Science Arts & Métiers (SAM) is an open access repository that collects the work of Arts et Métiers ParisTech researchers and makes it freely available over the web where possible.

This is an author-deposited version published in: https://sam.ensam.eu
Handle ID: .http://hdl.handle.net/10985/8422

To cite this version:


Any correspondence concerning this service should be sent to the repository Administrator: archiveouverte@ensam.eu
Friction behavior of laser cladding magnesium alloy against AISI 52100 steel

A. Fabre*, J.E. Masse

Arts et Métiers ParisTech, MécaSurf Laboratory, 2, Cours des Arts et Métiers, 13617 Aix-en-Provence, France

Keywords:
Magnesium alloy
Laser processing
Wear resistance
Friction coefficient

Abstract

The use of magnesium alloys in engineering applications is becoming increasingly important as a relatively low density allows savings in energy consumption and therefore reduction in air pollution. An associated reduction in inertia makes these alloys potential candidates for friction components, but they suffer from poor wear resistance. Laser surface alloying with appropriate powder mixture is an innovative technique to improve surface properties of metallic alloys. In this study, the effect of laser surface alloying using Al12%Si powder on wear resistance of a magnesium alloy ZE41 is investigated. Hardness and wear resistance of the alloy are significantly enhanced after treatment.

1. Introduction

The need for weight reduction in the aircraft industry has raised interest in using magnesium alloys to replace aluminum alloys in some structural and mechanical parts. Indeed, magnesium alloy densities are 36% lower than aluminum alloys, leading to a high strength to weight ratio (180 kN m/kg, comparable with that achieved in aluminum alloys). Magnesium alloys are also attractive owing to their electromagnetic interference shielding properties and their recyclability. However, magnesium alloys present low hardness and wear resistance, and adhesion or seizing phenomena easily occur with the opposed materials, when friction is happening. One of the most effective ways to prevent an untimely adhesive and abrasive wear is to harden the surface.

In the previous years, the laser treatment was already employed to improve wear properties of titanium [1] and aluminum alloys [2]. However, the research in the field of laser surface treatment of magnesium alloys to prevent wear is limited and this field is still under development.

Galun et al. published one of the first contributions about the improvement of magnesium alloy wear properties by laser surface treatment. The authors have investigated the feasibility of laser surface alloying of some Mg base alloys with Al, Cu, Ni and Si and different combinations of these elements [3,4]. In all cases the laser alloying process led to an increase of hardness caused by the formation of intermetallic compounds. This resulted in improved wear resistance and in some cases additionally in improved corrosion resistance.

Dutta Majumdar et al. have performed the laser surface alloying of MEZ\(^1\) magnesium alloy with SiC powder [5] or Al+Al\(_2\)O\(_3\) [6] powders. In another work, the same authors studied the effect of a laser surface melting on wear resistance of the MEZ alloy [7].

Laser surface alloying of AZ91\(^2\) with Si, SiC, TiC and Ni, (Al and Si) is reported to enhance sliding wear resistance of the alloy [8–10].

As can be seen, the studies on this subject are not numerous and often come from the same authors. In addition, most of the work concerned primarily with the process of surface treatment (laser parameters, injected powder, etc.). On surface properties, these studies compare mainly the wear loss of the as-received magnesium alloy and the same following laser surface modification. In most of cases, the superior wear behavior of laser surface modified layer is attributed to improved microhardness in the surface layer because of the presence of hard phases. The grain refinement in the treated area is also referred to as probable factor of improved wear resistance [7]. In these works, the authors provide little explanation of the wear mechanisms. Some point to the possibility that these mechanisms are complex and include adhesion, surface and abrasive wear [11].

In this investigation, the effect of laser surface alloying of commercial ZE41 magnesium alloy using Al12%Si powder on tribological properties is studied. A special effort is made to try to understand the mechanisms involved in friction and wear behavior.

\(^*\) Corresponding author. Tel.: + 33 442938198.
E-mail address: agnes.fabre@ensam.eu (A. Fabre).

