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The Mechanical Properties of Aluminium Metal Matrix Composite (AlMMCs) Reinforced with Ni and SiC_p

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Abstract. This investigation studies the effects of nickel (Ni) particles combined with silicon carbide (SiC_p) particles on the microstructural and mechanical properties of aluminium(Al)-magnesium(Mg)-manganese(Mn) matrix alloys under different sintering temperatures. The Al-Mg-Mn-SiC_p/Ni_p composite samples were produced via the powder metallurgy route. The sintering process was performed on a green compact of Al-Mg-Mn matrix/SiC_p/ or Ni_p composites at 400 °C and 600 °C for 1.5 hours at a constant heating rate of 50 °C/min. The Al-Mg-Mn-SiC_p/Ni_p samples were evaluated and characterised using a scanning electron microscope and X-ray diffraction. Additionally, the Al-Mg-Mn-SiC_p/Ni_p samples were measured for Vickers hardness and compressive strength. The outcomes show that Al-Mg-Mn-5%SiC_p-6%Ni_p gave the highest Vickers hardness. The results showed that the optimal sintering temperature performed on the Al-Mg-Mn-SiC_p/Ni_p sample was 400 °C compared with 600 °C because the overall dissolution of alloying elements within the Al-matrix led to an enlargement of grains, thus, reducing their mechanical properties.

Keywords: Additive strengthening; Al-Mg-Mn composite; Strength

1. Introduction

Five thousand-series aluminium alloys have acquired prominence in the naval, automotive and aerospace industries due to their specific strength, excellent corrosion resistance, fracture toughness, weldability and thermal and electric conductivities [1, 2]. Many applications need high strength with low density and good formability. A host of techniques, such as heat treatment, thermo-mechanical processing and severe plastic deformation have been used to improve the strength of Al-alloys. In other words, the Al-5000 series is considered a non-heat-treatable alloy, thus, techniques that can improve strength and retain ductility are very limited. Therefore, impediments can be overcome using composite materials to reinforce hard metals or ceramic particles within the matrix of aluminium metal. The technology of aluminium metal matrix composites (AlMMCs) is a powder metallurgy technique used to improve the strength of alloys. AlMMCs are usually reinforced by promising ceramic particles, such as Al₂O₃, SiC, AlN or Y₂O₃ [3–4]. The improvement in mechanical properties of AlMMCs depends greatly on how well the particles are distributed in the metal matrix composite. It also depends on the proper selection of the reinforcing phase and processing techniques [5–6].

Powder metallurgy (PM) is one of the most advantageous techniques in the solid-state process of fabricating AlMMCs because of an isotropic distribution of particles in the matrix and good dimensional



accuracy in an economical manner [7–9]. Silicon carbide (SiC) powder is a covalently bonded ceramic material with very stable chemical properties. Other remarkable properties include superior hardness and wear and corrosion resistance, which make it an ideal reinforcing material in metal matrix composites, such as Fe, Al and Mg-based materials [10–11]. Chemical reactions that can occur on the SiC surface during the preparation of SiC metal matrix-composites can worsen the performance of the composite materials. Therefore, metal modification on the SiC surface is often utilised to restrain interface reaction and enhance the interface combination [12–16].

Nickel is a good bonding choice and provides strong reinforcement because of its high strength, stiffness and high-temperature properties. Recently, the production of an Al-based matrix composite has been successfully carried out using powder metallurgy to obtain an Al/Ni-SiC composite with good microstructure and high densification [17–18]. It is also known that the 5000-series aluminium alloys do not respond to different types of heat treatments. Therefore, this study will attempt to change the crystalline and microstructure of the reinforced Al-Mg-Mn (SiCp + Nip) matrix by undergoing the impact of sintering heat treatments.

