Umudike Journal of Engineering and Technology (UJET); Vol. 9, No. 1, June 2023, pp. 46 – 54; Michael Okpara University of Agriculture, Umudike. Print ISSN: 2536-7404, Electronic ISSN:2545-5257; http://ujetmoua.com; https://doi.org/10.33922/j.ujet_v9i1_6

OPTIMIZAION APPROACH FOR EVALUATION OF MECHANICAL PROPERTIES OF HIGH PRESSURE DIE CAST ALUMINUM ALLOYED PRODUCT

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ABSTRACT

This work produces a machine component-motor cycle hand clutch using a high pressure cold chamber die casting machine. The aluminum cable coil was alloyed with 10%wt silicon and 0.6%wt of magnesium and 0.5%wt of copper while the chemical composition of aluminum alloyed coil contains 97.82% aluminum, 1.17% of silicon, 0.54% of copper 0.35% magnesium, and traces of iron and chromium. Taguchi method was adopted for optimization of the response parameters and mechanical properties of the cast to obtain the optimum performance of porosity using density as response factor. The optimal value was obtained with sample specimen 3 with charging masses of Si = 0.7; Cu = 0.8 and Mg = 0.7 at density of 2.7533 and porosity of 0.3632, while at this optimal value, the following corresponding values for mechanical properties were obtained: impact = 136/416 Joules; UTS = 58.487 N/mm^2; Hardness = 41HRB, %Elongation = 11.3649; Y.M = 882.3998; Flexural Strength = 105.9556 N/mm^2 with a yield strength of 2.0763 N/mm^2.

Keywords: *Optimization, Die-Cast, mechanical properties, taguchi, Aluminum alloyed.*

1.0 INTRODUCTION

Materials processing is the technology that converts a material into a product of a desired shape. Casting is the first step in making most of the products. It is one of the oldest manufacturing processes. Casting is a process in which material is melted and allows to flow by gravity or other force into a mold where it solidifies in the shape of the mold cavity. A typical casting is produced by pouring molten metal into a suitably prepared mold cavity containing the topology of the part to be manufactured (Mohammad, 2015). The term casting also applies to the part made in the process. Aluminum is a silvery-white metal; it is the most widespread metal on Earth, making up more than 8% of the Earth's core mass and is also the third most common chemical element on our planet after oxygen and silicon.

Aluminum offers a rare combination of valuable properties. It is one of the lightest metals in the world but is also very strong, extremely flexible and corrosion resistant because its surface is always covered in an extremely thin and yet very strong layer of oxide film. It doesn't magnetize, it's a great electricity conductor and forms alloys with practically all other metals. In addition to these wonderful properties both aluminum and its alloys can be melted down and be reused over and over again without any detriment to its mechanical properties. All these qualities make aluminum one of the key engineering materials of our time. We can find aluminum in the homes we live in, in the automobiles we drive, in the trains and aeroplanes that take us across long distances, in the mobile phones and computers we use on a daily basis, in the shelves inside our fridges and in modern interior designs. Aluminum products are made in a variety of ways that aim to improve the mechanical properties of the finished products or to achieve a desired property within a specific range, some of the common methods of manufacturing aluminum products include extrusion, forging, drawing, rolling, and casting. Each of these processes have their own merits and demerits and also improve the mechanical properties of the finished products in different ways, but one common factor among them apart from casting is that they are expensive, usually involve highly skilled manpower, huge machinery, and large energy consumption. Casting is a simple, inexpensive and versatile way of forming aluminum into a wide array of products it is the method that is easily accessible and affordable to large section of the population in developing countries like Nigeria. Pure aluminum is soft having comparatively poor casting features and little strength, that's why aluminum castings are prepared from aluminum alloys (Mohiuddin *et al*., 2015). Aluminum alloy castings are extensively used in general engineering, automobile, aerospace industries due to their excellent cast-ability, machinability, corrosion resistance and high strength-to-weight ratio (Mohiuddin *et al* 2015). Aluminum alloys are widely used in die casting process because of their good combination of strength and light weight (Hu *et al*., 2006). Manufacture of a machine part by heating a metal or alloy above its melting point and pouring the liquid metal/alloy in a cavity approximately of same shape and size as the machine part is called casting process. Casting is an economical way of producing components of required shape either in small lots orin larger lots.

