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**Original Research Article**

**Evaluation of Mechanical and Electrical Properties of Squeeze Cast 1xxx Aluminium**

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**ABSTRACT**

*The effect of squeeze cast pressure on the mechanical and electrical properties of 1xxx aluminium was experimentally studied. Aluminium (1xxx) metal was melted and poured into a preheated split die at 700±10 °C. Varying values of pressures were applied on the cast using Vega hydraulic press to produce sound cast samples. Mechanical, microstructural and electrical properties of cast products were examined on Monsanto universal tensile testing machine (UTM), Rockwell hardness tester and DC 4 probes wire respectively. The results of the investigations revealed that squeeze cast pressure influenced the microstructure through grain refinement which led to enhancement of the mechanical properties of the metal. Improvement of 41.03 % in hardness at applied pressure of 190 MPa and 200% in tensile strength at applied pressure of 127 MPa were obtained for the squeeze cast metal. There was an increase in electrical conductivity by 18.5 % at 127 MPa applied squeeze cast pressure. Squeeze casting is thus presumed to be a suitable processing route for improving the mechanical and electrical properties of aluminium metal of 1xxx series.*



## 1. INTRODUCTION

Aluminium (Al) and its alloys are fast becoming high ranking value engineering material as a result of broad range of its versatile use in household to industrial applications (Bello et al., 2017). Aluminium is readily available and easily processed into various desirable shapes and sizes through one or more forms of manufacturing techniques. Its excellent properties of lightweight, resistance to atmospheric corrosion, electrical conductivity, recyclability and formability with improved strength when processed has made it a more attractive material in many areas of engineering applications (Nakata et al., 2006; Babić et al., 2013; Bello et al., 2017; Pakiela et al., 2017). Such applications include packaging materials, domestic utensils, building materials, automobile/aerospace components and architectural decorations (Babić et al., 2013; Usman et al., 2014; Bello et al., 2017). These and many others properties has made it an object of research and is fast becoming a substitute for other metals for different applications (Souissi et al., 2014). The use of aluminium as an alternative to copper in transmitting electrical energy from source to consuming areas and in the production of electrical conductors due to its several advantages over copper is becoming a norm (Karabay and Uzman 2005; Karabay 2006; Florián-Algarín et al., 2018). Generally, 1xxx aluminium are used as electrical grade conductor, however, despite its high electrical conductivity (62%IACS – International Annealed Copper Standard), it has low tensile strength (Pakiela et al., 2014). The alloying of pure Al, or precipitation strengthening options may increase its mechanical properties but may result in negative effect in its electrical conductivity due to the presence of some impurities in the alloy (Florián-Algarín et al. (2018). This assertion was evidenced in the work of Murashkin et al. (2015) in which a high mechanical property was recorded at the expense of electrical conductivity of an ultrafine-grained Al 6101 alloy processed via equal channel angular pressing (ECAP). Similar results were reported in the work of Florián-Algarín et al. (2018) where incorporation of A206/alumina nanocomposite in aluminium wire increased the strength but with a decrease in the electrical conductivity. According to European Standard EN 50183 (2002) and Valiev et al. (2014), the selection of good metallic materials for power transmission lines lies within a compromise between their mechanical and electrical properties. This implied that the two properties need to be strengthened for improve performance.

Squeeze casting is a modern hybrid permanent mould casting technique combining die forging and extrusion operation techniques, in which a measured quantity of liquid metal is poured into a metallic mould under high pressure application (Aweda, 2008; Yang et al., 2009). It is usually adopted for the production of non-ferrous metals and their alloys. Its advantages over other conventional casting techniques include the elimination of processing steps, production of near-net shapes, and good surface integrity with enhanced mechanical properties (Aweda and Kolawole, 2014; Raji and Khan 2006).

