

Dry sliding wear behaviour of powder metallurgy Al-Mg-Si alloy-MoSi₂ composites and the relationship with the microstructure

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Summary

The effect of the microstructure on the dry sliding wear of six aluminium alloy 6061 matrix composites reinforced with 15 vol.% of MoSi₂ particles and two monolithic 6061 alloys processed by powder metallurgy with and without ball milling has been studied. Wear testing was undertaken using pin-on-ring configuration against an M2 steel counterface at 0.94 m/s and normal load of 42, 91 and 140 N. The wear resistance of the aluminium alloys was significantly improved by ball milling and the addition of reinforcing MoSi₂ particles due to a more stable and more homogeneous microstructure,

which avoids the detachment of the mechanically mixed layer. Wear rate of materials in T6 decreases as solutionized hardness of the materials increases. This behaviour is rationalized by taking into account the precipitation state of the matrix. In addition, wear rate follows a Hall-Petch type relationship, showing that the reduction of matrix grain size plays an important role in the increase in the wear resistance of the composites. The results indicate that the present intermetallic reinforced composites can be considered potential substitutes for ceramic reinforced aluminium alloys in tribological applications.

Keywords: Sliding wear; Metal-matrix composite; Intermetallics; Hardness; Wear testing; Grain size.

1. Introduction

Aluminium matrix composites (AMCs) are attractive because they can present a good combination of properties, such as high elastic modulus, tensile strength and wear resistance [1,2]. Brake rotors, pistons, connecting rods and integrally cast AMCs engine blocks are some of the successful applications of these materials in the automotive industry [3].

As reviewed by Sannino and Rack [4], the wear behaviour of AMCs can be influenced by both extrinsic (applied load, sliding velocity, etc.) or intrinsic factors (material characteristics). Most studies [4,5,6] indicated that the wear resistance of AMCs manufactured by powder metallurgy (PM) techniques increased with increasing particle size and/or volume fraction of particles. However, as far as reinforcement distribution and matrix grain size are concerned, few studies are available in the literature. By applying suitable processing conditions, both parameters can be modulated during the mixing step of the AMCs prior to consolidation, especially by ball milling, that is a high-energy procedure involving repeated deformation-welding-

fracture mechanisms [7]. Ball milling has been successfully used to improve particle distribution throughout the matrix [8,9] and it is also well known that it promotes a high degree of deformation, reduces grain size and produces an extremely fine distribution of oxide dispersoids in the structure of the alloy matrix.

Hard ceramic particles, such as SiC or Al₂O₃, are widely employed as reinforcement of AMCs because of their high hardness and elastic modulus [2]. However, their high abrasiveness complicates machining steps and severely damages counterfaces in tribological applications. Indeed, some authors [10] have found that hard ceramics can actually increase the wear rate of the mating counterface, due to their abrasive action, and thus reduce the overall wear resistance of the tribo-system. In the last years, intermetallics have emerged as possible substitutes for ceramic reinforcement. It has been shown that nickel aluminides can improve the wear resistance of aluminium alloys to a level similar to that of a SiC reinforced composite, whilst at the same time reducing counterface wear rate [10,11]. There is another type of intermetallic, MoSi₂, that is an excellent candidate to be used as reinforcement in AMCs as it confers high thermal stability and mechanical properties on the composite [9,12].

The aim of this work is to investigate the influence of the matrix and reinforcement characteristics on the dry sliding behaviour of six powder metallurgy AA6061/MoSi₂/15p composites against a tool steel counterface, acting at different applied loads. Wear properties of PM AA6061/MoSi₂/15p are compared with those of ceramic reinforced AMCs from the literature.

2. Experimental

2.1 Materials and characterization

The AA6061 powder with particle diameter < 50 µm and nominal composition in mass%: 0.45 Si, 0.96 Mg, 0.27 Cu, 0.0023 Mn, 0.16 Cr, 0.15 Fe, balance Al, was

produced by argon gas atomisation and supplied by Alpoco, Sutton Coldfield, UK. Two initial ranges of irregular shaped MoSi₂ particles were selected: <3 μm (composites Group 1) and 10-45 μm (composites Group 2) which were obtained by self-propagating high temperature synthesis (SHS) at INASMET-Tecnalia, San Sebastian, Spain. To get different sizes and distributions of reinforcement, the AA6061 powder was blended with 15% volume of MoSi₂ by three methods: rotating cube, wet blending and planetary ball milling operating at 200 rpm for 4 and 10 hours with a ratio of balls to material of 7:1 and without any process control agent. The powders were encapsulated and consolidated by extrusion in a horizontal direct hot extrusion press at a temperature of 450°C, a ram speed of 0.4 mm/s and an extrusion ratio of 27:1; this gave 8 mm diameter bars that were left to air cool. Table 1 lists all the materials prepared, which include two unreinforced matrix alloys used as reference. The consolidated materials were studied in solutionized and T6 (maximum hardness) states. Solution heat treatment was performed at 520°C for 0.5 hours and water quenched, and peak hardness was determined at 170°C [9].

