1. Introduction

At present, when humanity becomes increasingly aware that preservation and protection of human environment, as well as conservation of energy, are the ultimate must, this holds for all and every branch of industry, including the automotive. Along with the severe market challenges, requests for energy consumption reduction and raise of efficiency, it faces the ecology caused legal barriers. Europe, USA and Japan are the world leaders on this matter, and include the need for recycling as one of the best ways of natural resources preservation.

Annually, globally, about 18 millions of vehicles reach the end of their life cycles. If all of these were disposed as waste, this would equal 20 million tons (or 70 million cubic meters of volume) of new solid waste per year /1/.

Present tendency is to decrease the percent of vehicles mass apt to be disposed as waste or combusted without energy regeneration, so e.g. Europe plans to reduce it from 15 % in year 2002. - to 5 % in year 2015.

Reduction of friction and wear in vehicles' motive components is a way of energy
consumption and preservation of natural resources. According to some US government projects, reduction of friction and wear in engines and drive train components would save to US economy 120 billions dollars per year /2/.

Satisfaction of the outlined requests calls for introduction of new materials and technologies of parts production in the automotive industry. New materials must have appropriate physical, mechanical and tribological properties as well as low price, which is the main reason for not applying in automotive industry several materials that are used in aerospace and computer industries.

Materials that are mostly investigated and used to replace the massive steel and gray cast iron parts are, light non-ferrous materials, aluminum and magnesium. Density of these materials and their favourable mechanical properties are of great significance for reducing the total mass of a vehicle.

Being able to conserve its density and strength properties during alloying, deforming and thermal treatment, aluminum is increasingly used in the automotive industry. Possibilities of recycling aluminum are good too.

Numerous authors have analysed the possibility of replacing the cylinders and whole engine blocks of gray cast iron by aluminum, and the use of Al alloys in brakes, power transfer systems, pistons and valves /3, 4, 5, 6, 7, 8/.

Unfortunately, aluminum alloys lack the satisfactory tribological properties, so e.g. gray cast iron cylinder liners are still used in engine blocks, which increases the production costs. To overcome this problem, the following activities have been initiated:

- development of coatings with anti-wear properties

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...
New wear resistant Al based materials and their application in automotive industry

- development of new Al alloys – MMCs (Metal Matrix Composites) with Al matrix and various reinforcements, and
- development of new technologies of Al alloys production.

2. Ways of upgrading the tribological properties of Al alloys

Coating is an often used method for upgrading the tribological properties of Al alloys. Coatings are made of anti-wear and thermal stress resistant materials. The particular way used for applying them onto the main material is significant as well, since it influences the properties of the coating itself and bond strength to the main material /9/.

2.1 Composite materials

Composite material is a mixture of two or more materials or phases of the same material, insoluble in one another, possessing properties which are superior to any of the component materials /10/.

Volume fraction of component materials should be above 5 % of total volume and their properties must be different from one another. Usually, volume fraction of one material is significantly higher than the volume fractions of the others and that material is called – matrix. Matrix can be ceramic, metal and polymer.

Reinforcements are usually fibres or particles of different orientation and shape (Fig. 1). The arrangement of the particles can be random, in most cases (Fig. 1a), or preferred, in the shape of sphere, cube or any close-to-regular geometrical form.

A fibrous reinforcements are characterized by its length and diameter so we distinguish, long (continuous) fibres (Figs. 1d and 1e) and short (discontinuous) fibres (Figs. 1b and 1c). Arrangement can be, as
well, preferred (Fig. 1b) and random (Fig. 1c), and often the direction of fibres is changed from one layer to another (Fig. 1e). Hybrids are a newer type of composites and there we have two or more fibre types, or combined fibres and particles, mixed throughout the layers or in the same layer.

Two mostly used reinforcements are alumina (Al$_2$O$_3$) and silicon carbide (SiC), and their basic properties are given in Table 1.

Influence of these two reinforcements upon the mechanical properties of composites is shown in Table 2, by comparing the values for some Al alloys with and without the reinforcements, respectively.

* материалы различных производителей (different manufacturers materials)
New wear resistant Al based materials and their application in automotive industry

Numerous authors have investigated tribological properties of composite Al alloys and, therefore, different influences have been analysed.

