Wear behaviour of a spontaneously liquid infiltrated aluminum alloy matrix composite in pin-on-disk high velocity dry sliding wear tests

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Spontaneous liquid infiltration of alumina preforms is a well known method for the production of disks to be used in brakes for motorcycles, automobiles and even rail transportation. The pin on disk wear testing is a mean to evaluate the suitability of the Alumina-Aluminum alloy composite for such applications and moreover allows to evaluate the stability of the surface of the rotating composite disk in contact with a stationary counterpart. A series of high velocity dry sliding wear tests were carried out on a properly modified horizontal lathe, against metallic and brake lining counterparts. Friction coefficients as well as the wear rates were determined during pin-on-disk and flat-on-disk tests carried out at different sliding speeds, up to 15 m/s. The sliding speed heavily affects the stability of the composite which showed increasing degradation rate with increasing speed. The microstructural examinations carried out by means of light and scanning electron microscopy showed the important role played by the third body, which enhances delamination, especially during the tests carried out at the highest sliding speed.

Parole chiave: materiali compositi, alluminio e leghe, tribologia, metallografia

INTRODUCTION

In recent years the utilization of Metal Matrix Composites (MMCs) for the production of brake disks and drums is increased and is now one of the most promising fields for the utilization of such materials, both for road and rail transportation vehicles, due to the reduced weight compared to the traditional materials, namely gray cast iron and steel. In fact the reduction in weight which can be expected when substituting an Aluminum alloy based MMC for cast iron, ranges roughly between 50 and 60%. Moreover inertia of the rotating parts is reduced which turns out in an additional fuel saving which can be estimated to produce the effect of a further reduction of the weight of the rotating parts of roughly 50%. On the other hand it may be foreseen that the acceleration of the vehicle will be improved and the braking distance will decrease [1].

Since the first utilization of such materials as brake disks on the Ford Lincoln Town car model [2], other car and motorcycle producers have decided to resort such solution. Brake disks have also been tested in the railway applications giving promising results, being this application extremely interesting for high speed trains.

A matter of concern is, however, the mechanical resistance of the composite at the high temperature which may be produced during a long lasting braking from high speed, as well as the consistency of working parameters such as the friction coefficient or the geometrical stability of the material during its working life. Though being the heat conduction coefficient of the MMC roughly twice (or even more than twice) as high as that of the traditional cast iron, to this end the density of the MMC, which was a positive characteristic when evaluating energy savings due to weight reduction, turns out to be a negative characteristic because it negatively affects the thermal diffusivity. As a matter of fact the heat capacity of a gray cast iron component can be evaluated to be roughly 25% higher than that of an aluminum-based one. To this respect the Maximum Operating Temperature (MOT), which is peculiar to the material and depends on the composition of the matrix and on the nature and volume fraction of the reinforcing phase, is a parameter which is to be compared with the maximum temperature reached during operation [3].

While cast iron can undergo very high operating temperatures, its MOT being of the order of nearly 900 °C, the operating temperatures of Aluminum-base MMCs must be kept to a much lower value, being their MOT of the order of 420-530 °C at best. It has been evaluated that the slowing down of a car weighting 1650 kg from 60 m/s (216 km/h) to 2.78 m/s (10 km/h) in 7.3 s and 208.7 meters braking distance produced peak temperatures in Al-SiC brakes as high as 700 °C, while in Al-Al2O3 the maximum temperature reached "just" 530 °C, which corresponded to the MOT of that composite [2].

The present work is focussed on the evaluation of the tribological behaviour of an Aluminum Alloy - 30% Alumina composite against the classical AISI 52100 steel in pin-on-disk wear tests and against brake lining in flat-on disk wear tests.

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EXPERIMENTAL

The disk surface on which the tribological tests would be performed was accurately ground and the surface smoothed. The pins consisted of 3 mm dia. AISI 52100 cylinders, whose flat surfaces, which were to slide against the disk, were obtained by transversally sectioning with a diamond coated blade in a Struers Microtom cutting machine. The edges we-

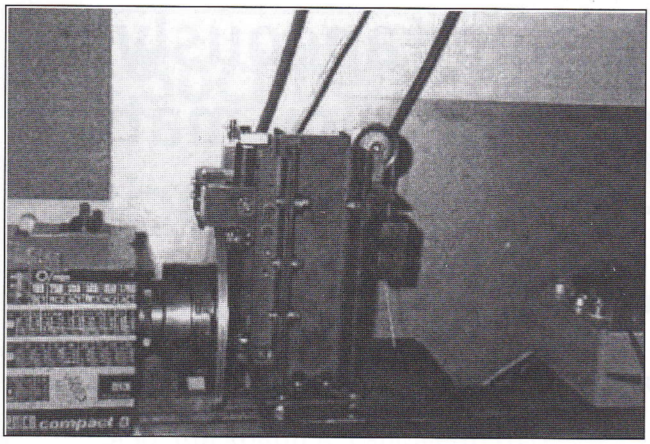


Fig. 1 - Columns supporting the articulated joint mounted on ball bearings (fig. 2) which afford to transfer the force deriving from the masses on the right of the column to the pin. On the right of the picture the strain gauge feeder-signal amplifier unit is visible. The instrumented cantilever, at the back, is out of sight being almost completely covered by the columns and the articulated joint housing.

