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Comparing the Effects of Squeeze Casting on the Mechanical Properties of Selected Aluminum Alloys

Markson I. E.[1], Agwu O. E.[2], Ihom A. P.[3], Umana M. O.[4]
[1,2,3,4]Department of Mechanical and Aerospace Engineering, University of Uyo, Uyo, Nigeria
([1]idymarks@yahoo.com, [2]o.agwu4@yahoo.com, [3]paulihom@yahoo.co.uk, [4]m.o.umana@uniuyo.edu.ng)

Abstract- This study has detailed the changes in mechanical properties of selected aluminium alloys when produced using the method of squeeze casting as compared with conventional gravity castings. The alloys that were studied are: Al-12wt.%Si, Al-12wt.%Si with sodium modifier, Al-1.3wt.%Cu-5wt.%Si-0.5wt.%Mg and Al-4.5wt.%Cu. The squeeze pressure was varied over a range of 50 MPa. The results and measurements show a marked improvement in ultimate tensile strength, ductility and hardness for samples produced by the method of squeeze casting as compared to the gravity cast samples. For instance, at 50 MPa, the ultimate tensile strength of the Al-4.5wt.%Cu alloy was found to be 60% higher than that of the same alloy produced by the conventional procedure of gravity casting. The trend was found to be similar for the other mechanical properties and alloys studied and these have been presented in the work. Further, material properties were seen to improve in all the alloys studied as cast pressure increased with the optimal pressure being in the neighbourhood of 50 MPa.

Keywords- *Aluminum Alloy, Squeeze Casting, Mechanical Properties*

I. INTRODUCTION

Aluminum and its alloys are widely utilized in the transport industry largely because of their excellent strength to weight ratio. Other than this, aluminum displays a number of attractive qualities including excellent cast ability, workability and machinability as well as relatively high corrosion resistance [1]. Also, aluminum has high scrap value and the process of recycling used aluminum results in 95% energy savings compared to raw material processing [2]. Consequently, almost 40% of all aluminum used today is re-melted metal [2].

However, several mechanical properties of aluminum alloys including strength, hardness and ductility vary depending on the quality of casting. Gas porosity and micro-voids are two of the defects that accompany conventional or even more advanced casting techniques [3-5]. Porosity is probably the most common defect in aluminum castings and is the result of molten alloy solidifying faster than the rate at which gas within it escapes the melt. A pore is disadvantageous for two main reasons. First, it cannot sustain external load. Second, and more importantly, it acts as a stress concentrator thereby leading to micro crack initiation and propagation [6]

To address these shortcomings and thereby improve cast quality, the method of squeeze casting was developed. Squeeze casting achieves cast quality improvement by promoting molten metal solidification under applied pressure in a re-useable die. [4] Reports that components fabricated by this method – a combination of permanent mold casting with die forging – present with excellent surface finish and almost zero porosity. High pressure prevents development of gas bubbles in the cast thereby eliminating porosity which invariably increases the density of the casting [7,8]. The method of squeeze casting is employed in the production of combustion engine castings, casings for compressors, pistons and brake discs [9]

Many researchers have reported an improvement in mechanical properties of squeeze cast aluminum alloys over the conventionally cast type. These improvements, particularly in the case of Al-Si alloys, are attributable to the shape and distribution of eutectic Si phase, the porosity and secondary dendrite arm spacing [10]

[11] Studied the effect of the squeezing process on the A380 alloy and reported significant increments in ultimate tensile strength and elongation values as squeeze pressure increased. Again, the reason cited for these improvements include decreasing secondary dendrite arm spacing with increasing pressure as well as the elimination of porosities in the alloy. Optimal squeeze casting pressure range from 30 MPa to 50 MPa [11,12]

Clearly then, the squeeze casting process, its effect on the mechanical properties of casts and the reasons for the observed material changes have been well researched on. Even so, there are few detailed studies on squeeze cast Al-4.5wt.%Cu alloy and fewer studies on the comparison of the properties of this alloy and other aluminum alloys cast using the same technique.

The mechanical properties of four separate Al-alloys produced with the technique of squeeze casting have been compared in this study. The comparative improvement in mechanical properties for the studied alloys have, for the first time, been discussed.

