JOURNAL OF THEORETICAL
AND APPLIED MECHANICS
43, 1, pp. 3-35, Warsaw 2005

WEAR DEBRIS: A REVIEW OF PROPERTIES AND CONSTITUTIVE MODELS

Alfred Zmitrowicz

Institute of Fluid-Flow Machinery, Polish Academy of Sciences
e-mail: azmit@imp.gda.pl

Wear appears as gradual removal of a material from contacting and rubbing surfaces of solids during their relative sliding. The mechanism of wear involves formation of debris particles. The particles have small sizes and different shapes. The wear debris can be "rolled over" into cylindrical, spherical and needle-like particles. Particles are detached from rubbing surfaces and they form a more or less continuous interfacial layer. They transmit forces, moments and displacements (translational and rotational) at the contact interface. The presence of wear debris between sliding surfaces affects frictional and wear behaviour significantly. Constitutive relations characterize quasi-solid, quasi-fluid and granular-like behaviour of wear particles. In the paper, two constitutive models of wear debris are discussed: (a) material continuum, (b) granular medium. The continuum models are formulated for a micropolar thermoelastic material, micropolar fluid and thermo-viscous fluid.

Key words: contact mechanics, wear, friction, constitutive equations

1. Introduction

The friction process of elements operating in contact conditions always involves heat generation and wear of their surfaces. Wear and frictional heat, apart from fatigue, fracture and corrosion are main factors which restrict a life time of machines and mechanical devices. Numerous machine component parts must be taken out of service not due to failure caused by exceedance of the limit stress, but due to wear manifested in removal of a material. Theoretically, wear of machine component parts should not occur if their surfaces are separated with the aid of a lubricant film, but from many reasons (e.g. frequent starts, stops and reversals of motion of a machine, operations in dusty air conditions, etc.) breakdown of a lubricant film occurs, and wear cannot be avoid. Many machine components operate in conditions of partial fluid-lubrication (mixed lubrication), where an average lubricant film thickness is of the same order of an average surface roughness. Then, an applied load is carried partially by a hydrodynamic action of the lubricant film and partially by contacts of surface asperities. In general, "dry" and marginally-lubricated contacts are as common as "wet" contacts and also govern operating conditions of machines. Understanding and controlling the friction and wear places is of considerable practical importance in engineering. Phenomena of friction and wear are inseparable. Wear in sliding systems is usually a very slow process, but it is very steady and continuous.

The first wear experiments were carried out at the beginning of 19th century. With the aid of a special test device, Hatchett (1803) investigated abrasion of gold, silver and copper coins. Rennie (1829) investigated wear of solid surfaces of metals, wood and other materials. Contemporary wear investigations belong to fundamental tests on mechanical properties of engineering materials. Quantitative prediction of wear is difficult. At present, there are a few very simple calculation procedures of wear, see Archard (1953), Rabinowicz (1995).

In this study, wear appears as gradual removal of a material from contacting and rubbing surfaces of solids during their relative motion (sliding). Normal pressure and sliding action are necessary for wear as they depend, first of all, on the rubbing process. The mechanism of wear involves formation and circulation of debris particles in any sliding system. Particles detached from solids circulate in the contact region and form a more or less continuous interfacial layer. The presence of a thin layer of wear debris separating two sliding bodies is an extremely important topic of the present analysis. When there is a layer of particles in the interface between contacting solids instead of a liquid, then the modelling situation requires new methods and theoretical tools. The present study is devoted to phenomenological models of properties and constitutive relations of wear debris.

2. An outline of wear physics

Many mechanical, physical and chemical phenomena are responsible for wear of materials. Several types of wear have been recognized, e.g.: adhesive, abrasive, contact fatigue, fretting, oxidation, corrosion, erosion. In machinery, wear occurs most frequently as an abrasive or contact fatigue process. Each wear type has a different mechanism, cause and effect. For example, fretting is a wear process of contacting solids occurring during oscillatory sliding of small amplitudes. A low amplitude of displacements typical in fretting is usually less than $30\,\mu$m, and a low velocity amplitude is expressed in μm/s. Oscillatory tangential relative movements arise from vibrations or cyclic stressing of one of the components. In the case of fretting, wear debris is trapped and accumulated in the area between the oscillating surfaces.