The die casting process involves the use of a furnace, molten metal, die casting machine, and die (Amitkumar *et al*., 2015). The casting process is as follows: clamping of die, injection of molten metal, cooling of molten metal, ejection of cast, and trimming of cast (Mohamad *et al*., 2020). The metal, typically a non-ferrous alloy such as aluminum, magnesium, copper or zinc, is melted in the furnace and then injected into the dies in the die casting machine. In this process, the metal is injected into the die at high speeds (30–100 m/s and typically 40–60 m/s for aluminum alloys) and under high pressure through complex gate and runner systems (Amitkumar *et al*., 2015). High-pressure die casting (HPDC) is a cost-effective process for the production of castings in large quantities and with high dimensional accuracy. Parts produced by this process conform accurately to the die size, have favorable mechanical features, and are low in cost. This process also enables production of parts with complex shapes. In line with the objective of this work that made it different from other existing or previous works, this work developed an optimal setting for achieving a combination of process parameters that yield a set of mechanical properties which is suitable for a desired application.

2.0 MATERIALS AND METHODS

The materials that were used for the study are aluminum coil sourced from Cutix Plc Otolo, Nnewi, Anambra State. While the aluminum alloying materials such as Silicon, magnesium and copper were bought from Pascal Scientific Laboratory, Akure, Ondo State.

The method adopted in this work involves determination of chemical compositions of the aluminum alloy; design of experiment with Taguchi method and determination of mechanical properties of aluminum alloyed product through experimental tests.

Taguchi method is a design of experiment technique that provides a systematic and efficient methodology for process or response optimization and this is a powerful tool for the design of high quality systems. Taguchi parameter design provides a means of both reducing cost and improving quality by making effective use of experimental design methods (Senthiil *et al*., 2014). It is an experimental technique that helps to investigate the best combinations of response parameters, changing quantities, levels and combinations in order to obtain results that are statistically reliable (Verran *et al*., 2008).

2.1 Raw Sample Preparation

The experimental setup consists of die casting cell comprising of die casting machine, an electric holding furnace, shot monitoring system. The die casting machine was ladled molten metal from the melting cum holding furnace with the help of the tong. The various settings required for the experiment were set manually and it was monitored through the shot monitoring system. The shot monitoring system helps us in monitoring the parameters set so that we can check its status during each shot.

A total of nine (9) different combinations were run. To accomplish a casting operation, the metal is first heated to a temperature high enough to completely transform it into a liquid state. The molten metal, which is maintained at a set temperature in the furnace, is next transferred into a chamber where it can be injected into the die. It was observed that the heating temperature during the casting process that transformed the metal to molten state was 725^{O}C with the aid of Non-Contact thermometer, of D:S= 20:1 Class II Laser Radiation instrument. The method of transferring the molten metal is dependent upon the type of die casting machine, whether a hot chamber or cold chamber machine is being used.

2.2 Casting

The casting of the machine product/component used in this research was achieved with cold high pressure die casting machine and sample specimen were used to test for mechanical properties (response parameters). Taguchi method was used for optimization of the process and response parameters

2.3 Density and Porosity Measurement

Density (ρ) measurement was performed in accordance with Archimedes' principle on the samples. Distilled water will be used as the immersion fluid. The samples were weighed using digital electronic balance, with an accuracy of ± 0.0001g.The castings were first weighed in air and then weighed when completely immersed in water.

The casting density being directly related to its porosity were considered and measured in each trial conditions using Archimedes' principle. Density of the castings for each combination was calculated using eqn. (1) (Senthiil et al., 2014; Rathinam et al., 2021).

$$\rho = \frac{w_1}{w_1 - w_2}\rho_{water} \qquad (1)$$

where ρ is the density of casting (g/cm^3), ρ_{water} is the density of water (g/cm^3), w_1 is casting weight in air (g) and w_2 is the casting weight in water (g).

The porosity is related to density. Casting with less porosity will have higher density than casting with more porosity. The porosity was determined using eqn. (2) (Tsoukalas, 2008).

$$porosity\ \% = \left(1 - \frac{\rho}{\rho_0}\right)100 \qquad (2)$$

Where, ρ_o is the theoretical density of the casting without porosity.

2.4 Tensile Test Apparatus

Tensile testing of the samples were conducted on the aluminum alloy cast in accordance with the ASTM E8 standard on round tension test specimens of gauge length 25mm using Ametek Ez-250 digital tensile and compression tester. It was conducted at room temperature.

