FORMATION OF WEAR DEBRIS IN POLYMERIC TRIBOSYSTEMS

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Abstract. This paper aims to contribute to the understanding of how the wear debris are originated in pin-on-disc systems, the pin being a thermoplastic engineering material. In addition to the traditional classifications of polymers wear mechanisms mentioned in the literature, it was also expected to characterize morphological aspects such as shapes, sizes and level (qualitative) of the debris agglomeration. The wear tests were carried out on a pin-on-disc tribometer, being the pins made of polymeric material (UHMWPE and POM copolymer) and the discs made of alumina (Al_2O_3) and duplex stainless steel (austenític-ferrític). Three (3) load values, three (3) sliding velocity and two (2) counterface surface finish levels were used in these tests. The distance traveled by the pins on the disc was 3,500 meters within an environment with the relative air humidity controlled at 50 ± 5 %. For the analysis of the then existing wear mechanisms, the temperature of the contact region was measured and the adhesion work values (Wab) were determined by the sessile drop method and the Harmonic Average Equation proposed by WU. In order to identify the then existing wear mechanisms, the images of the contact surfaces (optical and scanning electronic microscopy) as well as images of the debris which were near the sliding track were used. The microscopic observations have shown evidences of the occurrence of three wear mechanism types: abrasion, fatigue, and film transfer (adhesion). The wear mechanism of the polymeric film melt transfer was identified by measuring the temperature near to the contact region, which was reached for some PV values.

***Keywords**: tribology, wear mechanisms, polymer, abrasion, adhesion, debris*

1. Introduction

The tribological characteristics of the polymers, either the friction coefficient or the behavior as to wear, are thought to be due to the occurrence of two main mechanisms: deformation and adhesion (Hutchings, 1992). The wear mechanism arising from the adhesion forces between a polymer and a rigid counter-face leads to an interfacial energy dissipation process. It is believed that the adhesion component has a "primary energy dissipation zone", usually located near the interface, with a typical thickness of 2 to 10 nm (Briscoe, 1990). The other component is called deformation and it generally includes much larger volumes, which are comparable to the apparent contact length. These components are responsible for the wear mechanisms classes involving surface and subsurface phenomena, and are called adhesion wear and abrasion wear, interfacial process, and cohesive process respectively (Hutchings, 1992) or interfacial wear and wear by bulk deformation as well (Briscoe, 1990). The understanding of the wear mechanisms actuating on a polymeric tribosystem has been a widely studied tribology issue (Bahadur, 2000; Bartenev and Lavrentev, 1981; Yamagushi, 1990; Briscoe and Tabor, 1978). The main wear mechanisms of polymeric materials involving interfacial processes (film transfer) and cohesive processes (abrasion and fatigue) are shown below.

1.1 Adhesion Mechanisms (Film transfer)

The literature says that some sliding conditions promote the formation of constant thickness films during the wear tests (Tanaka, 1982), since there is a balance between the removal and deposition mechanisms, therefore admitting that only the upper transfer film layers are removed. The stability of such films also depends on greater adhesion between them and the counterface: the greater the adhesion, the less the wear rate, the more oriented their chains, the greater the deposited film crystallinity (Marcus *et al*., 1981).

If the adhesion mechanism can be considered the main friction mechanism for dry-sliding polymers on a "plain" surface, it is reasonable to believe that the electrostatic and/or Van Der Waals interactions taking place at the contact play a fundamental role in the friction coefficient (Lee, 1974). However, the understanding of the adhesive phenomena and their correlation to the adhesion work (or surface energy) becomes a little more difficult when the sliding occurs on "rough" surfaces, since the deformation component starts playing its decisive role in the friction coefficient value and in the wear mechanisms.

“Normal” Transfer

Considering that polymer and counterface junction is stronger than the polymer intermolecular bonds, the material failure occurs by debris transfer. Repeated sliding leads to a progressive transfer of layers, which will eventually detach. Such irregular films have thicknesses ranging from 0.1 to 1.0 μm.

This phenomenon is known as “normal transfer” or “high friction regime”, when the polymer is transferred to the counterface with no significant chain breaking and/or chemical degradation. It is the most common transfer mechanism among the polymers (Briscoe, 1990). Lancaster (1990) and Hutchings (1992) state that said mechanism is related to an inter- or polycrystalline detachment, since the intense shearing tensions exceed the interlamellar joints.