Wear of solids is usually treated as a mechanical process. However, oxidation, corrosion and other chemical processes are exceptions of this general rule. In some contacts, chemical reactions can play an important role. Furthermore, it can be supposed that mechanical energy may provide the energy for chemical reactions directly or indirectly by means of thermal energy (i.e. it may accelerate chemical reactions in solids).

During dry, boundary and mixed lubricated sliding, wear particles are generated by a number of different physical mechanisms, depending on materials and sliding conditions. The wear particles are generally detached mechanically by micro-stresses resulting from the applied load and relative sliding. Wear particles are detached from sliding solids by the following microscopic mechanisms: micro-cutting of adhesive junctions between surfaces, mechanical failure of contacting asperities (i.e. non-elastic deformations, cutting, abrasion, break off, fracture, fatigue of surface asperities etc.), surface spalling, plastic deformations of surfaces in a form of grooves and scratches, nucleation and propagation of surface and subsurface cracks and voids, oxidation, corrosion, chemical reactions, see Fig. 1. Wear particles are also generated as a consequence of ploughing. Surfaces can be plowed by the wear particles, hard particles entrapped from the environment and by hard asperities of the counterface. Certain forms of surface damage do not occur slowly and continuously but may suddenly cause a gross disruption of rubbing surfaces, after which large wear particles are removed. This mechanism is called scuffing or galling.

The wear process can be examined in three stages. The first stage is concerned with debris generation and deals with various mechanisms of material removal from sliding surfaces. The second one is devoted to the evolution of debris inside contact (i.e. mechanical physical and chemical changes). The third stage refers to own behaviour of debris, which can be either eliminated out of the contact, or accumulated between sliding surfaces.

Taking into account an amount of the removed material from solids, measures of wear have been formulated with respect to changes of the following quantities: mass, volume and linear dimensions of sliding bodies (Rabinowicz, 1995).

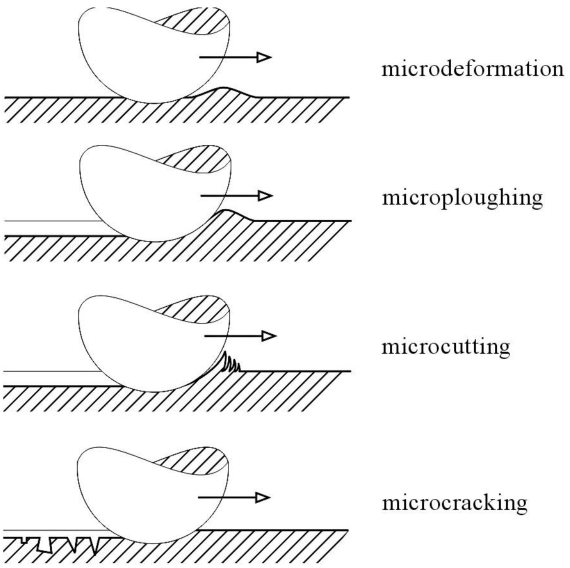

Fig. 1. Wear micro-mechanisms and possible ways to produce wear debris

Most wear observations are carried out indirectly (post factum). It has many disadvantages, i.e. the rubbing process must be stopped, wearing elements must be disassembled, and after that the effects of the wear process can be observed. All what can be done is to measure or weight the rubbing bodies before experiments, repeat this procedure after the experiment, and note the differences. Weighting is the simplest way of detecting wear. It gives the total amount of wear in the form of a single number, but the distribution of the removed material in the sliding surface is unknown.

Formation of loose wear particles is of crucial importance in the wear process. In pin-on-disc test machines, as in many other friction and wear test devices, wear particles are observed inside and outside of the wear track, see Fig. 2. In every-day life, one can easily observe wear debris during abrasion, e.g.: pencil drawing marks on paper, a piece of chalk writing on a blackboard, a rubber eraser rubbing out pencil marks on paper.

