TRIBOLOGICAL PROPERTIES OF ALUMINIUM MATRIX NANOCOMPOSITES

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Abstract:
The paper provides an overview of tribological properties of nanocomposites with aluminium matrix. Nanocomposites represent a new generation of composite materials with better properties than conventional composite materials. The paper presents and explains the most common methods of nanocomposites production. In addition, the overview of tribological properties is presented through the equipment used for testing; amount, size and type of reinforcement; matrix material and manufacturing process; and test conditions.

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KEYWORDS
Aluminium, nanocomposites, manufacturing process, tribological properties.

1. INTRODUCTION

Intensifying demands in terms of increasing life service and reducing weight, and thus the prices of products, initiate the development and application of new materials. The increased use of composite materials is primarily due to their physical-mechanical and tribological properties that are better than the properties of the matrix material [1,2].

Due to its good characteristics, such as low density, good thermal conductivity and corrosion resistance, relatively low cost of production and good possibility of recycling, aluminium and its alloys are most often used as composite matrix [3,4]. Composite materials with aluminium alloys base are increasingly used in the aviation, aerospace, automotive and military industry. They are used for production of engine blocks, cylinder liners, connecting rods crankshafts, camshafts, cardan shafts, propellers of helicopters, as well as for production of brake discs and drums of cars and trains [5-15].

The improvement in mechanical and tribological properties of the aluminium composites is made by adding the appropriate reinforcements and improvers. Commonly used reinforcements are carbides, borides, nitrates, and oxides, i.e. Al₂O₃, SiC, TiC, TiO₂, B₄C, TiB₂, WC and others [16-18]. The choice of size and amount of reinforcement depends on the manufacturing process as well as on the practical application of composite material. By adding two or more reinforcements to the matrix material, a hybrid composite is obtained. However, in recent years, there is a trend of using the nanoscale reinforcements and production of nanocomposites [19-21].

This paper gives the overview of tribological properties of modern nanocomposites with aluminium matrix, with certain trends concerning test condition parameters influences. Classification of tribological properties was carried out on the basis of matrix material, amount, type and size of reinforcements, and manufacturing process as well as on the basis of counter-body material and equipment on which the test is conducted, together with the test conditions (sliding speed, load, and sliding distance). Our review is limited to studies with unlubricated sliding conditions conducted in the air, at room temperature.

2. MANUFACTURING PROCESS

The process for preparing nanocomposite materials based on aluminium base can be divided into three groups [22,23]:

- solid state processes include different powder metallurgy techniques with modifications in the processing steps such as high-energy ball milling, hot pressing, hot...
isostatic pressing, cold pressing followed by sintering treatment and extrusion;
- liquid state processes include different casting processes such as stir casting and squeeze casting;
- semi-solid processes include rheocasting technique with its variants such as compocasting or in combination with squeeze casting.

Mechanical milling is a process of milling the powder mixture by different methods. All these methods are based on the same principle of insertion of particulate material to the mill where they are subjected to high-energy collision with other particles and with the added steel balls that accelerate the procedure. The example of mechanical milling is presented through the research conducted by Sharifi and Karimzadeh [19]. They produced aluminium matrix nanocomposites by mechanical milling, followed by hot pressing. Aluminium powder with average particle size of 60 μm was milled with various amounts (5, 10 and 15 wt. %) of Al₂O₃–AlB₂ nanopowders (average particle size ranging from 50 to 120 nm). Ball milling was carried out at rotation speed of 600 rpm and the ball-powder mass ratio was 10:1, for 5 h without interruption. The used steel balls were made of chrome-plated steel with a diameter of 20 mm. To prevent oxidation, the process was carried out under an argon atmosphere.

Stir casting represents a process very similar to the conventional casting method. The difference is that in stir casting there is a light stirring of the melt in order to obtain the equal distribution of the reinforcement in the matrix. Infiltration of the nanoparticles is performed into the overheated melt, with stirring in order to attain their favourable distribution. Compocasting method is similar to the stir casting method and the main difference is that the matrix is in semi-solid, not in liquid state. Basically, it is a variant of rheocasting or thixocasting method applied for composite production [6].