First of all, influence of the type and properties of materials was analysed. Aluminium and its alloys: Al-Cu, Al-Si, Al-Mg-Si and Al-Zn were mostly used as the matrix, and SiC and Al₂O₃ of different size and volume fraction were mostly used as the reinforcements. Influence of additives (graphite) and surface roughness was analysed as well.

Aside from analysing the influence of different materials and composite manufacturing processes, investigations were performed on influence of different conditions (pressure, temperature, type of relative motion, with and without the lubricant), and that is summed in Table 3.

Author from Turkey /11/ has used pure aluminium as the matrix, reinforced with different particulate materials. He has analysed the influence of type and volume fraction of the reinforcement, by varying the normal load (50 – 200 N) and the contact temperature (20, 50, 100, 150 and 200 °C). Area of the contact surface was 113 mm². Physical and mechanical properties of the materials tested are given in Table 4.
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<table>
<thead>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>17</td>
<td>Block on ring</td>
<td>2014</td>
<td>Particles SiC (20% and 14 μm)</td>
<td>-</td>
<td>Steel, 63 RC</td>
<td>9.35 N</td>
<td>0.16 m/s</td>
</tr>
<tr>
<td>18</td>
<td>Block on ring</td>
<td>Al-Si-Cu</td>
<td>Particles (5.13, 38 and 50%) SiC (55, 11.5 and 57 μm)</td>
<td>Combination of infiltration and melt stirring</td>
<td>Steel SAE 52100, 63 HRC</td>
<td>Dry</td>
<td>55 N</td>
</tr>
<tr>
<td>19</td>
<td>Pin on disc</td>
<td>Al-9%Si 80 HV30</td>
<td>Particles (20 and 26%) SiC</td>
<td>Gravity poured and centrifugal cast</td>
<td>Nodular cast iron, 149 HV30</td>
<td>Dry</td>
<td>5 N</td>
</tr>
<tr>
<td>20</td>
<td>Pin on disc</td>
<td>Al-12Si</td>
<td>Fibres (58%)Al2O3, (42%)SiO2 (8% and 10-12 x 400-800 μm)</td>
<td>Squeeze casting</td>
<td>Nodular cast iron, 206 HV</td>
<td>Dry</td>
<td>10 - 80 N</td>
</tr>
<tr>
<td>21</td>
<td>Pin on block (oscillating motion)</td>
<td>Al-20Si-3Cu-1Mg 454 HV Ra=1,1 μm</td>
<td>Particles SiC (15% and 6 μm)</td>
<td>Powder metallurgy</td>
<td>Stainless steel, 490 HV, Ra = 1.2 μm</td>
<td>Dry Water</td>
<td>25 - 175 N</td>
</tr>
<tr>
<td>22</td>
<td>Block on ring</td>
<td>Al-12Si</td>
<td>Carbon fibres (0-6% and 6-8 x 2000-4000 μm) and/or Al2O3 fibres (0-12% and 10-14 x 300-700 μm)</td>
<td>Squeeze infiltration</td>
<td>Steel, 62±2 HRC</td>
<td>Dry</td>
<td>49 - 294 N</td>
</tr>
<tr>
<td>23</td>
<td>Sphere on block (oscillating motion)</td>
<td>A356 Ra = 0.25 μm</td>
<td>Particles SiC (20% and 10 μm)</td>
<td>-</td>
<td>Челник, 60 HRC</td>
<td>Dry Boundary</td>
<td>9.8 - 78.4 N</td>
</tr>
<tr>
<td>24</td>
<td>Pin on disc</td>
<td>6061</td>
<td>Fibres SiC (0.05-1.5 x 200 μm) and/or Al2O3 fibres (3 x 500 μm)</td>
<td>Powder metallurgy</td>
<td>SKH 51, 66 RC</td>
<td>-</td>
<td>49 N</td>
</tr>
<tr>
<td>25</td>
<td>Pin on disc</td>
<td>7091</td>
<td>Particles and fibres SiC (2-10 μm and 0.5 x 3 μm)</td>
<td>Powder metallurgy</td>
<td>Steel, 35 RC</td>
<td>-</td>
<td>14.2 N</td>
</tr>
</tbody>
</table>