Lamellar transfer

This kind of transfer mechanism is also known as “low friction regime”, “lamellar shearing mechanism” or “microscopic asperity wear”. Such mechanism refers to a “special” behavior of polymers such as PTFE, POM, HDPE, and UHMWPE, in which the transfer occurs with no polymer chemical degradation. Such polymers are called “plain or even molecular profile polymers” (Briscoe, 1990 and Speerschneider, 1962), since their molecular structures are characterized by the linearity of their chains and the absence of polar or volumetric groups. These characteristics lead to a high crystallinity degree and weak intermolecular joints. The lamellar films are more uniform, and is distinctive for having thicknesses ranging from 1 to 40 nm, and contains molecular chains strongly oriented towards the sliding direction (Makinsom and Tabor, 1964).

Melt Transfer

Polymers have low thermal conductivity and low crystalline melting temperature (Bartenev and Lavrentev, 1981). Such factors lead to softening under much less severe load and speed conditions than those for metals. The melt transfer phenomenon is seen as a “hot”, “undegradated” transfer mechanism. As the temperature rises, the spherulites are destroyed and the shearing resistance drops, leading to amorphization and the material’s plastic yelding. With the ensuing temperature rising, it may become a process with chemical degradation (Briscoe, 1990).

1.2 Abrasion

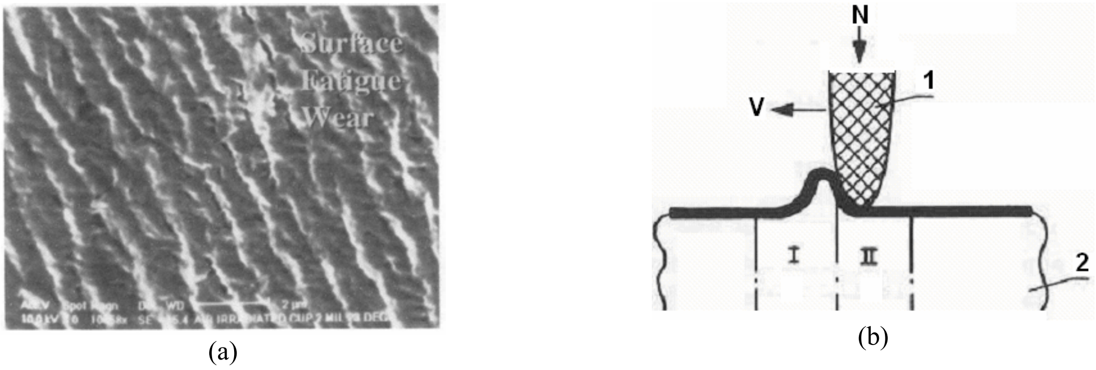
Ratner *et al. apud* Lancaster (1969) suggest that three consecutive phases are involved in the particle detachment: deformation by penetration of a harder asperity, resistance to the relative movement, and finally detachment, the latter involving fracture work and microcut mechanisms. These researchers show that the polymers resistance to abrasion is strongly connected to the material “failure energy”, which is related to the cohesion between the polymeric chains, called cohesive energy (Rimuza, 1990). The advantage of introducing such concept is the possibility of relating the wear properties of polymers to the chemical constitution of their chains (Giltron, 1970).

1.3 Fatigue

Fatigue due to cyclical deformations

With regard to the wave-like wear morphology shown on Figure 1 (a), there is a certain divergence as to the wear mechanisms that originate them (the waves). It is known that whenever thermoplastics sliding occur against surfaces with Ra roughness parameters over 0.3 μm, the plastic deformation (abrasive) mechanisms prevails over the adhesive mechanisms (Pleskachevsky *et al.*, 1995). It is believed that, due to the major efforts at the contact surface, even for low loads, there is a marked plastic deformation, to the point of practically making the material yeld and therefore cause the wave-like aspect. Briscoe *et al.* (1996) states that, for semi-crystalline polymers, a partial micro-structural reorganization takes place when they are subject to the surface tensions. As a result of continuous effort repetition, pieces of said material are detached due to the fatigue mechanism.