There is a large number of modern devices which only operate in such a way so that the friction and wear can be closely controlled. Wear cannot be eliminated completely, but it can be reduced to a high degree. The simplest methods of reduction of friction and wear are as follows: lubrication, formation of sufficiently smooth surfaces, modification of near surface layers of metal components (e.g. achieved through surface treatments and/or coatings which increase surface hardness and wear-resistance). It can be supposed that some-

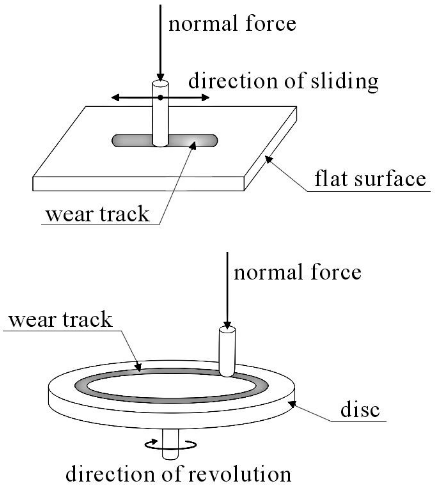

Fig. 2. Wear traces observed in typical friction and wear test devices: (a) pin-on-flat surface, (b) pin-on-disc

times considerable advantages can be achieved by optimization of friction itself or by an optimal choice of structural, kinematical and material parameters of the rubbing system. In general, consequences of wear are negative, however one should remember the advantages of many methods for producing surfaces on manufactured objects exploiting the abrasion phenomenon (e.g. finishing operations).

3. Morphology and kinematics of wear debris

Morphology of wear debris deals with its structural properties and it is characterized by: forms (shapes), dimensions (sizes), concentration (number), distribution. Furthermore, particles generated by friction and wear can be described by: colour, texture, etc. (see Myshkin *et al.*, 2001). In some cases, the transfer of a material between contacting surfaces is obvious to a unaided eye because of associated colour changes. Interfacial films are seen as layers of a different colour than that of parent bodies.

Wear debris has been observed and studied for a very long time. There are many research studies in the field of tribology about size, shape, number and nature of wear particles, see e.g. Finkin (1964), Crone (1967), Larsen-Badse (1968), Wilson and Eyre (1969), Scott *et al.* (1974), Bowen and Westcott

(1976), Samuels *et al.* (1980), Anderson (1982), Don and Rigney (1985), Swanson and Vetter (1985), Georges and Meille (1985), Murti and Philip (1987), Hunt (1993), Dowson *et al.* (1992, 1996), Lin *et al.* (1992). Therefore, a large body of empirical data has been collected so far.

Both optical and scanning microscope studies on wear debris revealed that the particles did not have one particular morphology. Generated wear debris is of different shapes (e.g. flakes, chips, thin platelets, slices, filings, powder-like particles, etc.) and different sizes. There are various classifications of shapes of wear particles, e.g.:

- A rough division of shapes of wear debris into two categories, flake and non-flake, can be made. The flake-type debris refers to a particle that has a relatively uniform thickness whereas non-flake includes such debris types as powder, plates ribbons, cylinders, spheres, irregular chunks and loose clusters.
- Debris can roughly be divided into two groups: long fibrous debris and very thin platelet debris. Both types of particles appeared e.g. in lubricant samples.
- There are following types of wear debris: sheet-like, roll-like, long rope-like, aggregated and granular particles.
- Wear particles can be classified into several types according to their origin (their generation process) for instance: fatigue chunk particles, severe sliding particles, laminar particles.

Morphology of wear debris can be defined with the aid of the following dimensions: length, width and thickness. The flake debris can be characterized by their outline, e.g. straight edges/irregular edges or by curvature radii of arcs and by apex angles of corners, etc.

