Article

Wear Resistance of Aluminum Matrix Composites' Coatings Added on AA6082 Aluminum Alloy by Laser Cladding

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Abstract: Ceramic-reinforced metal matrix composites are known for their high wear resistance. A coating based on these materials would be helpful to improve the wear behavior of aluminum alloys. Laser cladding has been used to deposit a coating consisting of an aluminum alloy reinforced with SiC particles on an AA6082 aluminum alloy. Laser cladding is a very energetic technique that causes the SiC particles to react with the molten aluminum to form Al_4C_3 , which degrades the particles and reduces the properties of the coating. The formation of this detrimental compound was successfully achieved with the addition of Silicon and Titanium to the composite matrix. The microstructures of the newly developed material were characterized and the wear behavior was studied under dry sliding conditions on a pin-on-disc tribometer. The relationship between the microstructure and wear behavior was identified. The absence of Al_4C_3 in the Al40Si/SiC and Al12Si20Ti/SiC coatings' microstructures resulted in an abrasion mechanism instead of a delamination mechanism. The wear behavior changed along the sliding distances. During the first 200 m of sliding distances, the wear rate of all coatings was lower than the uncoated one due to their higher microhardness. For longer sliding distances, the wear resistance of the uncoated AA6082 was higher than the coated ones due to the formation of a lubricant oxide layer on the AA6082 worn surface. For 1000 m of wear distances, the wear behavior was different for each coating. The wear rate of the Al12Si/SiC coating continued growing due to the delamination mechanism and the presence of Al_4C_3 that acted as starting crack points. The wear rate of the Al40Si/SiC coating decreased due to the formation of a thin, superficial oxide layer. The wear rate of the Al12SiTi/SiC progressively decreased along the sliding distance to below the substrate wear rate.

Keywords: laser cladding; coatings; AA6082; wear

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1. Introduction

Nowadays, the growth of social ecological awareness highlights the search of lightweight materials in order to obtain the weight reduction of the components used in the aerospace and automobile sectors, which is considered a priority in these sectors. The use of light materials is associated with the decrease of greenhouse gas emissions. However, the lightest metals' applications are limited due to their low mechanical properties. Intrinsically, the development of new materials with improved properties is mandatory [1–3]. Surface engineering could provide solutions and increase the applications of these alloys. In this sense, the possibility of manufacturing coatings of metal matrix composites on aluminum alloys has been extensively researched [4–6]. A reference material due to their favorable mechanical properties is the aluminum matrix composites reinforced with SiC particles (Al/SiC) because the integration of a ceramic phase into a matrix can enhance their mechanical properties [7,8].

To improve the behavior of a light material such as the aluminum alloys, the use of coatings is a very interesting strategy as all the wear phenomena are associated with

the most external part of a sample. Many different techniques have been used to deposit coatings on aluminum alloys such as CVD, PVD, or thermal spray. CVD and PVD provide good wear results but the coatings are very thin and do not last for long; also, the coating of big samples is not possible with them and composite coatings cannot be deposited [9]. Thermal spray has been also used to deposit different materials. This technique provides thick coatings and allows depositing composite materials. However, with this technique there is an abrupt limit between substrate and coating that may cause the detachment of the coating and the failure of the coated samples [10,11].

Laser cladding is a useful fabrication process to obtain composite coatings as it provides efficient coatings with high adhesion to the substrates, good metallurgical matrix-reinforcement bonding, and good reinforcement distribution in the matrix [12–14]. Due to these characteristics, laser cladding allows manufacturing high wear resistant coatings that are highly adhered to the substrate; so, it is very adequate to coat samples that are submitted to severe wear conditions.