There has been broad consensus as to considering the wave-like wear morphology a phenomenon greatly related to the fatigue mechanism (Briscoe, 1990 and Wang *et al.*, 1998). Bartenev and Laventrev (1981) show that the waves are formed as a result of a marked deformation, which can be produced either by a blunt indentor (Figure 1- b 1) or an asperity, sliding on the polymer surface (Figure 1 b - 2) and creating a stretching zone posterior to the asperity path, where healing cracks appear (Williams, 1991). As in many cases, such deformation will take place again when the penetrator passes through the same location, making the cracks propagate and the material be removed, producing the wave-like aspect on the polymer surface.



(a)

(b)

Figura 1– (a) SEM micrographic of UHMWPE, surface of total joint replacement (Wang et all., 1998), (b) Illustration of the wear mechanism that leads to the wave-like formation: (I) compression zone, (II) stretching zone (Bartenev and Lavrentev, 1981).

Fatigue due to stress concentration

The 'macroscopic polymer asperity wear process' (Cooper *et al.*, 1993) is characterized by the material removal, which support great deformations due to the surface and subsurface stress concentration, generated by the polymers surface high asperity level (see Figure 2). This wear mechanism is associated to:

- Low severity, leading to a discontinuous film;
- Residual shear deformations on planes perpendicular to the sliding direction;
- Deformation of a nominally flat surface by repeated interactions with the counterface microscopic asperities.

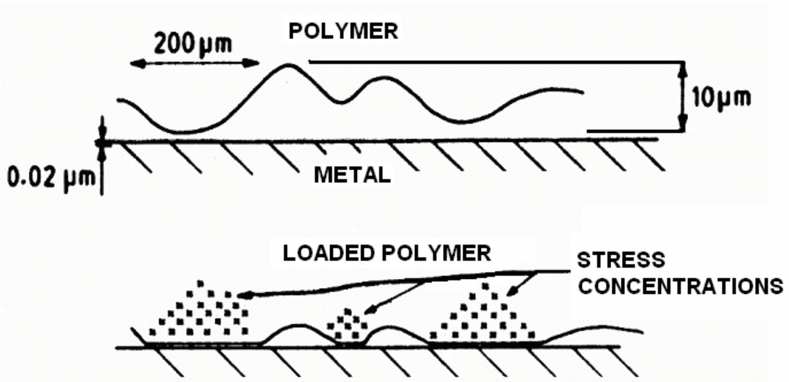


Figure 2 – Illustration showing the formation of points with stress concentration in the polymer (Cooper *et al.*, 1993).

This paper aims to contribute to the understanding, of how the wear mechanisms of POM copolymer and UHMWPE occur, through experimental tests and microscopic analyses of the wear surfaces.

2. Materials and Methods

A TE-67 model pin-on-disc tribometer, manufactured by PLINT & PARTNERS LTD. was used to determine the systems tribological behavior. In the tribological tests, following the ASTM G99 standard's recommendations, it was used pins made of POM copolymer (Hostaform® - TICONA) and UHMWPE (UTEC/6540 – BRASKEN), as well as duplex stainless steel (austenitic-ferritic) and pure alumina discs (Al_2O_3). The pins dimensions were: 20mm length and 5mm diameter, and the discs dimensions were: 5mm thickness and 65mm diameter. Table 1 shows some tribologically important polymer properties.

The duplex stainless steel discs material is composed by an austenite matrix (58%) and ferrite grains (42%). The ceramic material discs were obtained by sintering pure A-1000 ALCOA alumina powder. Table 1 shows some important properties of the discs materials.

Table 1 – Properties of the pins and discs materials (Silva, 2003)

Properties	Units	POM	UHMWPE
Melting temperature	[°C]	168	142
Thermal conductivity	[W/mK]	0.30	0.40
Thermal diffusivity	[m^2/s]	1.42 x 10^{-7}	2.57 x 10^{-7}
Tensile Strenght, Yield	[MPa]	66	25
Impact resistance (Charpy 23°C)	[MPa]	9.3	80
		ALUMINA	DUPLEX STEEL
Thermal conductivity	[W/mK]	17	30
Thermal diffusivity	[m^2/s]	7.84 x 10^{-6}	2.21 x 10^{-5}
Elasticity Modulus	[GPa]	370	170

The preparation of the discs´ surface was carried out by unidirectional hand sanding using abrasive sandpapers of different grit. Table 2 shows the finish conditions, the abrasive paper grit and an identification code for each finish range.