2.5 Hardness Test Apparatus

The Rockwell method was adopted. A standard block of hardness of 101.12 HRB, a minor load of 10kg was used. A hand wheel used manually to raise the spindle towards the interior until the small needle has made full turn which signals the application of the pre-load to the exact zero setting of the scale ring of the dial gauge. The application of the test load and the release was affected by means of a motor drive eccentric. The motor stopped automatically after the test is completed.

2.6 Impact Test Apparatus

The equipment that was used for this test was the pendulum impact testing machine with a capacity of 500J calibrated in both in Izod and Charpy with 1Div equivalent to 2 Joules. The length of specimen/sample used for impact tests = 55mm while notch depth =1.5mm

2.7 Characterization of the Aluminum Coil

The elemental compositions of the aluminum coil were determined using Shimadzu EDX-720 X-ray fluorescence (XRF) and analyze while the system was cooled using liquid nitrogen gas.

2.8 Determination of charging mass

The mass of the various constituents (i.e. aluminum, silicon, magnesium, and copper) that were used in the production of the casting were evaluated with respect to the volume of machine product. The samples were produced by keeping the percentage of aluminum constant and varying that of alloying elements during the casting processes.

2.9 Experimental Design

Taguchi robust design of experiment was adopted for the experimental design and a total of 9 runs of the composition variables were generated with three different levels.

Table 1: The Number of Runs (L9 Orthogonal Array)

RUNS	F	G	H
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

Table 2 -COMPOSITION VARIABLES

Designation	ELEMENTS	LEVEL 1	LEVEL 2	LEVEL 3
F	Si	0.7	0.9	1.1
G	Cu	0.4	0.6	0.8
H	Mg	0.3	0.5	0.7

Table 3: ACTUAL VALUES

RUNS	F	G	H
1	0.7	0.4	0.3
2	0.7	0.6	0.5
3	0.7	0.8	0.7
4	0.9	0.4	0.5
5	0.9	0.6	0.7
6	0.9	0.8	0.3
7	1.1	0.4	0.7
8	1.1	0.6	0.3
9	1.1	0.8	0.5

Table 4: Characterization/Chemical Composition of Aluminum Coil

Analyte	Content
Al	97.82%
Si	1.17%
Cu	0.54%
Mg	0.35%
Fe	0.10%
Cr	0.01%

Table 5: Impact Energy strength

Samples	Izod Reading (Joules)	Charpy Reading (Joules)
1	164	444
2	144	424
3	136	416
4	148	428
5	160	440
6	128	408
7	136	416
8	140	420
9	152	432

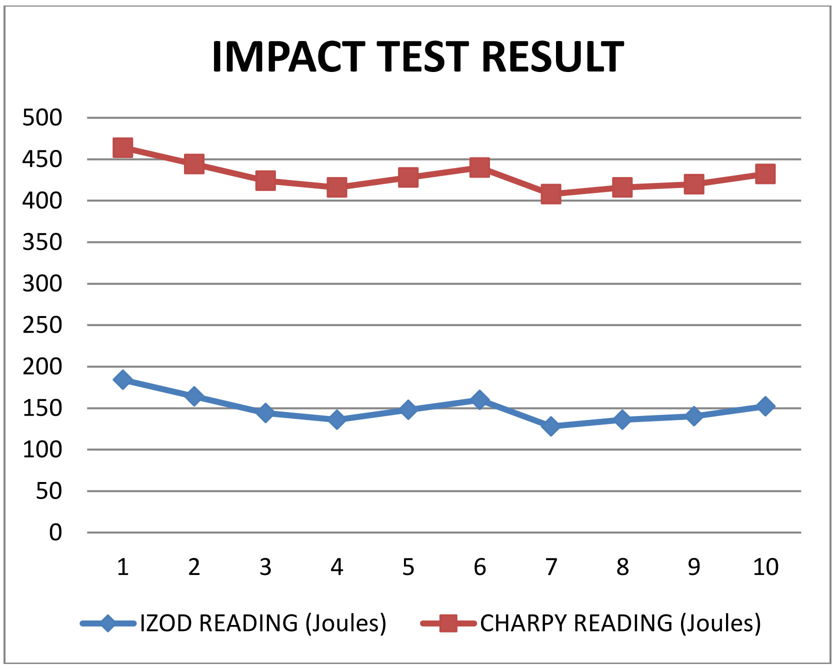

Figure 1: Plot of impact Energy strength

Table 6: List of Engineering properties (EP) against loading conditions.