Fig. 1 - Colonne di supporto del braccio porta pin montato su giunto oscillante provvisto di cuscinetti. Il giunto consente di trasferire la forza derivante dal peso delle masse visibili alla destra della colonna mediante un cavo flessibile ed inestensibile. All'estrema destra della figura si nota la centralina di alimentazione-amplificazione del segnale. La barra a sbalzo strumentata con estensimetri, in posizione posteriore rispetto al punto di osservazione, è quasi completamente coperta dalle colonne di sostegno del giunto.

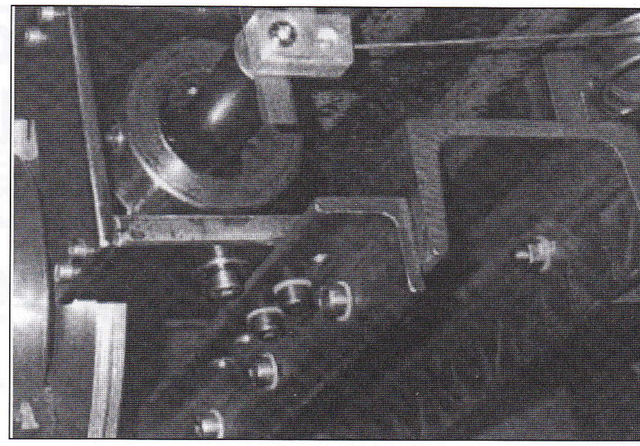


Fig. 2 - Close up picture of the articulated joint with disk mounted on the mandrel.

Fig. 2 - Particolare del giunto articolato, con il disco in composito montato sul mandrino del tornio parallelo.

re round off and the contact surfaces polished.
The tribological tests were carried out on a properly modified parallel lathe whose speed of rotation ranged between 350 and 1700 rpm.
The modification consisted in a rigid four columns structure which supported an articulated joint which affords, via an non-extensible and flexible steel cord, to transfer the force deriving from the weight of suitable masses to the pin. The rotation of the pivot bearing the pin around an axis parallel to the axis of rotation of the mandrel, was prevented by a thin high strength steel bar which connected, through hinges, the pin stand to a cantilever on which electric strain gauges had been bonded and then connected in a full bridge circuit so that, after a calibration, it was possible to determine the sliding force and compute the friction coefficient as a function of time and, consequently, of sliding distance.
The axis of rotation is horizontal, so that the effect of the "third body" is probably reduced to some extent with respect to the conditions which would be set up in a pin-on-disk wear test carried out with a vertical axis of rotation (fig. 1 and 2).
The pin holder can fit cylindrical as well as square prismatic pins, and also "flat" pins, so that so-called flat-on-disk tests can be carried out. The versatility of the design affords to perform also pin-on-cylinder and flat-on-cylinder wear tests, by simply connecting a rod which holds both the pin and the load to the instrumented cantilever mentioned above via a

TEST IDENTIFICATION	No. 1	No. 2	No. 3	No. 4
TEST CONDITIONS				
Rotation speed [Rpm]	350	850	1700	1700
Sliding speed [m/s]	3.3902	6.764	14.06	15.755
Wear track mean radius [mm]	92.5	76.0	79	88.5
Sliding distance [m]	10000	10000	10000	10000
Number of revolutions	17206	20941	20146	17984
Load on pin [N]	10	10	10	10
Contact area [mm^2]	7.068	7.068	7.068	184
Lubrication	No	No	No	No
MATERIALS				
Disk	Al-2Mg+30 vol.% Al_2O_{3p}	Al-2Mg+30 vol.% Al_2O_{3p}	Al-2Mg+30 vol.% Al_2O_{3p}	Al-2Mg+30 vol.% Al_2O_{3p}
Pin	No. 1 - heat treated AISI 52100	No. 2 - heat treated AISI 52100	No. 3 - heat treated AISI 52100	brake lining
weight of the pin before the test [g]	0.6812	0.6791	0.6807	31.5503
weight of the pin after the test [g]	0.6811	0.6790	0.6779	31.5435
weight loss [g]	0.0001	0.0001	0.0028	0.0068
ENVIRONMENTAL FACTORS				
Room Temperature [°C]	16.5	18	18	16
Relative humidity [%]	68	69	70	58

Tab. 1 - Experimental parameters of the wear tests

Tab. 1 - Parametri sperimentali delle prove tribologiche.

hinge. The output of the amplifier connected to the strain gauges bridge was transferred via serial port connection to a laptop PC and recorded for subsequent elaboration.
The tests were carried out at room temperature and humidity, over a sliding distance of 10 km, which means that the number of rotations was different from one test to another, having the wear tests been performed on concentric tracks.
The pins and the flat brake linings were weighted before and after the tests in order to check the extent of wear on the pins, and light (LM) and scanning electron microscopy (SEM) examinations were carried out in order to identify the wear mechanisms, together with X-Ray energy dispersive spectroscopy examinations. Just visual examination was carried out on the worn surfaces of the disk, being its dimensions too large to fit in a microscope.

RESULTS AND DISCUSSION

This difference in the number of revolutions presumably did not affect the pins significantly, but has probably some effect on the disk material. In fact it can be reasonably supposed that, as the pins slide along similar distances, the only difference in the behaviour of the pin material might be related to different temperature build-ups in correspondence with higher power (thermal power) released in the contact zone during the tests carried out at the higher speed, while, being the radiuses of the tracks different, this increases the number of times a single point of the wear track belonging to the disk is in contact with the counterpart. It can be easily evaluated that a maximum increase of the order of 20% is produced to this respect, being the maximum reduction in radius of a similar amount.
Table 1 summarizes the experimental conditions for the wear tests.