2. Materials and experimental procedures

Synthesising aluminium with alloy elements using the elemental powder precursors has already been performed (as shown in Table 1). Powder mixtures were used to fabricate four types:

A (Al–5.5%Mg–1%Mn–0.5%Cu–0.4%Zn–0.2%Fe–0.1%Cr)

B (Al–5.5%Mg–1%Mn–0.5%Cu–0.4%Zn–0.2%Fe–0.1%Cr–5%SiC)

C (Al–5.5%Mg–1%Mn–0.5%Cu–0.4%Zn–0.2%Fe–0.1%Cr–5%SiC–3%Ni)

D (Al–5.5%Mg–1%Mn–0.5%Cu–0.4%Zn–0.2%Fe–0.1%Cr–5%SiC–6%Ni)

All compositions are expressed in weight percentage (wt. %). The powder mixture composition analyses for types A, B, C and D were carried out using X-ray fluorescence spectrometry, as listed in Table 1. Al-mixture samples were produced via powder metallurgy processing, which included mixing the elemental powders (Al, Mg, Mn, Cu, etc.) using a turbulent mixer, followed by a cold press by uniaxial-die compaction (hand-operated hydraulic press at 350 MP) to produce the green compact-bulk (Figure 1). Finally, sintering treatment was carried under the two conditions given in Table 2.

To evaluate the microstructural characterisation and phase components of the sintered Al-matrix composite samples, scanning-electron-microscopy (SEM) and X-ray diffraction analysis (XRD) was used. Subsequently, Vickers hardness and compressive strength were tested according to ASTM E92–82.

Table 1: Chemical compositions of the four types of Al-composite samples with and without additives

Standard ident	Solid specimen A	Solid specimen B	Solid specimen C	Solid specimen D
Al	92.36 %	87.415%	84.443%	80.5%
Mg	5.2%	5.28%	4.97%	5.61%
Mn	1.03%	0.901%	0.95%	1.2%
Cu	0.45%	0.501%	0.504%	0.57%
Cr	0.35%	0.297%	0.291%	0.25%
Fe	0.306%	0.301%	0.31%	0.29%
Zn	0.301%	0.295%	0.303%	0.41%
Ni	-	-	3.00%	6.00%
SiC	-	5.00%	5.00%	5.00%



Figure 1: Macro-structure of Al-composite samples under (a) 400 °C and (b) 600 °C sintering conditions

Table 2: Sintering conditions during this study

Sintering conditions	Soaking time and heat rating	Name of compacted Al-composites
400 °C	1.5 h with a heating rate of 40 °C/ min.	A, B, C, D
600 °C		A1, B1, C1, D1

3. Results and discussion

The SEM in Figure 2 shows the microstructure of the sintered Al-Mg-Mn samples. The dark areas denote the alpha aluminium and contain alloying elements within the matrix. Furthermore, some pores were noticed in the matrix because of the sintering operations [20].