Table 3 (extension)
Table 3

<table>
<thead>
<tr>
<th>Lit</th>
<th>Apparatus</th>
<th>Matrix material</th>
<th>Type, size and volume of the reinforcement</th>
<th>Production process</th>
<th>Counterpart material</th>
<th>Lubricant, lubrication</th>
<th>Load</th>
<th>Sliding speed</th>
<th>Temperature</th>
<th>Sliding distance / time</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>Pin on disc</td>
<td>Aluminium</td>
<td>Particles 5, 10, 15 and 20% M2C3 (~ 20 μm) 20% SiC (4.2 μm) 20% SiFe 10% Al2O3 (3.9 μm) 10% SiFe – 10% Al2O3</td>
<td>Powder metallurgy</td>
<td>Low alloy steel, 55 HRC</td>
<td>-</td>
<td>5 - 20 N</td>
<td>~ 1 m/s</td>
<td>20, 50, 100, 150 and 200 °C</td>
<td>4000 m</td>
</tr>
<tr>
<td>12</td>
<td>Pin on disc</td>
<td>Aluminium</td>
<td>Steel fibres with and without Cu and Ni coatings (5% and 120 x 350-550 μm)</td>
<td>Casting</td>
<td>Steel, 63 RC</td>
<td>Dry</td>
<td>10, 20, 30 and 40 N</td>
<td>1.8 m/s</td>
<td>Room</td>
<td>2000 m</td>
</tr>
<tr>
<td>13</td>
<td>Oscillating motion tribometer</td>
<td>2024 80-95 HRB</td>
<td>Particles 15, 20 and 30% SiC (3, 5, 10 and 20 μm)</td>
<td>Powder metallurgy</td>
<td>Si3N4</td>
<td>Dry</td>
<td>0.6 - 3.8 MPa</td>
<td>0.01 m/s</td>
<td>-</td>
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</tr>
<tr>
<td>14</td>
<td>Pin on disc</td>
<td>A201 Rm = 0.1 μm</td>
<td>Particles 22.2% Al-Fe-V-Si (75, 150 and 250 μm)</td>
<td>Squeeze casting</td>
<td>Steel, Rm = 0.1 μm</td>
<td>-</td>
<td>15, 25 and 35 N</td>
<td>1.1, 1.5, 2.5 and 3.15 m/s</td>
<td>Room, 200 and 300 °C</td>
<td>6000 m</td>
</tr>
<tr>
<td>15</td>
<td>Sphere on block (oscillating motion)</td>
<td>2618 Rm = 0.6 μm</td>
<td>Particles 15% and 7.5 μm</td>
<td>-</td>
<td>Tempered steel, 797 HV</td>
<td>-</td>
<td>25 N</td>
<td>0.3 m/s, frequency 10 Hz, amplitude 15 mm</td>
<td>20 - 200 °C</td>
<td>2700 m</td>
</tr>
<tr>
<td>16</td>
<td>3 pins on disc</td>
<td>2024 Rm = 0.4 and 2.5 μm</td>
<td>Particles 10% SiC</td>
<td>Powder metallurgy</td>
<td>S45C (UB) steel, 250 HV, Rm = 1.1 and 3 μm and S45C with TiN coating, 2200 HV, Rm = 1.6 μm</td>
<td>Dry</td>
<td>Water bath, Oil film, Oil bath</td>
<td>8.3 MPa</td>
<td>0.02 m/s</td>
<td>20 ± 1 °C</td>
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<td>Номера</td>
<td>Текст</td>
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<td>17</td>
<td>Блок на прстену 2014 Делићи SiC (20% и 14 μm) - Челик, 63 RC Челик SAE 52100, 63 HRC Без 55 N 0,94 m/s - 1800 m</td>
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<td>18</td>
<td>Блок на прстену Al-Si-Cu Делићи SiC (5, 13, 36 и 50%) SiC (5, 11, 15 и 57 μm) Комбинација инфилтрације и мешања у раст Челик SAE 52100, 63 HRC Без 5 N 0,1 - 1,5 m/s 22 - 300 °C 3000 m</td>
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<td>19</td>
<td>Епрувета на диску Al-Si-9% Si 80 HV30 Делићи SiC (20 и 26%) SiC Гравитациона и центрифугално ливење Челик SAE 52100, 63 HRC Без 5 N 0,1 - 1,5 m/s 22 - 300 °C 3000 m</td>
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<td>20</td>
<td>Епрувета на диску Al-12Si Влакна (58%) Al2O3 · (42%) SiO2 (8% и 10-12 x 400-800 μm) Ливење под приписком Челик SAE 52100, 63 HRC Без 10 - 80 N 1 m/s 20 °C 2000 m</td>
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<td>21</td>
<td>Епрувета на блоку (осцилаторно кретање) Al-20Si-3Cu-1Mg 454 HV Ra = 1,1 μm Делићи SiC (15% и 6 μm) Синтеровање Челик SAE 52100, 63 HRC Без 25 - 175 N 0,3, 0,6 и 1,2 m/s, амплитуда 15 mm 20±5 °C 270 m</td>
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<td>22</td>
<td>Блок на прстену Al-12Si Влакна угљенична (0-6% и 6-8 x 2000-4000 μm) или Al2O3 (0-12% и 10-14 x 300-700 μm) Инфилтрација под приписком Челик, 62±2 HRC Без 49 - 294 N 0,837 m/s Собна 1005 m</td>
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<td>23</td>
<td>Сфера на блоку (осцилаторно кретање) A356 Ra = 0,25 μm Делићи SiC (20% и 10 μm) - Челик, 60 HRC Без 9,8 - 78,4 N 0,1 m/s, амплитуда 25 mm Собна 5-2500 m 20-25000 m</td>
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<td>24</td>
<td>Епрувета на диску 6061 Влакна SiC (0,05-1,5 x 200 μm) или Al2O3 (3 x 500 μm) Синтеровање SKH 51, 66 RC Без 49 N 0,08 m/s Собна -</td>
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<td>25</td>
<td>Епрувета на диску 7091 Делићи и влакна SiC (2-x μm и 0,5 x 3 μm) Синтеровање Челик, 35RC Без 14,2 N 0,8 - 3,6 m/s Собна -</td>
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Преглед коришћених уређаја, материјала и услова испитивања у литератури