IDENTIFICATION OF THE WEAR MECHANISMS FOR THE PINS AND THE DISKS

For the tests carried out with the steel pins, whose conditions are summarized in table 1, three different wear mechanisms can be hypothesized to be involved in each test. The wear mechanism in the case of test No. 1 can be identified as a mild oxidation wear. In fact the contact surface of the pin, besides very evident surface scratches produced by the sliding composite disk, dark areas are clearly visible, which can be attributed to an oxidized surface. No traces of seizure were observed, just some debris smeared onto the contact surface (fig. 3). SEM examinations confirmed such observations (see fig. 4a and 4b where some loose debris is visible) as well as the X-ray energy dispersion spectra and maps of fig. 5 and 6, where evidence of localized concentrations of Aluminum and Oxygen is clearly visible. Of course it is likely that the presence of aluminium oxide, possibly also in the form of hydrated alumina due to the oxidation of the debris originated from the matrix of the disk and rapid uptake of environmental humidity, is concomitant with that of the reinforcing alumina.
Considering test No. 2 and examining the surface of the contact area of the pin (see fig. 7), it appears evident that stiff aggregations of debris are stuck onto its surface. During the test such aggregations undergo alternate apposition and detachment of material, which mechanism affects the friction coefficient value as determined during the test (fig. 8a, b). In fact the friction coefficient during the second test is continuously increasing, while this was not the case of test No. 1, carried out at a rotational speed of 350 rpm. Indeed while the trend is continuously decreasing with sliding distance in the case of the test carried out at the lower rotational (and

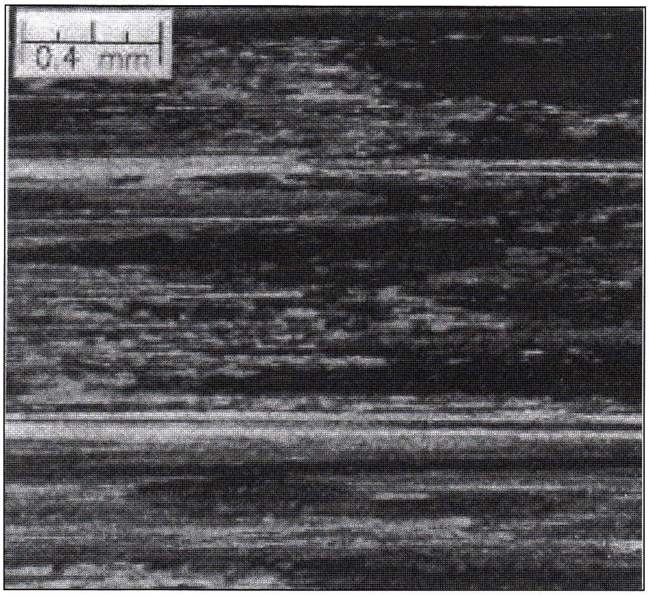


Fig. 3 - Surface wear track on pin No 1. Dark areas are produced by a mild oxidation wear mechanism.

Fig. 3 - Superficie della traccia di usura sul pin N. 1. Le zone scure sono dovute ad un meccanismo prevalente di usura con ossidazione leggera.

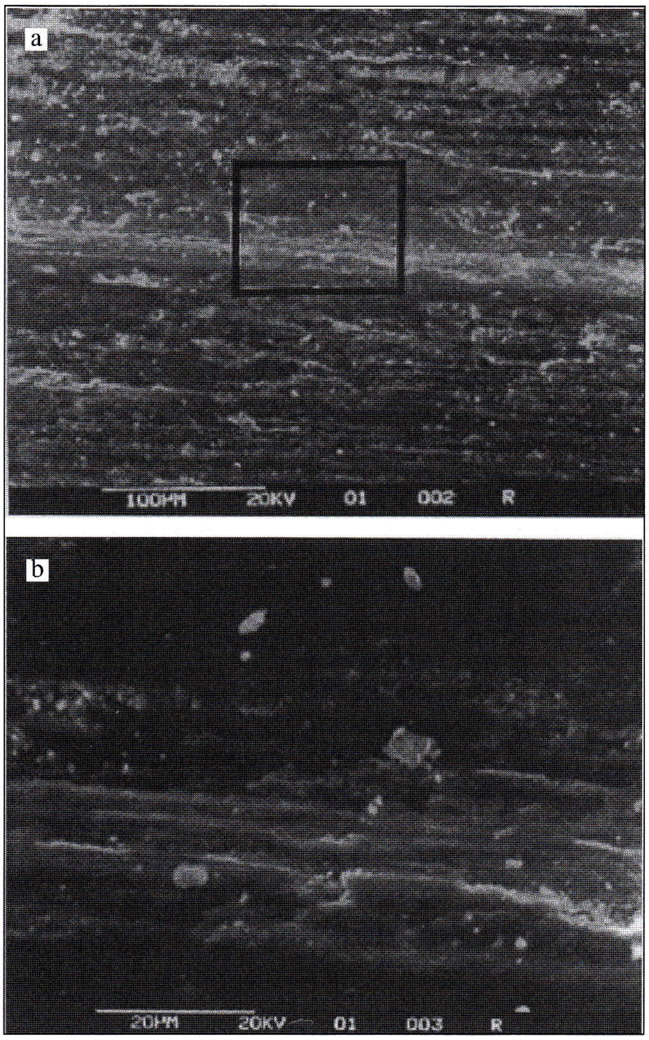


Fig. 4a, b - SEM micrographs of the surface of the pin of test No. 1. Smeared debris and some loose debris is visible on the surface.