Muley et al. [21] studied aluminium based hybrid nanocomposites obtained by stir casting process, where the reinforcements were SiC and Al₂O₃ nanoparticles added in equal ratios (0.5, 1, 1.5 and 2 wt. %). The average size of nanoparticles was 25 – 50 nm (SiC) and 40 nm (Al₂O₃). The nanoparticles were preheated, in order to be free from moisture and to improve wettability with matrix alloy, and feed into crucible containing matrix alloy at the temperature of about 10 – 20 °C above its melting point. The stirring, with low carbon steel stirrer, was carried out at constant speed of 400 rpm for 4 – 5 min. To avoid oxidation, they carried out the whole process under an argon environment.

Friction stir processing is a solid state processing technique which has been used for the fabrication of a surface composite on aluminium substrates, and the homogenization of powder metallurgy aluminium alloys, metal matrix composites, and cast aluminium alloys. This technique is based on friction stir welding, with the aim to obtain a surface layer without porosity, with homogeneous distribution of reinforcement particles in matrix and strong bonding between reinforcements and matrix. It produces localized microstructural modification for specific property enhancement [24]. For example, Anvari et al. [25] applied friction stir processing on aluminium alloy plate coated with Cr₂O₃ powder by the atmosphere plasma spray process. Due to thermomechanical condition, Cr₂O₃ was reduced with aluminium so that pure Cr and Al₂O₃ were produced and, as a result of reaction between Al and Cr, some intermetallic compounds were obtained. As a final result, an Al–Cr–O nanocomposite was produced on the surface of Cr₂O₃ coating.

3. TRIBOLOGICAL PROPERTIES OF ALUMINIUM MATRIX NANOCOMPOSITES

There are many factors influencing tribological properties of nanocomposites. In this paper, an overview of literature data on nanocomposites with aluminium matrix is presented. Only the studies conducted in unlubricated sliding conditions, in the air, at room temperature, were analysed. Even those studies where the surrounding conditions (surrounding medium and its temperature) were not stated were analysed, assuming that they were conducted in the air, at room temperature.

The overview is given through the presentation of the main influencing factors such as: matrix material, type, amount and size of reinforcement, and the production process. In addition, testing conditions and obtained values of coefficient of friction and wear are also presented, together with the method used for materials characterisation (Table 1).

To compare the obtained tribological results is not an easy task. Aside from the influence of different aluminium alloy matrix materials and nanocomposite production process, the type, amount and size of reinforcements differ a lot and make the comparison difficult. In addition, testing conditions (type of contact and sliding direction, counter-body, sliding speed, load and sliding distance) in the analysed studies varied.
Table 1. Tribological properties in dry sliding of aluminium based nanocomposites and the performed analyses

<table>
<thead>
<tr>
<th>Powder metallurgy</th>
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<tbody>
<tr>
<td>Reference</td>
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<tr>
<td>Sharifi and Karimzadeh [19]</td>
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<tr>
<td>Apparatus</td>
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<tr>
<td>Matrix material</td>
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<tr>
<td>Reinforcement</td>
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<tr>
<td>Reinforcement amount</td>
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<td>Reinforcement size</td>
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<tr>
<td>Production process</td>
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<tr>
<td>Sliding speed</td>
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<tr>
<td>Load</td>
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<tr>
<td>Sliding distance</td>
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<tr>
<td>Coefficient of friction</td>
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<tr>
<td>Total wear</td>
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<td>Analyses</td>
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<table>
<thead>
<tr>
<th>Powder metallurgy / Friction stir processing</th>
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<tr>
<td>Apparatus</td>
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<tr>
<td>Matrix material</td>
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<tr>
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<tr>
<td>Reinforcement size</td>
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<tr>
<td>Production process</td>
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<tr>
<td>Counter-body</td>
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<tr>
<td>Sliding speed</td>
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<tr>
<td>Load</td>
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<tr>
<td>Sliding distance</td>
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<td>Coefficient of friction</td>
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<tr>
<td>Total wear</td>
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<tr>
<td>Analyses</td>
</tr>
</tbody>
</table>

Gr – graphite; GNP – graphene nanoplatelets; CNT – carbon nanotubes; OM – optical microscopy; SEM – scanning electron microscopy; EDS – energy dispersive spectroscopy; XRD – X-ray diffraction; AFM – atomic force microscopy
Table 1. Continued

