The Effects of Binders on the Strength and Hardness of Aluminium (Al) and Silicon Carbide (SiC) Particulates

By

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Abstract
This paper investigates the effects of sodium silicate and polyvinyl acetate as suitable binders for an aluminium-silicon carbide metal matrix composite (MMC). 20 wt % silicon carbide in 80 wt % aluminium matrix composite was used for the study. 15 wt %, 10 wt %, 5 wt % and 1 wt % of Na2SiO3 was added to the MMC, compacted and sintered. Subsequently, the sintered products were subjected to tensile and hardness tests on a Hundsfield extensometer. The procedure was repeated for polyvinyl acetate as the binder, instead of sodium silicate. The results of the investigation show that the strength and hardness of all the samples investigated decreased with increasing percentages of either of the binders. Comparatively, the strength and hardness characteristics of the MMC with polyvinyl acetate were better than those of the same composite with sodium silicate as binder.

Keywords: Composite, strength, hardness, binder, green compacts.

Introduction
Composite materials are a result of the continuous attempts to develop new engineering materials with low weight to strength ratio and improved properties. They are important engineering materials due to their outstanding properties (Sujit Das et al., 2011). According to Chawla (2003), “a composite material is a material consisting of two or more physically and/or chemically distinct, suitably arranged or distributed phases, having characteristics different from those of any components in isolation”. In general, composite materials, whether metal-matrix, ceramic-matrix, polymer-matrix or intermetallic-matrix, have the potential to be the next generation of matrix for application at high temperatures (Chang and Kao, 1994).

The basic attributes of metals reinforced with hard ceramic materials (such as in the case of Al-SiCp MMC) or fibres are improved strength, stiffness, creep and
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fatigue resistance (Adem et al., 2006). They also exhibit increased hardness, wear and abrasion resistance, combined with the possibility of higher operating temperatures than the unreinforced metal or competing reinforced plastics (Eckold, 2001). Metal matrix composites are one of the widely known composites because of their superior properties such as high strength, hardness, light weight, stiffness, wear and corrosion resistance (Palash et al., 2007). These properties offer potentials for exploitation in a range of pump and engine applications, including compressor bodies, vanes and rotors, piston sleeves and inserts, connecting rods, and so forth (Adegbenjo, 2002).

The interface region in a composite is important in determining its ultimate properties (Chawla, 2003). One major problem that plagues the successful compounding of composites is the choice of a suitable binder required to hold the components together (Cheng et al., 2006), hence, the need for this study. Binders are polymer or colloids that absorb on particle surfaces and promote interparticle bridging or flocculation (Kok, 2005, Cheng et al., 2006). They are used to impact strength to a green or unfired ceramic body for handling and green machining (Chawla, 2003).

Different attempts had been made in the last two decades to find suitable binders for the Al-SiCₚ composite to enhance its properties. Chiou (1993) observed that incorporating acid phosphate as binder in the composite system resulted in improved temperature resistance, higher compressive strength and better machinability while Sujit Das et al. (2011) posited that the addition of SiC particles to Al-SiCₚ composite blended with zinc stearate binder led to a reduction in the ductility of the composite and as such enhanced its machinability. However Rack (2002) submitted that if we can predict the behaviour of any given composite accurately, then we can have confidence that the material we have designed will meet the service requirements of the application concerned.

In the present study, a modest attempt has been made to investigate the effects of sodium silicate and polyvinyl acetate binders on the strength and hardness of the developed aluminium based silicon carbide particulate MMCs.

**Experimental Details**

**Materials:** The materials used in this study include silicon carbide particle (SiCₚ) fines, aluminum particle fines and binders (Polyvinyl Acetate, Sodium Silicate) were all sourced locally. A Mettler chemical balance with maximum design capacity of 151 g and an accuracy of 0.0001 g was used for weighing SiC and aluminium particle fines. The composition used was 20 wt % SiC and 80 wt % Al matrix. Four mixes were prepared to which 15 wt %, 10 wt %, 5 wt % and 1 wt % sodium silicate was added to the first, second, third, and fourth mixes respectively. Similar mixes were also prepared but using polyvinyl acetate as binder instead of sodium silicate. In each case, compounding of composite components was carried out with a hand (manual) mixer. The particle fines and the binders were mixed together and stirred mechanically to effect proper blending of the particles; this was carried out in a plastic film container. Tumbling and
scooping of the mixtures were done so that particles would be given the chance of relocating themselves within the mixture. The mixing was a dry blending process without lubricant.

