

## Research Article

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# Fabrication of aluminium covetic casts under different voltages and amperages of direct current

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**Abstract:** Aluminium Covetic metallurgical synthesis along with the characterization of cast material results were presented in this paper. Aluminium- 3% graphite (carbon) composites were fabricated by applying different voltages and amperages of direct current through the stir-casting process. This process, called Covetic based on patent applications of Third Millennium Metals. Obtained casts were tested for their chemical composition, density, tensile strength, hardness, microstructures, and electrical conductivity measurements using an Oxford PMI-Master Pro spark emission spectrometer, a DA-300M density measurement device, a WDW-200 universal tensile test machine, a HBA-3000S automatic Brinell Hardness Tester, a scanning electron microscope with Energy-Dispersive Spectroscopy and an AT512 Precision Ohmmeter, respectively. Moreover, increasing of amperages and/or decreasing of voltages of direct current ensured considerable increasing of electrical conductivity ( $\approx 34\%$ ), the notable decrement in the density ( $\approx 0.94\%$ ), an enhancement in the tensile strength ( $\approx 18\%$ ) and the hardness ( $\approx 15\%$ ) of aluminium Covetic casts compared to the parent metal. In summary, results show that the increasing of amperages and/or decreasing of voltages of direct current has a superior influence on improving electrical conductivity of aluminium-graphite Covetic casts with better mechanical properties.

**Keywords:** Covetic materials, aluminium wires, graphite powder, stir casting

## 1 Introduction

Shugart and Scherer of Third Millennium Metals LLC invented the Covetic process, this process is used to produce Covetic materials by applying a sufficient direct current (DC) to molten metal, whereas activated carbon powder additives are mixed with the molten metal [1, 2].

The chemical reaction which occurs during application of DC through the Covetic process forms exceptionally strong bonds between carbon and host metal atoms, even though their existence is not found in conventional metals. The fine dispersion of carbon particles has high stability and remains even after re-melting and re-casting the metal, with no segregation. The large concentration of carbon atoms ( $> 5$  wt.%) in the molten metal, the performing of the carbon addition in the molten metal is expected to lower production costs for Covetic materials in the long term, with the incorporation of carbon atoms in a metal lattice as a single-phase can have a beneficial effect on the resulting covetic materials [1–6]. For example, aluminium covetic materials were reported to exhibit improved strength, higher conductivity, and proportionally lower density compared with the base metals from which they were produced [7–9].

DC is the essential parameter through the Covetic process but much still unknown about the necessary amount that should be applied to produce a Covetic cast with enhanced characteristics. Many studies mentioned using hundreds of amperes without determination of exactly the needed amount of the direct current [2, 10–12]. Thus, we seek three goals the first one is to determine the required amount of direct current to produce improved Covetic materials, we focus especially on aluminium, by applying different values of the amperage and/or the voltage of direct current. Secondly, the possibility of using car batteries as a direct current resource instead of a DC power supply. Assess the relationship between processing and the needed properties such as enhanced electrical conductivity, improved strength, and low density is our third goal to expand the range of applications of the Covetic aluminium materials especially in the saving energy field. The Covetic aluminum could substitute for conventional cop-

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per in electrical wiring and motor windings, which provides lighter weight wiring, improved electrical conductivity with high strength [10]. We hereon improve the characteristics of the aluminium Covetic materials by applying different amperages and voltage values of direct current.

## 2 Experimental

### 2.1 Materials

One commercial type of aluminium used wires (Al) and graphite powder (Gr) were used to produce aluminium-graphite (Al-Gr) Covetic casts. The Gr density was  $2.267 \text{ g/cm}^3$  with a  $D_{50} = 43 \mu\text{m}$ . Carbon additive particles in micron size are used in the Covetic process of producing 20 metals, including aluminium [1, 10, 11].