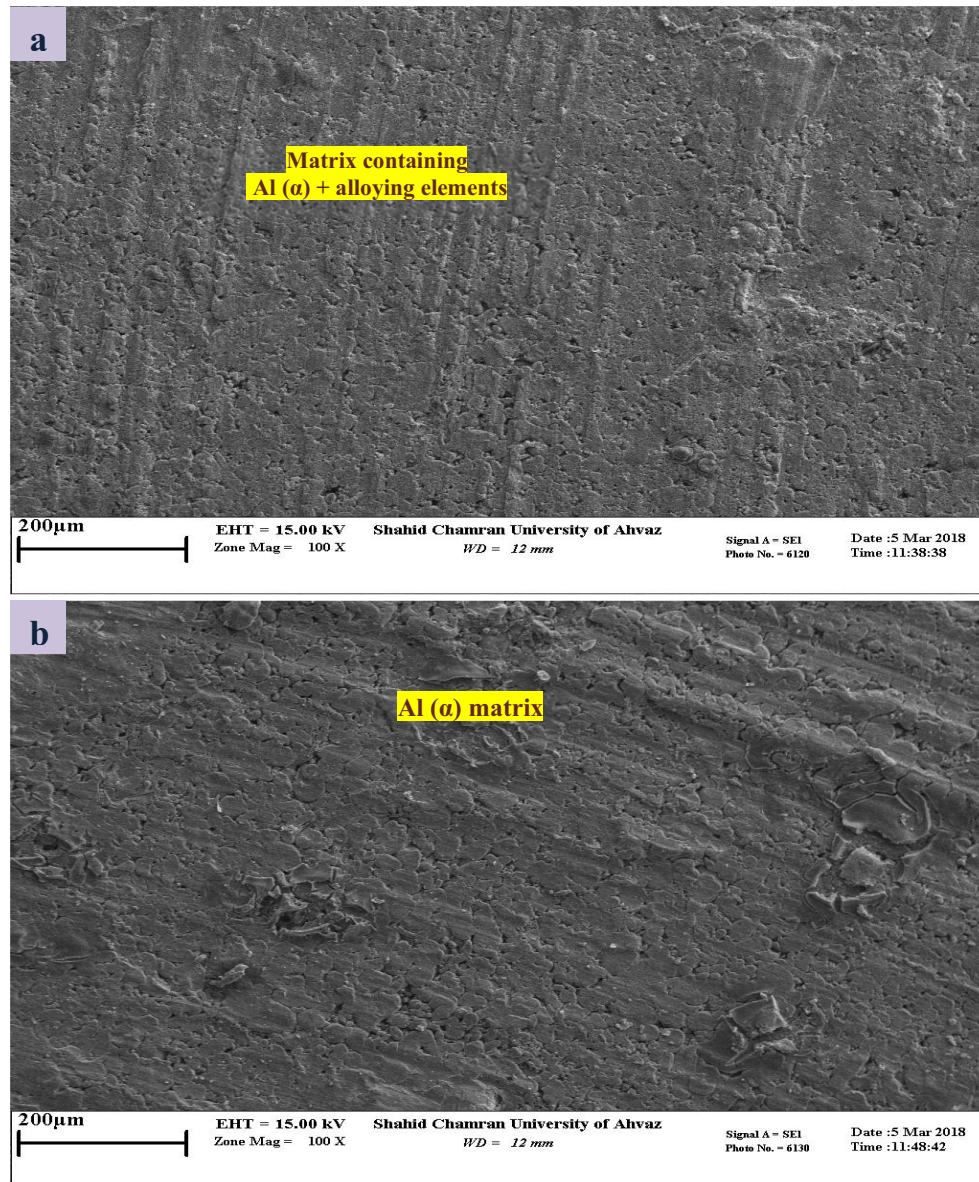


Figure 2: SEM micrographs of the compacted Al-5000 alloys under sintering treatment at (a) 400 °C and (b) 600 °C

The micrograph of the Al-Mg-Mn-5%SiC composite sample under sintering treatment at 400 °C is shown in Figure 3 (a). It indicates the presence of SiC particles that have attached and dispersed throughout the aluminium mixture. The high magnification of SEM (as shown in Figure 3b) noted the good bonding interface between the SiCp within the Al-Mg-Mn matrix.