As indicated before, Al/SiC composites are references for wear resistance, and its deposition by laser cladding is of great interest. Al-SiC composites are used as coating on aluminum alloys for different applications, for example, automotive engine components [15,16]. However, laser cladding of Al/SiC involves a reactivity problem when the temperatures reached are between 667 °C and 1347 °C. The Al and the SiC react to form Al_4C_3 and Si due to the high energy provided to the coating. The formation of brittle and hygroscopic Al_4C_3 must be avoided [17,18]. Previously, the deposition of Al/SiC coatings on AA6082 aluminum alloy by laser cladding was carried out, and the effect of the addition of other alloying elements (silicon and titanium) to the matrix of the composite coating was researched [19].

The addition of silicon and/or titanium can avoid the Al_4C_3 formation and, in addition, can increase the surface microhardness. The addition of silicon into the Al matrix displaces the reaction between Al and SiC_p to the products, inhibiting the aluminum carbide formation. Additionally, the addition of Ti favored the formation of TiC and TiSi_2 instead of producing other carbides [19].

As these materials' applications will be subject to extreme wear, the effect of these elements on the wear resistance of these composite coatings needs to be analyzed. Furthermore, the formation of different phases in the composite matrix could seriously affect the wear characteristics of the metal. The present study focused on developing a methodology to deposit Al/SiC on AA6082 alloy, avoiding the degradation of the SiC_p and the formation of aluminum carbide by modifying the matrix used with Si or Ti. This allowed improving the stability and wear properties of the deposited material. The evolution of the wear behavior with wear distance was studied and the effect of the modification of the materials used on the wear mechanisms was studied. Models to explain the results observed are proposed.

2. Materials and Methods

Different composition Al/SiC coatings on AA6082 aluminum alloy were made. Cladding commercial powders of aluminum, silicon carbide, silicon, and titanium (Table 1) were mixed on a ball mill (5 h) with different proportions in order to obtain different composite powders (Table 2). The first aluminum alloy selected, i.e., Al with 12 wt.% of Si, is one of the most used silicon alloys because it is very close to the eutectic point. As a result, the alloy was not in a phase where segregation between α and the liquid were formed, resulting in coatings or materials with much greater quality.

Table 1. Powder properties.

Product	–	D50 (µm)	ρ (g·cm ^{−3})
Al 12 wt.% Si	Metco 52C-NS	71	2.7
SiC	Navarro S.A F-360	26.2	2–2.25
Si	Alfa Aesar	44	2.33
Ti	Alsa Aesar	74	1.6–2.1

Table 2. Cladding powder proportions.

Percentage	Abbreviated Name
Al12 wt.% Si–30 wt.% SiC	Al12Si/SiC
Al40 wt.% Si–30 wt.% SiC	Al40Si/SiC
Al12Si wt.%–20 wt.% Ti–30 wt.% SiC	Al12Si20Ti/SiC

The hypereutectic Al-Si alloy used (Al 40 wt.% Si) allowed reducing the reactivity between the molten alloy and the SiCp. The reaction that dissolved the particles was:

To displace the equilibrium to the right for the high temperatures used with this technique, it was observed in previous works [19,20].

The 45 mm × 45 mm × 10 mm AA6082 coupons with a T6 treatment were used as substrate (Table 3). The substrates were in T6 condition and were cut in coupons of 30 mm × 30 mm × 5 mm. The surface of the substrates was prepared by blasting using brown corundum (D50 = 60 µm) for 1 min.

Table 3. Substrate composition.

Alloy	Composition (wt.%)
AA6082	1.05 Si; 0.23 Fe; 0.03 Cu; 0.57 Mg; 0.57 Mn; 0.02 Zn; 0.02 Ti, balance Al

The coatings were prepared by laser cladding using a 1300-W and 808–940-nm wave-length continuous wave diode laser (ROFIN DL013S) connected to an ABB IRB2400 robot with a coaxial nozzle Fraunhofer IWS COAX 8. The process parameters used were optimized on preliminary researches [20]. Table 4 shows the laser control parameters used during the test. After the cladding deposition, the specimens were cross-sectioned and mounted in an electrically conductive resin, wet grounded using a sequence of abrasive silicon carbide papers (400 to 4000 grit), and, finally, were polished using a 1-µm diamond with ethylene glycol as a lubricant.