Table 2 – Topographic characteristics of alumina and duplex stainless steel discs.

Discs	Rougness	Grit	Code
Al_2O_3	1.5 < Ra < 2.0 µm	60	R4
	0.3 < Ra < 0.6 µm	320	R3
Duplex steel	0.3 < Ra < 0.6 µm	180	R3
	0.05 < Ra < 0.2 µm	320	R2

The wear rate [µm/m] was determined by measuring the pins height variation during the tests, by using a linear position sensor (Linear Variable Differential Transformer - LVDT) and the distance covered by the pin on the disc (3,500 meters). The wear tests were carried out with loads of 50, 100, and 200 N, and sliding velocity of 0.1; 0.5 e 1.0 m/s. The tests were carried out in an environment with a relative air humidity controlled at 50 ± 5 %.

A temperature measuring device with a k-type thermocouple (cromel-alumel) was used in the measurement of the pin surface average temperature during the wear tests. Holes with 1mm diameter were drilled at the pins side and the thermocouple was placed, under pressure, in their interior.

For the determination of the surface energy values the sessile drop method was used, through which the contact angles of a liquid are measured in relation to a solid surface. The polar liquid utilized was distilled water and the dispersing liquid was diiodomethane. The Folks method was used for the determination of the adhesion work (Wu *apud* Folkes, 1971).

3. Results and Discussion

3.1. Adhesion work

The results of the adhesion work values (W_{ab}) determination, calculated from the measured contact angles and the Harmonic Average Equation proposed by Wu (1971), are shown on Table 3.

Table 3 – Average adhesion work (W_{ab}) of the pairs of materials studied.

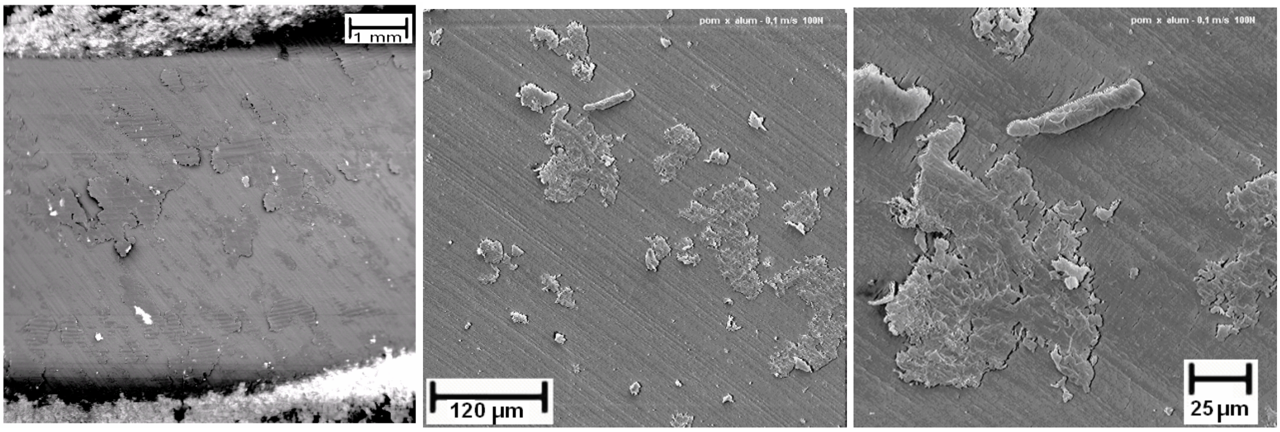
Polymer	**Counterface**	**W_{ab} [x 10^{-4} J/m^2]**
POM	Alumina	101 ± 2 .
	Duplex Steel	96 ± 1
UHMWPE	Alumina	85 ± 4
	Duplex Steel	85 ± 2

Table 3 shows that the tribological pairs with POM present adhesion work values higher than those with UHMWPE, thus suggesting a greater possibility of adhesive mechanisms occurrence. Data on UHMWPE show that no disc material presents a major tendency to adhesion phenomena.