To metallurgists, the knowledge and understanding of casting parameters (temperature, applied pressure, die preheat temperature) in metals and alloys is as significant as the cast products for properties enhancements (Ndaliman and Pius, 2007). Therefore, improvement in mechanical, thermal and electrical properties of the sample cast is subject to control of casting parameters that will result in enhanced material properties (Ndaliman and Pius, 2007). Various researchers have reported the effects of casting parameters on cast quality and submitted that, properties and qualities of cast product is greatly influenced by cast parameters including applied pressure, pouring temperature and pouring rate amongst others (Li et al., 2005; Aweda, 2008: Chen et al., 2009; Aweda and Adeyemi 2009; Regula et al., 2011; Florián-Algarín et al., 2018). It is therefore presumed that, a good control of these parameters during casting may lead to improved properties of the cast. Besides, different approaches had been explored and reported for improving the electrical conductivity of aluminium metal and its alloys without compromising its mechanical properties. Valiev et al. (2014) achieved a combination of improved strength and electrical conductivity through nanostructural approach of Al-Si- Mg alloy. The improvement of both properties was credited to refining of grains of the nanoparticles within the boundaries. It will be noted that effect of applied squeeze pressure on the solidification rate and tensile strength of squeeze cast purity aluminium has been reported (Aweda, 2008; Aweda and Kolawole, 2014; Cui et al., 2017).

In this paper, the influence of applied pressure on the mechanical properties, microstructure and electrical properties of 1xxx aluminium metal obtained through squeeze casting technique was experimentally examined.

M.Y. Kolawole et al. / Nigerian Research Journal of Engineering and Environmental Sciences
3(2) 2018 pp. 946-956

## 2. MATERIALS AND METHODS

### 2.1. Materials

The materials and equipment used in this work included aluminium metal with percentage composition as shown in Table 1, split steel mould (50 x 120) mm, Type-K thermocouple, tong, mild steel crucible, bench-top muffle furnace, universal testing machine (UTM), Rockwell Hardness Tester and ASPEX 3020 scanning electron microscope (SEM) model SIRIUS50/3.8.

Table 1: Percentage composition of 1xxx aluminium (Aweda, 2008)

| Al | Cu | Si | Mn | S | P | Ni | Cr | Zn |
|---|---|---|---|---|---|---|---|---|
| 99.847 | 0 | 0.06 | 0.03 | 0.002 | 0.003 | 0.001 | 0.00 | 0.03 |

### 2.2. Squeeze Casting Process

The aluminium metal used was melted in a bench-top electrical muffle furnace using a steel crucible following the method adopted earlier (Aweda, 2008; Aweda and Kolawole, 2014). A quantity of molten aluminium with melting point of 660 oC and superheat of 50 oC was carefully poured into a die preheated to 200 ± 20 oC. A Vega hydraulic press (VHP), (model number UTM3C and serial number 1061) with a maximum operating capacity of 89 KN was used for the direct squeeze casting as showed in Figure 1 observing a delay time of 10 s in accordance with the procedure of Aweda and Kolawole (2014). Six sets of aluminium specimens were squeeze – cast with one as control (no pressure application). The pressures of between 64 MPa and 190 MPa, at a retention time of 50 s were observed to obtain a squeeze cast specimen. The microstructures, mechanical and electrical conductivity properties of the squeeze cast products were then examined.


Figure 1: Experimental setup of squeeze casting process

### 2.3. Test Procedures

#### 2.3.1. Mechanical properties and microstructural examination

The tensile property of the squeeze cast samples with and without pressure application (0 -190 MPa) were carried out on Monsanto Universal Tensometer with serial number UTM 10584. The tensile test specimens with dimensions 30 mm x 6 mm gauge length and diameter, 24 mm x 12 mm grip length and diameter were machined to size on the conventional Lathe machine as shown in Figure 2. Tensile test was performed on the UTM where the specimen was firmly held on the machine jaws and gradually loaded until it fractured. Rockwell hardness tester was used to evaluate the macro hardness properties of squeeze cast metal using

1/16" steel ball indenter at a load of 100 kgf for 30 s at four different locations on each sample and applied to all specimens (10 x 10) mm. The average values of the resulting hardness output were presented in this paper. Enhancement in property examined due to pressure application (tensile and hardness) was evaluated from Equation 1. The microstructures of both squeeze and control cast specimens were examined with the aid of scanning electron microscope (SEM) (ASPEX 3020, model SIRIUS50/3.8). The samples were machined to (10 x 10) mm sizes with one surface ground with varying sizes of grinding papers and etched in aqueous solution of 5 % HNO3 + 95 % ethanol for 15 s as in Regula et al. (2011).

$$Property\ Enhancement = \frac{Peak\ Tensile\ strength/Hardness\ value}{Tensile\ strength/Hardness\ (control\ sample)} \times 100 \quad (1)$$