II. MATERIAL PREPARATION

The equipment and materials utilized for the study were locally sourced and produced. First off, the squeeze casting equipment was designed and produced. Then the aluminum alloys of desired composition was prepared and cast.

A. Squeeze casting Equipment

The squeeze cast equipment fabricated for use were made of two parts – a permanent mold and a punch. The material used for the fabrication of the mold was mild steel with a cylindrical cavity of internal diameter of 48 mm, a height of 56 mm and a wall thickness of 2 mm. The purpose of the mold was to produce the required shape of casting. Consequently, the material used for the fabrication of the punch was mild steel with diameter of 46 mm. The purpose of the punch was to apply the required pressure during casting of the aluminum alloys. Plate 1 shows the fabricated squeeze casting mold and punch used for the casting of the aluminum alloys.

B. Alloy Preparation

The alloys were prepared with the help of liquid metallurgy. The important process parameters of the synthesized alloys were: amount of alloy, squeeze pressure, melting temperature, pouring temperature, mold temperature, mold type and size.

400 grams of aluminum alloy with varying weight percentage of alloying element (as in Table 1) were prepared by mixing of their molten charges. Aluminum and all the alloying elements were 99.9% pure. Sodium served as modifier where utilized. The crucible with the metal charged was placed inside the furnace and the melt was held at 850°C for one hour in order to attain homogeneous composition. Where modification was required, as in Al-12%Si, sodium metal was introduced into the melt for modification of microstructure. Stirring was done by hand with the help of a metal rod for the mixing of the charge. Each melt was stirred for 30 seconds after the addition of the modifier and held for 5 minutes.

Squeeze casting was carried out in a permanent mold made of mild steel pictured in Plate I. The upper die (punch) was essential for the application of requisite pressure. The mold was coated with a Boron Nitride Aerosol lubricant and then air dried. Prior to the squeeze casting, the mold was preheated to required temperature of 150^0C. The temperature of the molten metal in the crucible was checked and at the required pouring temperature of 700^0C, the molten aluminum silicon alloy was quickly and carefully poured from the crucible into the lower die (mold) with a 48 mm diameter and 56 mm height. The required pressure was applied on the punch for a period of 30 seconds. The pouring took between 5 and 7 seconds per mold.

In pouring the metal from the crucible into the mold, the stream of metal was kept continuous and as short as possible and pouring was rapid to prevent back pressure resulting from gas entrapment. Undue agitation of the melt was avoided at all times. All precautions were taken at every other point in the foundry to avoid gas pickup and the formation and entrapment of oxides and dross. After casting, the mold was loosened and samples were taken out. For each batch cast, the first cast was allowed to cool and solidified in the shape of the mold without pressure application. Similarly a total of 48 samples were prepared with different alloy compositions and squeeze pressures of 30, 35, 40, 45 and 50 MPa were used. The prepared alloy chemical compositions are shown in Table 1.

Figure 1. Fabricated Squeeze Casting Equipment

C. Tensile Testing

Tensile test samples were used to assess the mechanical behaviour of the alloy composition. The aluminum alloy samples were machined from each alloy composition to obtain a tensile specimen with a diameter of 5 mm and gauge length of 28 mm. Round tensile test bars were used in this investigation. The test bars were machined in accordance with the ASTM standard E8M-1990. All of the test bars were subjected to mechanical property test in the as-cast condition, at room temperature on an INSTRON tensile tester. Tensile tests were carried out with a crosshead speed of 1 mm/min, which corresponds to nominal strain rate of 0.001 per second. During the test, the load elongation data were recorded for all test bars. The percentage elongation was both calculated from the loaded-elongation curves and measured after fracture of the test bars, by fitting the two halves of a broken test bar together and measuring the change in length over the original gage length of the bar. The yield strength at 0.2 percent offset was calculated from load-elongation curves recorded during the testing operation.