Fig. 4a, b - Micrografie SEM della superficie del pin del test N. 1. Sfridi distribuiti aderenti e qualche agglomerato di sfridi staccati, ma appoggiati, sulla superficie.

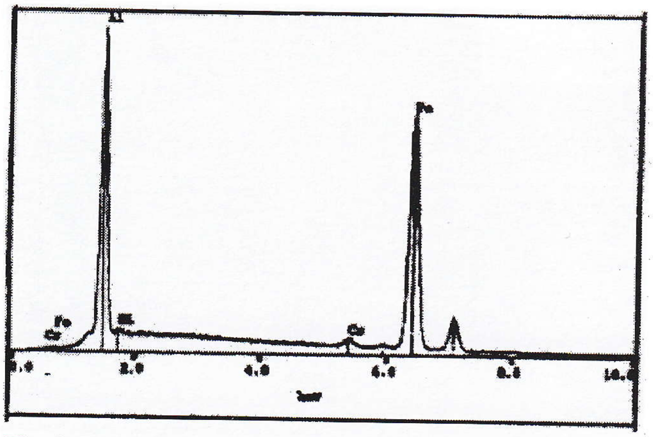


Fig. 5 - X-Ray Energy Dispersion Spectrum of the surface of the pin of test No. 1. Al and Si originate from the composite disk, while Fe and Cr originate from the AISI 52100 pin.

Fig. 5 - Spettro ai raggi X in dispersione di energia, ricavato dalla superficie di contatto del pin del test N. 1. Al e Si sono originati dal disco in composito, mentre Fe e Cr sono originati dal pin di AISI 52100.

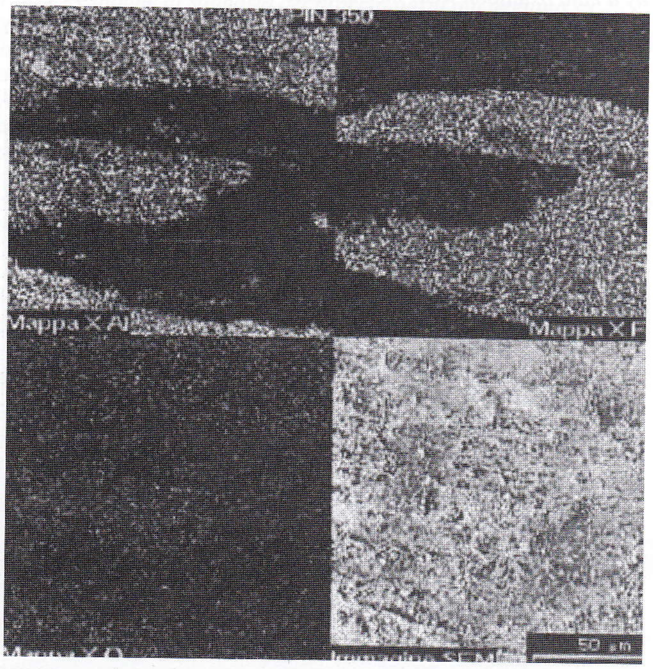


Fig. 6.- X-Ray Dispersion Energy Maps of Aluminum, Iron, Oxygen showing the distribution of the elements on the contact surface of the AISI 52100 pin.

Fig. 6 - Mappe ai raggi X in dispersione di energia di Alluminio, Ferro, Ossigeno illustranti la distribuzione degli elementi sulle superfici di contatto del pin di AISI 52100.

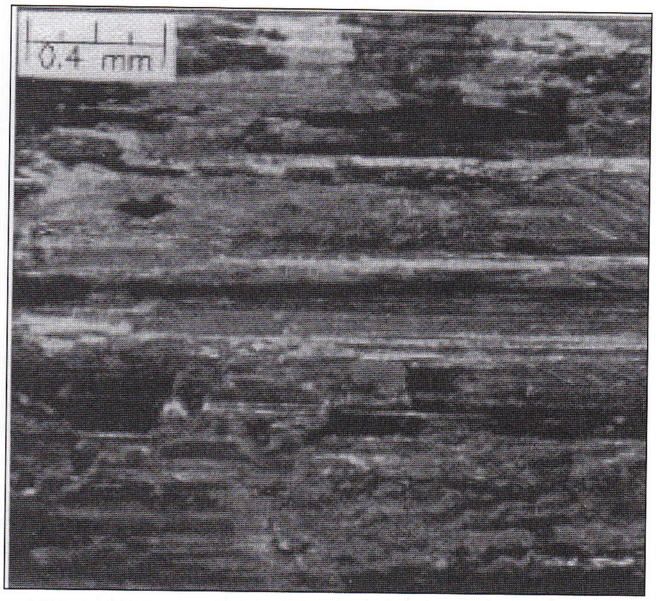


Fig. 7 - Surface of pin from test No. 2. Debris aggregates covering the surface of the pin, with delamination of such aggregates and deep grooves on the compact debris deposit.