Figure 2: Samples of specimen prepared for tensile testing

**2.3.2. Determination of electrical conductivity**

The conductivity of the squeeze cast sample was determined using D.C four probes wire method via the experimental set-up in Figure 3. Samples' shapes and dimensions were as shown in Figure 4. Thirty (30) set of readings of electrical resistance for each of the sample were recorded and the average values obtained were used to compute the corresponding conductivity values according to Equation 2.

$$\sigma = \frac{l}{RA} \quad (2)$$

Where $\sigma$ =Electrical conductivity $(\Omega m)^{-1}$, $l$ = length of the sample $(m)$, $R$ = resistance (Ω) and $A$ = Cross-sectional area of the sample $(m^2)$

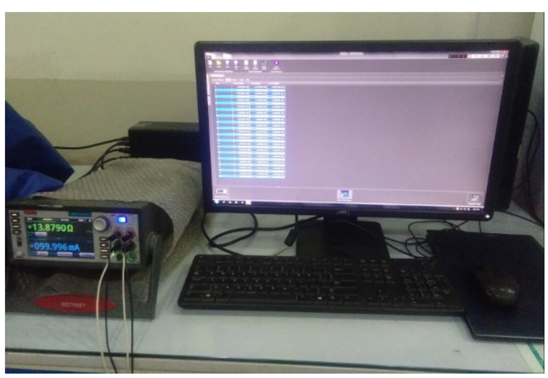



Figure 3: Cross-section photograph of DC conductivity test set-up

M.Y. Kolawole et al. / Nigerian Research Journal of Engineering and Environmental Sciences
3(2) 2018 pp. 946-956

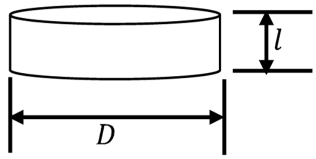
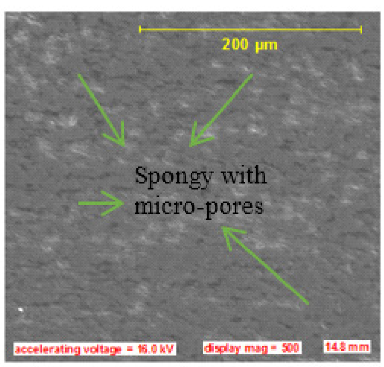



Figure 4: Schematic diagram of specimen for conductivity test

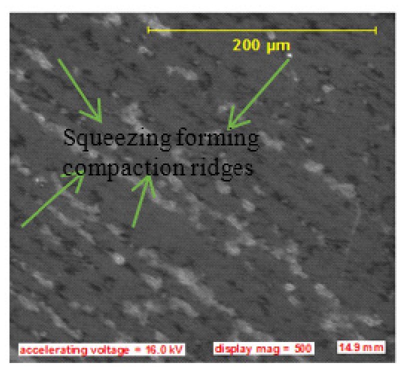
## 3. RESULTS AND DISCUSSION

### 3.1. Microstructure Examination

The results of microstructural examination of the squeeze cast specimen without and with pressure applications are as shown in Figure 5(a-f). Figure 5a is a situation without pressure application where a spongy morphology with micro pores was formed. This can be as a result of gravity pouring of molten aluminium without any pressure application causing natural solidification (Raji and Khan 2006). When a pressure of 64 MPa was applied on the solidifying cast, a compaction effect of the applied pressure was noticed where a gradual bridging of the pores was noticed as in Figure 5b. This indicates the commencement of grains refinement through the application of squeeze cast pressures. Further increase in applied pressures up to 127 MPa (Figure 5c) improved the refinement in the microstructure with no noticeable micro pores. Beyond this value of pressure application (Figure 5d-e), faint lines begin to resurface indicating a highly stressed straining effect, a phenomenon that was clearly shown at 190 MPa squeeze pressure application (Figure 5f). The microstructural grains at this pressure value begin to buckle and break into smaller mismatched grains. The scenario of this morphological characteristics was attributed to large straining of the grains due to high squeezing pressure effect higher than what can be accommodated by the grains of the aluminium under investigation. These observations were similar to that reported by previous authors (Raji and Khan 2006; Florián-Algarín *et al.,* 2018), where it was reported that pressure application not only has effect on the microstructure of the metal but also enhances grain refinement.