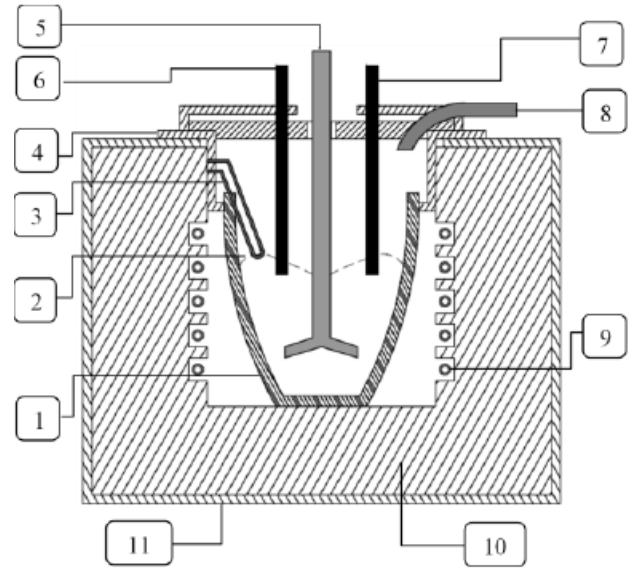
### 2.2 Preparation of Samples

A special design of the Covetic-casting system was made for producing Al-Gr Covetic casts (see Figure 1), including: an electric furnace (ORH5-F102200), an electric blender, a graphite crucible, four Solite batteries ( $2 \times 150$ ,  $1 \times 100$  and  $1 \times 40$  Amp) as DC resources, a CENTURY model battery charger (for recharging batteries after each casting process), and a BT-121 model battery tester (to measure the batteries amperages and voltages).

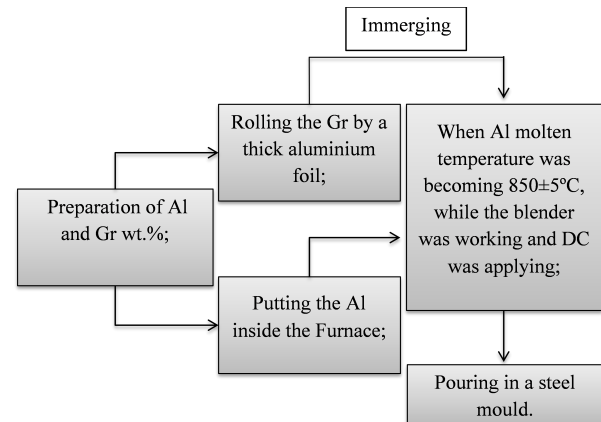
The production of an Al-Gr Covetic cast was completed (see Figure 2), as follows: A required amount of Al and Gr was prepared; the graphite powder was dried and rolled up in a thick aluminium foil then, immersed (the Al molten temperature had risen to  $850 \pm 5^\circ\text{C}$ ) in the Al molten when the blender was worked and the DC was applied. Subsequently, the molten was poured into a preheated steel mould.

The graphite powder was dried under vacuum conditions in an SRJX-5-13 oven at  $250^\circ\text{C}$  for one hour to remove the moisture content and increase wettability. The molten of each cast was held in a high temperature  $850 \pm 5^\circ\text{C}$  for 3 minutes to decrease the porosity level [13]. The steel mould was lubricated with graphite powder and heated to  $450^\circ\text{C}$  to facilitate taking off a cast and to ensure a moderate cooling rate. All casts were left inside the mould to cool in air.

Many trials were conducted before the Casting-Covetic System operated as desired. All of Al-Gr Covetic casts were cast under argon inert gas and they were subjected to the conditions shown in Table 1. The Non-Covetic Al cast (C1) was used for comparison.



**Figure 1:** Covetic-casting system for producing Al-Gr Covetic casts: the graphite crucible (1); molten metal level (2); thermocouple (3); heat saver container (4); electrical blender (5); DC electrodes (6,7); inert gas tube (8) and an electrical furnace body (heater 9, inside body 10, outside cover 11).



**Figure 2:** Production steps of an Al-Gr Covetic cast.

**Table 1:** Production conditions of Al-Gr Covetic casts.

Cast No.	Graphite (Gr%)	Al wires, g	DC Current		
			Amp	V	Flow Time, min
C1	0			–	
C2	3	145	170	12	6
C3				24	6
C4			290		8
C5		250	400	36	16

## 2.3 Investigation Process

All of the produced casts were operated mechanically to test their tensile properties according to ASTM E8/E8M - 13A at room temperature by using a universal tensile test machine (WDW-200) with a speed rate of applied load 0.5 mm/min (gage length =  $25 \pm 2$  mm, working part diameter  $d_1 = 6 \pm 1$ ). The tested samples are presented in Figure 3.

Density was measured according to Archimedes' principle by using a density measurement device (DA-300M). Each produced cast was prepared with the dimension  $\phi 12$  mm  $\times$  20 mm, polished, and sanded sufficiently before the test.