Table 1. Materials, MoSi₂ particle size ranges (Dr_o), blending methods and codes.

Material	Dr _o (μm)	Blending method	Code
AA6061	-	As-received	0AR
		Ball mill: 4 h	0M(4h)
AA6061/ MoSi ₂ /15p Group 1	< 3	Wet blend	1W
		Ball mill: 4 h	1M(4h)
		Ball mill: 10 h	1M(10h)
AA6061/ MoSi ₂ /15p Group 2	10-45	Rotating cube	2C
		Ball mill: 4 h	2M(4h)
		Ball mill: 10 h	2M(10h)

Microstructural characterization of extruded materials was performed by scanning electron microscopy (SEM) equipped with energy dispersive X-ray spectroscopy (EDS) using a FEG-JEOL 6500 microscope. Image analyses of the composites were performed

by Image-Pro Plus software on back-scattered electron images to quantify reinforcement size and distribution. The degree of particle clustering was quantified by CProbe software to measure the coefficient of variation of the mean near-neighbour distance (COV_{λ}) [13] that varies between 0 and 1 and decreases with increasing homogeneity of the distribution. Investigation of the aluminium grain size was undertaken using a fully automatic HKL Technology EBSD attached to FEG-SEM microscope described above. Chemical analysis was carried out on all samples to determine the amount of Fe by a Varian SpectrAA 220FS atomic absorption spectrometer and O by infrared absorption in a LECO TC-436 instrument. Vickers hardness of consolidated materials was measured in solutionized and T6 (maximum hardness) condition. At least 5 indentations were performed for each condition by applying a load of 1 kg for 15 seconds. The results are presented with an accuracy of ± 0.03 GPa. More experimental details of the microstructural characterization techniques employed and hardness measurement can be found elsewhere [9].

2.2 Wear testing

The wear behaviour was investigated on transverse cross sections of T6 samples. With the purpose of comparing both aging conditions, some solutionized materials were also studied. The wear tests were performed under dry sliding conditions using a Cameron–Plint TE-53 multi-purpose friction and wear tester with a pin-on-ring configuration. The samples were prepared as round pin specimens of 8 mm diameter, with the contact surface metallographically polished to a 1 μm diamond finish prior to testing. An M2 tool steel counterface (nominal composition in mass%: 0.95-1.05 C, 0.15-0.40 Mn, 0.2-0.45 Si, 3.75-4.5 Cr, 0.3 max Ni, 4.5-5.5 Mo, 5.5-6.75 W, 1.75-2.2 V, balance Fe) was used, hardened in the range 800–850HV, in the form of a crowned ring of 10 mm width and 60 mm diameter. The counterface was also polished to a 1 μm

diamond finish prior to every testing. Testing was undertaken at a constant sliding velocity of 300 rpm (0.94 m/s) for loads of 42, 91 and 140N (applied via a cantilever beam). All wear test specimens were cleaned in acetone and weighed to an accuracy of ± 1 mg prior to testing and at intervals of 2.5 km during the test up to 10 km of sliding distance. The worn surfaces were characterized by the FEG-SEM described above.

3. Results and discussion

Back-scattered electron (BSE) SEM micrographs of composite cross sections at the same magnification are shown in Figure 1. Qualitatively, it is evident that MoSi_2 particle size decreases with milling time and that MoSi_2 distribution is quite homogeneous, except in the wet blended composite (1W) where agglomerates can be seen.