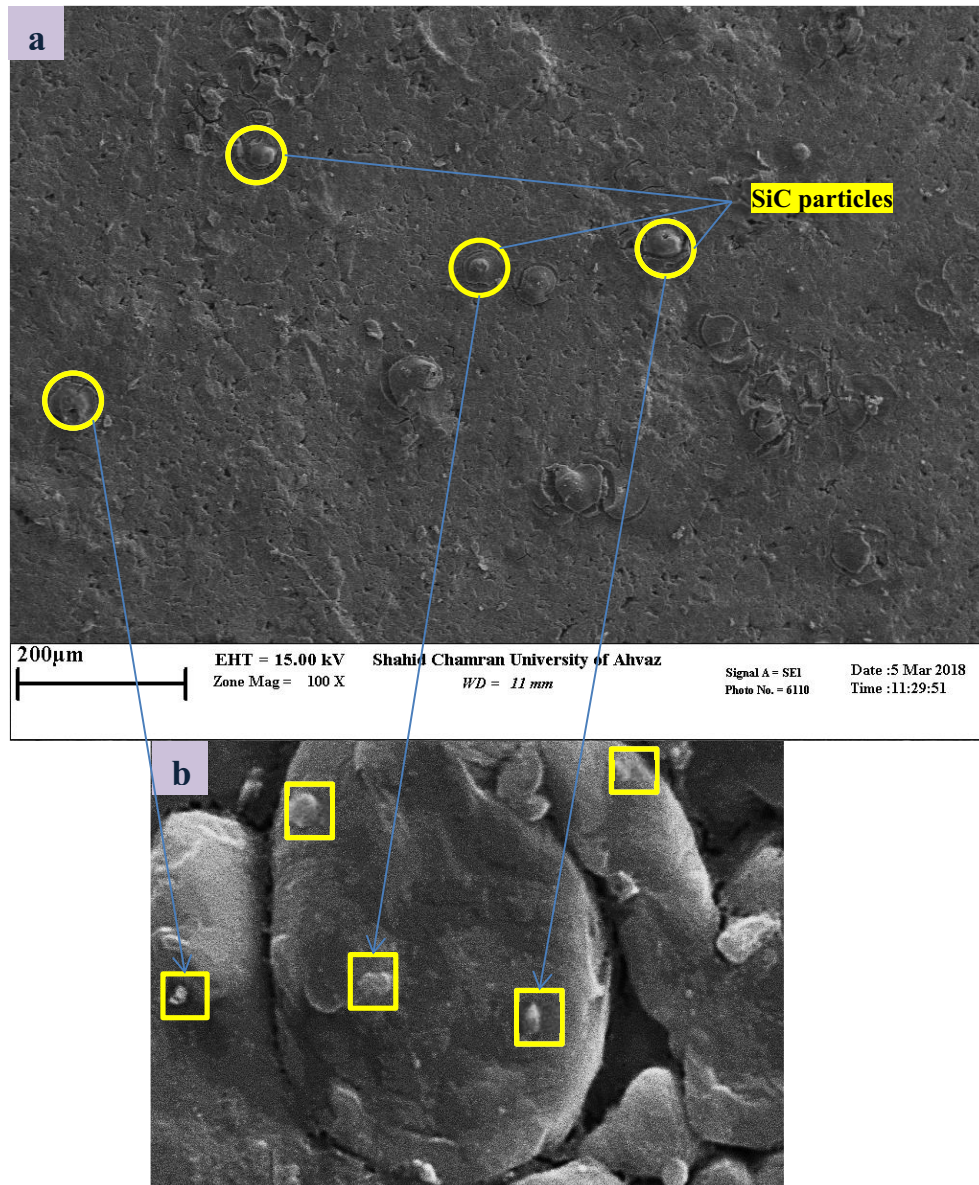


Figure 3: SEM micrographs of the compacted Al-Mg-Mn-5%SiC composite under sintering treatment at (a) 400 °C and (b) high magnification

Figure 4 (a) exhibits the micrograph of the Al-Mg-Mn-5%SiC composite sample under sintering treatment at 600 °C. It shows voids and pores due to micro-cracks throughout the aluminium mixture-reinforced SiCp. These impurities were created due to overheating at 600 °C as reported in [20–21], despite the good distribution and adherence of SiCp within the aluminium-nickel mixture.