The four-wire digital multi-meter method (AT512 Precision Ohmmeter) was performed to measure the electrical resistance ( $R$ , ohm) of all produced casts (see Figure 4). Then, the electrical resistivity ( $\rho$ , ohm-meter) was calculated according to Equation 1 [12]. Subsequently, Equation 2 [14], was applied to find the electrical conductivity in a specific conductivity per length ( $\sigma$ , S/m):

$$\rho = R(A/I) \quad (1)$$

$$\sigma = 1/\rho \quad (2)$$

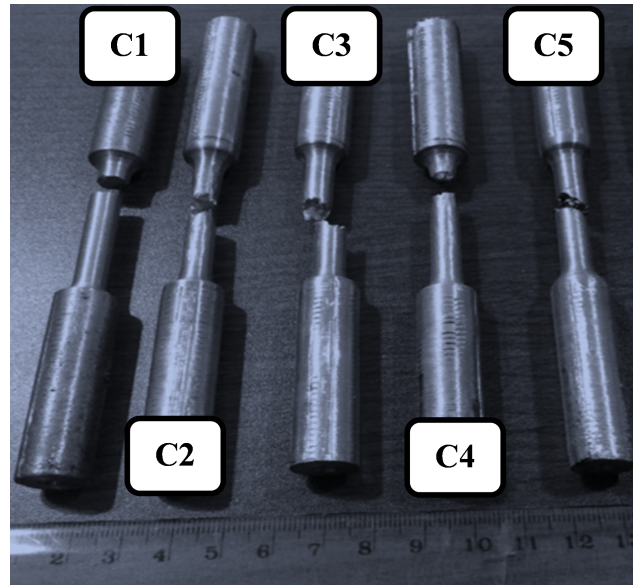
Where:  $I$  = the distance between clips, mm;  $A$  = cross-sectional area of the tested sample, mm<sup>2</sup>.

Then, the results of the electrical conductivity were divided by the conductivity of annealed pure copper,  $\sigma = 5.8 \times 10^7$  S/m (100% meeting the International Annealed Copper Standard) (IACS); the electrical conductivity of each Al-Gr Covetic cast was presented as a percentage of IACS [15].

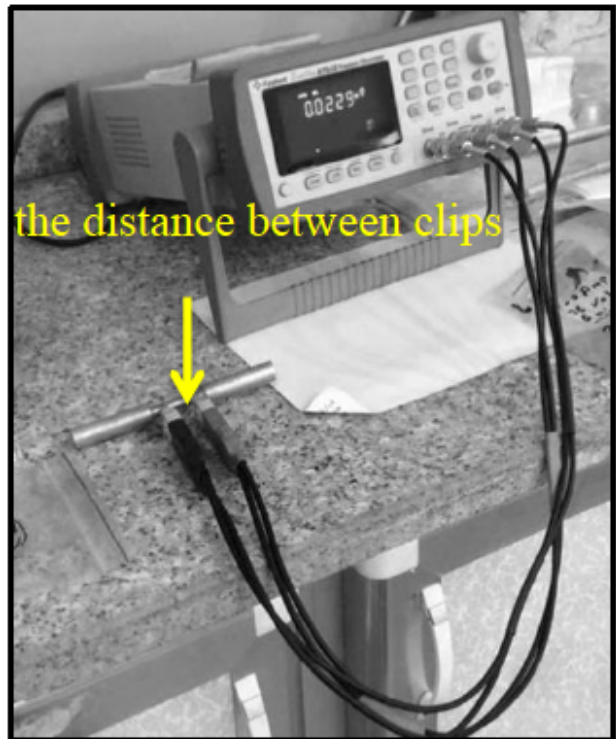
The chemical composition analysis for all produced casts was conducted using an Oxford PMI-Master Pro spark emission spectrometer. Three points were taken for each prepared sample ( $\phi 12$  mm  $\times$  10 mm) as shown in Figure 5(a).

In this study it wasn't preferred to use the X-ray diffraction (XRD) method for the chemical composition analysis because, simply it is hard to reveal any existence of a carbon in aluminium Covetic materials with low carbon content ( $< 5$  wt.% carbon) regarding to [2, 6].