Royalance *et al.* (1992, 1994, 2000) used different morphological attributes of the particles. Quantitative data, obtained by using image analysis techniques, provided measurements of shape, size, edge detail, surface roughness. The edge detail was based on a curvature pattern derived for a particle periphery and on statistical analysis performed to establish mean values of dispersion, skewness R_{sk} and kurtosis R_{ku} (these parameters are often used in topographical analysis of rough surfaces). Two additional parameters, an aspect ratio and a roundness factor, were also applied.

Fractals have been used to describe morphology of wear debris by Berthier *et al.* (1988), Kirk *et al.* (1991), Zhang *et al.* (1997) and Wrona (2003). There have been attempts to automate the analysis of wear particles, see Peng *et al.* (1997), Xu and Luxmoore (1997), Podsiadlo *et al.* (1997), Peng and Kirk

(1997, 1998). Laser scanning microscopy has been applied to obtain three-dimensional images of wear particles and to surface roughness analysis of a single wear particle by Peng *et al.* (1997). Several numerical parameters to describe profiles of wear debris, based on automated computer image analysis systems, were developed by Kirk *et al.* (1995), Stachowiak (1998), Podsiadlo and Stachowiak (1998, 1999a,b, 2000), Stachowiak and Podsiadlo (1999), Peng and Kirk (1999a,b).

Geometrical (morphological) characterization of wear particles were made with the aid of neural networks (Umeda *et al.*, 1998), fuzzy systems (Cheng and Yang, 1998), and other techniques (Unchung and Tichy, 2000).

The particle shape yields qualitative information while the concentration and size distribution provide quantitative data. It is necessary to know, or to estimate, the maximum size of different kinds of particles. Obviously, the shape and size of debris differ for different materials and sliding conditions. For example, when two metal surfaces slide against each other under a load, wear debris is produced in the form of both macroscopic (size from a few to several micrometers) and microscopic (size from sub-micrometer to a few micrometers) particles. It was found that the number of microscopic wear particles generated during sliding can be estimated as an exponential function of the particle size.

The number of wear particles and their size distribution were studied in detail by Rabinowicz (1995), Xuan and Cheng (1992), Mizumoto and Kato (1992), Hou *et al.* (1997). In order to visualize the wear debris layer, high wear rate materials were used by Kohen *et al.* (1980) and Godet *et al.* (1991). Godet recorded, on a video tape, a dynamic contact in which solids were separated by layers of chalk, graphite, etc., of a few tenth of micrometers in thickness.

Godet and Play (1975) and Godet (1988) conducted experiments on numerous material combinations with included polymers (PMMA, PC, etc.), elastomers, metals (various steels, aluminum alloys, titanium alloys, copper, etc.), ceramics (Al_2O_3, SiC, etc.), chalk, glass, sapphire, carbon etc., under both continuous and reciprocating motion, and all proved that wear debris are produced quasi-immediately, then trapped in the contact for some time and finally eliminated after the next time interval. A small particle (e.g. 10^{-6} m) cannot be instantly eliminated from a comparatively wide contact (e.g. 10^{-2} m), for purely geometrical reasons, see Fig. 3.

Hou *et al.* (1997) measured interfacial layers in rolling-sliding contacts consisting of wear debris and contaminants. The size of most particles was of $1\,\mu$m in magnitude, with some larger particles measuring about $10\,\mu$m.

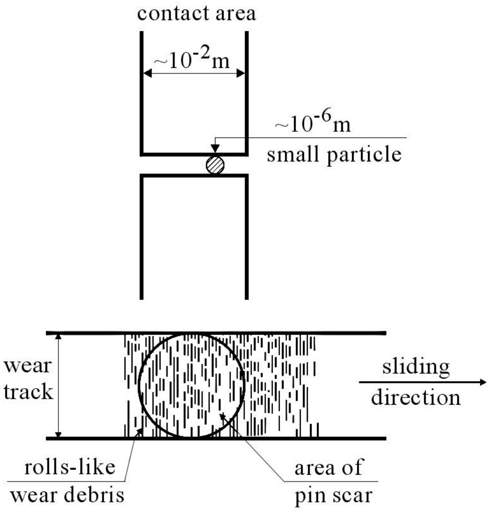

Fig. 3. Schematic view of a small particle at a comparatively wide contact area and rolls-like wear debris observed in a wear track

The thickness of the agglomerated and compacted layer was about $20\,\mu$m. Rabinowicz (1995) investigated wear debris in a sliding pair of copper on a low-carbon steel (unlubricated). He concluded that small particles are seen to be much numerous than large ones.