Sample ID	UTS, N/mm²	Y/modulus, N/mm²	Yield Strength, N/mm²	Tensile toughness, J.m⁻³	%Elongation, %	Flexural strength, N/mm²	Hardness, HRB
1	55.604	234.77	1.853	6.318	19.88	126.04	57
2	62.655	653.65	11.089	7.388	13.08	114.15	63
3	58.487	882.4	3.93	4.216	11.37	105.96	64
4	74.341	158.68	2.17	15.26	31.92	120.22	62
5	63.894	863.98	6.016	14.02	17.47	123.76	60
6	73.158	488.95	8.705	14.76	27.93	126.05	69
7	83.442	571.31	7.45	9.42	19.78	142.85	60

8	60.223	263.92	1.34	9.09	23.5	104.72	65
9	45.350	700.2695	3.64	7.68	14.83	138.44	61

Table 7: Determination of density of mass samples

Samples	M (g)	V (cm3)	ρ = m/v (g/cm^3)
1	88.2	36	2.45
2	91.1	40	2.2775
3	82.6	30	2.7533
4	88.55	38	2.3303
5	86.6	33	2.6242
6	86.58	34	2.5465
7	86.55	36	2.4042
8	85.54	34	2.5159
9	84.53	32.5	2.6009

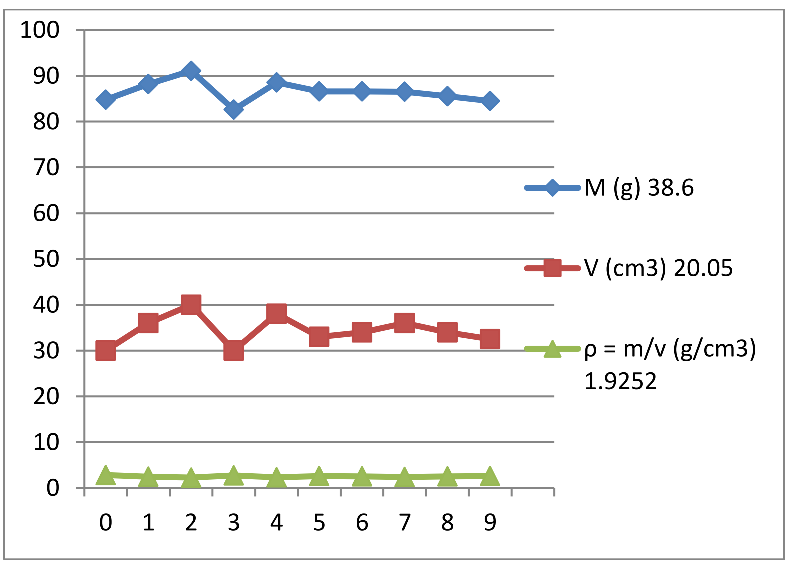

Figure 2: Graph of mass, density and density of each sample

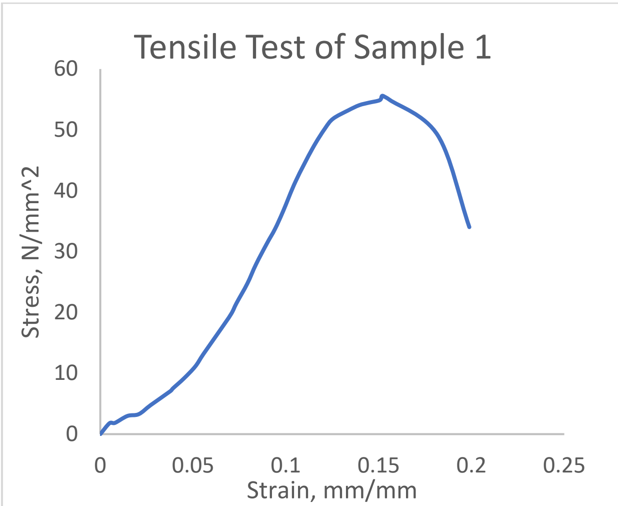

Figure 3: Stress-strain curve of sample 1

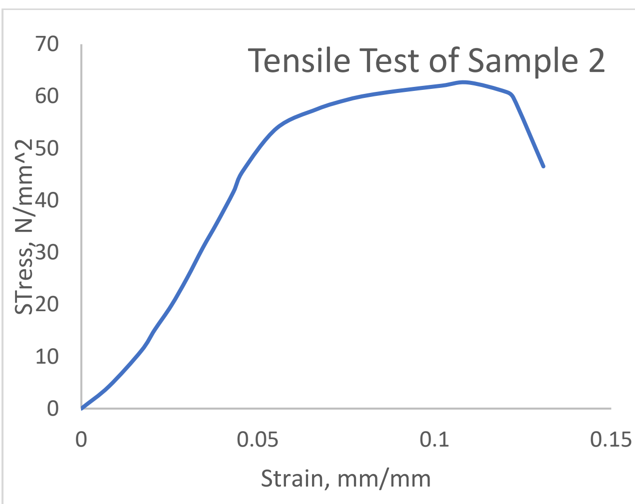

Figure 4: Stress-strain curve of sample 2

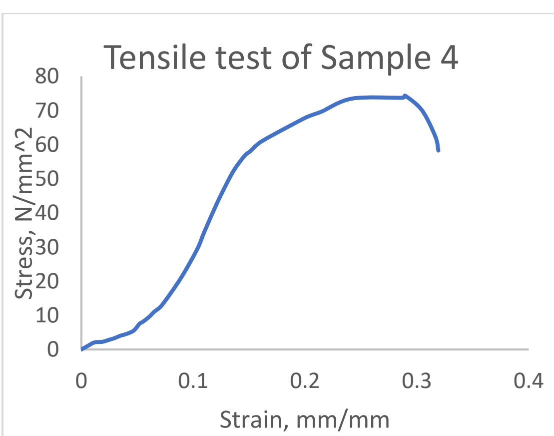

Figure 5: Stress-strain curve of sample 4

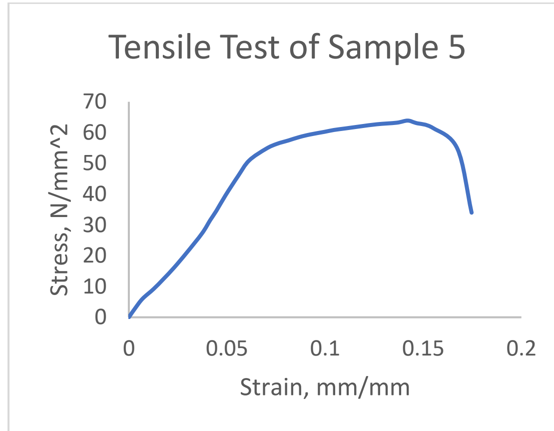

Figure 6: Stress-strain curve of sample 5

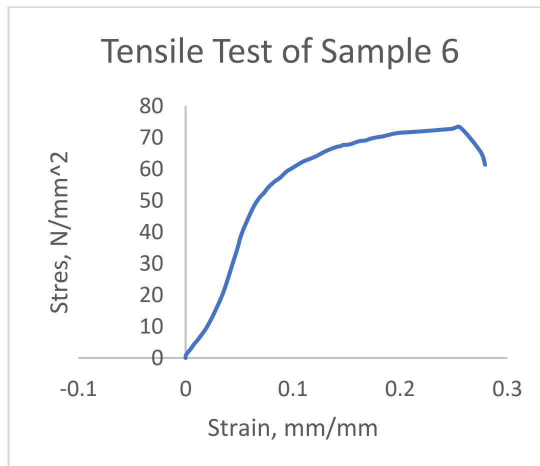

Figure 7: Stress-strain curve of sample 6

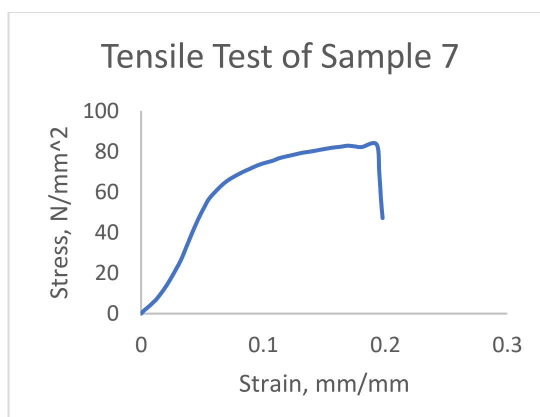