Table 4. Fabrication control parameters.

Laser Power (w)	Scan Speed (mm/s)	Distance between Consecutive Laser Lines (mm)	Powder Feed Rate (g/min)	Focal Position of the Laser Beam (mm)
1000	10	0.7	3	0

Microstructures and chemical composition were examined by a scanning electron microscope (SEM, Hitachi S3400N, Tokyo, Japan) equipped with an energy dispersive X-ray spectrometer (EDX).

The wear tests were carried out on the surface of the uncoated AA6082 and on the different clad coatings under dry sliding condition at room temperature and relative humidity (25 °C and 40%) on a pin-on-disc Microtest MT/10/SCM tribometer using 10-N load, 4-mm diameter, and 200 rpm. The effect of the wear length was analyzed by testing

the samples at three different distances: 200, 500, and 1000 m. Each test was repeated at least three times. The surface of the samples was grinded with 800-grit SiC paper.

The wear test conditions chosen were conditioned, on the one hand, by the equipment used: loads between 1 N and 10 N and sliding speed from 0 to 200 rpm. In this range, we selected the most demanding conditions in load (10 N) and sliding speed (200 rpm). The distance selected (1000 m) was long enough to test the substrates and coatings in steady-state wear conditions. The wear parameters produced strong wear to the substrates and, therefore, were very demanding for the coatings. The wear testing machine recorded continuously the friction coefficient. Loss mass was measured by Sartorius BP 211S scales with precision of ± 0.0001 g. Additionally, the wear rate was determined by image analysis using a Z20 3D Optical profilometer. A Shimadzu microhardness tester was used to obtain a Vickers microhardness ($HV_{0.5}$) of the specimens.

The wear tracks, the worn surfaces in the transversal section, and the debris formed during the wear tests were examined by a Scanning Electronic Microscope (SEM) equipped with an Energy Dispersive X-ray spectrometer (EDS).

3. Results and Discussion

3.1. Coatings' Microstructure

The cross-section of the different Al/SiC coatings on AA6082 are shown in Figure 1. Al12Si/SiC, Al40SiC, and Al12SiTi/SiC coating cross-sections are shown in Figure 1a–c, respectively. In all cases, a good metallurgical interface between the substrate and coating can be observed. However, differences in the thickness of the coatings can be observed, which denotes differences in the deposition efficiency.

Figure 1. Laser cladding coatings on AA6082 aluminum alloy cross-section (a) Al12Si/SiC, (b) Al40Si/SiC, and (c) Al12Si-Ti/SiC.

The deposition efficiency was calculated by Equation (1) [21].

$$\text{Deposition efficiency} = \frac{\text{deposited cross-section area} \cdot \text{scanning speed} \cdot \text{powder density}}{\text{Powder feed ratio}} \quad (1)$$

According to Equation (1), the deposition efficiency of the Al12Si/SiC coating was 42%. The deposition efficiency of the Al40Si/SiC coating was 26%, and 46% in the case of

the Al₁₂Si-Ti/SiC coating. In addition, the microstructure of the coating was changed by the addition of Si or Ti. These microstructure particularities are shown in Figure 2.

Figure 2. Microstructure of (a) Al₁₂Si/SiC coating; (b) detail of (a); (c) Al₄₀Si/SiC coating; (d) detail of (c); (e) Al₁₂Si-Ti/SiC coating; and (f) detail of (e).

The Al₁₂Si/SiC average thickness was $350 \pm 50 \mu\text{m}$. The Al₁₂Si/SiC microstructures shown in Figure 2a,b were formed by partially degraded SiC particles on the aluminum matrix. The reaction products (Al_4C_3 and Si) between the SiC particles and the aluminum matrix can be observed. The Al_4C_3 platelets appeared with lines' shape, and primary Si had particle shape. The extension of interfacial reactivity in Al-SiC systems during liquid processing has been widely studied by other authors. SiC reinforcing particles react with molten aluminum and form Si and Al_4C_3 , which is a brittle and hygroscopic compound, which degrades the properties of composites when this reaction occurs [22,23]. Under

high-energy conditions in which a high temperature is reached, such as arc and laser welding processes and laser cladding, Al_4SiC_4 can be formed together with Al_4C_3 [24].