D. Hardness Testing

Tensile Hardness is defined as the resistance of a material to indentation, and it is determined by measuring the permanent depth of the indentation. More simply put, when using a fixed force (load) and a given indenter, the smaller the indentation, the harder the material. Hardness measurements can be made on a Rockwell hardness testing machine as it were in this work. First, a preliminary test force is applied to a sample using a diamond indenter. This load represents the zero or reference position that breaks through the surface to reduce the effects of surface finish.

TABLE I. COMPOSITION OF THE ALLOYS USED IN THE STUDY

Alloy Composition	Si	Cu	Mg	Na	Al
Sample 1	12%	–	–	–	Rest
Sample 2	12%	–	–	0.01%	Rest
Sample 3	5%	1.3%	0.5%	–	Rest
Sample 4	–	4.5%	–	–	Rest

After the preload, an additional load, called the major load, is applied to reach the total required test load. This force is held for a predetermined amount of time (dwell time) to allow for elastic recovery. This major load is then released and the final position is measured against the position derived from the preload, the indentation depth variance between the preload value and major load value. This distance is converted to a hardness number.

Sample used for Rockwell hardness testing in the present work was standardized with the help of a standard steel sample. Steel ball indenter of size 1/16 was chosen. A mass of 10 kg was employed as preload and applied with a steel ball indenter causing an initial penetration. Then, the dial was set to zero and a major load of 100 kg was applied. Upon removing the load the dial of the Rockwell tester gives the direct reading on Rockwell B scale. Similar processes were repeated three times for each sample to get an average value of Rockwell hardness (HRB).

III. RESULTS AND DISCUSSION

A. Tensile Test

From the load and extension value obtained from the Instron tensile tester, corresponding engineering stress and engineering strain were calculated and plotted to get stress-strain graphs for different samples of Al-12 wt.% Si unmodified, Al-12 wt.% Si modified with 0.01% Na, Al-4.5wt% Cu and Al-1.3wt% Cu–5wt% Si– 0.5wt% Mg as shown in Figs. 2-5.

Stress-strain curves describe the extent of deformation (strain) at distinct intervals of tensile or compressive stress. The curves are unique for each material and reveal many properties of the material including data to establish the modulus of elasticity – a parameter which defines the resistance of a material to elastic deformation. Consequently, the shape of a stress - strain curve is important to the Materials Engineer [13]. Fig. 2 shows the stress-strain curve for Al-12wt.%Si alloy at 0 MPa. There are also similar graphs (in the same chart) for squeeze casting of the alloy at different pressures (ranging from 30 MPa to 50 MPa in steps of 5 MPa).

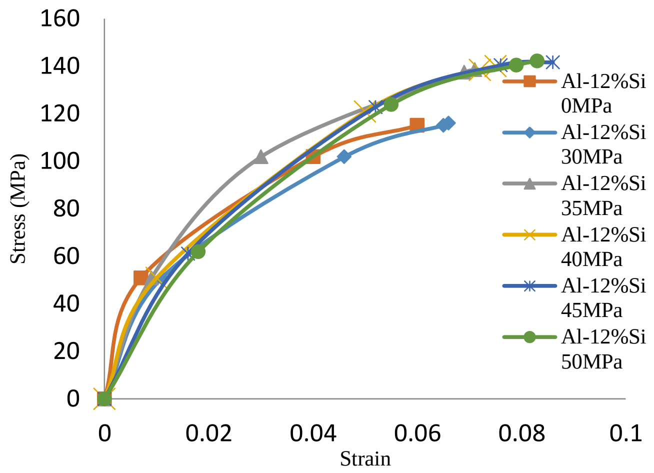

Figure 2. Stress-strain graph for Al-12wt.%Si unmodified for various squeeze pressures from 0 – 50 MPa