<table>
<thead>
<tr>
<th>Лит.</th>
<th>Уређај</th>
<th>Материјал матrice</th>
<th>Врста, величина и садржај ојачивача</th>
<th>Процес производње</th>
<th>Други материјал у контакту</th>
<th>Мазиво, подмазивање</th>
<th>Оптерећење</th>
<th>Брзина клизања</th>
<th>Температура</th>
<th>Пут / време клизања</th>
</tr>
</thead>
<tbody>
<tr>
<td>/1/</td>
<td>Епрувета на диску</td>
<td>Алуминијум</td>
<td>Делићи 5, 10, 15 и 20%, M₇C₃ (~ 20 μm) 20% SiC (4,2 μm) 20% SiFe 20% Al₂O₃ (3,9 μm) 10% SiFe – 10% Al₂O₃</td>
<td>Синтеровање</td>
<td>Нисколегирани челик, 55 HRC</td>
<td>-</td>
<td>5 - 20 N</td>
<td>~ 1 m/s</td>
<td>20, 50, 100, 150 и 200 °C</td>
<td>4000 m</td>
</tr>
<tr>
<td>/2/</td>
<td>Епрувета на диску</td>
<td>Алуминијум</td>
<td>Челична влажна без и са превлакама од Cu и Ni (5% и 120 x 330-350 μm)</td>
<td>Ливење</td>
<td>Челик, 63 RC</td>
<td>Без</td>
<td>10, 20, 30, 40 N</td>
<td>1,8 m/s</td>
<td>Собна</td>
<td>2000 m</td>
</tr>
<tr>
<td>/3/</td>
<td>Трибометар са осцилаторним кретањем</td>
<td>2024 80-95 HRC</td>
<td>Делићи 15, 20 и 30% SiC (3,5, 10 и 20 μm)</td>
<td>Синтеровање</td>
<td>Si₃N₄</td>
<td>Без</td>
<td>0,6 - 3,8 MPa</td>
<td>0,01 m/s</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>/4/</td>
<td>Епрувета на диску</td>
<td>A201 Rₚ₀ = 0,1 μm</td>
<td>Делићи 22,2% Al-Fe-V-Si (75150 и 250 μm)</td>
<td>Ливење под притиском</td>
<td>Челик, Rₚ₀ = 0,1 μm</td>
<td>-</td>
<td>15, 25 и 35 N</td>
<td>1, 1,5, 2,5 и 3,15 m/s</td>
<td>Собна, 200 и 300 °C</td>
<td>6000 m</td>
</tr>
<tr>
<td>/5/</td>
<td>Сфера на блоку (осцилаторно кретање)</td>
<td>2618 Rₚ₀ = 0,6 μm</td>
<td>Делићи SiC (15% и 7,5 μm)</td>
<td>-</td>
<td>Темпер ливења вождје, 797 HV</td>
<td>-</td>
<td>25 N</td>
<td>0,3 m/s, фреквенција 10 Hz, амплитуда 15 mm</td>
<td>20 - 200 °C</td>
<td>2700 m</td>
</tr>
<tr>
<td>/6/</td>
<td>Епрувете на диску</td>
<td>2024 Rₚ₀ = 0,4 и 0,2, 5 μm</td>
<td>Делићи 10% SiC</td>
<td>Синтеровање</td>
<td>S45C (JIS) челик, 250 HV, Rₚ₀ = 1,1 3 μm и S45C са превлаком од TiN, 2200 HV, Rₚ₀ = 1,6 μm</td>
<td>Без Водом Уљни филм Уљно купатило</td>
<td>8,3 MPa</td>
<td>0,02 m/s</td>
<td>20 ± 1 °C</td>
<td>150 m</td>
</tr>
</tbody>
</table>
Физичко-mekhanickе karakteristike ispitivanih materijala
(Physical and mechanical properties of the materials tested)