\(^1\) MEZ is a magnesium alloy with 2% rare earths, 0.5% Zn, 0.1% Mn and 0.1% Zr.
\(^2\) AZ91 is a magnesium alloy with 8–10% Al, 0.35–1% Zn and 0.13–0.15% Mn.

doi:10.1016/j.triboint.2011.06.030
2. Experimental

2.1. Materials

The base material is a RZ5 commercial magnesium alloy (ASTM ZE41) produced by Honsel Foundry GMB, whose nominal composition is described in Table 1. Fig. 1 is a scanning electron micrograph of the microstructure of ZE41-T5. The micrograph shows an equiaxed grain structure of \( \alpha \)-Mg consistent with cast plate, with a grain size about 50–150 \( \mu \)m. A second phase is clearly visible at the grain boundaries. It contains a main quantity of zinc and rare earths (RE: lanthanum and cerium) that has been identified as Mg\(_2\)Zn\(_3\)RE [11]. Zirconium is dissolved in the \( \alpha \)-Mg matrix. The measured value of Vickers microhardness is about 70 HV\(_{0.050}\).

The surface laser alloying was performed using Trumpf YAG laser HL3006D in the “Laboratoire Laser et Traitements des Matériaux” of Bourgogne University (France). The laser beam was transmitted at the interaction zone by an optical fiber with an inside diameter of 600 \( \mu \)m. Since nozzle diameter was selected as 4 mm, we also adapted the circular laser spot to 4 mm for a better coupling effect between the powder stream and the laser beam. Fiber output, the laser beam occurs in the form very close to a Gaussian beam.

Al–Si powder (12 wt% of Si) deposition and melting was done with a power of 1500 W, on a ZE41-T5 substrate. Beside the as-cast substrate from magnesium alloy, a surface treatment (conversion treatment) was applied, in order to have a better coupling efficiency between the laser beam and the substrate. The working parameters that led to the best results in single-layer coating process constituted the start point for the multi-layer coating process. Five consecutive passes were performed with increasing speed (300 mm/min for the first pass, 400 mm/min for the second and the third and 500 mm/min for the two last). The laser speed was increased from pass to pass in order to take into account of the sample heating during previous passes.

The details of laser processing can be found in Ref. [12].

Due to the heat diffusion inside the substrate, the coat layers height is not constant on layer’s length. The samples were machined to achieve flat surface and polished. The surfaces were cleaned with rectapur alcohol and methyl alcohol. Microstructure analysis and hardness characterization were performed on cross-section of as-cast and laser treated samples. The microstructure observations were conducted after 4%-Nital etching. The scanning electron microscope observations (SEM) and the chemical composition were obtained by using JEOL 6400 scanning electron microscope (accelerating voltage 20 kV and working distance 25 mm) coupled with an Oxford INCA X-ray microanalysis system or dispersive energy spectrometer (EDX).

The Vickers microhardness measurement on the cross-section of coated samples was performed in air, at room temperature and atmospheric pressure. The flat sample was polished: the value of roughness, \( R_a \) is about 0.04 ± 0.02 \( \mu \)m. The arithmetic roughness of the ball, \( R_a \), was less than 0.125 \( \mu \)m. The surfaces were cleaned with alcohol rectapur before the beginning of the tests. The test conditions are defined in Table 2: on one cycle, the sliding distance is 20 mm (10 mm forward and 10 mm backward stroke), 2 replicate tests per condition were done. Friction coefficient was continuously recorded during test. Wear volume indicator is defined by the product of this value by the stroke about 10 mm. The wear rate is calculated using the wear volume divided by the sliding distance.

3. Results and discussion

3.1. Coat structure

The coat is composed by five overlapping clads with a little more than 1.8 mm depth of penetration into the base material.