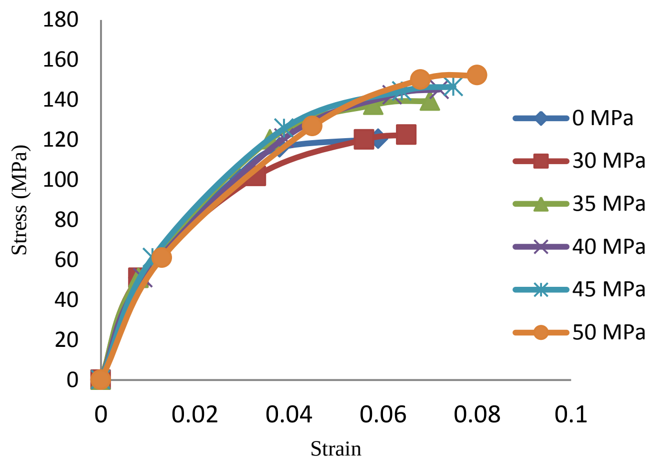

Figure 3. Stress-strain graph for Al-12wt.%Si Na-modified for various squeeze pressures from 0 – 50 MPa

The curves clearly show that material ductility increases with casting pressure. In other words, the material undergoes more deformation (strain) before failure as squeeze pressure increases. This is evident in Fig. 3 as well where the breaking stress of the alloy is found to be farthest for the 50 MPa sample. In Fig. 3, the amount of strain possible before breakage occurs is about 23% more in the 50 MPa sample compared to the 30 MPa material. It is worthy to point out here that the material cast under gravity (0 MPa) presents a stress-strain curve which flattens out as stress approaches 120 MPa signifying that the UTS is reached at that stress value.

The other curves are not as flat and enjoy further deformation at higher stress values. This represents a clear mechanical strength advantage – the very essence of squeeze casting. The underlying reason for this improvement in strength has to be the absence of gas porosity and shrinkage pores in the squeeze cast alloy [14,15]. On the other hand, the piece solidified under atmospheric pressure is observed to have more pores thereby impacting negatively on alloy tensile strength.

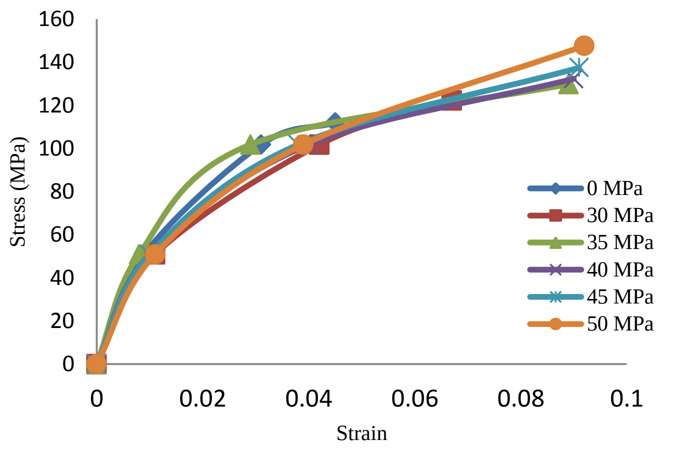

Figure 4. Stress-strain graph for Al-1.3wt.%Cu-5wt.%Si-0.5%Mg for various squeeze pressures from 0 – 50 MPa

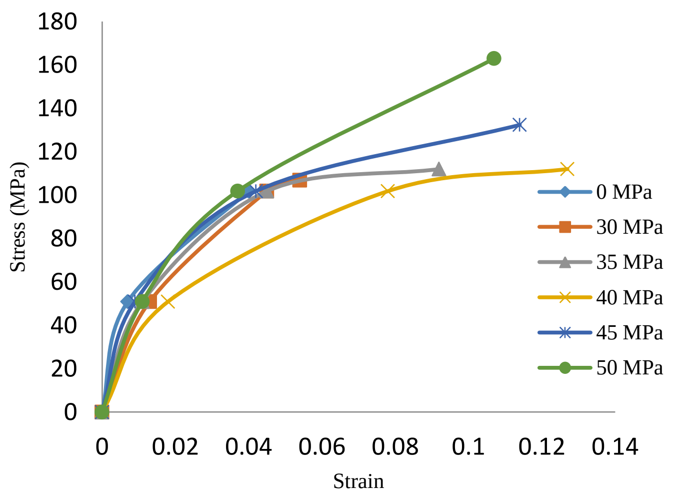

Figure 5. Stress-strain graph for Al-4.5wt.%Cu for various squeeze pressures from 0 – 50 MPa

The curves of Fig. 4 follow the nature of those in Fig. 3. All six samples have a linear stress-strain curve up to about a stress of 40 MPa.