Sections with dimensions of  $\phi 12$  mm  $\times$  10 mm were prepared to study the microstructure, see Figure 5(b), of all produced casts by using the grinding papers of silicon carbide with different grit sizes ( $-400$ ,  $-800$ ,  $-1000$ ,  $-1500$ , and  $-2000$ ). They were polished using a diamond paste to obtain a mirror surface. The examination was conducted using a scanning electron microscope (SEM) with Energy-Dispersive Spectroscopy (EDS). In addition, these sections

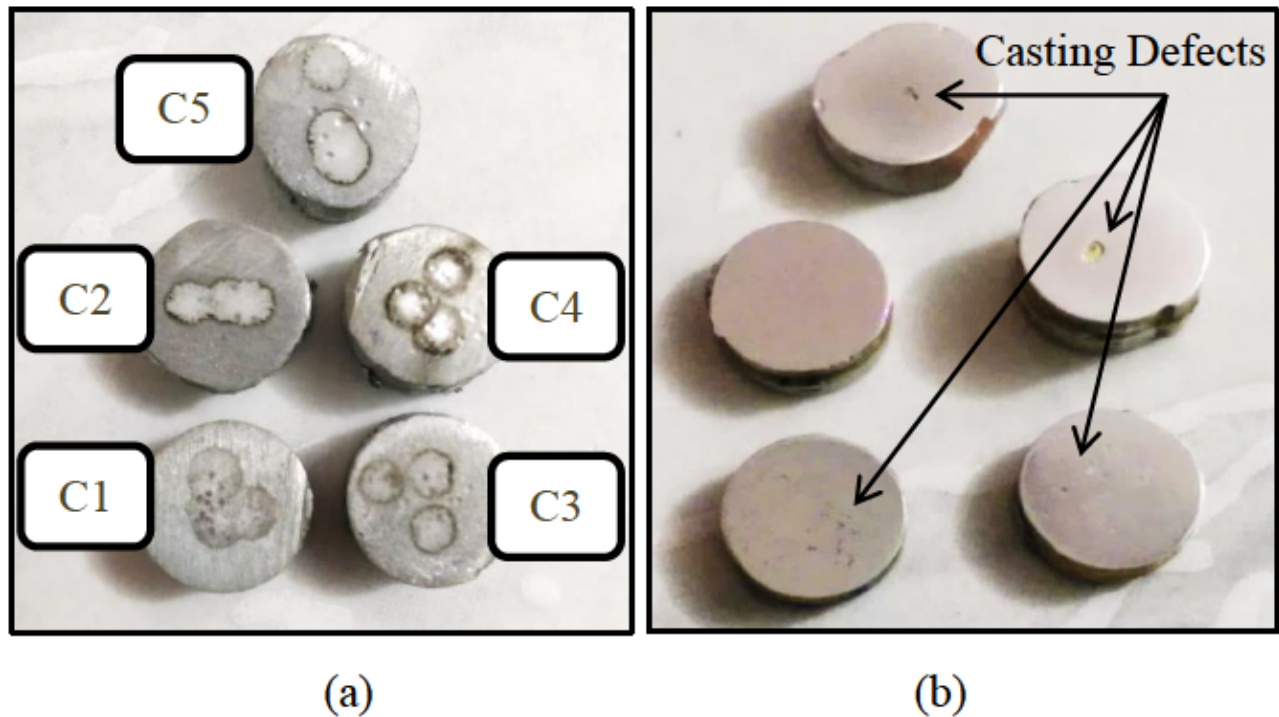


**Figure 3:** Tensile failure of Al with no current cast (C1); Al-3% Gr Covetic casts at 170 Amps with 12V (C2) and 24V (C3); Al-3% Gr Covetic casts at 290 Amps with 36V (C4) and 400 Amps (C5).



**Figure 4:** The four-wire digital multi-meter (AT512 Precision Ohmmeter).

were used for the calculations of their hardness. These calculations were performed using an automatic Brinell Hardness Tester (HBA-3000S) according to ASTM E10-15a with a ball indenter diameter (2.5 mm) and applied load (31.25



**Figure 5:** Prepared sections of Al-Gr Covetic casts after chemical analysis (a) see the burned surfaces, next for the microstructure analysis (b) the mirror surfaces and casting defects.

kg) for 10 s. The average of the three measurements was recorded.

### 3 Results and discussion

#### 3.1 Density

Reads of a Measurement Density Device are presented in Table 2. These reads show that the density of Al-Gr Covetic casts decreased from  $2.674 \text{ g/cm}^3$  to  $2.644 \text{ g/cm}^3$  with decreasing DC voltage from 24 to 12 V at 170 Amp and from  $2.675 \text{ g/cm}^3$  to  $2.66 \text{ g/cm}^3$  with increasing DC amperages from 290 to 400 Amp at 36 V.