In terms of observation of the phenomenon of the polymer adhesion to the counterface, it should be emphasized that, notwithstanding the difficulty in quantifying the volume of material deposited on the discs, it can be said that the tests with alumina always showed a larger quantity of material transferred in comparison to the tests with duplex steel.

3.2. Wear Mechanisms

The observation of the discs surface at the contact track region showed the presence of polymer debris deposited both on the alumina discs (greater quantity) and the duplex steel discs, forming a discontinued and heterogeneous layer (Figure 3 - a).



(a) (b) (c)

Figure 3 - (a) SEM micrographs of the alumina disc surface showing POM film transfer; (b)POM pin surface (Al_2O_3 R3, 0.1 m/s and 100 N) with debris of different sizes and formats; (c) detail of the region with debris agglomeration.

The presence of polymeric material adhered to the discs surface at the contact track area can be explained as follows:

1°) The wear debris removed from the pin surface remain on the contact track. Later pin sliding on such debris causes the latter to crush (rolling) onto the tracks and their consequent adhesion. During such process, the new debris can agglomerate with the first ones and therefore cause a gradual size increase of the region with adhered material, forming plates and, at the limit, a film throughout the contact track. As the tests proceed, the plates of adhered material are removed from the track, moving to the edges or being transferred to the pin itself (Figure 3 – b);

2°) The debris previously on the contact track sides (Figure 3 – a) return to the track, mainly during tests with higher speed, because of the centrifugal force. The sequence of removing material, exiting the contact track, returning to track, new crushing, agglomeration and adhesion to the contact track, causes the large plates of adhered material to present a surface aspect with high deformation level.

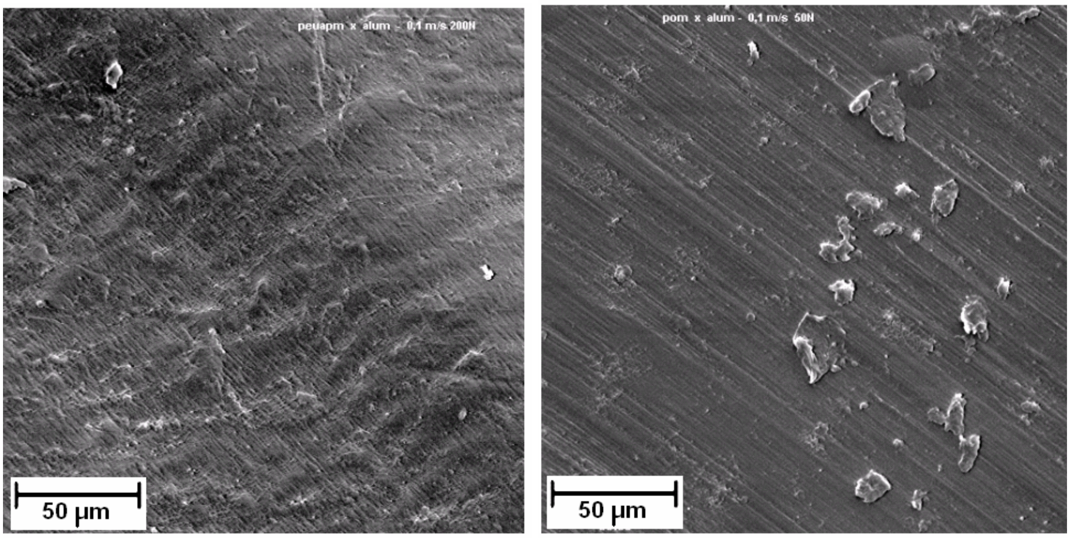
3°) It is believed, as an hypothesis, that part of the material present on the discs surface may have been deposited by traditional film transfer mechanisms (“normal” and lamellar transfer). However, no categorical evidence was obtained as to the occurrence of such mechanisms.