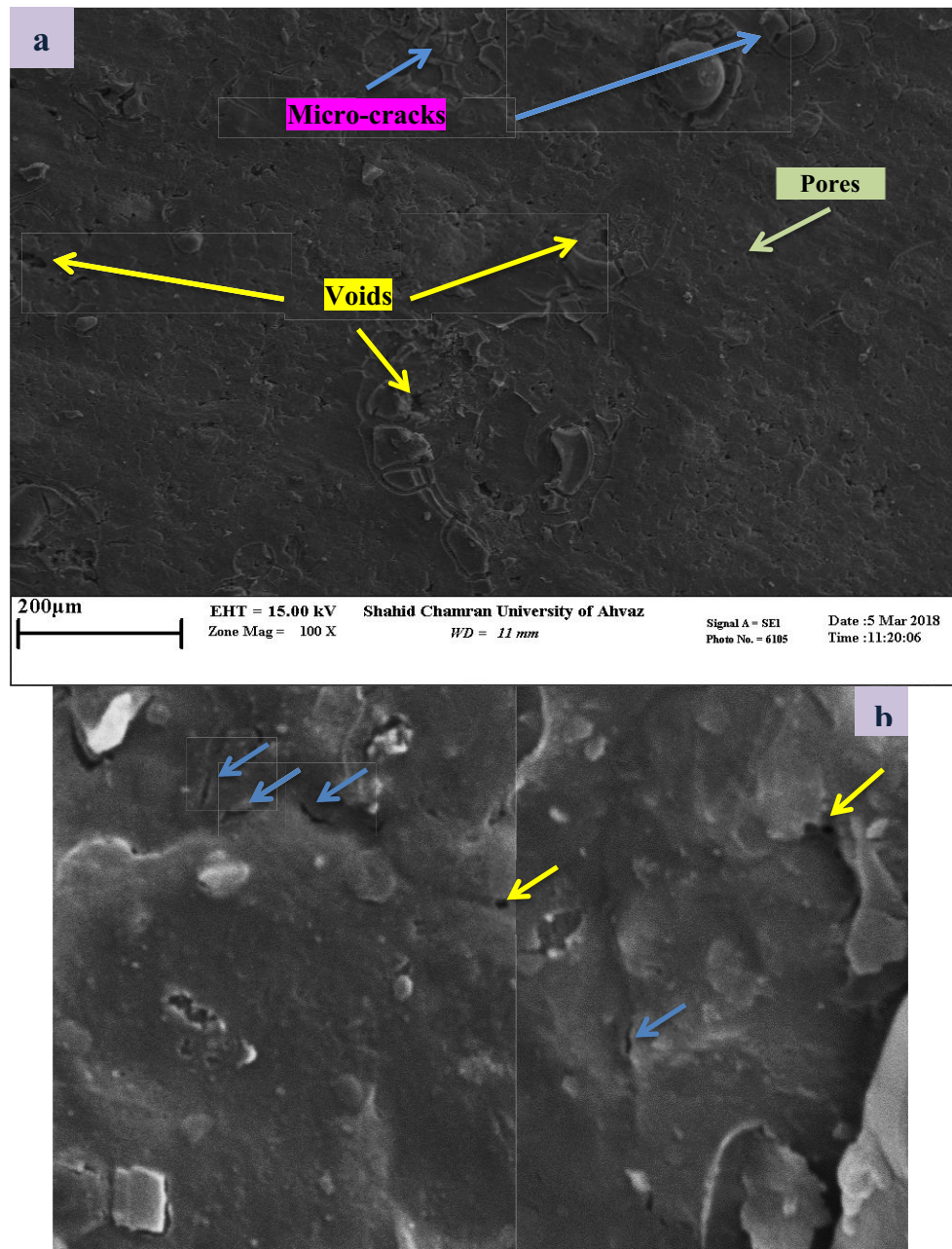


Figure 4: SEM micrographs of the compacted Al-Mg-Mn-SiC-6%Ni composite under sintering treatment at (a) 600 °C and (b) high magnification

Figure 5 presents the XRD spectrum of the aluminium composites (A, B, C, D samples) after sintering treatment at 400°C for 1.5 hours. The X-ray diffraction patterns of mixture A (Figure 5 A) for the Al-alloy represents Al-5.5%Mg-1%Mn-0.5%Cu-0.4%Zn-0.2%Fe-0.1%Cr and exhibited three high peaks

corresponding to Al and AlMgMn. The peak intensities decreased after applying the sintering treatment due to the partial dissolution of Mg, Mn, Zn, and Cu in the Al lattice to form a solid solution, the reduction in grain size of the elemental powder induced by the heat and the loss of very small particles to their crystalline structures. The XRD profiles of the aluminium matrix-SiC composite (shown in Figure 5 B) represents **B** (Al-5.5%Mg-1%Mn-0.5%Cu-0.4%Zn-0.2%Fe-0.1% Cr-5%SiC). During this stage, new peaks were observed for SiCp and Al₂MgMn. All constituent elements were identified in the initial powder. In Figure 4 **C** diffraction peaks are strong but peaks containing nickel observed in Al₃Ni₂, AlMgNi and AlMnNi were weak. The peaks of other additive elements were not observed because of the limitation of the filtered X-ray to detect phases with volume fractions less than 2% wt. [22].