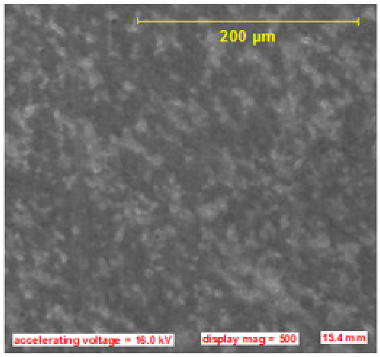



a




b

M.Y. Kolawole et al. / Nigerian Research Journal of Engineering and Environmental Sciences
3(2) 2018 pp. 946-956



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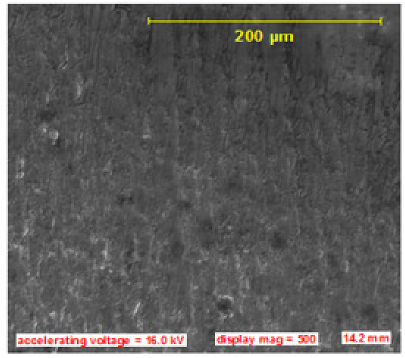

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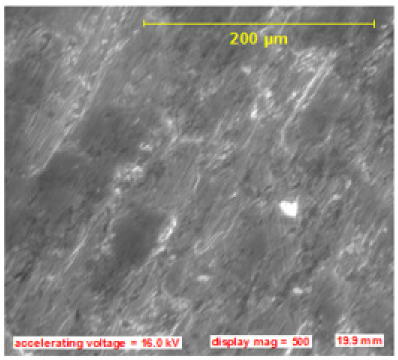

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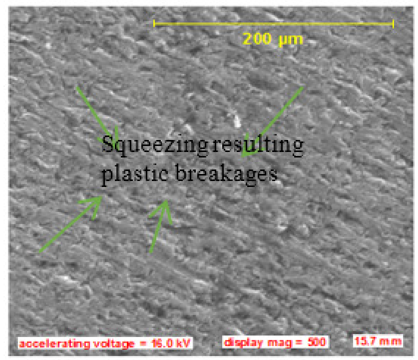

f

Figure 5 (a-f): Microstructure of squeeze cast purity aluminium (a – 0 MPa, b – 64 MPa, c – 95 MPa, d – 127 MPa, e – 159 MPa & f – 190 MPa)

### 3.2. Hardness Property of the Squeeze Cast Aluminium

At no pressure application, the hardness value was 48.75 HRB and at applied pressure of 64MPa, the hardness value increases by 10 % amounting to 53.625 HRB (Figure 6). Further increase in the applied pressure steadily increased the hardness value from 53.625 to 57.65 HRB for pressures of 64 and 159 MPa respectively. At applied pressure of 190 MPa, the hardness value of the squeeze cast sample became 63.75 HRB giving an increase of 41.03 % when compared to control sample. The obtained hardness values are presumed to be as a result of the squeeze action on the cast metal caused by the applied pressured (Kamara and Ramesh 2015). This tends to eliminate porosity, increase contact interface between the solidifying metal and the die to reduce the solidification time. The implication of reduced solidification time was as a result of fast abstraction of heat due to high thermal conduction rate (Aweda and Kolawole 2014). This result was in good agreement with that obtained and reported in the literatures (Rahman and Rasheed, 2014; Kamara and Ramesh 2015). They reported that the enhancement in hardness was as a result of fast abstraction of heat during solidification of squeeze cast metal which led to grain refinement for enhanced strength and hardness properties.