Table 1

<table>
<thead>
<tr>
<th>Material</th>
<th>Zn</th>
<th>RE</th>
<th>C</th>
<th>Zr</th>
<th>Mn</th>
<th>Si</th>
<th>Fe</th>
<th>Cu</th>
<th>Mg</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnesium alloy</td>
<td>3.21</td>
<td>1.23</td>
<td>0.83</td>
<td>0.013</td>
<td>0.009</td>
<td>0.007</td>
<td>0.004</td>
<td>Balance</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AISI 52100 steel</td>
<td>0.95–1.05</td>
<td>0.25–0.45</td>
<td>0.15–0.35</td>
<td>Balance</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2

<table>
<thead>
<tr>
<th>Tribological test conditions.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load</td>
</tr>
<tr>
<td>Countertop</td>
</tr>
<tr>
<td>Contact geometry</td>
</tr>
<tr>
<td>Motion</td>
</tr>
<tr>
<td>Motion amplitude</td>
</tr>
<tr>
<td>Motion frequency</td>
</tr>
<tr>
<td>Ambient temperature</td>
</tr>
<tr>
<td>Number of cycles</td>
</tr>
</tbody>
</table>
The general coat macrostructure obtained is similar to the Al powder laser cladding of the same alloy described in [12]. There were no pores, either on the surface layer or at the interface between surface layer and base metal. The coat layer presents a very good bond aspect. The link between the deposited and the base alloy materials is a very solid and uniform one. Fig. 2 shows a typical example of the microstructures found in transverse cross-sections of the alloyed tracks. It can be observed that three different zones with microstructure varied from the original base material, throw the interfacial heat-affected zone (HAZ) to the solidified melt, which has a complex microstructure with a great number of precipitates. No grain coarsening within the heat-affected zone was observed. But a liquation of the grain boundaries adjacent to the fusion boundary was observed in the HAZ. The melting of some low melting point intermetallics at grain boundaries caused this. For the matrix, Al, Mg, Al,Mg2 and Al12Mg17 phases are detected by X-ray diffraction analysis, in complement of Mg2Si dendrites. Al-rare earths were detected only on the HAZ, more than 1 mm beneath the surface.

At the bottom of clad layer, solidification started by epitaxial growth from the partially molten magnesium grains (Fig. 2). A specific microstructure is observed combining dendrites as well as squares or rectangles (Fig. 3) and (Al and Mg) matrix. The chemical composition and the crystal structure were determined by EDX analysis and TEM microdiffraction in a previous work [13]. Dendrites are formed by equilibrium fcc Mg2Si phase. Nevertheless, high stability and easy formation of Mg2Si phase are confirmed by thermodynamic calculations. In previous study, some interesting features for tribological behavior are observed on the microstructure: the dendrites size decreases with the increase of the laser pass speed, but their surface fraction in the solidified melt stays about 22 ± 4% for all coats. Beneath the surface from the top to 100 µm in-depth, range size of Mg2Si dendrites is about 4–50 µm.

In the base material, Zn was detected in a second phase at grain boundaries. In the treated area, Zn was detected in the matrix. This is also the case for rare earths. These elements stay mainly at the interface between the melted layer and the base material. This effect may be attributed to the low diffusion coefficients and the formation of very stable refractory binary compounds with Al that precedes even the formation of Mg17Al12-phase. Zr, dissolved in the α-Mg in base material, is found in the coated area in the form of precipitates. In previous work, we identified these precipitates as Al3Zr [13].

### 3.2. Microhardness measurements

In-depth microhardness values are presented in Fig. 4. The stable microhardness value in the coating zone, from the top to 1.2 mm in-depth is near 230 HV0.050. At 1.65 mm in-depth, near the interface zone between layer and substrate, microhardness reaches a maximal value about 291 HV0.050. All these values are high for Al or Mg alloys, and for the ZE41 as-cast alloy, which hardness is about 70 HV0.050. The Vickers microhardness of Mg2Si phase was evaluated at 450 HV in agreement with literature [14]. The evolution of hardness is explained by the contribution of the hard dendrites Mg2Si. Moreover, combining with the presence of Al-rare earths precipitates, smallest size of the Mg2Si dendrite,
wear rate for the test of 6000 cycles of fiction is noted

In Fig. 5, for as-cast ZE41 and laser treated ZE41, of the number of cycles: smaller slope, characterizing a stable
of wear volume indicator present a linear evolution with the raise
between 1 and 200 cycles of friction, in the case of laser treated
samples. The wear process seems to be the same for the both types
samples. The wear process seems to be the same for the both types
of samples: with an accommodation of the tribological system
involves an increase of the maximum hardness value at the
interface between layer and substrate [13].