After increasing the percentage of nickel up to 6% wt. within Al-composite alloy **D** (Al-5.5%Mg-1%Mn-0.5%Cu-0.4%Zn-0.2%Fe-0.1%Cr-5%SiC-6%Ni), the XRD analytic was presented in Figure 5D. There was a noticeable presence of several peaks of AlNi because of the dissolution of nickel particles within the Al-Mg-Mn matrix alloy. Figure 6 shows the X-ray diffraction peaks in the Al-Mg-Mn matrix-reinforced SiCp-Nickel undergoing sintering treatment; **A1** presents AlMg peaks and **B1** displays the XRD results of the Al-Mg-Mn matrix alloy after adding 5% SiCp, which changed the microstructure of the Al-composite. It reveals many peaks (Al, AlMg, AlMn, AlMgMn and SiC). Furthermore, sintering the Al-composite at 600 °C for 1.5 hours led to saturated dissolutions of alloying elements (Mg, Mn, Zn, and Cu) within the aluminium matrix. Moreover, it showed new peaks of alloys **C1** and **D1** (Figure 6 **C1** and **D1**) compared to those in Figure 5 **C** and **D**, respectively.

Vickers hardness values for the Al-matrix composite samples (listed in Table 1) underwent sintering as shown in Figure 7. Sample D has the highest hardness value compared to sample A under the same sintering conditions at 400 °C. A significant increase in hardness for sample D was because of the presence of reinforced 5% wt. SiCp coupled with 5% wt. nickel within the Al-Mg-Mn matrix. Generally, the bonded nickel particles with aluminium created stronger compounds that strengthened the matrix of the alloy (the XRD analytics above provide many compounds of Ni), as evidenced by previous studies [22–23]. That resulted in growth grains are too much and precipitate compounds outside grains boundaries than the weak in hardness property.