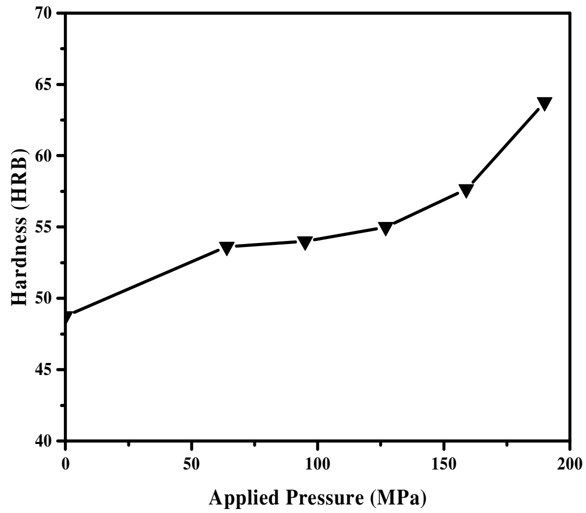


Figure 6: Effect of applied pressure on hardness property of 1xxx aluminium

**3.3. Tensile Property Variation with Applied Squeeze Cast Pressure**

Figure 7, shows an increase in the tensile strength of the material with an increase in the value of applied pressure. For the situation when the cast was performed without pressure application, the tensile strength was 12 MPa and increased by about 10 % at applied pressure of 64 MPa which further increased to 33 MPa at applied pressure of 95 MPa. The peak of 34 MPa was recorded when 127 MPa was applied giving a marginal increase with increase in pressure. As the applied pressure was increased further there was a decline in the values of the tensile strengths recorded thus becoming 17 MPa at applied squeeze cast pressure of 190 MPa. The initial increase in tensile strength may be as a consequence of applied squeeze cast pressure, which leads to a higher degree of undercooling that favoured rapid solidification. This fast solidification favoured grain refinement and densification caused by reducing the grain sizes which eventually lead to corresponding increase in the number of grains. The increase in the number of grain size reduction can lead to a corresponding increase in the amount of grain boundaries thereby raising the dislocation density and making it difficult for inter-atomic grains to glide against one another and hence increase in the strength of cast metal (Azhagan et al., 2014; Souissi et al., 2017). In addition, applied pressure in squeeze casting tends to minimize gas porosity and consequently compensate for solidification shrinkage during casting as was evidenced in the microstructural examination (Figure 5). The minimization of gas porosity reduced the tendency of crack initiation sites for premature failure in the material to be propagated which in turn improves the strength (Obiekea et al., 2014). The decline in the tensile strength at applied pressure above 127 MPa may be attributed to the fact that at such a higher applied pressure, the aluminium metal grains can no longer withstand such high-pressure intensity (Raji and Khan, 2006). This causes cracking due to excessive plastic deformation as depicted in the microstructures of the material which was abruptly followed by decrease in the tensile strength. From the result, it can be observed that applied pressure for optimum tensile strength was 127 MPa. This result was similar to that obtained on the effect of specific pressure on the mechanical properties of ZA27 alloy (Obiekea et al., 2014) and that earlier reported in the study of ultimate tensile strength with applied pressure (Azhagan et al., 2014). The results of the study of the effect of squeeze cast of Al-8%Si alloy (Raji and Khan, 2006) corroborated with the present study. It was reported that, the ultimate tensile strength increased to a maximum value of 232 MPa at an applied pressure of 125 Mpa after which it remained almost constant with further increase in applied pressure. Similar trends were obtained in the works of Chadwick, (1996), Obiekea et al. (2014), Raji and Yue (2010).

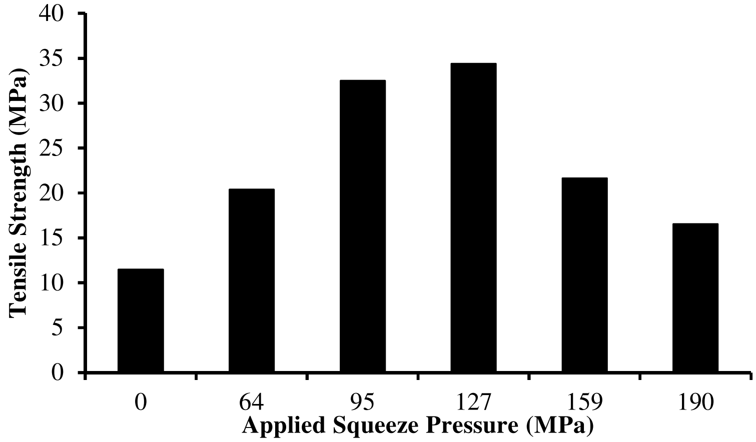


Figure 7: Variation of tensile strength with applied pressure of squeeze cast aluminium