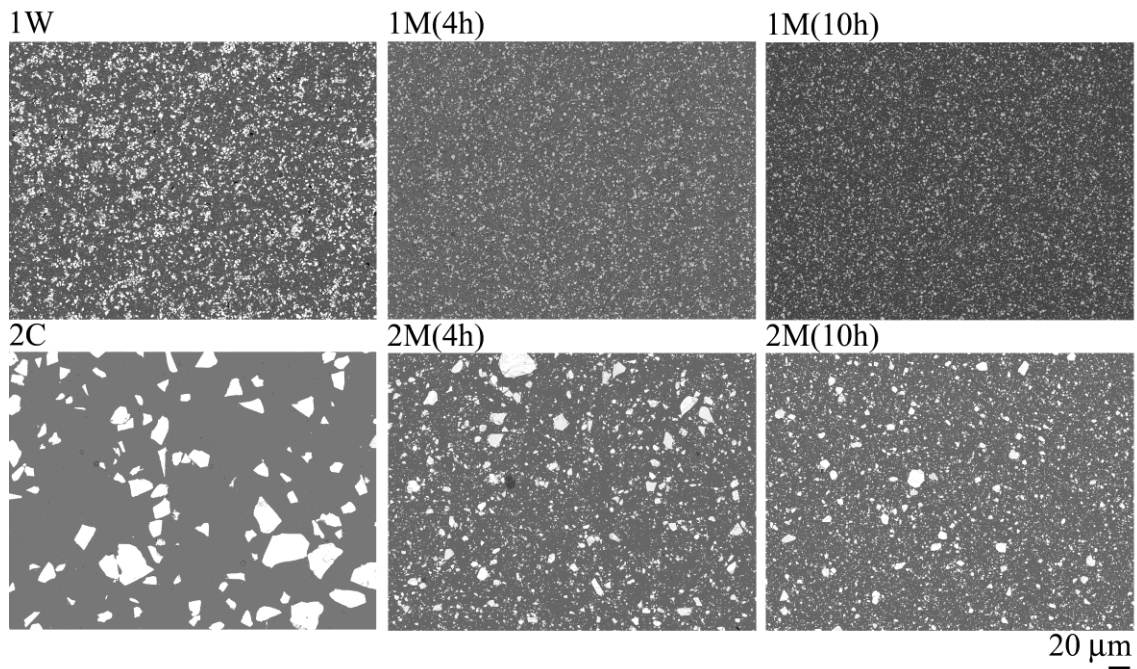


Figure 1. Back-scattered SEM micrographs on cross sections of AA6061/ MoSi_2 /15p: composites of Group 1, top; composites of Group 2, bottom (with reference to Table 1).

Table 2 summarizes all microstructural parameters quantified: size and distribution of MoSi_2 particles, aluminium matrix grain size and oxygen and iron contents, and the

Vickers hardness values in solutionized and T6 conditions in the eight extruded materials. As can be seen, high energy ball milling reduced the reinforcing particle size to sub-micrometric level and increased the homogeneity of their particle distribution throughout the matrix, except for 2M(4h). As expected, the more heterogeneous distribution is obtained in composite 1W which should be attributed to the large difference between particle size of reinforcement, $< 3 \mu\text{m}$, and aluminium, $< 50 \mu\text{m}$ [14]. The determination of aluminium matrix grain size was performed on cross sections through the EBSD maps presented in [9]. Ball milling reduced the average values of matrix grain size to 0.6-0.7 μm in the reinforced materials and to 1 μm in the monolithic materials which is due to the generation and movement of dislocations due to the strong deformation occurring in the collisions between the stainless steel balls and the powders. Another consequence of ball milling is that oxygen reacts with both Al to form alumina as well as Fe from the container and media and enters the powder as worn fragments [7,9]. It is seen that oxygen and iron content increased with ball milling time in each group of materials.

The values of Vickers hardness are also given in Table 2. It can be appreciated that the composites follow the expected general trend of higher solutionized hardness and less age-hardening than the unreinforced alloys. For each group of materials, solutionized hardness increases as ball milling time increases. In the T6 condition hardness does not follow the same rule. In this case, the as-received unreinforced 6061 alloy 0AR is harder than the ball milled (BM) alloy 0M(4h) and the 1M(4h) composite presented the highest hardness value, followed by 2C, 1W and 1M(10h) composites. This behaviour has been attributed to the fact that, in these materials, hardening ability decreases with decreasing grain size, indicating that the ability of the matrix to age-harden is mainly dependent on grain size and quite independent of the presence of reinforcing particles [9].

Table 2. Materials, sample code, mean MoSi₂ particles size after blending (Dr_f), coefficient of variation of the mean near-neighbour distance (COV_d), aluminium matrix grain size (d), oxygen (%O) and iron (%Fe) contents and Vickers hardness in solutionized (H_s) and T6 (H_{T6}) conditions.

Material	Code	Dr_f (μm)	COV_d	d (μm)	%O (%mass)	%Fe (%mass)	HV (GPa)	
							H_s	H_{T6}
AA6061	0AR	-	-	2.2	0.18	0.16	0.64	1.14
	0M(4h)	-	-	1.4	0.44	0.20	0.70	1.06
Group 1 AA6061/ MoSi ₂ /15p < 3 μm	1W	1.54	0.55	1.9	0.26	0.15	0.90	1.30
	1M(4h)	0.80	0.51	1.0	0.39	0.19	1.04	1.41
	1M(10h)	0.59	0.41	0.6	0.90	0.24	1.24	1.27
Group 2 AA6061/ MoSi ₂ /15p 10-45 μm	2C	17.85	0.41	2.0	0.19	0.12	0.82	1.34
	2M(4h)	1.96	0.46	1.1	0.40	0.19	0.96	1.26
	2M(10h)	0.83	0.41	0.7	0.80	0.21	1.17	1.20

