and 710°C as well as 660°C and 740°C. Discarding the pairs that produced approximately same strength, we see that maximum strength was produced at the pouring temperature of 690°C which set the optimum pouring temperature for tensile strength at 690℃ [3]. From Table 4b, Since F_{Cal} =3.198 >F_{tab} = 19.585 there is scarcity of evidence to accept the null hypothesis, H_0, Therefore, we reject the null hypothesis and state that the pouring temperature significantly affects the tensile strength of aluminum cast.

Table 4a. ANOVA Data for Tensile Strength

Pouring T...	660℃	690℃	710℃	740℃
Tensile strength (n/mm^2)	141.5	151.2	141	131.7
	149	162.2	153.3	133.5
	134.1	154.1	155.1	150.1
	134.1	149.3	150.2	145.3
	139.4	154.1	150.3	140.7
	130.3	153.2	144.2	132.2
	129.8	159.6	148.1	131.9
	132	158.4	147.4	129.5
Total	1090.2	1242.1	1189.6	1094.9
Average	136.275	155.2625	148.7	136.8625
Variance	43.47929	19.39982	21.21714	57.09696

Table 4b. ANOVA Result for Tensile Strength

Source of Variation	Degree of Freedom	Sum of Square (SS)	Mean of Square	F(cal)	F (tab)
Among Means (Pouring Temperature)	3	SSA=2074.008	MSA=691.3358	MSA/MSE=19.58553	2.946685
Error	28	SSE= 988.3525	MSE=35.2983		
Total	31	SST=3062.36			

3.5 Hardness Test Results

The Hardness test data from Table 5a showed that the maximum hardness level was produced for pouring temperature of 690°C and 710°C which clearly shows that 690°C produced optimum temperature for hardness. Therefore, the overall analyses have confirmed 690°C as the optimum pouring temperature for optimum quality in density, tensile strength and hardness of aluminum alloy cast. From Table 5b using ANOVA**,** Since Fcal = 19.91603 >F_{tab} = 2.946, our data provides us sufficient evidence to reject the null hypothesis, HO. Therefore, we accept the alternate hypothesis and therefore conclude that there are sufficient differences among the mean hardness of the test samples. In other words, the difference in the means is not due to chance error.

Table 5a. Values for Hardness

Temperature	660°C	690°C	710°C	740°C
Hardness (N/mm2)/(MPa)	41.6	44.5	41.5	38.7
	43.8	47.7	45.1	39.3
	39.4	45.3	45.6	44.1
	39.4	43.9	44.2	42.7
	41	45.3	44.2	41.4
	38.3	45.1	42.4	38.9
	38.2	46.9	43.6	38.8
	38.8	46.6	43.4	38.1
Total	320.5	365.3	350	322
Average	40.0625	45.6625	43.75	40.25
Variance	3.75125	1.656964	1.811429	4.857143

Table 5b. ANOVA Result Table for Hardness

Source of Variation	Degree of Freedom	Sum of Square (SS)	Mean of Square	F(cal)	F (tab)
Among Means (Pouring Temperature)	3	SSA=180.3913	MSA=60.13042	MSA/MSE= 19.91603	2.946685
Error	28	SSE= 84.5375	MSE=3.019196		
Total	31	SST=264.9288			

4 CONCLUSIONS

Obviously, results from the study revealed that the pouring temperature of 690°C yielded maximum value for density, tensile strength and hardness. This led to the optimum pouring temperature, among the selected temperatures being 690°C and the optimum range of temperature is 690°C and 700°C all inclusive. This is in agreement with previous researches that pegged optimum pouring temperature at 700°C. It is at these temperatures that good quality casts could be produced especially in terms of the aforementioned mechanical properties. It has been observed that lower pouring temperatures than optimum will bring about too rapid solidification and intercept directional solidification. On the contrary, higher pouring temperatures cause shrinkage of the casting. Seeing, such mechanical properties are very crucial and of uttermost importance to the effectiveness and efficiency of the cast in particular and the material engineering industry in general, the derivation of this experiment should be looked into for further research for improved and more reliable solution. Pouring temperature of 690°C should be adopted when maximum value for density, tensile strength and hardness are required. Further research can also be done in future to establish an accurate mathematical model between pouring temperature and density, tensile strength, hardness for easy of prediction. Casting method adopted could influence the quality of Aluminum Alloy produced.

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