Subsequently, the green composite was compacted on a laboratory hydraulic press using cylindrical steel die and steel punch. Both the punch and die were lubricated with virgin SAE 40. The procedure for preparing the green compact of the mixes involved three steps viz; filling of the die with the particles and binder mixture, application of a compressive force of 20 metric tons and final ejection of the green compact from the die. Sintering was done at a temperature of 600°C in a muffle furnace in order to obtain the solid aluminium matrix composite.

**Characterization:** Three samples were characterized under the scanning electron microscope to show the distribution of phases in the microstructures. The micrographs were taken at a magnification of ×366. The surface distributions of two samples were also characterized.

**Hardness Testing:** The samples were first ground on the hand grinder using different grades of the emery paper (240, 320, 400 and 600) grits to effect an even distribution of the surface. Brinell hardness test was carried out on the samples with a steel ball indenter 5 mm in diameter. Loads were held on samples for 15 s before readings were taken. The diameters of indentation were read off using the microscope’s calibrated hand lens. The Brinell’s Hardness Value (BHN) is given by

\[
BHN = \frac{2P}{\pi D (D - \sqrt{D^2 - d^2})}
\]

Where \( P \) = Applied Load (kgf)
\( D \) = Diameter of Ball Indenter
\( d \) = Diameter of Indentation on Sample

**RESULTS AND DISCUSSION**

The results of this investigation show that the load carrying capacity of the Al-SiC\(_p\) MMC increases as the percentage of the proportions of the various binders investigated decreases (Table 1). This is not surprising as Chiou and Chung (1993) observed that the determining parameters for the compressive strength of Al-matrix reinforced with SiC particles are the relative amount of the binder and the relative reactivity between the SiC\(_p\) and the binder. It could then be explained from the foregoing that the amount of binder used in this study affects the strength within the composite system in an inverse relationship. This is also consistent with the findings of Thurnauer (1990) that not more than three percent binder is required for optimum strength in a composite system.

The samples with sodium silicate as binder had a higher load carrying capacity (strength) as compared with the samples with polyvinyl acetate as binder because sodium silicate offered better bond strength to the composite system than polyvinyl acetate (Fig. 1). It follows then on one hand that sodium silicate binder must have had a stronger chemical reactivity with SiC particles than that which is obtainable with polyvinyl acetate. On the other hand, the difference in strength properties obtained with the binders (sodium silicate and polyvinyl...
acetate) was due to the more uniform binder distribution in the composite made with sodium silicate binder. These assertions are consistent with the findings of Chiu and Chung (1993) when they used silica and phosphate binders in Al-SiC, MMC. This was further corroborated by Sujit Das et al. (2010) that uniformity in binder distribution increases composite strength and machinability. The composite with sodium silicate binder had a fairly constant load bearing capacity of 1.90 KN but 1.99 KN at 1 wt % composition of binder. The load bearing capacity of the composite increased steadily with polyvinyl acetate binder between 1.00 and 1.70 KN.

The hardness of the composite increased as the percentage of binders added to the system decreased (Table 1). The control sample in sintered condition showed a fine microstructure (Fig.3 (a)). This is an indication that it had the highest resistance to crack propagation which served as crack growth arrester, evident in the observations made on the samples after the removal of load. This is in line with the submission of Pfeifer (2001), that the toughness of MMCs depend on the matrix alloy composition and microstructure, the reinforcement type, size, orientation and processing in so far as it affects microstructural variables such as distribution of reinforcement, porosity and segregation.

In general, the hardness values of all the samples increased as the percentages of the binders used decreased (fig. 2). This could be explained from the fact that using more percentages of binder decreases bond strength as more pores/voids were produced as the binder percentage added increased (Sujit Das et al., 2010). These pores could be due to the binders being burnt up during the sintering process. Reduction in void content expectedly affected mechanical properties significantly, as higher void contents usually mean greater susceptibility to water penetration, weathering and increased variation in strength properties (Lawrence and Richard, 2005). The sample with 15 wt % polyvinyl acetate shattered during testing, so its hardness value could not be determined. The sample with 1 wt % polyvinyl acetate however had the highest hardness value; this stems from its microstructure having not as much voids as obtained in the sample with sodium silicate ( Figs. 3 (c) and 3 (b) ).