<table>
<thead>
<tr>
<th>Reference</th>
<th>Apparatus</th>
<th>Matrix material</th>
<th>Reinforcement</th>
<th>Reinforcement amount</th>
<th>Reinforcement size</th>
<th>Production process</th>
<th>Counter-body</th>
<th>Sliding speed</th>
<th>Load</th>
<th>Coefficient of friction</th>
<th>Total wear</th>
<th>Analyses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anvari et al. [25]</td>
<td>Cylinder-on-plate</td>
<td>6061 (AlMg1SiCu)</td>
<td>Particles: Cr + Al₂O₃</td>
<td>/</td>
<td>/</td>
<td>Friction stir</td>
<td>Cylinder: AISI 52100 steel</td>
<td>0.14 m/s</td>
<td>10 N</td>
<td>0.17</td>
<td>0.005 – 0.01 mg/m</td>
<td>SEM, EDS, XRD, TEM</td>
</tr>
<tr>
<td>Maurya et al. [33]</td>
<td>(reciprocating motion)</td>
<td>6061 (AlMg1SiCu)</td>
<td>Particles: Gr; CNT; G</td>
<td>/</td>
<td>/</td>
<td>Friction stir</td>
<td>Ball: Stainless steel</td>
<td>0.5 mm/s</td>
<td>5 N</td>
<td>0.30 – 0.53</td>
<td>3 – 8 × 10⁻⁵ mm/s²/m</td>
<td>SEM, EDS, XRD, TEM</td>
</tr>
<tr>
<td>Vatankhah Barenji et al. [34]</td>
<td>Ball-on-disc (reciprocating motion)</td>
<td>6061 (AlMg1SiCu)</td>
<td>Particles: Al₂O₃ + TiB₂ (35/65 wt. %)</td>
<td>/</td>
<td>/</td>
<td>Friction stir</td>
<td>Disk: GCr15 steel (55 HRC)</td>
<td>0.5 m/s</td>
<td>50 N</td>
<td>0.28 – 0.54</td>
<td>approx. 4 × 10⁻³ mg/m</td>
<td>OM, SEM, XRD</td>
</tr>
<tr>
<td>Eskandari et al. [35]</td>
<td>Pin-on-disk</td>
<td>8026</td>
<td>Particles: TiB₂; Al₂O₃; TiB₂ + Al₂O₃ (40/60 wt. %)</td>
<td>/</td>
<td>/</td>
<td>Friction stir</td>
<td>Disk: Steel (60 HRC)</td>
<td>0.5 m/s</td>
<td>15 N</td>
<td>/</td>
<td>2.0 – 6.8 × 10⁻³ mg/m</td>
<td>OM, SEM, TEM</td>
</tr>
</tbody>
</table>

**Note:**
- SEM – scanning electron microscopy
- EDS – energy dispersive spectroscopy
- XRD – X-ray diffraction
- TEM – transmission electron microscopy
- ANN – artificial neural network

**References:**
- Veličković et al. [1]
- Lekatou et al. [36]
- Friction stir processing
- Stir casting
- Ekka et al. [39]

**Materials:**
- Gr – graphite
- G – graphene
- CNT – carbon nanotubes
- OM – optical microscopy
- SEM – scanning electron microscopy
- EDS – energy dispersive spectroscopy
- XRD – X-ray diffraction
- TEM – transmission electron microscopy
- ANN – artificial neural network