Figure 2 shows the volume loss of the unreinforced alloys and the composites after 10 km of sliding distance for all tested loads. As expected, for each material, volume loss increases as load increases. The beneficial effect of the reinforcing MoSi₂ particles is clear, especially at higher loads, since the monolithic alloys lost more than double the volume than the composites. Moreover, due to the severity of the wear at 91 N it was not even possible to finish the test in the case of the as-received alloy 0AR. For both monolithic alloys, the wear at 140 N can be described as catastrophic since the whole test specimen was consumed within the first few minutes of sliding. From the comparison of both unreinforced alloys, it is seen that the alloy ball milled for 4 hours 0M(4h), lost much less volume than the non-milled alloy 0AR, showing that ball milling improves the aluminium alloy wear resistance. The same occurs in the composites, especially at 140 N, where the wet blended composite 1W clearly exhibited the worse behaviour, followed by 2C. Although less evident, also for 42 and 91 N the

ball milled composites exhibited superior wear resistance than the non-milled composites. Another noteworthy feature that is derived from Figure 2 is that there is no practical difference between the wear behaviour of composites in solutionized and T6 conditions, which indicates that in this study the wear resistance is not influenced by the aging state of the matrix.

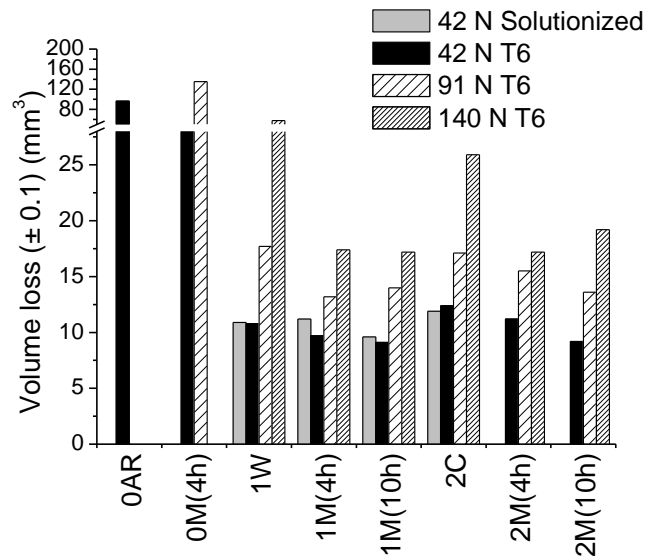


Figure 2. Volume loss of the unreinforced alloys and composites materials after 10 km of sliding distance for each load tested.

Figure 3 a) b) c) gives the volume loss as a function of sliding distance for all loads and materials in T6. Roughly, three sections can be appreciated according to the slope of the curves. An initial one before 2.5 km; a second one that starts at 2.5 km, which has a lower slope that increases with load and corresponds to a mild wear regime or steady state region; and a third one with a high slope. These three regions are better appreciated when the wear rate Q (volume loss divided by sliding distance) is represented against load, as shown in Figure 3d). In this plot it is observed that the severe regime is present in the unreinforced alloys for all loads and that it is less severe in the ball milled alloy. For the composite materials, the wear rate for all tested loads can be considered as mild,

except for the non ball milled 1W and, less pronounced, 2C composites at 140N, which are more likely to be considered as severe. During the wear tests, the strong volume loss coincides with heavy noise and vibration, together with transfer of pin material to the ring. This type of seizure has been referred to as galling seizure [15].