The Al/SiC interfacial reaction depends on various manufacturing parameters such as temperature, residence time, atmosphere, and chemical composition of the matrix. The most widely used strategies to inhibit this reaction and improve weldability are the generation of coatings on the SiC particles by oxidation and/or sol-gel [25,26] and the modification of the matrix composition, such as adding Si to delay the reaction [19].

The study of matrix-reinforcement reactivity is once again very relevant due to the importance that in recent years the use of metal matrix composite materials has taken to develop coatings that improve the surface mechanical properties of alloys with the aim of reducing wear phenomena [19,27–29].

In the Al40Si/SiC coating (Figure 2c,d), the average thickness was $190 \pm 30 \mu\text{m}$. The SiC particles were not degraded and there was no presence of Al_4C_3 . In addition, a high amount of primary Si particles was observed.

Finally, the Al 12Si 20Ti/SiC average thickness was $300 \pm 50 \mu\text{m}$. The microstructure was characterized by SiC particles, TiC, and TiSi_2 in an Al-Si matrix (Figure 2e,f). A particular Al inner ring and an outer TiC ring can be observed around the SiC particles. Al reacts with SiC to form Al_4C_3 and Si. In addition, Ti reacts with SiC_p and forms TiC. Moreover, Ti reacts with the Si and forms TiSi_2 . Due to the reactivity between the titanium with the SiC particles, the initial amount of reinforcement decreased. This reaction mechanism has been described in greater detail in an anticipated work [19].

3.2. Wear Testing

Figure 3 shows the average microhardness. All of the coatings present higher microhardness than the uncoated AA6082 aluminum alloy. This increment was higher than $\times 1.35$ for the Al12Si/SiC coating, $\times 2.7$ for the Al40Si/SiC coating, and $\times 2.5$ for Al12Si20Ti/SiC coating.

Figure 3. Microhardness measurements for the substrate and coatings on the AA6082 aluminum alloy.

The lower microhardness increment of the Al12Si/SiC in comparison with the other coatings was due to, despite Al_4C_3 increasing the coating hardness, the hydration of these

components, which can reduce the mechanical properties of the coating [17,18,27]. Even though similar microhardness values were obtained in Al40Si/SiC and Al12Si-Ti/SiC coatings, these values were slightly lower for the Al12Si20Ti/SiC one because the Al-SiC-Ti reactivity formed phases with lower hardness than primary silicon and SiC.

The average coefficients of friction (COF) obtained in the wear test measurements of the different samples using a 10-N load, a 4-mm diameter, and 200 rpm for a total wear length of 1000 m are shown in Figure 4. These values are the result of the COF measurement after COF stabilization. In all cases, the sliding distance of stabilization was around 50 m.

Figure 4. Average friction coefficient for the substrate and coatings on the AA6082 aluminum alloy.

In all cases, coatings present higher friction coefficients than the substrate, due to the presence of the reinforcement particles that activate three body friction mechanisms. However, the friction coefficient of the coatings without Al_4C_3 (Al40Si/SiC and Al12Si-Ti/SiC) were more similar than the substrate friction coefficient (only increments of 10% were detected). However, the Al40Si/SiC coating had a 60% higher friction coefficient with respect to the substrate. The existence of Al_4C_3 in the Al12Si/SiC coating resulted in a higher friction coefficient because the Al_4C_3 detached and generated abrasive wear. In the Al40Si/SiC and Al12Si20Ti/SiC coatings, the friction coefficient increment was because the primary silicon particles or SiC particles came off, respectively [11,30].