3.3. Wear and friction results

Fig. 5 allows us to compare the wear volume indicators after
friction tests: analyses were conducted after tests of 10–6000 cycles.
For short tests, values of wear volume indicator seem to be higher for
the laser treated samples than those obtained for as-cast ZE41
samples. The wear process seems to be the same for the both types
of samples: with an accommodation of the tribological system
between 1 and 200 cycles of friction, in the case of laser treated
ZE41. It seems happening only for few cycles, no more than 100, after
test begin for ZE41. In this case the strong increase of wear informs
about the accommodation of the contact zone in the friction system.

After the tests between 200 and 6000 cycles of friction, values
of wear volume indicator present a linear evolution with the raise
of the number of cycles: smaller slope, characterizing a stable
wear regime. In Fig. 5, for as-cast ZE41 and laser treated ZE41,
results are fitted by linear curves. Profiles of wear tracks on
magnesium alloy samples have demonstrated that as-cast ZE41
surfaces wore much faster than laser treated samples after 1000
cycles of friction.

The precise value of normalized wear rate is defined by the
quotient of the wear volume by the sliding distance. The mean
value is close to 3.2 × 10⁻³ mm³/m for the tests of 800–6000
cycles on the as-cast samples. This value is quite similar for the
tests of 800–1000 cycles on the laser treated samples. But after
1000 cycles of friction this value decreases considerably to
1.2 × 10⁻³ mm³/m, value obtained for the 6000 cycle’s test. The
wear rate for the test of 6000 cycles of fiction is noted \( \frac{v_{6000}}{m} \) in

Fig. 6. It is clear that the surface of as-cast ZE41 sample presents
no big wear resistance: lower than 2.5 times that of the laser
treated ZE41. The microhardness value of as-cast ZE41 is lower
than 3.3 times that of the laser treated ZE41.

It is difficult to compare these results with the results obtained
by Anbu selvan and Ramanathan in [15]. The wear rate on ZE41A is
2.4 × 10⁻⁵ mm² for sliding speed about 0.05 m/s and 120 N for load.
This result is seven more times over than the result obtained in this
present study after 6000 cycles of friction. Even if the hardness value
for this magnesium alloy and the counterpart steel are close to the
values of ZE41 and AISI 52100 steel in current study, the conditions
of test are significantly different: the pin-on-disk motion is continu-
ous, with a plane contact zone in Anbu selvan’s study. The levels of
the mean pressure are different in these two cases. Effectively,
the mean value of the contact pressure on ZE41A during the test of wear
is about 4 MPa for the Anbu selvan’s study. In our current study this
value is about 60 MPa.

In conclusion, for the current study, the laser treatment
improves significantly the wear resistance: the wear rate of as-
cast material is 2.5 times higher than that of the laser treated
ZE41. A similar improvement of wear resistance is analyzed on
AZ91D due to the Mg2Si formation in the clad layer in [16]: for the
resistance of the surface layer, an increase more than 3 times that
of the AZ91D is obtained for a sliding distance about 100 m.

Kinetic friction coefficients were recorded during the tests.
Complementary tests were done on roughing milled surface, the
roughing and finishing milling as-cast ZE41 materials exhibited
essentially the same steady-state friction coefficient (0.27), which
is about half observed for the laser treated samples (0.43) after
6000 cycles. In Fig. 6, the steady-state friction coefficient, \( \mu_{5950-}
6000 \) is defined by the average of values recorded between the
5950 and 6000 cycles. The friction coefficient in the beginning of
the test is noted \( \mu_{2-10} \) in Fig. 6. The value is lower for as-cast
sample than the value for laser treated sample (0.43 and 0.51).