Figure 3 (b) shows wear debris of different sizes, showing blade (flakes or scales) and rod shapes (Figure 3 – c). Both the rod and the blades are formed by smaller wear debris, which agglomerate as they are pressed against the disc by the pin. Such agglomerated debris can result from the damaging action of some wear mechanism, which actuated at a certain point of the test, or else they are debris which returned to the contact track after detaching from the pin and remaining on the sides of the wear track.

It is more evident on Figure 3 (c) that, as the wear process proceeds, the debris tend to accumulate at the same region, forming a heterogeneous plate (blades) composed of small crushed (rolled) debris.

In addition to the typically adhesive wear mechanisms, the microscopic observation of the pins wear surfaces showed that the wear mechanisms that actuated both in the tests with alumina and the tests with duplex steel were: fatigue (wave-like morphology) and abrasion. Figure 4 shows micrographics of the pins contact surfaces, in which characteristic aspects of the fatigue mechanisms (a) and abrasion (b) can be observed.

By observing the pins surface under all test conditions, it can be said that there was a change in the wear surface morphology by increasing the contact conditions severity. Under less severe PV values scratches caused by the counterface asperities could be observed. On the other hand, by increasing the PV value, in addition to the scratches, the waves morphology could also be observed (figure 4 –a), and this became the prevalent phenomenon. The occurrence of such mechanism could be related to the cyclical actuation of the counterface asperities, which would cause a marked deformation on the polymer surface, leading to the cracks nucleation and propagation and the consequent production of wave-like morphology on the surface.



(a) (b)

Figure 4 - Wear mechanisms: (a) wave formation – fatigue (Al_2O_3 x UHMWPE, R3, 0.1 m/s and 200 N) and (b) abrasion scratches (Al_2O_3 x POM, R3, 0.1 m/s and 50 N).

Figure 5 shows, in a schematic manner, the process of the wear debris origin from the actuating wear mechanisms (scratches, waves and film transfer). Characteristic aspects are also described, both of the wear debris that moved from the contact track and those debris that remained (or returned) on the contact track, adhering to the pin or disc during the test. In summary, this Figure tries to show, in a general manner, the possible phenomena that took place at the contact region. It is thought that the phenomena described were present, in a greater or lesser degree, in every pair of materials tested.