### 3.4. Conductivity Versus Applied Squeeze Cast Pressure

Figure 8 shows the conductivity and resistivity versus applied squeeze casting pressure of cast 1xxx aluminium metal. It is evident that applied squeeze pressure has influence on the conductivity and resistivity of aluminium metal. The conductivity increased from 2.85 x107 (Ωm)-1 at no applied squeeze pressure to 3.39 x107 (Ωm)-1 at 127 MPa. Meanwhile, the corresponding resistivity at 127 MPa and no applied pressure were 23.35 x 10-6 (Ωm) and 26.69 x 10-6 (Ωm) respectively. There was a decrease in the conductivity and corresponding increase in resistivity with further increase in the applied pressure as seen from the Figure 8. This characteristic behaviour illustrated the inverse relationship between resistivity and conductivity of a metallic conductor as propounded by Ohms. The maximum conductivity obtained at 127 MPa when converted to the International Annealed Copper Standard (IACS) was equivalent to 58.5 % IACS which translates to 18.5 % conductivity increment. The increase in conductivity can be attributed to the refining of grain structure and increase in the grain contacts which was presumed to have decreased the intra-grain distance between the atoms (Lu et al., 2004). The decrease enhanced the conduction properties of squeeze cast metal due to lower resistivity compared to that cast without pressure application. However, at applied pressure above 127 MPa, the conductivity started declining with rise in resistivity, a phenomenon that became more apparent when the applied squeeze pressure was 190 MPa. This result has similar pattern to that obtained by Aweda and Adeyemi, (2007) in their works with purity aluminium. Comparing their results with the present investigation, the maximum conductivity obtained was 3.5 x 107 (Ωm)-1 as against 2.9 x 107 (Ωm)-1 obtained in the present study at no pressure application and 6.8 x 107 (Ωm)-1 and 3.4 x 107 (Ωm)-1 when the applied pressure was 105 MPa and 127 MPa respectively. For both situations, the conductivity declined in values thereafter. The difference in values of applied pressures, material composition, processing conditions and mould preheating temperature may have caused the variations in their conductivity values in the two compared results. The reduction in conductivity beyond 127 MPa pressure application can be attributed to impaired microstructure at such a higher pressure causing some defects in the grains as it is evidenced in Figure 5(f) due to severe plastic deformation (Karademir et al., 2017). It could also be proposed that, the higher squeeze cast pressure was able to dislodge the conducting electrons fueled with resulting defects formation due to high straining effect of excessive plastic deformation. This behaviour was similar to that reported by Lu et al (2004) and Cui et al., (2017).

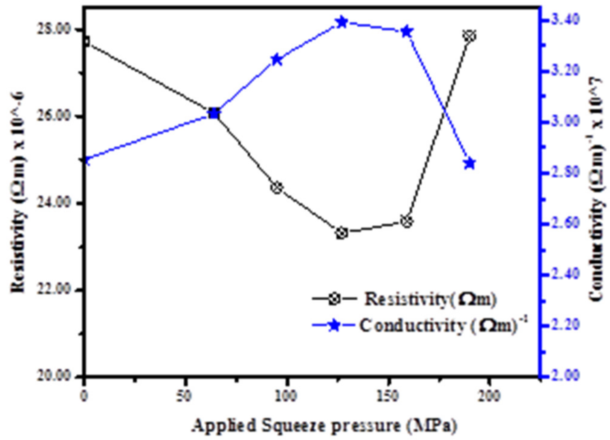


Figure 8: Electrical conductivity and resistivity properties versus applied squeeze pressure

## 4. CONCLUSIONS

The effect of applied squeeze cast pressure on the mechanical and electrical properties on 1xxx squeeze cast aluminium metal was experimentally investigated. Mechanical, microstructural and electrical properties were evaluated. The following specific conclusions were drawn based on the results of this work:

1. Squeeze cast pressure aids in the refinement of microstructure of squeeze cast 1xxx aluminium metal with optimum squeezing pressure of 127 MPa.
2. An enhancement of 200% in tensile strength at 127 MPa applied pressure and 41.03% in hardness value at 190 MPa pressure application were obtained for the squeeze casting of 1xxx aluminium metal.
3. An improvement of 18.5% electrical conductivity was achieved at 127 MPa applied squeeze pressure for 1xxx aluminium.
4. Squeeze casting technique can be used to improve both the mechanical and electrical conductivity of 1xxx aluminium metal for improved performance in electrical application with a recommended applied pressure of 127 MPa

## 5. ACKNOWLEDGMENT

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## 6. CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

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