<table>
<thead>
<tr>
<th>Materijal (Material)</th>
<th>Тврдоћа (Hardness), HV500</th>
<th>Густина (Density), kg/m³</th>
<th>Напон течења (Yield stress), MPa</th>
<th>Затезна чврстоћа (Tensile strength), MPa</th>
<th>Издуђење (Elongation), %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Алуминијум (Aluminium)</td>
<td>37</td>
<td>2720</td>
<td>71,5</td>
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<td>Al/5M7C3</td>
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<td>161</td>
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<td>98</td>
<td>2905</td>
<td>183</td>
<td>300</td>
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<tr>
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<td>62</td>
<td>2753</td>
<td>122,7</td>
<td>212,3</td>
<td>12,5</td>
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<tr>
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<td>85</td>
<td>2735</td>
<td>120</td>
<td>191,2</td>
<td>15,9</td>
</tr>
<tr>
<td>Al/20Al2O3</td>
<td>59</td>
<td>2740</td>
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<td>167</td>
<td>17,3</td>
</tr>
<tr>
<td>Al/10SiFe - 10Al2O3</td>
<td>92</td>
<td>2739</td>
<td>153</td>
<td>262</td>
<td>15,4</td>
</tr>
</tbody>
</table>

Plot of wear rate vs. normal load at room temperature indicates that growth of normal load induces the wear rate to increase as well (Fig. 2).

Слика 2 Зависност интензитета хабања од нормалног оптерећења при брзини од 1 m/s (Figure 2 Dependence of wear rate on normal load at sliding speed of 1 m/s)

There is a significant reduction of wear rate of reinforced materials compared to pure aluminium. Differences in wear rates among the reinforced materials, which

Приметно је значајно смањење интензитета хабања за ојачане материјале у односу на чист алуминијум. Разлике у интензитетима хабања између
New wear resistant Al based materials and their application in automotive industry

grow with load increase, are explained by the difference in bond strength of reinforcement and matrix. Under high loads, certain reinforcements leave the matrix and act as abrasive particles.

Influence of contact temperature upon the wear rate is shown in Figure 3. Appearance of critical temperature is noticed (around 100 °C), above which the wear rate increases rapidly. Simultaneously, surface layers of tested materials soften and they are subject to adhesive wear.

Influence of volume fraction and size of reinforcement particles was analysed by several authors /13, 14, 18/. In one of them /13/ the testing was performed on a 2024 Al alloy reinforced by SiC particles. Figures 4 and 5 present the dependence of wear rate on normal stress for the matrix and material reinforced by SiC particles 3.5 μm large and of different volume fraction, and for the material reinforced by SiC particles of different size and with the same volume fraction of 15 %, respectively.
Слика 4 Зависност интензитет хабања од нормалног напона за делите различитих величине 3,5 μm, различитог проценатног садржаја
(Figure 4 Dependence of wear rate on normal stress for 3.5 μm particles, of different volume fraction)

Слика 5 Зависност интензитет хабања од нормалног напона за делите различитих величине и проценатног садржаја 15%
(Figure 5 Dependence of wear rate on normal stress for particles of different size and the same volume fraction 15 %)

It is observed that increase of volume fraction and size of SiC particles reduces the wear rate, i.e. that the reinforced materials have significantly better wear properties. The authors also conclude that further increase of particles’ volume fraction above 30% doesn't reduce the wear rate, i.e. that the dependence between the particle size and the wear rate isn't always directly proportional. It depends upon the load and the type of particle volume fraction and one can expect none or even inverse influence of particle size upon the wear rate.