The wear rates for the substrate and coatings on AA6082 aluminum alloy are shown in Figure 5. In addition, the wear distance influence was analyzed.

For 200 m of wear distance, the laser cladding coatings had a very improved wear resistance in comparison with the substrate. In fact, the coated materials wear rates were around 50% lower than the uncoated ones. The reason is related to the increment of microhardness in the coatings, which is inversely proportional to the wear rate [11,30]. For this wear distance, the different coatings had minimal differences in their respective wear rates.

However, for 500 m of wear distance, the coatings' wear rates were higher than the uncoated substrate ($\sim \times 3$ in the case of Al12Si/SiC and Al40Si/SiC coating and $\sim \times 1.4$ in the case of Al12Si20Ti/SiC coating). This was probably due to the formation of an oxide protective layer on the substrate. This layer could act as lubricant layer. It is possible that the low friction coefficient of the AA6082, observed in Figure 4, was also related to the formation of this lubricant layer.

In addition, an $\times 100\%$ increment in the wear rate of the Al12Si/SiC and Al40Si/SiC coatings was observed for 200 m in comparison with 500 m of wear distance. In the case of the Al12Si/SiC, the presence of Al_4C_3 in the coating microstructure caused the detachment of large pieces of material, which, moreover, increased the friction coefficient (Figure 4). In the case of the Al40Si/SiC coating, the high amount of primary silicon and SiC particles caused their breaking off and resulted in three body wear mechanisms that increased the wear rate.

Figure 5. Wear rate for the substrate and coatings on the AA6082 aluminum alloy.

However, for the Al12Si20Ti/SiC coating, a decrease of $\times 20\%$ in the wear rate for 200 m of wear distance was observed in comparison with the 500 m ones because of the smaller reaction product formed and the higher matrix–reinforcement interface resistance.

For 1000 m of wear distance, the Al12Si/SiC coating wear rate increased 80% compared to the substrate and 15.5% compared to the wear rate for 500 m of wear distance. The breaking of big pieces of material increased the wear rate. This was confirmed by the increment of friction coefficient observed in Figure 4. However, the Al40Si/SiC coating wear rate decreased 20% in comparison with the wear rate for 500 m of wear distance. A stabilization of the wear rate was possible due to the better interface of particle–matrix in those coating strata, which was confirmed by the lower coefficient rate, similar to the substrate one (Figure 4). Nevertheless, the wear rate was higher than 100% of the substrate one at this wear distance. For the Al12Si20Ti/SiC coating, a consecutive decrease in the wear rate was observed and the wear rate values were similar to the uncoated substrate, probably due to the formation of a superficial lubricant oxide protective layer, which was, again, confirmed by the lower friction coefficient of this kind of coating (Figure 4).

3.3. Wear Mechanisms

The worn surfaces and the wear debris were observed by SEM, in order to identify the different mechanisms that took place during the wear of the substrate and the coatings. In addition, the effect of the wear distance in the wear mechanism was evaluated.

Changes in the worn surfaces of the uncoated AA6082 and the different coatings (Al12Si/SiC, Al40Si/SiC, and Al12Si20Ti/SiC) with the sliding distance are shown in Figure 6.

Figure 6. SEM micrographs of the worn surfaces of the uncoated AA6082 and the different coatings (Al12Si/SiC, Al40Si/SiC, and Al12Si20Ti/SiC) with the sliding distances (200 m, 500 m, and 1000 m); (a) uncoated AA6082 worn surface (200 m); (b) uncoated AA6082 worn surface (500 m); (c) uncoated AA6082 worn surface (1000 m); (d) Al12Si/SiC coating worn surface (200 m); (e) Al12Si/SiC coating worn surface (500 m); (f) Al12Si/SiC coating worn surface (1000 m); (g) Al40Si/SiC coating worn surface (200 m); (h) Al40Si/SiC coating worn surface (500 m); (i) Al40Si/SiC coating worn surface (1000 m); (j) Al12Si20Ti/SiC coating worn surface (200 m); (k) Al12Si20Ti/SiC coating worn surface (500 m); and (l) Al12Si20Ti/SiC coating worn surface (1000 m).