The decreasing density of Al-Gr Covetic casts compared with that of the Al cast was due to the slightly low density of graphite powder additives and the increased porosity of Al-Gr Covetic casts, as graphite additives increased the porosity level [16]. The large concentration of carbon atoms in the molten provides lighter weight of aluminum Covetic materials [10].

#### 3.2 Tensile Test

Tensile results in Table 2 confirmed that the ultimate tensile strengths (UTS) of Al-Gr Covetic casts were higher than those of Al cast. However, the increasing of applied DC amperage and the decreasing of the applied DC voltage have not caused a big changing in the UTS of the Al-Gr Covetic casts. The enhancement of their UTS is mostly due to the effect of electrical applied current, which induces the formation of covalent bonds between graphite and Al atoms according to [7]. This enhancement might also be due to the role of impurities in graphite powder, which serve as precipitations in the form of  $\text{AlFeSi}$  in the aluminium matrix [17].

#### 3.3 Electrical Conductivity

The electrical conductivities of Al-Gr Covetic casts are presented in Table 2 as IACS%. The results show that the conductivity is a function of amperage and voltage of direct current. It increases as the DC voltage decreases (IACS% for C3 = 39.77 at 24V while for C2 = 58.11 at 12V) and as DC amperage increase (IACS% for C4 = 38.07 and for C5 = 45.57 at 290 and 400 Amp, respectively).



**Table 2:** Physical, mechanical, and electrical properties results of Al-Gr Covetic casts.

Cast No.	Al-base casts	Investigated Properties				
		Density, g/cm <sup>3</sup>	IACS% Aver.	UTS, MPa	$\delta\%$	HBW
C1	Al, No current	2.679	24.48	109	26.95	95
C2	Al + 3% G, 170 Amp, 12V	2.644	58.11	133	35.74	112
C3	Al + 3% G, 170 Amp, 24V	2.674	39.77	127	34.28	104
C4	Al + 3% G, 290 Amp, 36V	2.675	38.07	129	33.2	118
C5	Al + 3% G, 400Amp, 36V	2.66	45.57	135	39.9	110