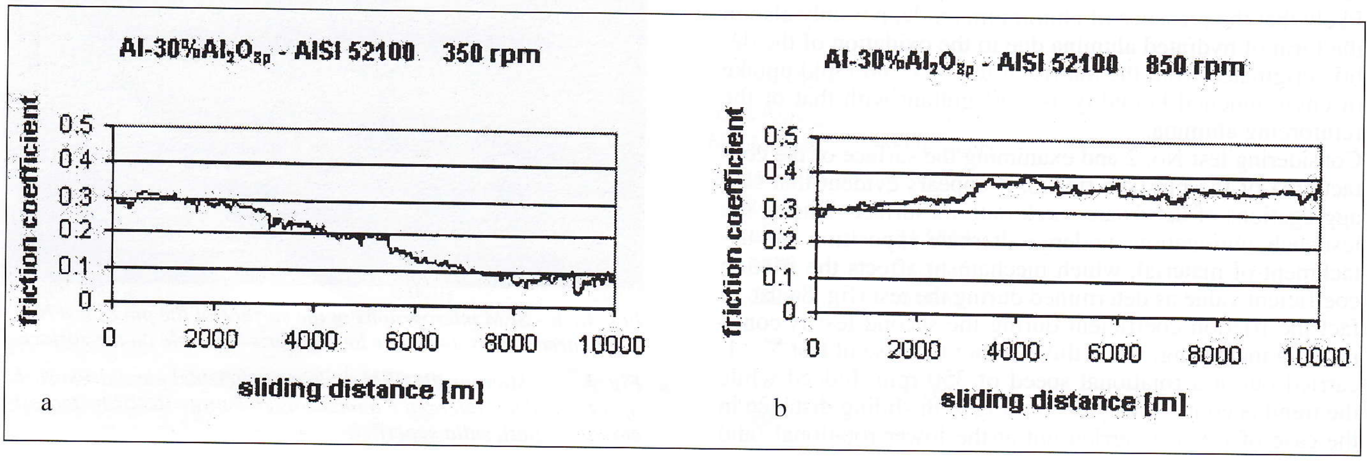
Fig. 7 - Superficie del pin del test N.2. Aggregati di sfridi ricoprenti la superficie del pin; fenomeni di delaminazione di detti aggregati e profondi solchi sul riporto compatto di sfridi.

sliding) speed, in the second case the friction coefficient increases with sliding distance and the plot appears more irregular, so that it can be hypothesized that seizure takes place between the disk and the surface of the compact debris aggregates which build up on the pin. It is worth pointing out that the net weight difference of the pins of the first two tests is very close to zero, so that it can be hypothesized that during the first stages of the test some steel is removed by abrasion from the surface of the pin and afterwards debris is deposited on its surface. It appears reasonable, though it was not checked, that the thickness of the removed layers and of the subsequently deposited ones should differ in tests No 1 and No. 2.

Considering the third test at 1700 rpm against an AISI 52100 pin, it can be pointed out that the friction coefficient appears to be lower than in the second test, with values that are almost constant in the second half of the test at a mean value of 0.18. It can be noticed as well that a running-in during the first 1000 m takes place and affords to settle the

Fig. 8a, b - Friction coefficient vs. sliding distance in tests No. 1 (a) and test No. 2 (b).

Fig. 8a, b - Coefficienti di attrito contro distanza di strisciamento nei test N. 1 (a) e N. 2 (b).



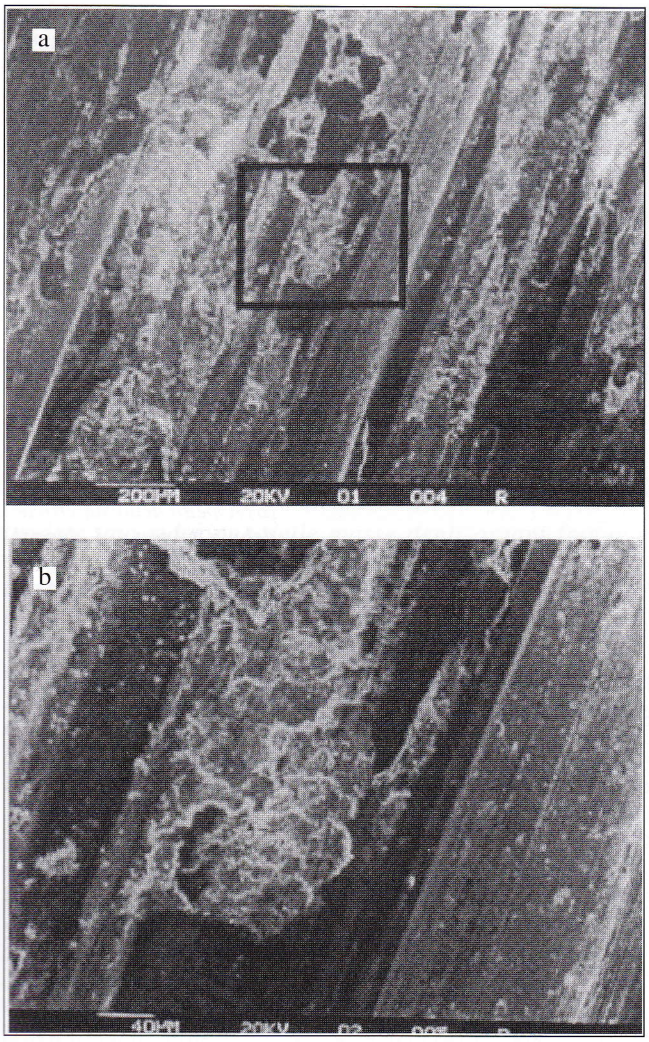


Fig. 9 a, b - SEM micrographs of the surface of the pin of test No. 2. Compact and well stuck debris which has been partially torn off the surface of the underlying AISI 52100 pin.