Xuan and Cheng (1992) conducted dry sliding wear tests on a three-pin-on disc machine using stainless steel pins and disc. Wear debris was collected in a test chamber, measured and examined. It has been found that the total wear debris comprises macroscopic and microscopic particles. Particles of sizes ranging from $0.2\,\mu$m to $12\,\mu$m and above were measured. The created particles have a size distribution to be described by an exponential function. Estimated numbers of generated particles were: 10 million of size $0.2\,\mu$m, 1 million of size $1\,\mu$m, and 500 of size larger than $12\,\mu$m. Xuan and Cheng (1992) found that the complete wear process from running-in to steady-state involved four distinguishable periods when considering the source and the mechanism for creating wear debris.

Mizumoto and Kato (1992) used a pin-on-disc frictional apparatus in a series of experiments to observe wear debris. Measured particles larger than $0.2\,\mu$m were classified into 11 ranges of diameter. Kato (1990) observed changes of wear modes and formation of powder-like and flake-like wear particles in reciprocating sliding of a diamond pin on a silicon carbide disc.

Freshly generated wear debris escape to the interface and they are processed further e.g. crushed into finer particles, compacted and agglomerated into large debris. Therefore, the evolution of particle morphology should be investigated. Wear particles undergo the following processes: they are heavily deformed, the particles are fragmented to a small enough size (by repeated plastic deformations and fracture), the particles are oxidized, coagulated together or agglomerated (due to adhesion forces), reattached to either of the contacting surfaces (i.e. they can be transferred to the counterface by mechanical interlocking and by adhesion). Agglomerated particles are formed progressively, by agglomeration of small particles. Some of the wear particles are removed from wear tracks to form loose particles. Ejection of particles from both the contact and wear track (sliding path) is predominant in most situations. Sometimes, wear particles are removed from the sliding interface by being brushed off (case of lubricated or open mechanical devices).

It is often observed that wear debris of flake and chip forms. etc. can be "rolled over" into cylindrical, spherical and needle-like particles, see Zanoria *et al.* (1995). It takes part especially, when contacting bodies realize relative oscillatory motions, see Fig. 3. For instance, large rolls are formed when using a rubber eraser.

An interaction between debris and bodies can govern the fact that the debris can roll. The roll-like wear debris are created by rubbing of two bodies. Each roll is subjected to opposing tangential forces at its top and bottom surfaces. The torque resulting from these forces causes the debris to roll. The axes of roll particles are aligned perpendicularly to the direction of sliding, indicating that they were actually rolling on the wear track (or that they were generated by rolling in the contact), and suggesting that the particle circulation is common in the contact, see Fig. 3. In experiments with a silicon ball on a silicon flat reported by Zanoria *et al.* (1995), roll lengths varied from 0.1 to $30\,\mu$m and a roll diameter ranged from 0.1 to $1.4\,\mu$m.

Observations revealed that those rollers are more or less compact agglomerates of finer wear particles. Very small grains are compacted and agglomerated (through physical and chemical effects, contact pressure, temperature and humid environments) in wear debris showing cylindrical morphology. Aggregates are subsequently rolled into dense cylindrical particles. The rolls can grow as snow balls by collecting more and more particles. The rolls, formed from elements of each contacting body, show a lamellar or composite structure. An increase in load can entail either destruction or fragmentation of the roll or its flattening without rapture.

A spherically shaped wear particle is a particulary intriguing type of wear debris, often observed and subject to much interest, see Rabinowicz (1977), Samuels *et al.* (1980), Davies (1986), Wang *et al.* (1986), Jin and Wang (1989).