In all cases, many fine grooves parallel to the sliding direction were observed on the worn surface. The presence of hard particles that plowed into the pin caused these lines due to the movement of these particles over the surface and subsequent material removal along the surface, which are typical from abrasion mechanism. In addition, the loss of the surface material was observed due to the delamination mechanism.

The delamination mechanism was predominant in the uncoated substrate and for the Al12Si/SiC coating and was more important for lower sliding distances (Figure 6a,b). The presence of Al_4C_3 in the Al12Si/SiC microstructure could be responsible for this mechanism.

In addition, the lubricant oxidative layer formation could be the reason for the reduction of the delamination mechanism.

For Al40Si/SiC, (Figure 6d–h) and Al12Si20Ti/SiC (Figure 6g–i) coatings, the main wear mechanism was abrasion for all sliding distances, probably due to the higher amount of SiC particles.

Figure 7 shows the SEM micrographs of the cross-section of worn surfaces for the different sliding distances, and Figure 8 shows the oxygen percentage [norm. at.%] present on the worn surface of the uncoated AA6082 and the different coatings (Al12Si/SiC, Al40Si/SiC, and Al12Si20Ti/SiC) for the different sliding distances.

Figure 7. SEM micrographs of the cross-section of the wear surface of the uncoated AA6082 and the different coatings (Al12Si/SiC, Al40Si/SiC, and Al12Si20Ti/SiC) compared to the sliding distances (200 m, 500 m, and 1000 m); (a) uncoated AA6082 worn surface (200 m); (b) uncoated AA6082 worn surface (500 m); (c) uncoated AA6082 worn surface (1000 m); (d) Al12Si/SiC coating worn surface (200 m); (e) Al12Si/SiC coating worn surface (500 m); (f) Al12Si/SiC coating worn surface (1000 m); (g) Al40Si/SiC coating worn surface (200 m); (h) Al40Si/SiC coating worn surface (500 m); (i) Al40Si/SiC coating worn surface (1000 m); (j) Al12Si20Ti/SiC coating worn surface (200 m); (k) Al12Si20Ti/SiC coating worn surface (500 m); and (l) Al12Si20Ti/SiC coating worn surface (1000 m).

In the uncoated AA6082, as the sliding distance increased, the formation of a continuous oxidative wear product layer was observed (Figure 7a–c). The increment of this kind of wear mechanism was confirmed by the increment of oxygen percentage present in the surface (Figure 8).

In the Al12Si/SiC coating, perpendicular cracks to the sliding direction were observed (Figure 7d–f). Despite this, SiC particle detachment was not observed; the Al_4C_3 could be crack starting points. Subsurface cracks grew during the wear test and resulted in the detachment of sheet-like fragments of the worn material and delamination mechanism, as can be observed in the previous Figure. These fragments of the worn material and other small particles formed a mechanically mixed layer (MML). The height of the MML increased with the sliding distance (Figure 7f). In addition, the oxidative mechanism was smaller, as is confirmed by Figure 8.

Figure 8. Oxygen percentage [norm. at. %] present on the worn surface of the uncoated AA6082 and the different coatings (Al12Si/SiC, Al40Si/SiC, and Al12Si20Ti/SiC) compared to the sliding distances (200, 500, and 1000 m).

In the Al40Si/SiC coating, for all sliding distances, the wear mechanisms were mainly abrasion (Figure 7g–i). SiC and Si particles were observed forming abrasion zones on the surface (Figure 7g,h). However, the MML layer was not observed. In addition, for 1000 m of wear distance (Figure 7i), a slim oxide layer on the surface was observed due to the oxidative mechanism. The increment of this oxide layer was confirmed by the increment of oxide percentage of this coating with the sliding distance (Figure 8).