Figure 8: Stress-strain curve of sample 7

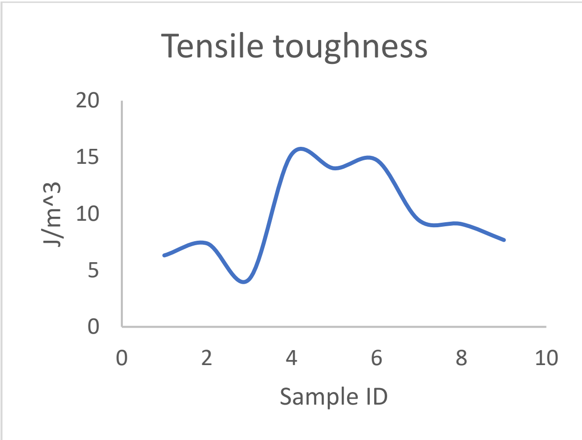

Figure 9: Graph of effect of loading on tensile toughness

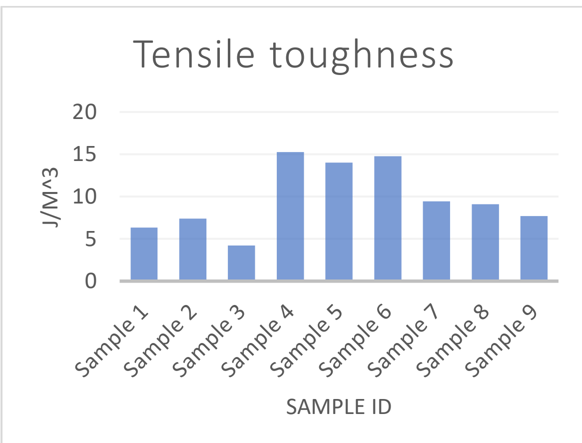

Figure 10: Chat of effect of loading on tensile toughness

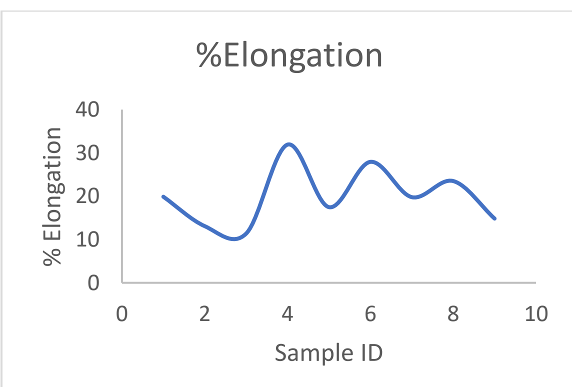

Figure 11: Graph of effect of loading on % of elongation

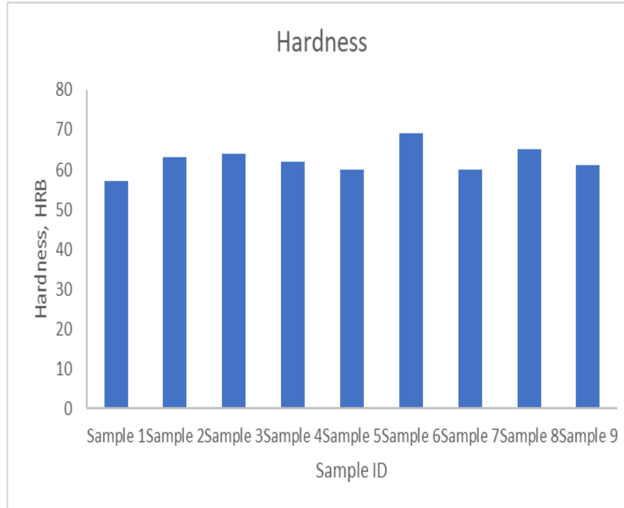

Figure 12: Chart of effect of loading on hardness

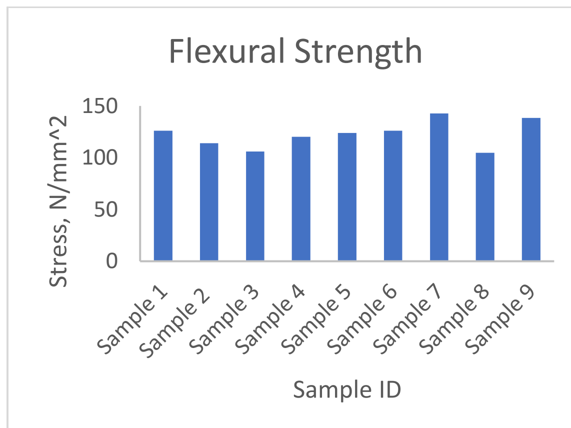

Figure 13: Chart of effect of loading on flexural strength

Table 8: List of samples with relatively better combination of engineering properties (EP) against loading conditions