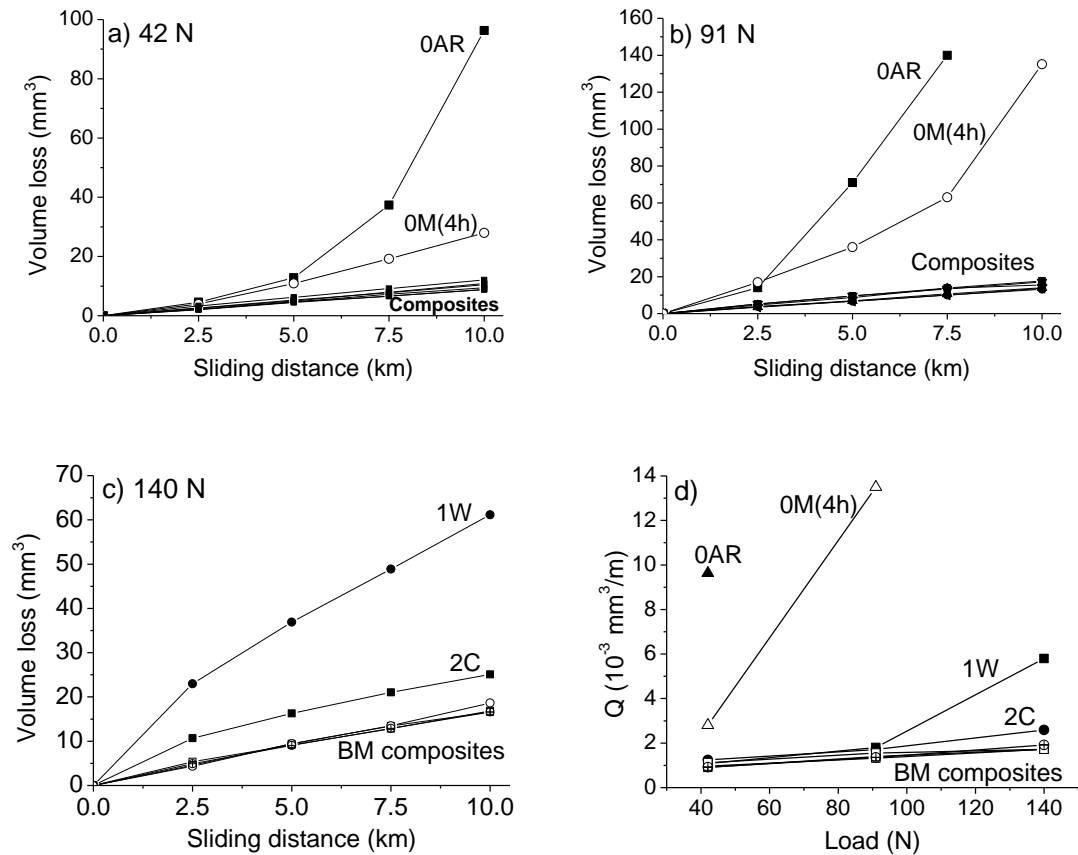


Figure 3. Volume loss as a function of sliding distance at: a) 42 N, b) 91 N and c) 140 N for materials in T6 condition. d) Wear rate Q as a function of load at 10 km.

To the naked eye, the worn surface of both monolithic alloys tested at 42 N was partly covered with a dark layer, the extent of which decreased with sliding distance until it disappeared in the non-milled alloy, 0AR, at 7.5 km, leaving a metallic surface which is consistent with the transition to a severe wear mechanism. At high magnification, Figure 4a), the worn surface of the 0AR alloy exhibited grooving, most

probably produced by ploughing by the harder asperities on the surface of the M2 counterface.

The aspect of the worn surfaces of the composites was significantly different to that of the monolithic alloys. In the ball milled composites, the dark surface layer increased in extension with the sliding distance and with the load tested. This agrees with the fact that wear of AMCs against a steel counterface produces a layer of material in the AMCs called a mechanically mixed layer (MML), which is formed by transfer and mixing of materials, under certain load and velocity range. Several studies [16,17,18] associate the high wear resistance of the composites under dry sliding with the formation of this stable tribolayer which acts as a protective layer that supports and distributes the load over the AMCs. Therefore, the wear mechanism in the ball milled composites can be considered mild oxidative, without which in the load range studied, the transition would have taken place to a severe regime. As example of ball milled worn surfaces, the one of the 10h-milled composite, 1M(10h), tested at 42 N is shown in Figure 4b). It is completely covered by a dark surface layer that is smoother than that of the unreinforced alloy.

For the non milled composite materials the behaviour is a mixture between the monolithic alloys and the ball milled composites. In 2C composite the wear regime is also mild but has a lower proportion of the dark layer at 140 N on the worn surface, which is consistent with the lower wear resistance than the ball milled composites. The surface layer in 1W composite decreases with increasing load, almost disappearing at 2.5 km at 140 N, leaving most of its surface with a rough metallic aspect at the end of the test, Figure 4c). This is consistent with the high wear rate exhibited at 140 N and, may be, with a transition of the wear regime to severe one. Therefore, MoSi₂ particles and ball milling delay the transition to the severe wear regime and significantly improve

the wear resistance of the aluminium alloy, especially at 140 N. In Figure 4d), EDS obtained on the worn surfaces show, apart from the elements that form part of the tested materials, a significant signal of Fe and some Cr and V that come from the M2 counterface.