**Apparatus Details:**
- Ball-on-disk
- Sphere-on-disc
- Pin-on-disk

**Matrix Materials:**
- 1050 (Al99.5)
- Aluminium
- A356 (AlSi7Mg)
- 7075 (AlZn5.56MgCu)

**Reinforcement:**
- TiC; WC
- TiB₂ + Al₂O₃
- TiB₂; TiO₂
- Al₂O₃; SiC

**Production Process:**
- Stir casting
- Disc: SAE 440 stainless steel
- Pin: 100Cr6 steel (62 HRC)

**Counter-body:**
- Ball: AISI 5210 steel
- Disc: SAE 440 stainless steel
- Pin: 100Cr6 steel (62 HRC)

**Load:**
- 1 N
- 700 MPa
- 10 – 40 N (0.13 – 0.53 MPa)
- 35, 55 and 75 N (0.7, 1.1 and 1.5 MPa)

**Sliding Distance:**
- 1000 m
- 1 m
- 1000 m
- 1200 m
Table 1. Continued

<table>
<thead>
<tr>
<th>Reactive casting / Squeeze casting</th>
<th>Reactive casting</th>
<th>Infiltration (squeeze casting)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Reference</strong></td>
<td>Kalashnikov et al. [40]</td>
<td>Babu et al. [41]</td>
</tr>
<tr>
<td><strong>Apparatus</strong></td>
<td>Pin-on-disc</td>
<td>Pin-on-disc</td>
</tr>
<tr>
<td><strong>Matrix material</strong></td>
<td>Aluminium (Al99.3)</td>
<td>A356 (AlSi7Mg)</td>
</tr>
<tr>
<td><strong>Reinforcement</strong></td>
<td>Particles: Ti + Ni + W / TiCN / W–C</td>
<td>Fibres: Gr + Al2O3</td>
</tr>
<tr>
<td><strong>Reinforcement amount</strong></td>
<td>3 wt. % Ti + 3 wt. % Ni + 0.25 wt. % W / 0.25 wt. % TiCN / 0.25 wt. % W–C</td>
<td>10, 15 and 20 vol. %</td>
</tr>
<tr>
<td><strong>Reinforcement size</strong></td>
<td>Ti (100 μm); Ni (20 μm); W (50 nm); TiCN (30 nm); W–C (30 nm)</td>
<td>Gr (0.05 × 10 μm); Al2O3 (3 × 120 μm)</td>
</tr>
<tr>
<td><strong>Production process</strong></td>
<td>Reactive casting</td>
<td>Infiltration</td>
</tr>
<tr>
<td><strong>Counter-body</strong></td>
<td>Disc: EN C45 steel</td>
<td>Disc: SUS 304 stainless steel</td>
</tr>
<tr>
<td><strong>Sliding speed</strong></td>
<td>0.39 m/s</td>
<td>240, 360 and 480 rpm</td>
</tr>
<tr>
<td><strong>Load</strong></td>
<td>18 – 60 N</td>
<td>10, 30 and 50 N (0.2 – 1 MPa)</td>
</tr>
<tr>
<td><strong>Sliding distance</strong></td>
<td>350 m</td>
<td>1000, 3000 and 5000 m</td>
</tr>
<tr>
<td><strong>Coefficient of friction</strong></td>
<td>/</td>
<td>0.52 – 0.62</td>
</tr>
<tr>
<td><strong>Total wear</strong></td>
<td>4 – 37 × 10^3 mm^3/m</td>
<td>8 – 50 × 10^6 mg/m</td>
</tr>
<tr>
<td><strong>Analyses</strong></td>
<td>SEM, EMPA</td>
<td>SEM, EDS, Taguchi</td>
</tr>
</tbody>
</table>

Gr – graphite; SEM – scanning electron microscopy; EDS – energy dispersive spectroscopy; EPMA – electron probe microanalysis

For example, sliding speeds were in the range from 1 mm/s to several m/s, and applied loads from 0.1 MPa to several hundreds MPa, and it is well-known that coefficient of friction and especially wear depend very much on these conditions. The important thing to note is that many authors did not present all the experimental details and that some of them even made mistakes in presenting the results. The obvious mistakes were corrected, while the presenting of testing conditions and results was uniform as much as it was possible.

The majority of studies were conducted by the authors from India and Iran, and powder metallurgy was the most popular process for nanocomposite production. Friction stir processing was also a commonly used technique for nanocomposite production, which was surprising since this is a relatively new technique. Particles’ reinforcements were used far more often than other types of reinforcements, since they are cheaper to produce in most cases. Among them, ceramic particles such as Al2O3, SiC, TiC, TiO2 and TiB2 prevailed, but graphite and some new reinforcements like graphene and carbon nanotubes were also used.

The amount of nanosized reinforcing ceramic particles was usually up to 5%, but was is also noticed that it can be up to 10%. Nevertheless, these amounts were lower than the amounts used for the micro-sized reinforcing particles, which can be up to 20% [9].