Fig. 9 a, b - Micrografie SEM della superficie del pin del test N.2 Sfridi compatti e bene aderenti sono stati parzialmente strappati dal sottostante pin di acciaio AISI 52100.

friction coefficient at values of the order of 0.16 till, at roughly 3850 m sliding distance, the friction coefficient boosts to over 0.2, but decreases down to 0.16 in the following 1150 m distance. On the other hand, if the weight variations of the pin are considered (see figures in table 2), it appears that in this case a significant weight loss was measured. It is the author's opinion that relatively high flash and bulk temperatures are reached in this test which are not compatible with the stability of a stuck debris layer as thick as that which was built up on the pin of test No. 2. Two facts could support such hypothesis:

- the friction coefficient is always lower than that of test No. 2 (but higher than that of test No. 1, on whose pin very shallow debris deposit was observed);
- two running-in events are observed. It can be supposed that the second one took place after a macroscopic seizure phenomenon took place, after 3850 m sliding distance.

Observing the SEM micrographs, and comparing in particular fig. 9b and fig. 11a, because they were taken at similar magnification, it can be observed that in the second case the surface of the debris deposit appears to be far smoother than in the first one, and that the surface is delineated by a interconnected network of cracks which appear to have been partially filled with fine debris. In order to better evaluate the phenomenon, the pin was embedded in epoxy resin, ground

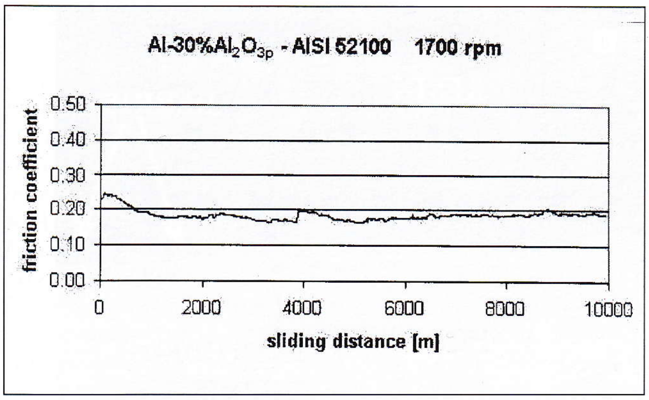


Fig. 10 - Friction coefficient vs. sliding distance in test No. 3.

Fig. 10 - Coefficiente di attrito contro distanza di strisciamento nel test N. 3.

with emery papers in order to obtain a longitudinal section and finally polished for subsequent optical microscopy observation. The micrograph (see fig. 12) can be interpreted considering that the metal was not etched and therefore it appears shiny, the resin is black and the debris is grey. It appears that the very fine debris, thanks to both the temperatu-

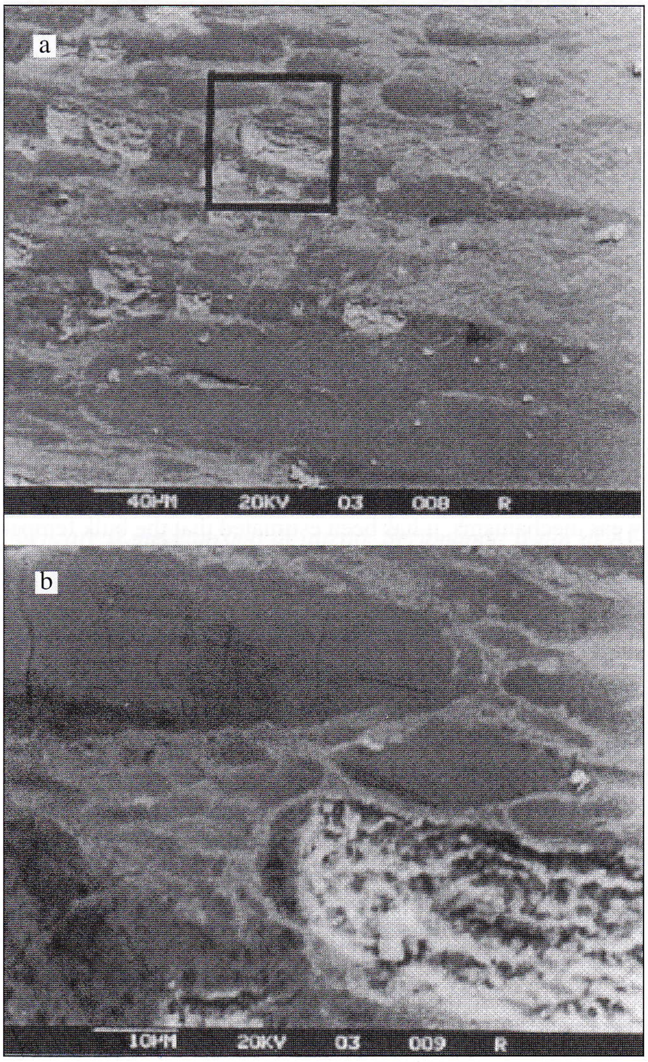


Fig. 11 a, b - SEM micrographs of the surface of the pin of test No. 3. Compact and well stuck debris which has been partially torn off the surface of the underlying AISI 52100 pin.

Fig. 11 a, b - Micrografie SEM della superficie del pin del test N.3. Sfridi compatti e bene aderenti sono stati parzialmente strappati dal sottostante pin di acciaio AISI 52100.