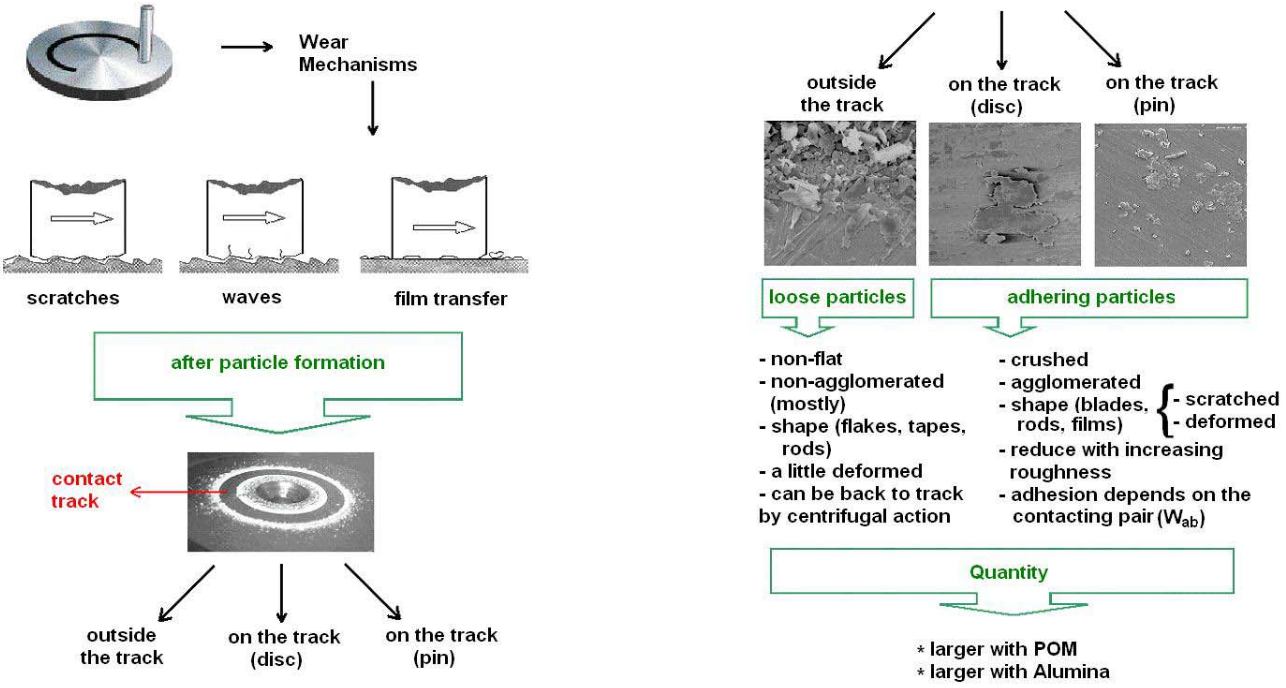


Figure 5 – Origin and characteristics of wear generated debris.

3.3. Contact temperature and melt transfer

The performance of preliminary tests was determinant in our opting for wear tests with temperature measurement, under PV values superior to 1.02 [MPa . m/s]. Such choice is due to the fact that during the tests carried out under less severe PV values, the heat generated at the materials interface did not lead to a significant increase of the pin average temperature, not exceeding 30°C. Figure 6 shows the values of the temperature measured in the pin after the running-in, in function of the several PV values and the surface finishes.

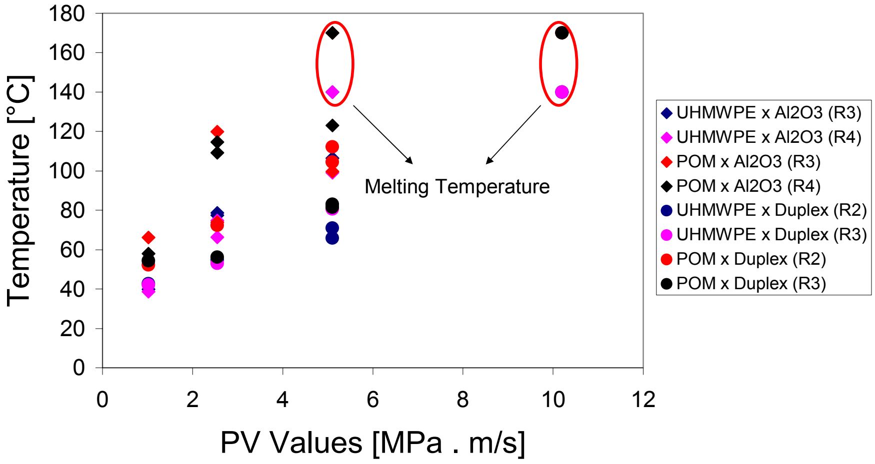


Figure 6 – Temperature in function of PV values.

Figure 6 shows that all of the tests carried out under PV values = 10.20 [MPa. m/s] led to the polymers melting. In the tests carried out under PV values = 5.10 [MPa . m/s] with alumina, the contact temperature reached levels close to those of the polymers melting. It was not possible to demonstrate notable temperature relationships to the wear mechanisms at the contact region.

4. Conclusions

The tribological tests carried out in a pin-on-disc system, under the tested conditions, showed that the wear mechanisms present were: film transfer (adhesion), wave formation (fatigue), abrasion scratches, in addition to the film melt transfer in the tests under more severe PV values.

The greater presence of polymeric material identified in the tests of POM copolymer in contact with alumina can be explained by the stronger tendency to adhesion evidenced by the adhesion work parameter (W_{ab}).

No influence of the surface finishing level on the types or intensity of occurrences of the observed wear mechanisms could be identified.

Under the less severe PV values, the abrasive mechanism (scratches) prevailed. With the increase of the PV value, in addition to the scratches, it could also be observed the presence of the fatigue mechanism (waves), which became the prevalent phenomenon.

Based on the microscopic analyses carried out in the wear debris, it can se affirmed that:

- The wear debris can have different shapes, from plain platelets, through scale-type morphologies, flakes, being capable of deforming to the point of rod and films formation;
- The debris agglomeration may occur due to mechanical aspects (debris crushed against each other) or thermal aspects (high temperature debris adhering to others for being in touch to each other);
- The debris size was an aspect which showed a large variation in a same test, regardless of the materials used and the test conditions present;
- There was a tendency to a larger amount of debris in the tests under higher PV value, particularly in the tests with POM.