In order to explain the wear process, analysis is conducted on
the friction coefficient. Examples of friction coefficient evolution
are presented in Fig. 7 for the steel ball sliding on the as-cast
sample. In Fig. 7(a), the average value oscillates between 0.27 and
0.28, after 100 cycles until 6000 cycles. This value decreases
slowly to the last value near 0.27. After the 20 first cycles, the
friction behavior seems to be regular all along cycles between the
cycle 22 and 6000. In Fig. 7(b), a main evolution can be observed
on the first 20 cycles: after that stabilization appears near to the
value 0.3. The accommodation contact zone seems to be realized
in the 20 first cycles. The third body appears quickly after few
cycles of friction. Some debris is ejected out of the sliding zone
because of the reciprocating motion. Wear on the as-cast sample,
then, seems to be regular to product third body in order to
generate a weak friction coefficient; the accommodation of
sliding speed between the ball and the sample on the contact
zone is surely done by the movement of the grains of third body.
Due to the creation of the third body, the modification of the tribological system induces an accommodation between the two solids, in term of velocity. The sliding between the two solids is changing in a rolling between the third body and the solids.

In Fig. 8(a), the oscillate value of friction coefficient can be observed between 0.4 and 0.45 for 200–6000 cycles for laser treated sample: the average value, $\mu_{500-6000}$ is equal to 0.43. In Fig. 8(b), the stabilization of the friction coefficient seems to be over 200 cycles. In these cases, the kinetic of accommodation is slowly in front of the as-cast sample. Longer time seems necessary to adapt the contact zone.

In all cases, a transfer effect took place between the sample and the ball: microscopic observations and chemical analysis showed Mg and alloying elements particles on the steel ball surface. On as-cast samples, particularly, Mg element was found on steel ball after the test of 10 cycles. The weight% of Mg and O increases with the raise of the number of friction cycles, as it is shown in Table 3. On the ball of the test of 100 cycles, some zinc is found. For as-cast adhesive wear is activated quickly on the first cycles of friction, that means the wear mechanism quickly moves into the adhesive wear regime.

Table 3
Main components in the transfer layer on the steel ball, in weight%, for different tests of friction against as-cast ZE41, or against laser treated ZE41.

<table>
<thead>
<tr>
<th>Chemical component</th>
<th>Mg, weight%</th>
<th>O, weight%</th>
<th>Al, weight%</th>
</tr>
</thead>
<tbody>
<tr>
<td>On steel</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ball/as-cast ZE41</td>
<td>After 10 cycle's test 9.3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>After 100 cycle's test 28</td>
<td>5.6</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>After 600 cycle's test  29.9</td>
<td>11.6</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>After 6000 cycle's test 29.9</td>
<td>15.6</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>On steel</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ball/laser treated ZE41</td>
<td>After 200 cycle's test 3.2</td>
<td>9.3</td>
<td>10.8</td>
</tr>
<tr>
<td>After 800 cycle's test  6</td>
<td>6.3</td>
<td>20.8</td>
<td></td>
</tr>
<tr>
<td>After 6000 cycle's test 5.1</td>
<td>7.3</td>
<td>23.8</td>
<td></td>
</tr>
</tbody>
</table>

On the laser treated samples, chemical analysis showed a presence of Mg, O and Al after the test of 200 cycles on the ball. In this case, the weight% of Al increases for the longer tests. For the laser treated surface, adhesive wear is activated.

In the two cases, adhesion is the same mechanism of wear; nevertheless, the transfer components are different.