Above that stress value, the curves lie one on top of the other as a result of the squeeze pressure. Again, for reasons of gas and shrinkage porosity absence, the highest UTS belongs to the most pressurized (50 MPa) sample [16]. Ductility is also seen to improve with increase in squeeze pressure. For the Al-4.5wt.%Cu alloy of Fig. 5, the tensile strengths of all samples are seen to improve compared with the Al-1.3wt.%Cu-5wt.%Si-0.5wt.%Mg alloy. The increased percentage of Copper in the former creates additional strength by precipitation of $CuAl_2$.

B. Ultimate Tensile Strength

Other than the Al-1.3%Cu-5%Si-0.5%Mg alloy where there is a 9% increase in UTS at a squeeze pressure of 30MPa, other samples (alloys) show no significant improvement in UTS at squeeze pressures less than 30 MPa. This is evident in the near-flat nature of the curves between 0 and 30 MPa (Fig. 6). This result agrees with those of Raji & Khan [17]. However, beyond 30 MPa, there is a general increase in UTS for all the alloys. When squeeze pressure reached 50 MPa, the UTS of the Al-4.5wt.%Cu alloy was 162 MPa, 60% higher than the same alloy produced by gravity casting. There are increments of 23.5%, 26.4% and 31.8% in the UTS of Al-12wt.%Si (unmodified), Al-12wt.%Si (modified) and Al-1.3wt.%Cu-5wt.%Si-0.5wt.%Mg respectively compared to their gravity-cast counterparts. At all squeeze pressures, the modified Al-12wt.%Si alloy exhibits higher UTS than the unmodified alloy. The increment in tensile strength as a consequence of Na modification agrees with Higgins [18]. Modification in the Al-Si alloy refines the eutectic phase particle shape and improves the mechanical properties (including UTS) of the cast [2].

C. Ultimate Tensile Strength

It is noticed that appreciable increase in material elongation (ductility) is evident beyond a squeeze pressure of 30 MPa (Fig. 7).

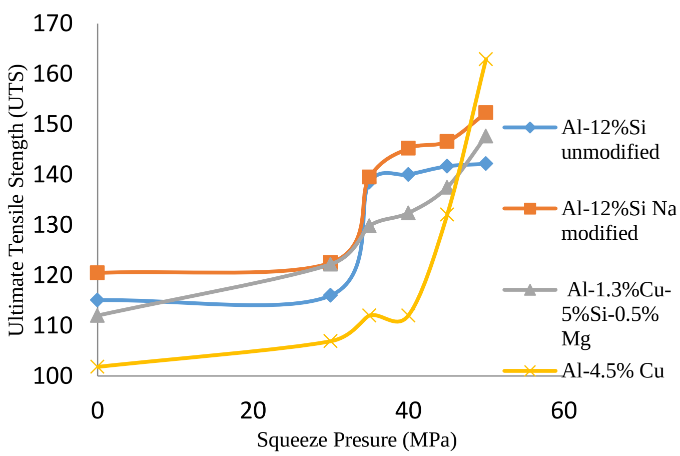

Figure 6. Effect of squeeze pressure on UTS for the aluminum alloys under study

The Al-4.5%Cu alloy starts off being the least ductile of all the alloys considered. But at 50 MPa, there is a 125% increase in its elongation compared to the 30 MPa value. The other alloys enjoy increments in ductility but not as much. The reason is probably that the presence of metallic Cu in the Al-4.5%Cu alloy improves the metallic properties (including ductility) of the alloy.

It is well known that the mechanical properties of an alloy consisting of a ductile phase and a hard brittle phase depend on the distribution of the brittle phase in the microstructure. If the brittle phase is present as a grain boundary envelope, the alloy tends to be brittle [19]. However, the brittleness of the alloy is reduced somewhat if the brittle phase is in the form of discontinuous particles at grain boundaries [20].