Formation of spherical wear particles during a dry grinding process of carbon steels by aluminum oxide (Al_2O_3) abrasive wheel was shown by Lu *et al.* (1992). An approximate percentage of spherical particles in the grinding swarf was about 50%. Spherical particles ranging in size from 1 to $80\,\mu$m were observed. Small (less than $1\,\mu$m) spherical particles were also seen by some investigators.

The rolls and spheres were obtained under a very wide range of running conditions, and for very different materials (steels, ceramics, polymers, etc.). The rolls are found on surfaces of silicon nitride, silicon carbide, alumina, yttrium barium, copper oxide, ceramic matrix composites and single-crystal silicon. There is a number of reports in the subject literature that wear of non-metallic solids produces debris in the shape of cylindrical rolls. In rubber, wear debris apparently develops as the rolls of rubber.

Numerous experimental investigations and every-day praxis indicate formation of a wear debris layer at the sliding interface (i.e. an intermediate layer between the sliding surfaces) practically immediately after the rubbing process starts. The surfaces slide on each other separated by the wear debris layer. In the case of the wear debris layer, friction occurs partially between the surfaces of contacting bodies, partially between the surfaces of each body and wear particles as well as inside the layer between the wear particles. Some component of the friction force originates from the rolling of particles over each other. The resistance to rolling (i.e. rolling friction) follows from rotations of a single particle with respect to neighbouring particles.

The interfacial layer can be also formed by hard particles and contaminants entrapped into the sliding system from the operating environment (e.g. airborne debris of dust and sand, combustion products such as fly ash, construction dirt, contaminant particles from the lubricant, corrosion scale, weld beads) or particles specially introduced into the sliding interface with respect to their beneficial role during the friction process (e.g. typical layer-lattice solid lubricants such as carbon graphite powder, molybdenum disulphide, PTFE, etc.) or abrasive debris (diamond, silicone carbide, etc.) in material-finishing operations.

At normal operating conditions of machines, a lubricant generates a very thin film which separates sliding surfaces. The lubricant film thickness is as follows: in elastohydrodynamic systems $0.1\,\mu\text{m}-1.0\,\mu\text{m}$, in hydrodynamic journal bearings $1.0\,\mu\text{m}-25.0\,\mu\text{m}$, in hydrostatic journal bearings $0.5\,\mu\text{m}-100\,\mu\text{m}$, in gears $0.05\,\mu\text{m}-0.5\,\mu\text{m}$, in roller bearings $0.1\,\mu\text{m}-1.0\,\mu\text{m}$. It is well-known that contamination of oils is a serious problem. Any lubricant sample may have considerable quantities of contaminant particles of various sizes and materials, see Nikas *et al.* (1998).

The size of contaminant particles found in a lubricant oil closes in a range from sub-micrometer to 1000 micrometers. The wear particles which are transported by the lubricant can pass easily through dynamic clearances in operating components. The largest particles will cross the contact by inducing plastic deformations, the smallest particles may only induce elastic deformations. The contamination and wear particles of the size that can reach the dynamic clearance and interact with contacting surfaces damage these surfaces, generate new particles and result in a catastrophic failure. Hard contaminant particles in an oil can induce additional elastic properties of the oil film.

Some researchers, who studied morphology of wear particles, assumed that the size, shape, concentration and composition of wear debris can reveal important information about friction and wear processes that generate the particles, see Reda *et al.* (1975), Barwell (1983), Santanam (1983), Hawthorne (1991), Hwang *et al.* (1999), Cho and Tichy (2000), Sherrington and Hayhurst (2001). Debris morphology can relate to wear processes. Analysis of wear debris which is transported by the lubricant and subsequently captured during filtration is often applied for machine condition monitoring and fault diagnosis.

4. Mechanical and physical properties of the wear particles

Physical properties of wear particles include composition, microstructure, density, thermal expansion, thermal conductivity, melting temperature, etc. Depending on a type of parent materials, different kinds of wear particles are created; there are particles formed by metals, metal oxides, alloys, plastics, ceramics, etc. In the case of plastics wearing out in contact with metals, wear debris forms a mixture of metal and plastic particles.