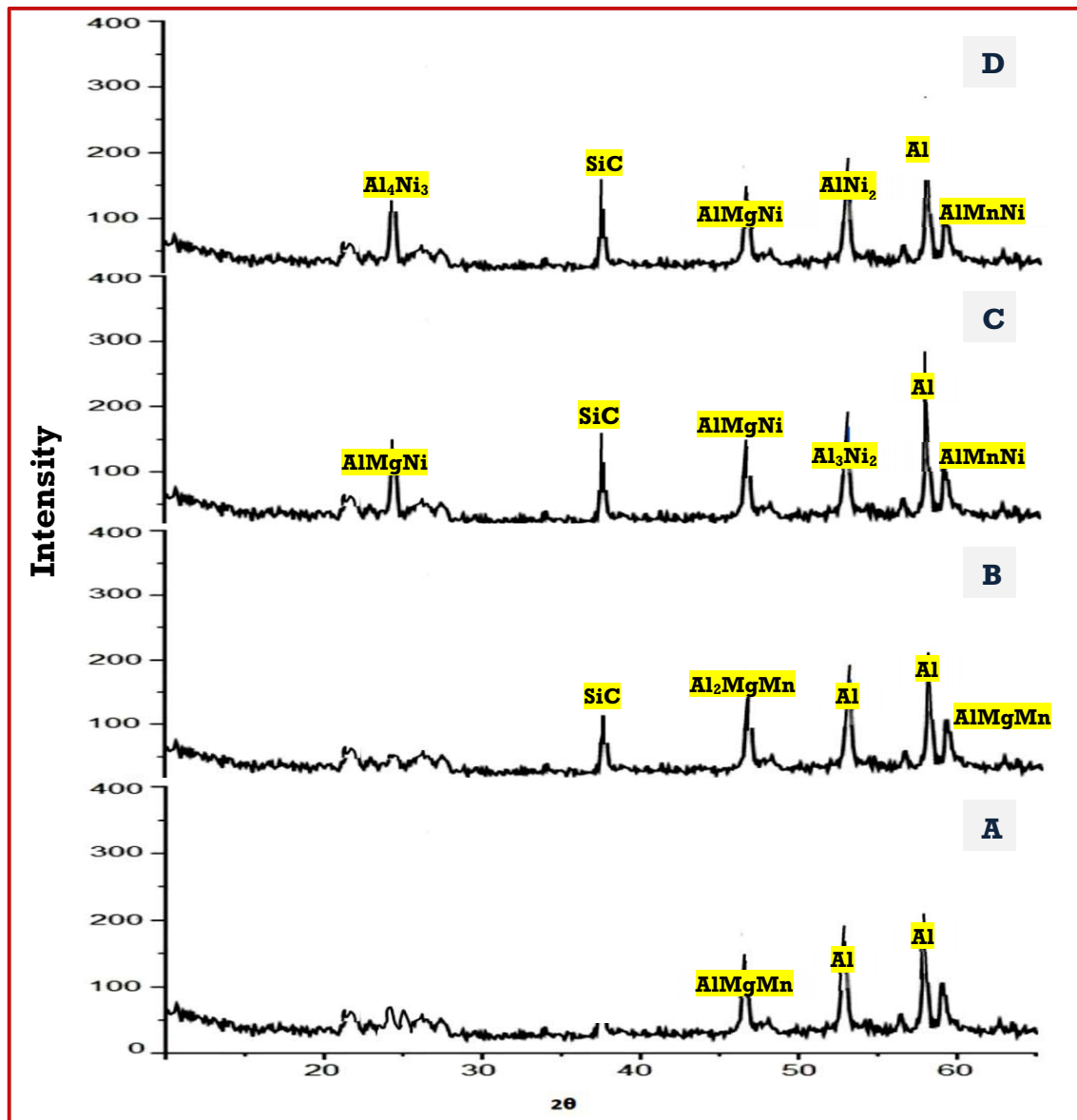


Figure 5: XRD analytic for the A, B, C, D samples undergoing sintering treatment at 400 °C