Authors from Japan /18/ have investigated the aluminium alloy Al-Si-Cu, the chemical composition of which is given in Table 5, also reinforced with SiC particles of different size and volume fraction. Dependence of worn material volume loss upon the sliding distance for the tested materials is given in Figure 6.

The authors have also obtained better wear properties for materials reinforced with particles of larger size and larger volume fraction. Metallographic examination by the scanning electron microscopy (SEM) has led to the conclusion that the wear is induced by plastic deformations in the sub surface layer. These plastic deformations have caused fracture of particles and finally their delamination. Thickness of the layer that plastic deformation occurs within is not the same for all specimens and decreases with the increase of size and volume fraction of particles in the specimen (Fig. 7), i.e. their wear resistance is better.
Figure 6 Dependence of volume loss upon the sliding distance for the tested materials.

Figure 7 Micrographic photo of the cross-section: a) matrix, b) composite with 13 % SiC (11.5 μm), c) composite with 50 % SiC (11.5 μm) and d) composite with 38 % SiC (57 μm).
New wear resistant Al based materials and their application in automotive industry

Aluminium based alloys with Si as the main alloying element, the so-called silumins, grace to their high yieldness and castability, have been largely investigated /18, 19, 20, 21, 22/.

A group of authors have analysed the influence of reinforcement in the form of short carbon and Al₂O₃ fibres /22/. Chemical composition of the Al-12Si matrix is given in Table 6 and the physical and mechanical properties of the fibres are presented in Table 7.

<table>
<thead>
<tr>
<th>Si</th>
<th>Mg</th>
<th>Cu</th>
<th>Ni</th>
<th>Fe</th>
<th>Mn</th>
<th>Zn</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>11-13</td>
<td>0,8-1,5</td>
<td>0,5-1,5</td>
<td>0,5-1,5</td>
<td>&lt; 0,2</td>
<td>&lt; 0,04</td>
<td>&lt; 0,01</td>
<td>Остатак (Balance)</td>
</tr>
</tbody>
</table>

Authors have varied the volume fraction of Al₂O₃ fibres (0-12 %) and carbon fibres (0-16 %), as well as the normal load (49 - 294 N). The tests were conducted at room temperature, at sliding speed of 0.837 m/s and sliding distance of 1005 m.

Mechanical properties of the tested materials are given in Table 8, and the dependence of the friction coefficient, i.e. the wear rate, upon the normal load is presented in Figure 8, i.e. in Figure 9, respectively.
Механичке карактеристике испитиваних материјала (Mechanical properties of tested materials)

<table>
<thead>
<tr>
<th>Материјал (Material)</th>
<th>Затезна чврстоћа (Tensile strength), MPa</th>
<th>Модул еластичности (Young's modulus), GPA</th>
<th>Тврдоћа (Hardness), HB на (at) 20 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>na (at) 25 °C</td>
<td>na (at) 300 °C</td>
<td>na (at) 25 °C</td>
</tr>
<tr>
<td>Al-12Si</td>
<td>303</td>
<td>216</td>
<td>57,5</td>
</tr>
<tr>
<td>4% C / Al-12Si</td>
<td>250</td>
<td>251</td>
<td>64,2</td>
</tr>
<tr>
<td>12% Al₂O₃ / Al-12Si</td>
<td>301</td>
<td>246</td>
<td>71,5</td>
</tr>
</tbody>
</table>

Слика 8 Зависност коефицијената трене од нормалног оптерећења (Figure 8 Dependence of friction coefficient on normal load)

Слика 9 Зависност интензитета хабања од нормалног оптерећења (Figure 9 Dependence of wear rate on normal load)
The lowest friction coefficient was observed for composite with 4% of carbon fibres that played a role of lubricant. Somewhat higher friction coefficient of the composite with Al₂O₃ fibres compared with the matrix material is explained by the fact that, because of the heating of the surface during the wear and plastic deformation of the matrix, the Al₂O₃ fibres are pulled-out to the surface where they are fractured and comminuted, that makes the surface more rough and increases the friction force. Presence of carbon fibres somewhat lowers this influence.