The geometry of samples and type of contact in most of the studies were flat and conformal (surface) contact, which indicates the possible applications of these materials. Non-conformal (line and point) contacts are not recommendable since in these cases there is a possibility that the contact would be in the region without nanoparticles (or with reduced amount), especially if they are not well distributed over the surface. Concerning the performed analyses for materials characterisation, scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS) were set as “standard” methods, as it was the case with characterisation of microcomposites. On the other hand, the use of transmission electron microscopy (TEM) was more often the characterisation of nanocomposites. This was expected since structural phenomena in nanocomposites occur at nanolevel.
3.1 Coefficient of friction

The coefficient of friction values obtained in different studies were easier to compare than the wear values, because the coefficient of friction in unlubricated sliding conditions is less dependent on testing conditions such as normal load and sliding speed. Its value was mainly in range from 0.2 to 0.6. Thus, with the increase of load, the coefficient of friction in some cases increases [29] or decreases [38], but, in most cases, it remains more or less constant [27,30,31,41]. The same happens with the change of sliding speed, i.e. with its increase, the coefficient of friction is more or less constant [30,41]. This is in accordance with the classical theory for metals in unlubricated sliding, which states that the coefficient of friction is independent of normal load and sliding speed.

The increase in the amount of hard particles/fibre reinforcements did not influence the coefficient of friction in the significant manner, so that the coefficient remained more or less constant [19,41]. Only in some cases it increased [38] or slightly decreased [29]. This is not in correlation with the microcomposite behaviour, since the increase in hard reinforcement amount in microcomposite decreases the coefficient of friction [6]. In microcomposite, this decrease occurs with the amounts higher than 15 to 20 %, so this could be the explanation, since in analysed nanocomposites the amount of hard reinforcement was smaller. On the other hand, the influence of graphite/graphene addition was in correlation with the microcomposite behaviour [5], i.e. the addition of graphite/graphene decreased the coefficient of friction of the matrix alloy [31-33].

3.2 Wear

Unfortunately, different authors have led investigations under different conditions, and this makes comparison of their results very difficult. In addition, wear values were often presented in different way, i.e. through the mass wear rate, volume wear rate or wear factor. A possible solution to the comparison of results would be a construction of wear mechanism maps [42], as it is the case with aluminium matrix microcomposites [43,44]. The increase of normal load induced higher wear in all analysed studies [19,26-31,38-41], which was expected and in accordance with the theory. On the other hand, there is no general rule for the influence of sliding speed on the wear value, i.e. higher sliding speeds were associated with a slight increase [30] of the wear value, its decrease [39], or did not show a significant influence on the wear value [41].

With the increase in the hard particles/fibre reinforcements’ amount, wear value mainly decreased [19,27,29,31,36], which was expected and in correlation with microcomposites behaviour [6], although there were cases when wear increased [32,38] or was more or less constant [39]. The increase of the wear value was attributed to the higher porosity [38], or absence of the lubrication effect of graphite particles which were also added to the nanocomposite [32]. Generally, the initial addition of graphite/graphene decreases wear value of the matrix alloy [26,31-33], and with further increase of the graphite/graphene this effect is less obvious. This is also in correlation with the microcomposite behaviour [6].

4. CONCLUSIONS

Comparing the tribological properties of aluminium matrix nanocomposites, obtained in different studies, certain conclusions can be drawn:

- First of all, composites with added nanosized reinforcement generally have lower coefficient of friction and higher wear resistance than unreinforced matrix alloys.

- Powder metallurgy is the most popular process for nanocomposite production and particles reinforcements are used far more often than other types of reinforcement.

- Ceramic particles such as Al₂O₃, SiC, TiC, TiO₂ and TiB₂ prevail as reinforcements, but graphite, graphene and carbon nanotubes are also used. The amount of reinforcement is usually up to 5 %.

- The coefficient of friction values were mainly in the range from 0.2 to 0.6, and were not significantly affected by the applied normal load, sliding speed or amount of hard particles/fibre reinforcements. On the other hand, addition of graphite/graphene decreased coefficient of friction of the matrix alloy.

- Wear values were higher for higher loads in all analysed studies, while there was no general rule for the influence of sliding speed on wear value. With the increase in hard particles/fibre reinforcements’ amount and with the addition of graphite/graphene wear value mainly decrease.

- The application of aluminium matrix nanocomposites is mainly for tribological pairs with conformal contact, since most of the studies simulated this type of contact. Characterisation of the worn surfaces was mainly performed with SEM and EDS analysis.
ACKNOWLEDGEMENT

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