Sample ID	UTS, N/mm^2	Y/modulus, N/mm^2	Yield Strength, N/mm^2	Tensile toughness, $J.m^{-3}$	%Elongation, %	Flexural strength, N/mm^2	Hardness, HRB
2	62.655	653.65	11.089	7.388	13.08	114.15	63
4	74.341	158.68	2.17	15.26	31.92	120.22	62
5	63.894	863.98	6.016	14.02	17.47	123.76	60
6	73.158	488.95	8.705	14.76	27.93	126.05	69
7	83.442	571.31	7.45	9.42	19.78	142.85	60

3.0 RESULTS AND DISCUSSION.

Table 1-3 depict the composition variables of the alloyed elements that were used, the number of runs (DOE L9 orthogonal array) and the actual values of the runs when the Taguchi design of experiment was adopted respectively.

Table 4 indicates the plot for the percentage compositions of aluminum coil. The result shows that Iron (Fe) and chromium (Cr) are insignificant in the characterization. Hence, the result equally shows that silicon (Si), copper (Cu) and magnesium (Mg) become the major constituents of the alloying elements.

Table 7 depicts the result of the experimental data generated for determination of density of each mass sample using the Archimedes principle. In this result, density was found to be at peak in machine component sample 3 (2.7533g/cm^3) and least at machine component sample 2 (2.2775g/cm^3), invariably, porosity as a major defect in aluminum alloyed die cast product will largely occur at this sample component.

Figure 1 presents the plot of impact energy strength from Izod/ Charpy hammer equipment. The result indicates that all the samples of the machine components acted in a ductile manner when subjected to sudden load. However, sample 1 with 444J has the highest ability to absorb energy upon the sudden loading, followed by sample 5 with 440J while machine component sample 6 has the least ability to absorb energy upon the same sudden loading shock.

From tables 6 and 8, the test results of tensile test showed that there is somewhat increasing trend as the loading is increased with sample 7 having the highest ultimate tensile strength of 83.442 N.mm^{-2}as seen in figure 8. However, this trend was reversed at loading above sample 7.

Samples 2, 6, 7 and 5 from Figures 4, 7, 8 and 6 respectively showed the highest yield strengths while sample 4 is lowest with values of 11.089, 8.705, 7.45, 6.016 and 2.17 N.mm^{-2} respectively. From engineering material selection point of view, the higher the yield strength of a material for a specific design application, the higher is its suitability.

Toughness of a material indicates how well a material can absorb energy. From Figure 9, it is observed that Sample 4 topped the list with tensile toughness value of 15.26 J.m^{-3}, followed by samples 6 and 5 with values of 14.76 and 14.02 J.m^{-3} respectively. A tough material combines strength, hardness and ductility. From Table 6 and Figure 12, it can be seen that samples 5 and 6 have comparatively good hardness of 60HRB and from figure 11; percentage of elongation (ductility) of 17.47% was seen. Figure 13 depicts also a flexural strength of 123.76 N.mm^{-2}, above the average value of 122.47 N.mm^{-2}.

The knowledge of yield strength guides in determining the maximum applicable load to a material in service. In view of this, Table 6was modified to Table 8, using yield strength as a benchmark, to take into consideration some other complementary properties in materials selection, viz: Ultimate tensile strength, Young's modulus, Tensile toughness, % of Elongation, flexural strength, and hardness.

The list of samples with relatively better combination of these engineering properties is presented in Table 8. Of the 9 samples under consideration, sample 4 made the list with yield strength above the average of 5.13N/mm^2.

4.0 CONCLUSION

Optimization approach for evaluation of mechanical properties of Aluminum high pressure die cast product has been undertaken using sample specimen of a machine component casted for carrying out the mechanical property (response parameters) tests analysis. The optimal response parameter was obtained with machine component sample specimen-3 and density was adopted here as response factor because it has a direct correlation with porosity which is vital casting defect and the value of density at sample-3 was 2.7533g/cm^3 at porosity of 0.3632cm^{3}g^{-1} and at respective charging masses of aluminum alloying element of Si =0.7; Cu = 0.8; Mg = 0.7

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