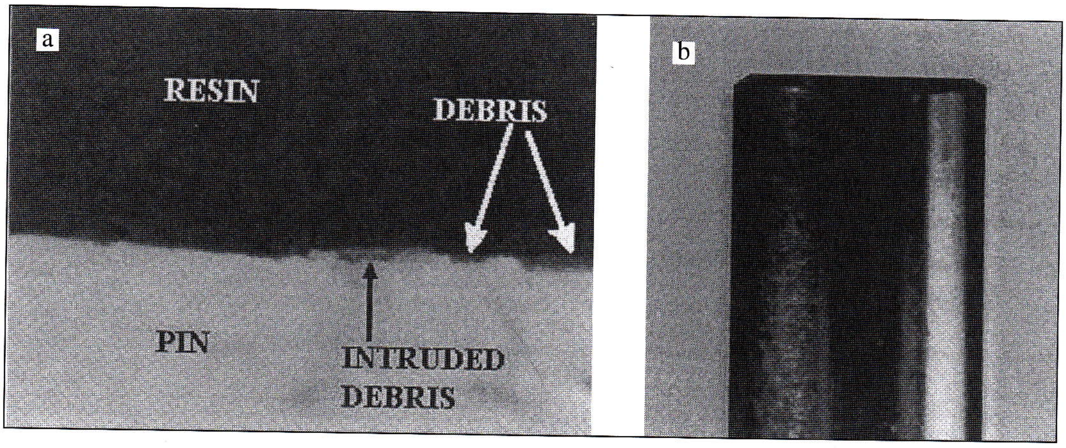


Fig. 12 – (a) Micrograph of the longitudinal section of the pin, close to the contact surface. Upper part: resin; lower part pin (not ethced). (b) Appearance of the surface of the pin of test No. 3 after the test. The bluish colour was compared to a colour chart for the tempering temperatures interval. (Mag 11X).

Fig. 12 - (a) Micrografia della sezione longitudinale del pin, vicino alla superficie di contatto. Parte superiore: resina; parte inferiore: pin (non attaccato). (b) Aspetto della superficie del pin del test n. 3, dopo il test. Il colore bluastro è stato confrontato con la mappa dei colori per detto acciaio, per l'intervallo di temperatura utilizzato per il rinvenimento (ingr. 11X).

TEST IDENTIFICATION	No 1	No 2	No 3
Pin identification	1	2	3
Weight of the pin before the test [g]	0.6812	0.6791	0.6807
Weight of the pin after the test [g]	0.6811	0.6790	0.6779
Weight loss [g]	0.0001	0.0001	0.0028
Normalized pressure	$1.813 \cdot 10^{-3}$	$1.813 \cdot 10^{-3}$	$1.813 \cdot 10^{-3}$
Normalized velocity	423.7	845.4	1757
Bulk temperature of the pin [°C]	95 °C	170 °C	355 °C
Hypothesized wear mechanism	Mild oxidation + debris formation	oxidation + debris formation and compaction	oxidation + debris formation and compaction and rheologically induced spalling of chips of AISI 52100 steel

Tab. 2 - Summary of wear test results for the AISI 52100 pins.

Tabella 2 - Riassunto dei risultati dei test tribologici.

re developed at the surface and the effect of the shear stress, is likely to undergo rheological phenomena which afford the intrusion beneath shallow chips which originate from surface discontinuities and propagate thanks to the disrupting effect of the semi-solid fine debris.
In fact, on the basis of an analytical approach according to Lim and Ashby's theory [4], modified by Rohatgi et al. [5], and adimensional treatment of the expression describing the wear mechanisms, it has been estimated that the bulk temperature reached 355 °C, which is consistent with a comparative colorimetric evaluation of the temperature reached by the AISI 52100 pin. It can be supposed that the temperature in the contact zone (flash temperature) might be sufficiently high as to afford the setting up of a semi-solid flow of debris which would cause the spalling of the above mentioned chips.
Table 2 summarizes the results of the wear tests involving metallic pins. For the reader's convenience some of the figures of table 1 have been quoted again
The final tests carried out against brake lining in a flat on disk configuration did not show any irregular behaviour and the friction coefficient appears to increase with increasing sliding distance and sliding velocity, and to settle up to values of 0.45.

CONCLUSIONS

Three different wear mechanisms have been identified in the sliding of metal matrix composite Al-30%Al_2O_3p against AISI 52100 pins depending on the sliding speed, in long distance tribological tests.

- At low sliding speed, of the order of 3.4 m/s, a mild oxidative wear with the formation of loose debris takes place.
- At intermediate sliding speed, namely about 6.8 m/s, a wear mechanism is developed which produces compaction of the debris which is stuck against the steel pin, so that adhesion takes place between the disk and the compacted third body, with increase of the friction coefficient.
- At high sliding speed,14 m/s, computed bulk temperature on pin appears to be sufficiently high so that the flash temperature is likely to reach the MOT of the alloy. A rheological behaviour of the very fine debris presumably enhances the spalling of chips from the flat surface of the pin.

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ABSTRACT

COMPORTAMENTO TRIBOLOGICO DI UN COMPOSITO A MATRICE DI LEGA DI ALLUMINIO OTTENUTO PER INFILTRAZIONE SPONTANEA IN TEST PIN-ON-DISK AD ELEVATA VELOCITÀ

L'utilizzazione di compositi con matrice in lega di alluminio per la produzione di dischi freno è recentemente aumentata ed è attualmente uno dei campi di applicazione più promettenti per tali materiali, applicati sia su veicoli destinati al trasporto su gomma che a quelli su rotaia. Tale tendenza è facilmente spiegabile considerando la riduzione della massa di tali organi in confronto a quelli realizzati con materiali tradizionali, tipicamente ghisa grigia, ghisa sferoidale ed in minor misura acciaio, quest'ultimo impiegato per lo più su motoveicoli. Dalla sostituzione dei materiali a matrice ferrosa con quelli a matrice in lega di alluminio ci si può attendere una riduzione delle masse degli organi frenanti compresa tra il 50 ed il 60%. Ciò ovviamente si traduce in una riduzione dei momenti d'inerzia delle masse rotanti, che a sua volta concorre a produrre un beneficio in termini di riduzione dei costi per il combustibile pari a quello che si otterrebbe riducendo le masse di detti organi di un ulteriore 50%, se si prende a riferimento il solo risparmio legato al moto di traslazione. Un ulteriore non trascurabile beneficio, a parità di altri parametri, si può individuare nelle più brillanti accelerazioni del veicolo e nella riduzione degli spazi di frenata.