On the other hand, it could be that nearly all the polyvinyl acetate (being a thermoplastic) got burnt and escaped before or at the sintering temperature giving rise to higher packing density and better bonding between the aluminium grains. The sample with sodium silicate had the coarsest microstructure and contained more pores when compared with samples containing 1 wt % polyvinyl acetate. The pores were probably due to insufficient compaction pressure or it is possible that all the sodium silicate had escaped after sintering leaving behind voids. If all did not escape however, then it could be that the void left behind by the escape of water in the silicate is partly responsible for the drop in hardness. The possibilities of bonding within the composite system could be between (i) the aluminium grains and SiC, (ii) the aluminium grains themselves through diffusion and (iii) the SiC / SiC in close proximity.
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proximity which is doubtful because the sintering temperature involved may not be able to influence diffusion between SiC particles and where they exist together may give room to brittleness. Then the drop in hardness could also probably be due to poor bonding between the silicate left behind and the aluminium matrix which could lead to the brittleness of the composite matrix. The sintered control sample (without binder) had 430 BHN and was able to withstand an applied load of 2.80 KN; its microstructure is as shown in Fig. 3(a). As mentioned earlier, it has a very finely distributed microstructure from which it achieved its high load carrying capacity, because bond strength was enhanced due to the proximity of its particles. The distribution of the surface of the samples with polyvinyl acetate and sodium silicate were also characterized and are shown in Figs. 4 (a) and (b) respectively in which a finer surface distribution was obtained with sodium silicate as binder from which it achieved the high hardness values as depicted (Fig. 2).

Conclusion
The results obtained in this research show that the strength and hardness values of the Al and SiC composite increased with decreasing percentages of the binders added. However, these properties of the composite maximized at 1 wt % composition of the binders in the composite system. Comparatively, the strength and hardness characteristics of the developed MMC with polyvinyl acetate were better than those of the same composite with sodium silicate as binder.

Table 1: Values of hardness and applied load with different percentages of binders

<table>
<thead>
<tr>
<th>Sample</th>
<th>Applied Load (KN)</th>
<th>Diameter of Indentation d(mm)</th>
<th>BHN</th>
<th>Observation on removing load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control 1 (Not sintered)</td>
<td>1.85</td>
<td>3.0</td>
<td>235.55</td>
<td>Crack opening on the surface</td>
</tr>
<tr>
<td>Control 2 (sintered)</td>
<td>2.08</td>
<td>2.4</td>
<td>430.57</td>
<td>No crack observed on the surface</td>
</tr>
<tr>
<td>15% binder G₄</td>
<td>1.00</td>
<td>-</td>
<td>-</td>
<td>Shattered</td>
</tr>
<tr>
<td>10% binder G₃</td>
<td>1.25</td>
<td>4.1</td>
<td>74.43</td>
<td>Cracked with opening</td>
</tr>
<tr>
<td>5% binder G₂</td>
<td>1.40</td>
<td>3.2</td>
<td>153.92</td>
<td></td>
</tr>
<tr>
<td>1% binder G₁</td>
<td>1.70</td>
<td>2.8</td>
<td>252.41</td>
<td>A thin line of crack on surface</td>
</tr>
<tr>
<td>15% binder C₄</td>
<td>1.90</td>
<td>3.5</td>
<td>169.26</td>
<td></td>
</tr>
<tr>
<td>10% binder C₃</td>
<td>1.90</td>
<td>3.4</td>
<td>151.35</td>
<td></td>
</tr>
<tr>
<td>5% binder C₂</td>
<td>1.90</td>
<td>3.2</td>
<td>208.88</td>
<td></td>
</tr>
<tr>
<td>1% binder C₁</td>
<td>1.99</td>
<td>3.2</td>
<td>218.78</td>
<td>A very thin crack observed on the surface</td>
</tr>
</tbody>
</table>

C- sodium silicate; G-polyvinyl acetate.
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Fig 1: Graph of applied load against the percentage of binders

Fig 2: Graph of hardness against the percentage of binders
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Fig 3: Microstructure of the prepared aluminium based composite with different binders (X366)
(a) as prepared (b) with sodium silicate (c) with polyvinyl acetate

Fig 4: Surface distributions of different binders in aluminium matrix
(a) with polyvinyl acetate (b) with sodium silicate

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