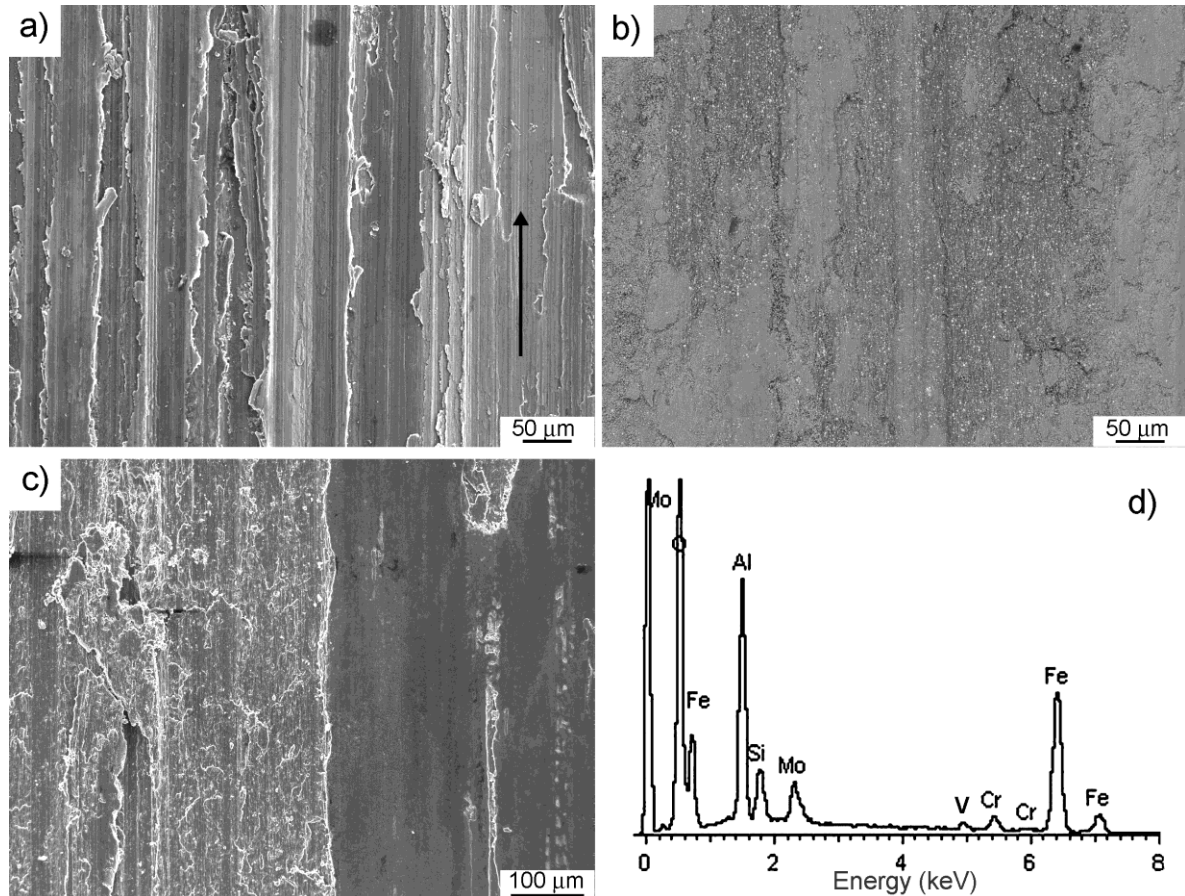


Figure 4. Worn surface after 10 km of: a) unreinforced alloys 0AR at 42 N, b) 1M(10h) composite at 42 N, c) 1W at 140 N and d) EDS of the worn surface of c). The arrow in a) indicates sliding direction.

The above observation on the wear behaviour indicates that the superior wear resistance of the composites with respect to the monolithic alloys is due to the formation and stability of the surface layer on the surface of the materials worn. According to Rosenberger *et al.* [16], the formation of the MML requires deposition of mechanically mixed materials until a steady layer is formed in which the rate of deposition equals the

rate of material lost by wear. In the materials with low hardness (monolithic materials) the softer substrate produces the detachment of the surface layer which is not longer formed, and the wear regime becomes severe. At 42 N and 91 N, the formation and stability of the surface layer in composites is independent of size and distribution of the reinforcing particles. At 140 N, the surface layer in the ball milled materials seemed to increase with the sliding distance but kept constant in 2C composite and not was longer observed in 1W. This can be attributed to the fact that the contact temperature increases due to the friction as the load increased which provoked the non-milled material to soften. Moreover, the more clustered MoSi₂ particle distribution in 1W accelerates the detachment of the surface layer.

In Figure 5a) the wear rate of composites in the mild region is plotted against the inverse of hardness of the composites in T6 condition (H_{T6}), except for 1W at 140N which that has been considered to be in the severe regime. According to the classic Archard law for sliding wear ($Q=KW/H$, where W is the applied load, H is the material hardness and K is a dimensionless coefficient) [19], for each load, Q should increase linearly with $1/H_{T6}$. However, this correlation does not hold in the present case for neither the composite or the monolithic alloy. This is evidence that the wear resistance of these materials is insensitive to the aluminium alloy hardness in T6 condition, as is the case in other Al alloys [20,21]. The explanation for this behaviour is that, under the abrasive contact conditions, the near surface would have experienced high enough strains (and temperature) to promote re-dissolution of the age hardening precipitates principally via shearing, i.e. work softening. This implies that the worn materials are actually in the solutionized condition, and not in T6, which is confirmed by the fact that volume loss of materials in T6 and in solutionized conditions are the same (Figure 2). According to this, is the plot of Q (of originally T6 materials) versus the inverse of

hardness of solutionized materials (H_s) the one that should give a linear relationship. Effectively, as can be seen in Figure 5b), where Q has been plotted against $1/H_s$, Q increases linearly with H_s at 42 N and 91 N, although at 140 N this relationship is not evident at all.