**Table 3:** Chemical composition of Al- 3% Gr Covetic casts.

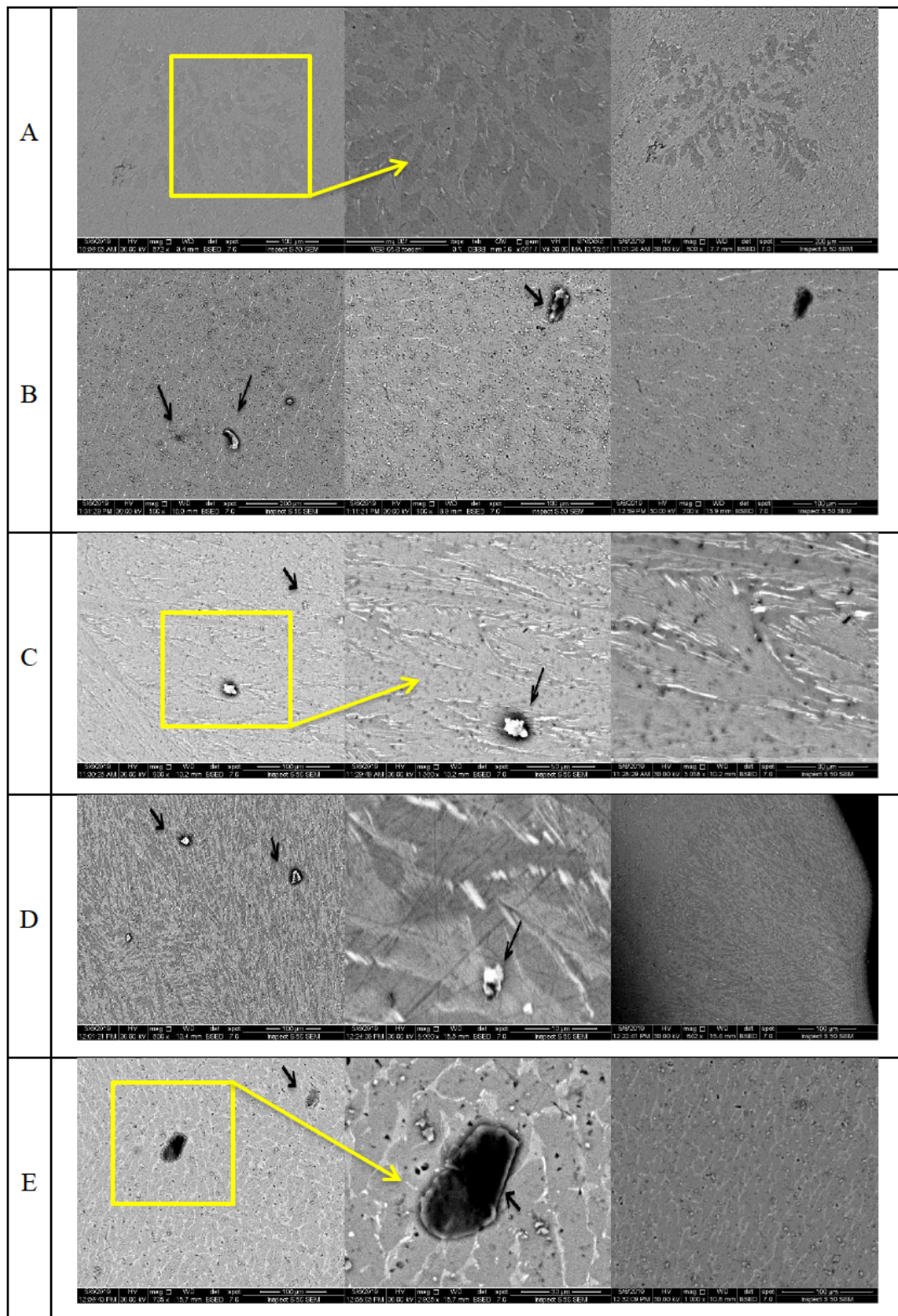
Cast No.	Si%	Fe%	Cu%	Mn%	Mg%	Zn%	Ni%	Ti%	Sn%	Al%
C1	6.50	0.17	2.94	0.37	0.15	0.95	0.22	0.10	0.27	Bal.
C2	6.58	0.63	3.57	0.11	0.06	0.39	0.35	0.08	0.28	Bal.
C3	6.87	1.01	3.27	0.20	0.07	0.44	0.43	0.08	1.01	Bal.
C4	6.51	1.07	3.05	0.20	0.06	0.43	0.38	0.08	1.07	Bal.
C5	6.40	0.90	3.71	0.19	0.08	0.45	0.53	0.08	0.20	Bal.

**Table 4:** Comparison of our work to other works' results.

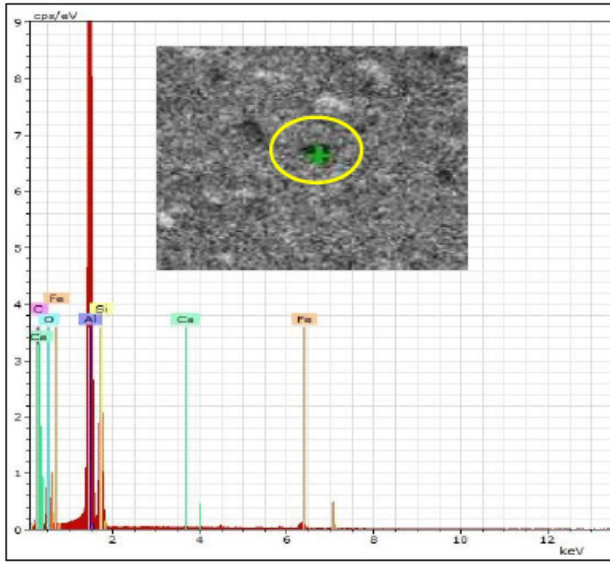
Material and process	UTS and/or YS	Conductivity, IACS%	Hardness	Density %	Work
As compared with base metal and/or alloy (non-Covetic)					
Covetic (6061 + 3% carbon nanoscale) as extruded at 400 F.	30% improvement in yield strength (YS).	Was significantly higher (43%) than that of 6061 T6.	23.4% harder.	Decreased by 0.186%	[7]
On warm-rolled (T0 conditioned) Al7075 Covetic materials + 3 wt.% C.	About 32% UTS and 25% of the yield strength (YS) increase was observed	Did not calculate	Vickers hardness, increased by 18%	Decreased by 0.716% $\pm$ 0.205	[8]
Al- 3 wt.% Gr Covetic casts	Increasing of UTS%	Increasing of IACS%	Increasing of HBW%	Decreasing in Density%	This work
V	Amp				
12	170	18.05	33.63	15.18	
24	290	14.17	15.29	8.65	
36	400	15.50	13.59	19.49	
		19.26	21.09	13.64	