La prima applicazione di tali materiali alla realizzazione di dischi freno è stata realizzata su un modello della Ford, ma l'utilizzo si è esteso anche ai freni montati sui carrelli di vagoni ferroviari di treni veloci.

Tuttavia un aspetto che deve essere seriamente considerato è la resistenza meccanica del composito alle elevate temperature che possono essere raggiunte durante una violenta e lunga frenata, oltre che la costanza del coefficiente di attrito e la stabilità geometrica del materiale durante il funzionamento.

Sebbene il coefficiente di trasmissione del calore dei compositi a matrice di alluminio sia doppio (e talvolta più che doppio) di quello della ghisa grigia, al fine dello smaltimento dell'energia termica sviluppata durante la frenata, la contenuta densità del composito, che è considerata generalmente una proprietà positiva, a questi fini risulta essere una proprietà penalizzante perché comporta una diffusività termica più bassa di quella della tradizionale ghisa. In effetti, si può stimare che la capacità termica di un componente in ghisa grigia sia circa il 25% più elevata di quella di un componente a base alluminio. In questo senso diventa fondamentale il ruolo della "massima temperatura di esercizio" ammissibile, che dipende in primo luogo dalla composizione della matrice, ed in particolare dalla sua temperatura di solidus ed in secondo luogo dalla natura e frazione volumetrica del rinforzo, che deve essere confrontata con la massima temperatura raggiunta (o raggiungibile) nel corso della frenata. Si addiviene quindi alla massima temperatura operativa, ovverossia di lavoro, del materiale (MOT, Maximum operating temperature).

Mentre dischi in ghisa possono resistere ad elevate temperature (fino a quasi 900 °C), la temperatura massima di esercizio alla quale i compositi a matrice di lega di alluminio possono essere utilizzati al più può aggirarsi tra 420 e 500 °C, in relazione alla matrice ed alla tipologia e alla frazione volumetrica di rinforzo. La combinazione più "performante" in termini di MOT attualmente appare, tra i compositi a base Al, il composito 30 % vol. Al_2O_3-AA3050 sviluppato da Lanxide, per il quale la casa produttrice indica un valore di MOT pari a 530 °C.

Il presente lavoro è stato focalizzato sulla valutazione del comportamento tribologico in test pin-on-disk di dischi di composito 30 % vol. Al_2O_3-AA3050, prodotto da Lanxide con la tecnica della infiltrazione spontanea di una preforma di allumina, contro pin cilindrici di acciaio AISI52100 (UNI 100Cr6) ricavati da rullini per cuscinetto e in test flat – on – disk contro guarnizioni d'attrito. Tutti i test sono stati condotti a secco, a temperatura ed umidità ambiente.

Una serie di tests condotti ad elevata velocità di strisciamento su un tornio parallelo appositamente attrezzato ha permesso di valutare comparativamente il comportamento del composito a matrice di lega di alluminio. Le velocità di strisciamento adottate variavano da 3.4 a circa 15 m/s. Gli sforzi di attrito sono stati rilevati in continuo durante tutta la durata delle prove, grazie al sostegno del pin strumentato mediante quattro estensimetri resistivi connessi in ponte completo.

Sui pin cilindrici, del diametro di 3 mm, agiva una forza di 10N. Forza della stessa intensità premeva contro il disco anche il materiale d'attrito per freno, la cui superficie di contatto con il disco tuttavia era più ampia di quella dei pin di acciaio.

Tutte le prove sono state condotte per un percorso di 10000m, al termine del quale sono stati esaminati disco e pin, valutate le perdite ponderali dei vari pin.

Esami microscopici condotti al SEM, con l'ausilio della analisi alla microsonda, hanno consentito di identificare i meccanismi di usura instauratisi nel corso delle prove condotte in diverse condizioni di velocità di strisciamento.

Per i test realizzati con pin cilindrici sono stati identificati differenti meccanismi di usura, in relazione alle velocità di strisciamento adottate, con moderata ossidazione alle basse velocità e via via l'intervento dello sfrido che agisce da "terzo corpo" si è dimostrato sempre più importante nell'influenzare il meccanismo di attrito. Sezionando il pin di AISI52100 utilizzato alla massima velocità di striscimanto, si è riscontrata la formazione di micro trucioli metallici di acciaio, tuttora connessi al pin, sotto ai quali era penetrato lo sfrido costituito dal materiale abraso.

Adottando la teoria di Lim e Ashby, modificata da Rohatgi e al., sono state inoltre valutate analiticamente le temperature raggiunte dai pin e stimato l'ordine di grandezza delle temperature di flash del disco.

La temperatura stimata sembra essere in buon accordo con una valutazione della temperatura del pin, condotta su base colorimetrica osservando l'ossido prodottosi in seguito all'incremento della temperatura superficiale del pin stesso.

E' stato anche evidenziato che il coefficiente di attrito e' influenzato dalla velocità di strisciamento, e per l'accoppiamento disco in composito-guarnizione di attrito si atabilizza, a 10000 metri di percorrenza, intorno al valore di 0.45.