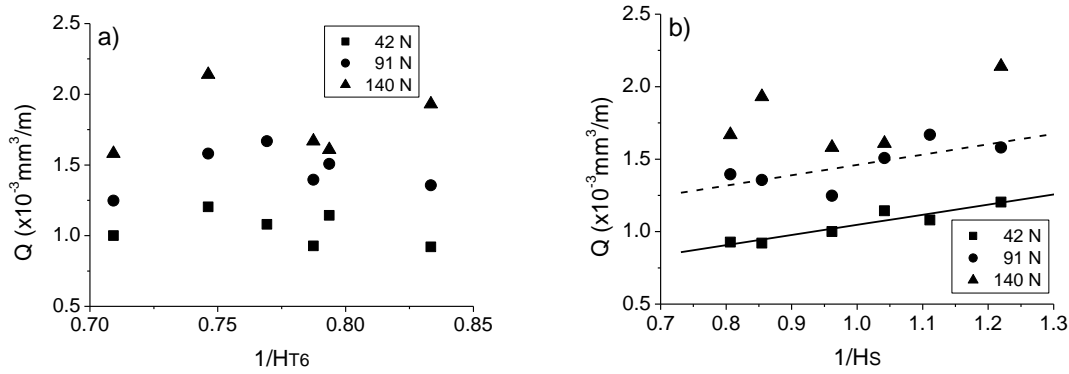


Figure 5. Wear rate (Q) in T6 composites as a function of $1/H$ in: a) T6 (H_{T6}) and b) solutionized (H_s) conditions.

In addition to the effect of the reinforcing MoSi_2 particles, the microstructure of the matrix should also influence the wear resistance, especially the grain size of the matrix [22]. The active strengthening mechanism in the matrices fabricated with the milled powders would be a combination of two factors, a reduction in matrix grain size as predicted by the Hall-Petch relationship, and an increase in oxide dispersoids, as predicted by the Orowan equation for the interaction between particles and dislocations. Corrochano *et al.* described in a previous work [9] that the solutionized hardness, H_s , of these materials follows a Hall-Petch mechanism, i.e. $H_s \propto d^{-1/2}$. Taking into account that Q is proportional to H_s^{-1} , it follows that Q should be proportional to $d^{1/2}$. This proportionality is confirmed in Figure 6 in the materials tested at 42 and at 91N, indicating that at these loads matrix grain size also plays a role in the wear resistance of the composites and matrix alloys, so that a decrease in grain size results in an

improvement of wear resistance. The high correspondence between Q and $d^{1/2}$ also indicates that the difference of wear resistance behaviour among the composites is mainly due to the difference in matrix grain size, so that the other microstructural variables such as dispersoids introduced during ball milling and size and distribution of MoSi_2 particles have a secondary effect. Obviously, they do have an influence not only by themselves but also through their effect on matrix grain size, so that a higher amount of dispersoids, a smaller MoSi_2 particle size and a more homogeneous distribution promote a smaller matrix grain size [9], which improves wear resistance.

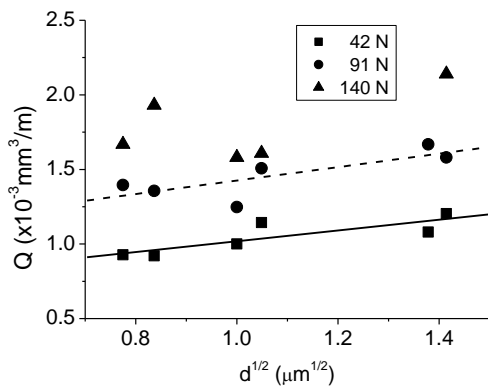


Figure 6. Wear rate (Q) as a function of square root of composites matrix grain size ($d^{1/2}$).

The failure of a direct relationship between wear resistance and grain size at 140 N should be explained by the temperature increase during testing. As demonstrated in [16], this increase can promote softening of the aluminium matrix. This is particularly important when comparing the ball milled composites with the non-milled materials 1W and 2C. While the ball milled microstructure is stable against long annealing time at high temperature due to the presence of fine oxide dispersoids and small MoSi_2 particles, Table 2, the non-milled composites, with a much smaller amount of dispersoids and larger MoSi_2 particles are more prone to experience grain growth. Moreover, in the case of 1W, which is the one that presents the highest wear rate, its

more clustered MoSi₂ particle distribution (highest COV_λ) favours cracks nucleation, fracture and decohesion of particles at reinforcement agglomerations, as they act as preferential sites for these phenomena [23]. In such a case, pulled out particles can act as third abrasive bodies producing a further decrease in wear resistance. In addition, the reinforcement free zones are soft and more capable of plastic deformation [24].

Therefore, ball milling improves the wear resistance of the composites at 140 N due to a more stable and more homogeneous microstructure being generated in the process.