Applying DC has decreased the grain size of the Al-Gr Covetic casts compared with that of Al cast microstructures, as shown in [7]. Furthermore, the lower voltage and/or higher amperage Al-Gr Covetic casts have more resistance to grain growth and coarsening. The decrease in grain size improves mechanical properties, but increases grain boundaries that can, in turn, increase the electrical resistivity. Nevertheless, decreasing the electrical conduc-

tivity of the Al-Gr Covetic casts is necessary, but the nature of the effect of bonds between graphite particles and the host metal (Al), and the relatively high electrical conductivity of graphite ( $2$  to  $3 \times 10^5$  S/m at  $20^\circ\text{C}$ ) [18], have increased the electrical conductivity instead of decreasing it. These results are in accordance with those obtained by [2, 10, 19, 20].



**Figure 6:** SEM images at different magnifications and positions of Al cast (a); Al-3% Gr Covetic casts at 170 Amp with 12V (b), 24V (c); Al-3% Gr Covetic casts with 36V at 290 Amp (d) and 400Amp (e).



**Figure 7:** EDX- SEM analysis of a dark point (inside the yellow circle) in the microstructure of Al-3% Gr Covetic cast (at 170 Amp with 12 V).

### 3.4 Chemical Composition and Microstructure Analysis

The chemical composition analysis results are shown in Table 3. The increased content of Fe, Cu, and Ni in the Al-Gr Covetic casts came from known impurities of graphite materials, a commercial instead of a pure graphite type was used in this study because of its availability.

The SEM images of all produced casts are presented in Figure 6. Dendritic structures of aluminium, see Figure 6(a), were formed due to non-equilibrium solidification (equilibrium solidification required a slow cooling rate, and it is not readily available in manufacturing processes) [21]. These images showed the graphite particles in the Al matrix of Al-Gr Covetic casts, which were distributed more uniformly (black arrows in Figure 6 indicate graphite particles). In addition, some inclusions look like dark points were noted in the Al-Gr Covetic casts; however, we observed no such defects in the Al cast. The contents of these points are presented in Figure 7.

The  $O_2$  content was affected by both the formation of  $Al_2O_3$ , as the oxidation of the aluminium base molten through the casting process is difficult to prevent, and the graphite additions. It was clearly detected by EDS-SEM analysis (see Figure 7) that the porosity was increased with increasing graphite additions [16]

Table 2 also shows that the hardness of Al-Gr Covetic casts was higher than that of the Al parent cast. This can be attributed to the strong bonds between graphite particles and the host metal (Al) [11, 19]. This can also be explained

by the fact that the graphite particles have higher hardness than the Al alloy, as discussed in [2, 22, 23].

The comparison between this study and other works' results is presented in Table 4. It shows that the Al-Gr Covetic casts have desirable properties even with no heat treatment and/or extrusion conditions compared to those reported in other studies [7, 8]. The Al-Gr Covetic casts at 170 Amp with 12V had the highest increase in electrical conductivity (33.63%), the highest decrease in density (0.94%), and a notable increase in UTS (18.05%) and HBW (15.18) among other Covetic casts in comparison to the Al parent cast. These improvements of the Al-Gr Covetic casts properties are attributable to the Covetic conversion - carbon infusion.

## 4 Conclusions

Generally, Al-3% Gr Covetic casts have better physical, electrical, and mechanical properties compared to those of the parent Al cast. There was no enormous effect through the changing of direct current's voltage and/or amperage on the ultimate tensile strength and the hardness of Al-3% Gr Covetic casts.

It can be concluded that the density and the electrical conductivity of aluminium Covetic casts are functions of the voltage and the amperage of direct current. The density decreases with decreasing voltage and/or increasing amperage of direct current while the electrical conductivity increases. It is enough to apply around 170 Amp with 12 V by using car batteries as a direct current resource, which was used for the first time as DC resource, to produce a low weight Al-3% Gr Covetic cast ( $\approx 250$  g) with enhanced electrical and mechanical properties. More studies will be needed to investigate the relationship between the weight of an aluminium Covetic cast and the necessary amount of the direct current (amperages and/or voltages).

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