As in the previous case, in the Al12Si20Ti/SiC coating, for all sliding distances, the wear mechanism was mainly abrasive and the MML was not observed (Figure 7j–l). In this case, the oxide layer observed in the previous cases was not observed (Figure 7j–l) and the oxygen percentage on the surface was very low (Figure 8). However, sharper SiC particles on the surface that increased abrasion mechanism were observed mainly for 200 m of sliding distance (Figure 7j).

Figure 9 shows the debris obtained in the different wear tests. The oxygen percentages [norm. at. %] present on these debris are shown in Figure 10. The debris of uncoated AA6082 (Figure 9a–c) and Al12Si/SiC (Figure 9d–f) coating were formed mainly by platelets. The debris of Al40Si/SiC (Figure 9g–i) and Al12Si20Ti/SiC (Figure 9j–l) coatings were formed mainly by particles. Particularly, the debris of Al40Si/SiC had a spherical shape. In all cases, the debris size decreased and the presence of oxide particles increased with the increment of the sliding distance, as was confirmed by the oxygen percentage shown in Figure 10. Despite the oxide layer from the oxidative mechanism not being observed in the

cross-section of the Al40Si/SiC and Al12Si20Ti/SiC coatings (Figure 9g–l), the debris from the wear test of these coatings (Figure 9g–l) was visibly coated with small oxide fragments, probably because in these coatings the oxide layer formed was not well adhered to the worn surface. The high percentage of oxygen in these coatings is shown in Figure 10.

Figure 9. SEM micrographs of the debris obtained in the wear tests of the uncoated AA6082 and the different coatings (Al12Si/SiC, Al40Si/SiC, and Al12Si20Ti/SiC) compared to the sliding distances (200 m, 500 m, and 1000 m); (a) uncoated AA6082 debris (200 m); (b) uncoated AA6082 debris (500 m); (c) uncoated AA6082 debris (1000 m); (d) Al12Si/SiC debris (200 m); (e) Al12Si/SiC debris (500 m); (f) Al12Si/SiC debris (1000 m); (g) Al40Si/SiC debris (200 m); (h) Al40Si/SiC debris (500 m); (i) Al40Si/SiC debris (1000 m); (j) Al12Si20Ti/SiC debris (200 m); (k) Al12Si20Ti/SiC debris (500 m); and (l) Al12Si20Ti/SiC debris (1000 m).

Figure 10. Oxygen percentage [norm. at. %] present on the debris obtained in the wear tests of the uncoated AA6082 and the different coatings (Al12Si/SiC, Al40Si/SiC, and Al12Si20Ti/SiC) compared to the sliding distances (200 m, 500 m, and 1000 m).

4. Conclusions

Variances in the microstructure resulted in differences in the wear behavior. The absence of Al_4C_3 in the Al40Si/SiC and Al12Si20Ti/SiC coatings' microstructures led to an abrasion mechanism instead of a delamination mechanism. In addition, the wear behavior changed along the sliding distances.

During the first wear stages, the first 200 m of sliding distances, the wear rate of all Al/SiC coatings on AA6082 aluminum alloy was lower than the uncoated one. The reason is predominantly the higher microhardness of the coated surfaces. However, for longer sliding distances (500 m), the wear resistance of the uncoated AA6082 was higher than the coated ones due to the formation of a lubricant oxide layer on the AA6082 worn surface. Nevertheless, for large wear distances (1000 m), the wear behavior was different for each coating. The wear rate of the Al12Si/SiC coating continued growing due to the delamination mechanism and the presence of Al_4C_3 that acted as starting crack points. However, the wear rate of the Al40Si/SiC coating decreased due to the formation of a thin, superficial oxide layer; instead, their wear rate was higher than the substrate one. Finally, the wear rate of the Al12SiTi/SiC continually decreased along the sliding distance to below the uncoated substrate, due to the small size of the components of the matrix and the good SiC reinforcement-matrix and the oxidation of the developed debris.

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