Presence of the hard Al₂O₃ fibres increases the strength, load-bearing capacity and thermal stability of the matrix, and reduces the plastic deformation. All this reduces the adhesive wear of composites and the temperature growth, and that effect in increasing of the wear resistance (Fig. 9).

The composite with 4% C and 12% Al₂O₃ has shown the best wear resistance which complies with the obtained mechanical properties at elevated temperatures (Table 8).

The influence of the volume fraction of Al₂O₃ fibres in composites is dual. Optimal volume fraction is determined by considering both effects (Fig. 10). Increase of the Al₂O₃ fibres volume fraction improves the mechanical properties of composites and reduces wear rate (ΔW₁) and, on the other hand, greater volume fraction means greater possibility of peeling of reinforcing fibres and occurrences of abrasion, i.e. increase of wear rate (ΔW₂). The lowest overall wear rate (ΔW) was obtained when the volume fraction of Al₂O₃ fibres equalled 12%.

Influences of other factors (sliding speed, roughness, etc.) are outlined in the article by authors from USA /26/.

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Најнижи коефицијент трења је имао композит са 4% угљеничких влакана која су одиграла улогу мазива. Нешто виши коефицијент трења композита са Al₂O₃ влакнима у односу на материјал матрице се објашњава чињеницом да, услед загревања површине током хабања и пластичног деформисања матрице, Al₂O₃ влакна бивају избачена на површину где долази до њиховог кидања и дробљења, што површину чини храпавом и повећава силу трења. Присуство угљеничких влакана само донекле смањује овај утицај.

Присуство тврдих Al₂O₃ влакана повећава чврстоћу, носивост и термичку стабилност матрице, а смањује пластичну деформацију. Све ово смањује адхезивно хабање композита и раст температуре, што утича на пораст отпорности на хабање (сл. 9).

Композит са 4% C и 12% Al₂O₃ је показао најбољу отпорност на хабање што је у складу са добијеним механичким својствима на повишен им температурама (таб. 8).

Утицај садржаја Al₂O₃ влакана у композитима је двојак. Оптимални садржај се добија узимањем у обзир оба утицаја (сл. 10). Са повећањем садржаја влакана Al₂O₃ побољшавају се механичке карактеристике композита, и смањује интензитет хабања (ΔW₁) а са друге стране већи садржај значи и већу могућност љуштања са површине и појаве абразије, односно повећања интензитета хабања (ΔW₂). Најмањи укупни интензитет хабања (ΔW) је добијен при садржају Al₂O₃ влакана од 12%.

Утицаји осталих фактора (брзина, храпавост, итд.) су прегледно дати у раду аутора из САД /26/.
2.2 New technologies of aluminium alloys production

Global development of science and technology has promoted the use of new technologies and upgrading of the existing ones. These are the so-called "in-situ" technologies, which provide the improvement of material properties by applying special conditions during casting, forging and extrusion. Materials produced in this way can conditionally be called "composites" only - their reinforcement component is not added but is obtained as the result of chemical reactions within the material during forming of the parts.

One of the most used and investigated technologies is thixoforming i.e. forming parts from the material that is in thixotropic state /27, 28, 29/. Thixoforming can be used for forming the parts from the composite material as well. The process generally consists of 3 steps: feed stock manufacturing, its reheating and forming the final product (Fig. 11).

2.2 Нове технологије добијања Al легура

Развој технике је омогућио примену нових технологија и унапређење постојећих. То су такозване "in situ" технологије, код којих се побољшање карактеристика материјала обезбеђује применом посебних услова током лијевања, ковања и истискивања. Овако добијени материјали се условно могу назвати композитима само што се код њих компонента која служи као ојачивач не додаје већ се добија као резултат хемијских реакција у материјалу током израде делова.