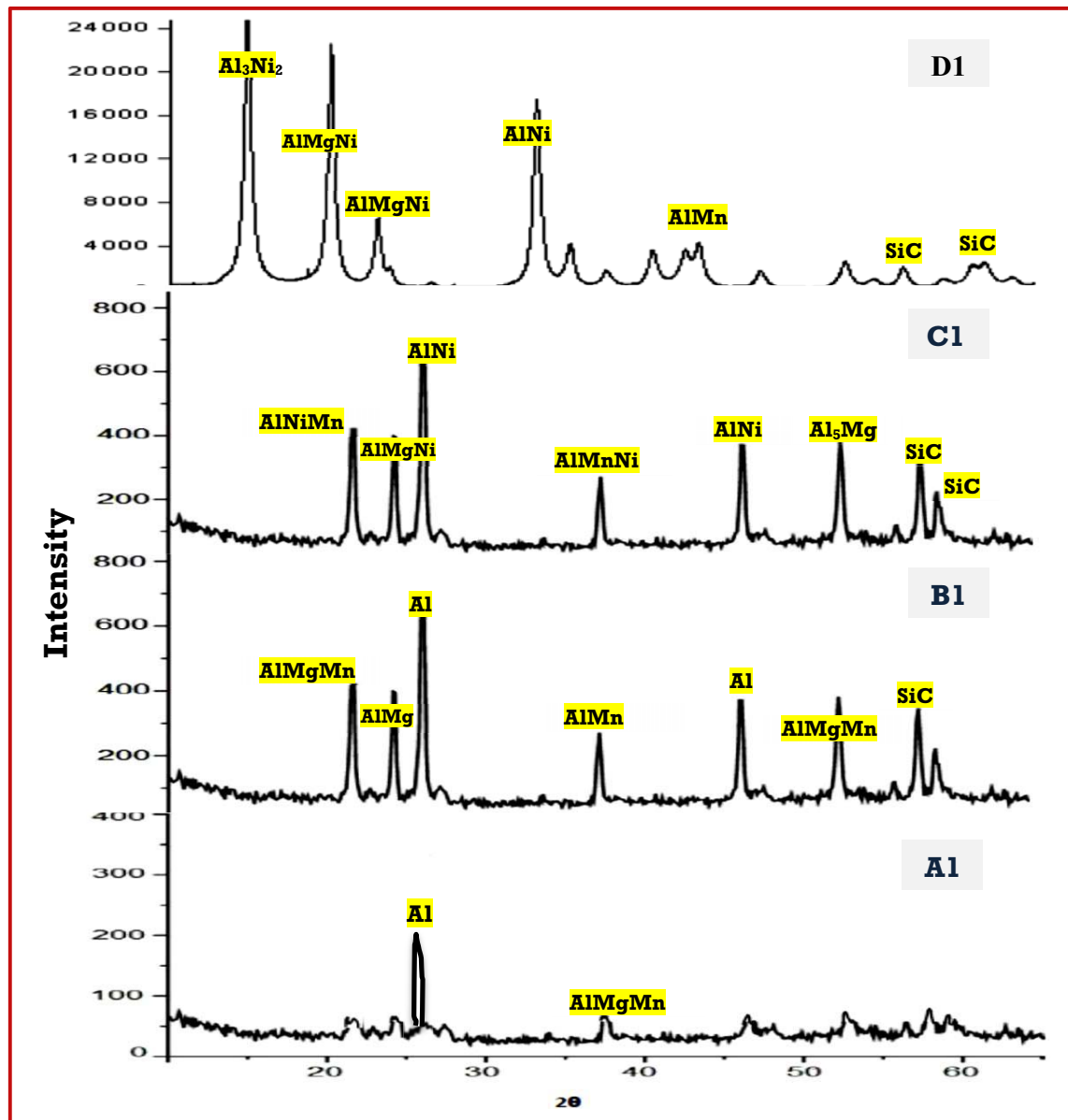


Figure 6: XRD analytic for the A1, B1, C1 and D1 samples undergoing sintering at 600 °C/1.5 h

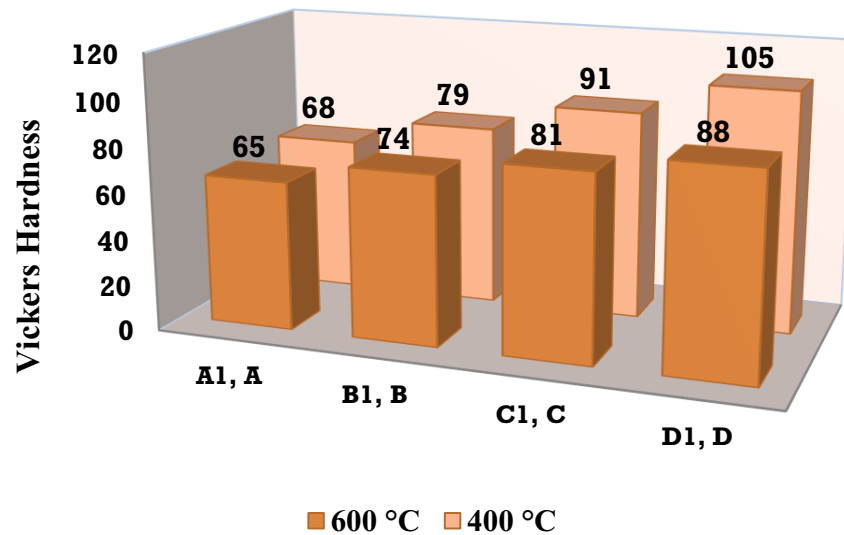


Figure 7: Vickers hardness values of different Al-composites undergoing sintering treatment at 400 °C and 600 °C

4. Conclusion

In this research, powder metallurgy was used to synthesise nickel particles combined with silicon carbide particles within aluminium-magnesium-manganese matrix alloys under sintering conditions of 400 °C and 600 °C for 1.5 hours at a constant heating rate of 50 °C/min. The Al-Mg-Mn-SiCp/Nip samples were evaluated and characterised using a scanning electron microscope and X-ray diffraction. The samples were also measured for Vickers hardness. Microstructural observations showed that after sintering treatment, the compacted Al-Mg-Mn-SiCp/Nip matrix had more precipitation particles with Ni-inter metallics in the sintered Al-matrix. Meanwhile, the Al-PM matrix was free from defects. The results demonstrate that the optimal sintering temperature on the Al-Mg-Mn-SiCp/Nip sample was 400 °C compared with 600 °C because the overall dissolutions of alloying elements within the Al-matrix led to the enlargement of grains, thus, reducing their mechanical properties.

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