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4. References

ASTM G 99-90 **Standard test method for wear testing with a pin-on-disk apparatus Metals test methods and analytical procedure**. Vol. 03.02 – Wear and erosion; metal corrosion. section 3, p. 387-391, 1992

BAHADUR, S. The development of transfer layers and their role im polymer trybology. **Wear**, Vol. 245, p. 92-99, 2000

BARTENEVEV, G. M. & LAVRENTEV, V. V. **Friction and Wear of polymers**, Tribology Series, n°6. Elsevier Scientific Publishing Company, p. 10-260, 1981

BRISCOE B. J., EVANS, P. D., PELILLO, E. & SINHA, S. K. Scrathing maps for polymers. **Wear**, Vol. 200, p. 137-147, 1996

BRISCOE, B,. J. & TABOR, F. R. S. **Friction and wear of polymers**. Cap. I, John Wiley & Son, p.1-46, 1978

BRISCOE, B.J. Material aspects of polymer wear. **Scripta Mettalurgica et Materialia.** Vol. 24, p. 839-844, 1990

COOPER, J.R., DOWSON, D. & FISHER, J Macroscopic and microscopic wear mechanism in UHMWPE. **Wear**, Vol. 162-164, p. 378-384, 1993

GILTRON, J. P. A relationship between abrasive wear and the cohesive energy of materials. **Wear**, Vol. 15, p. 71-78, 1970

HUTCHINGS, I. M. **Tribology: Friction and Wear of Engineering Materials**. Edward Arnold / London, p.51-57, 1992

LANCASTER, J. K. Abrasive wear of polymers. **Wear**, Vol. 14, p. 223-239, 1969

LANCASTER, J. K. Material specific wear mechanisms: relevance to wear modelling. **Wear,** Vol. 141, p. 159-183, 1990

LEE, L-H. **Effect of surface energetics on polymer friction and wear**. ASTM-STP. p. 31-68, 1974

MAKINSOM, K. R. & TABOR, D. The friction and transfer of PTFE. **Proceedings Royal Society London,** Ser A, Vol. 281, p. 49-61, 1964

MARCUS, K. , BALL, A & ALLEN, C. - The effect of the grinding direction on the nature of the transfer film formed during the sliding wear of UHMWPE against stainless steel . **Wear**, Vol. 151, p. 323-336, 1981

PLESKACHEVSKY, Y. M. , ZAITSEV, A. L.& SMIRNOV, V. V. Oxidation and its influence on low pressure polyethylene wear. **Wear**, Vol. 181-183, p.222-226, 1995

RYMUZA, Z. Predicting wear in miniature steel-polymer journal bearing. **Wear**, vol 137, p. 211-249, 1990

SILVA, C.H. **Degradação de UHMWPE e de POM devido à ação tribológica contra aço inoxidável e alumina**. Tese de Doutorado. EPUSP, p. 262, 2003

SPEERSCHNEIDER, C. J. & LI, C. H. - Some onbservations on structure of PTFE. **Journal of Applied Physics**, Vol. 33, n^{o} 5, p. 1871-1874, 1962

TANAKA, K. Transfer of semycristalline polymers sliding against a smooth steel surface. **Wear**, Vol. 75, p. 183-199, 1982

WANG, A.; ESSNER, A.; POLINENI, V.K.; STARK, C. & DUMBLETON, J. H. Lubrication and wear of ultra-high molecular weight polyrthylene in total joint replacements **Tribology International**, Vol. 31, n^{os} 1-3, p. 17-33, 1998

WILLIAMS, J. A. **Engineering Tribology**, Oxford Univerty Press, p.132-135, 1991

WU, S. Calculation of interfacial tension in polymer systems. **Journal of Polymer Science**, Vol. 34, p. 19-30, 1971

YAMAGUSHI, Y. **Tribology of plastic materials - Their characteristics and applications to sliding componentes**. Tribology series, n°16, Elsevier Science Publishers, p. 93-143, 1990