Једна од највише примениваних и истраживаних технологија је тиксоформирање тј. формирање готовог дела од материјала који је у тиксотропном стању /27, 28, 29/. Тиксоформирањем је могуће израђивати и делове од композитних материјала. Процес се генерално састоји од тре корака: производње припремка, његовог поновног загревања и формирања готовог дела (с. 11).
Feed stock manufacturing. The preconditions to realise the semi-fluid state, necessary for thixoforming, are a suitable alloy and an appropriate structural state of the feedstock. There are several methods for manufacturing the feed stock of the appropriate structure, and all these methods are based upon the existing techniques of continuous casting with certain modifications.

One method is electromagnetic stirring, that uses intensive stirring during the solidification to attain the needed, fine grain globular, non dendritic, structure. The second method is chemical grain refinement accomplished by introducing higher amount of grain refiner, and the third method is thermo-mechanical treatment that attains the better formability of feed stock parts.
Reheating. This is an important step in the thixoforming process since the microstructure of the material in semi-liquid state, adjusted during the heating, decisively influences its rheological behaviour relevant during the forming process.

Forming. As it is observed in Figure 3, all three conventional methods (casting, forging and extrusion) can, with appropriate modifications, be used for forming the final part.

Advantages of thixoforming are, besides obtaining the better material properties, higher material usage (in some cases up to 100%), possibility of achieving complex shape geometries as well as reduced need for subsequent machining and reduction of consumed energy since lesser forming energy is needed comparing to conventional methods.

Influence of the thixoforming process on the tribological properties of the Al-Si alloy was analysed by authors from Spain, within the EU-BRITE-EURAM project /28/.

Dry sliding wear test were performed using a pin on disc machine, at normal load of 46.51 N, sliding distance of 2000 m and sliding speed of 0.089 m/s. Chemical composition and hardness of two of the five materials tested are given in Table 9. Material H4 was manufactured by conventional casting and material 501 by thixoforming.

<table>
<thead>
<tr>
<th>Table 9 (Chemical composition and hardness of tested materials)</th>
<th>Таблици 9 (Хемијски састав и тврдоћа коришћених материјала)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Материјал (Material)</td>
<td>Хемијски састав (Chemical composition), %</td>
</tr>
<tr>
<td></td>
<td>Si</td>
</tr>
<tr>
<td>H4</td>
<td>12.29</td>
</tr>
<tr>
<td>501</td>
<td>15.70</td>
</tr>
</tbody>
</table>

Wear was determined by measuring the height of pin made of tested materials (Figs. 12 and 13).

Significantly better tribological properties, especially the better wear resistance, observed for the thixoformed material are explained by homogeneous structure and smaller distance between the Si particles. The main form of wear for this material

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was the wear induced by oxidation and for
the material H4, after the initial wear
induced by oxidation, it was replaced by
the adhesive wear.

3. Conclusion

From the ecological and economic aspect,
use of aluminium in the automotive
industry is the reality and necessity, and
need for improvement of tribological
properties of aluminium alloys is the task
that is intensively being solved.

In the past investigations it was shown
that, beside the use of coatings, use of
composites and development of new
technologies represent two possible
solutions of the tribological problems for
parts formed from Al alloys.

Alloys of aluminium with silicon as the
main alloying element and reinforcements
in the form of SiC and Al2O3 are the most
often used alloys in the automotive
industry, and the thixoforming process is
one more method for the improvement of
tribological properties and reduction of
energy consumption.

It is worth noting that, when analysing new
materials and techniques, it is always
necessary to consider the working
conditions and the second material in the
contact and possible presence of lubricants
i.e. the whole tribological system.

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3. Закључак

Коришћење алюминијума у моторној
индустрији са еколошког и економског
аспекта су реалност и нужност, а
потреба побољшања триболошких
карактеристика Ал легура је задатак на
кому се у свету интензивно ради.

У досадашњим истраживањима је
показано да су, поред наношења
превлака, коришћење композита и развој
нових технологија, могућа решења за
триболошке проблеме код делова
израђених од алюминијумских легура.

Легуре алюминијума са силицијумом као
главним легирајућим елементом и
ојачивачима у виду SiC и Al2O3 су
најчешће коришћене легуре у моторној
индустрији, а процес тихоформирања се
јавља као још један од начина за
побољшање триболошких карактеристика
и смањења утрошка енергије.

Битно је напоменути да је у разматрању
нових материјала и техника увек
потребно узети у обзир радне услове
као и други материјал у контакту и
eвентуално присуство мазива тј.
цело триболошки систем.

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New wear resistant Al based materials and their application in automotive industry


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