In all the tests, third body is created. Some investigations are conducted on the debris obtained after the 3000 cycles. SEM images are shown in the morphology of debris, in Fig. 9(a), debris obtained after friction with magnesium alloy against steel seem to be larger, and with appearance of shape more rectangular than the debris produced by friction between laser treated surface.
magnesium against steel, in Fig. 9(b). Table 4 presents result of chemical analysis. In the as-cast ZE41/steel sliding, debris is mainly composed by Mg and O. In the laser treated ZE41/steel sliding, debris essentially contains Al and O. But with the value of Mg (10.2%) is twice much more than the Si one (4%), the Mg2Si seems to be logically present. Maybe the Al component moderates effect of hard debris, avoiding large grooves on the laser treated sample, however Mg2Si debris presents a very high microhardness values (450 HV). This effect combining with the hardened effect on the surface, after laser treatment, increases significantly wear resistance. In Table 5, the highest level of weight% of O is observed on the smaller debris samples (maximum dimension less than 10 μm) in comparison with those having a maximum dimension greater than 20 μm. The results are opposed for weight% of Al. These average results are obtained on four debris, the standard deviation is no more than 3%. The high level of O on small debris can be linked with the time of debris staying in contact zone. Maybe larger debris is quickly ejected from the contact zone. More investigations are to be conducted in order to understand if Al and O present a main influence on the wear resistance: in particular if it decreases hardness of the debris and if there is a specific morphology of debris.

In Fig. 10, SEM observation on the flat samples, in the sliding zone after the tests of 6000 cycles show some parallel grooves and ridges as a scuffing effects: the width of grooves are more large for as-cast ZE41, in Fig. 10(a) than that of the laser treated one, in Fig. 10(b). The same effect is observed on the transfer zone on the balls after tests of 3000 cycles, Fig. 10(c) for ball/as-cast ZE41 friction test and (d) for ball/laser treated ZE41 friction test. The thickness of the transfer layer is not constant: then, the abrasive process seems to be combined with the adhesive wear.

Table 6 presents the difference between values of weight% for Mg, O, Si, Al and Zn components detected by EDX analysis in the wear scar and out the wear scar for the two surfaces of as-cast and laser treated ZE41 samples after the tests of 6000 cycles. These results show the presence of O for as-cast ZE41 and laser treated surface samples in the wear zone, as well on the transfer layer (Table 3) and on the debris (Fig. 9) such as an oxidation mechanism effect. This was observed on the literature [16,17].
and described such as the mild wear effect: magnesium oxide created under thermal loading due to caloric dissipation of friction energy combining with containment zone in the contact.

In conclusion, the wear behavior of coating surface is attributed to improve microhardness in the modified surface layer as compared to untreated material: the hardness is 3.3 times higher linked to the wear resistance, which is 2.5 times higher. The Mg2Si, which involves a hardness of the treated sample, is present in debris. Nevertheless, a limiting abrasive effect of this debris is observed conducting to a wear reduction.

Other study will be conducted in order to investigate the relationship between the size of Mg2Si dendrites and the wear rate. With adapted conditions of treatment, the capability of laser cladding to produce precise size of dendrites maybe an advantage to optimize the wear resistance of the laser surface alloying.

4. Conclusions

The microstructure and wear behavior of commercial alloy ZE41 modified by surface laser alloying with Al–Si powder mixture were studied. The coating is mainly composed of an Al–Mg matrix and dendrite precipitates of Mg2Si. Laser alloying process led to an increase of hardness with an improved microhardness, about 230 HV0.050, close to the surface, as compared to the 70 HV0.050 of the as-received substrate, caused by the formation of intermetallic compound Mg2Si.

The surface modification by laser cladding involves microstructural properties that increase the friction coefficient against AISI 52100 steel interface: the steady-friction coefficient is about 0.45 (0.27 for ZE41/AISI 52100 material). Nevertheless, the results indicate in increase wear resistance of laser treated parts more than 2.5 times that of the as-cast ZE41.

These results have given new information for the wear resistance of laser treated surface ZE41 with Al12Si% powder in the case of low sliding speed and high level of pressure. The wear is due to adhesive and abrasive mechanisms, which seem to be combined with oxidation process.

### References