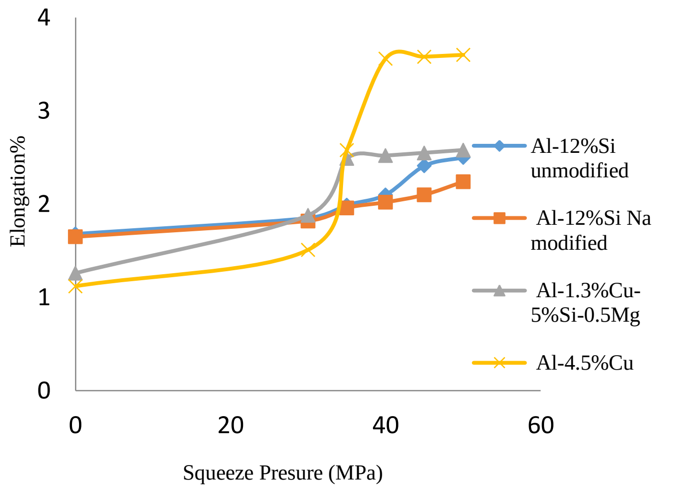

Figure 7. Effect of squeeze pressure on elongation of samples of the aluminum alloys under study

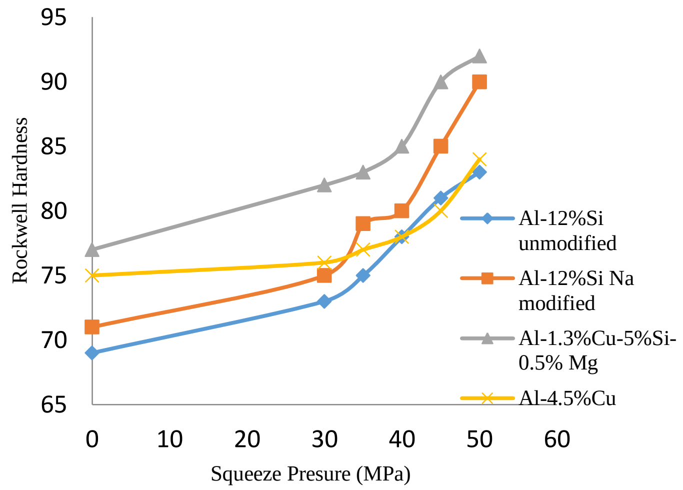

Figure 8. Effect of squeeze pressure on the hardness of samples of the aluminum alloys under study

D. Hardness Test

As it were with previous mechanical properties studied, hardness of alloys is seen to show positive increase as casting squeeze pressure increases (Fig. 8). Overall, hardness increases from a range of 69 – 75 HRB to about 83 – 92 HRB. The greatest increment occurred in the modified Al-12%Si alloy. The hardness test results agree with earlier work carried out by [2]. The applied pressure in the process of squeeze casting serves to suppress the nucleation of gas pores. Besides that, [2] further noticed a decrease in secondary dendrite arm spacing as squeeze pressure increases – all contributing to improvement in material hardness.

IV. CONCLUSION

An investigation has been carried out on the mechanical properties of squeeze cast aluminum alloys of different compositions. These properties of a squeeze cast aluminum alloy were compared with those of the gravity cast aluminum alloys. Improvements in three key mechanical properties of the alloys was noticed.

There is a considerable increment in material strength as casting pressure increases. Beyond 30 MPa, there is a general increase in strength for all the alloys. For instance, at 50 MPa, the UTS of the Al-4.5wt.%Cu alloy was found to be 60% higher than that of the same alloy produced by conventional gravity casting. The trend is similar for the other alloys studied. There are increments of 23.5%, 26.4% and 31.8% in the UTS of Al-12wt.%Si (unmodified), Al-12wt.%Si (modified) and Al-1.3wt.%Cu-5wt.%Si-0.5wt.%Mg respectively compared to their gravity-cast counterparts.

Also, material ductility and hardness was seen to improve as casting pressure increased. For example, the Al-4.5wt.%Cu cast under a pressure of 50 MPa experiences a 125% increase in its elongation compared to the 30MPa value. Further, alloys tend to become harder as casting pressure increases. The hardness of samples was found to increase from a range of 69 – 75 HRB to about 83 – 92 HRB, the biggest improvement occurring in the modified Al-12wt.%Si alloy.

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