Interesting to notice from the wear results of the AA6061/MoSi₂/15p composites is that wear resistance improves with decreasing particle size, although most studies [4,6,25,26] reported the opposite behaviour. The reason for this should be sought in the fact that, in our materials, homogeneity of the distribution also increases with decreasing particle size, in opposite to the general trend of worse distribution associated with smaller particles. Moreover, smaller particles suffer less internal fracture and debonding than larger ones, which should be added to the fact that they promote smaller matrix grain size and thus higher hardness. All these features contribute to this improve in wear behaviour with decreasing reinforcing size.

To conclude the evaluation of the present materials, a comparison between wear resistance of the 10h-milled AA6061/MoSi₂/15p composites, 1M(10h) and 2M(10h), with AMCs reinforced with NiAl, Al₂O₃ and SiC particles found in the literature is performed. Values are summarized in Table 3. It has to be noted that this is not straightforward because material processing history, microstructure and type and parameters of wear test may not be the same, and they may play a significant role in modifying wear properties. In addition, this information sometimes is not even available. As seen in Table 3, the wear resistance of AA6061/MoSi₂/15p is one order of magnitude better than AA6092/Ni₃Al/15p tested in identical conditions [24]. With regard to the AMCs reinforced with ceramic

particles, MoSi₂ particles promote superior wear resistance in aluminium alloys than those reinforced with Al₂O₃ at similar test loads [27,28,29,30,31]. In relation to the AMCs reinforced with SiC particles, the AA6061/MoSi₂/15p in this work present a slightly higher wear rate than AA6061/SiC/8p tested to 40 N but where the sliding velocity was 0.63 m/s [30], slightly lower than 0.94 m/s. Nevertheless, another study on SiC reinforcement showed a wear rate of three orders of magnitude higher, though the sliding velocity also was higher, 6.0 m/s [32].

Table 3. Al-based particulate reinforced composite materials after dry sliding at different conditions.

Material	Load (N)	Sliding velocity (m/s)	Wear rate, Q (x10 ⁻³ mm ³ /m)	Ref.
AA6061/MoSi ₂ /15p 1M(10h)	42		0.9	
	91		1.4	
	140	0.94	1.7	Present work
AA6061/MoSi ₂ /15p 2M(10h)	42		0.9	
	91		1.3	
	140	0.94	1.9	Present work
AA6092/Ni ₃ Al/15p	42		5.0	
	91		13.7	
	140	0.94	18.2	[24]
AA6061/Al ₂ O ₃ /20p	52		3.6	
	98	0.2	5.9	[27]
AA6061/Al ₂ O ₃ /20p	50	0.2	9	[28]
AA6061/Al ₂ O ₃ /20p	50		2	
	100	0.63	2.8	[29]
AA6061/Al ₂ O ₃ /8p	40	0.63	0.7	[30]
AA6061/Al ₂ O ₃ /10p	40	1.0	1.3	
AA6061/Al ₂ O ₃ /20p			1.2	[31]
AA6061/SiC/8p	40	0.63	0.6	[30]
AA6061/SiC /10p	10	6.0	600	
AA6061/SiC /20p			565	[32]

4. Conclusions

Different microstructures have been generated in six AA6061/MoSi₂/15p composites and two monolithic AA6061 alloys processed by powder metallurgy by varying initial reinforcement size and mixing method. The dry sliding wear behaviour of these materials has been studied as a function of processing and microstructural parameters.

- The composite materials present a much higher wear resistance than the corresponding monolithic alloys. MoSi₂ reinforcing particles delay the transition to severe wear regime of AA6061 aluminium alloy.
- Ball milling improves the wear resistance of the materials due to a more stable and more homogeneous microstructure generated by the introduction of dispersoids and the refinement of the microstructure. This avoids the detachment of the mechanically mixed layer, especially at high load. Ball milling also delays the transition to severe wear regime.
- In the present composites, wear resistance improves with decreasing reinforcing particle size mainly due to the simultaneous increase in the homogeneity of the distribution of the MoSi₂ reinforcing particles.
- The wear rate is independent of the aging state of the materials (T6 or solutionized), so that the values of hardness that should be used to analyse the results are those of the materials in solutionized condition.
- At 42 and 91N, wear rate of materials in T6 fulfils the Archard law, decreasing as hardness of solutionized materials increases.
- At 42 and 91N, wear rate follows a Hall-Petch type relationship, i.e. it varies with the square root of the matrix grain size, showing that wear resistance increases as matrix grain size decreases.
- At 140 N, the more clustered MoSi₂ particle distribution in 1W accelerates the detachment of the surface layer which promotes an earlier transition to a severe regime.

- The comparison of wear resistance of the 10h-milled AA6061/MoSi₂/15p composites to those of ceramic reinforced AA6061 alloys indicates that the present intermetallic reinforced materials can be considered as potential substitutes for ceramic reinforced aluminium alloys in tribological applications.

Acknowledgements

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