The material which was removed from surfaces is not in fact the same, either structurally or chemically, as the base material. Instead, it is a very fine-grained material which may be derived from both parts of the contacting system and may include components from the environment as well. It is clear that the worn surface and debris interact with the environment to yield reaction products. Chemical properties of the third body layer were investigated by Wirth *et al.* (1994).

Friction and wear imply the existence of a thin, uniform and almost continuous intermediate layer between sliding solids called sometimes the third body. A complete separation with full debris layer is not a rare occurrence. The third body is characterized by trapped particles changing their size, composition and morphology, and influencing in turn the particle detachment process. These particles will be active in a rubbing system until they are removed from the contact. The debris trapped in the interface will deform when subjected to high compressive and shear stresses. Therefore, the wear debris layer can undergo compression and tension. The stiffness of the third body can influence deformation of the rubbing system.

A significant amount of aggregated debris can be present on the sliding surface. Since aggregated debris is not a homogeneous solid, its strength under a particular loading condition is lower than the theoretical strength of the same material.

The interfacial layer differs both in microstructure and composition from the base material. The layer have certain characteristic properties which depend upon physical and mechanical properties of wear particles and the layer as a whole. Some properties of wear debris layer have been investigated by Sheasby (1983), Godet (1989), Berthier *et al.* (1989), Jiang *et al.* (1998), Descartes and Berthier (2002). Perhaps, hardness was the most widely discussed mechanical property of wear debris.

Mechanical behaviour of the third body, as it transports stresses and strains, is complicated enough. If the third bodies are to be prominent in theoretical models of contact mechanics, their mechanical properties must be properly represented. Identification and understanding of the third body behaviour is difficult since it requires direct observations of the interface during the wear process.

In general, the most adequate is to carry out measurements of mechanical properties of materials in real working conditions. Since, it is often not possible, then typical strength tests should be done, i.e. strength with respect to: tension, compression, bending, shear, torsion, creep, fatigue, hardness. Such fundamental tests have not been undertaken yet for the wear debris layer.

5. Contribution of wear debris to load and displacement transmission

Analysis of the contact problem of solid bodies generally requires determination of stresses and strains within individual bodies, together with information regarding distribution of displacements and stresses at the contact region. Figure 4 illustrates optical interference patterns representing stresses in a photoelastic model of rolling contact, Wuttkowski and Ioannides (1992).

Three different contact conditions were investigated: (a) surfaces separated by lubricant film, (b) solid contaminant particles contained in the interface, (c) a single contaminant particle being rolled over. Experiments show that contaminant particles considerably change stress distributions near the contact surfaces. Therefore, examinations of wear debris are important because the wear debris gives rise to a unique stress pattern and deformation behaviour in sliding solids.

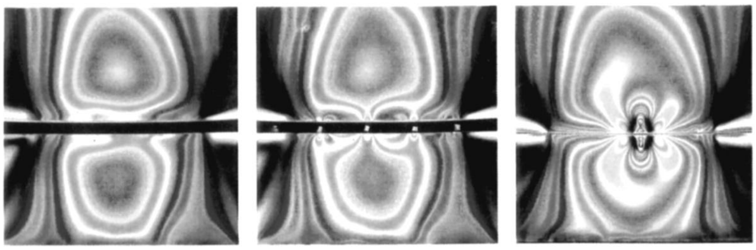

Fig. 4. Optical interference patterns representing stresses in a photoelastic model of the rolling contact, (a) clean surfaces completely separated by the lubricant film, (b) solid contaminant particles contained in the lubricant film, (c) dent in the raceway caused by a contamination particle being rolled over, see Wuttkowski and Ioannides (1992)

Godet suggested to model wear debris accumulated between sliding surfaces and separating the surfaces as a medium with a load carrying mechanism as occurs in fluid lubrication. In Godet's opinion load carrying phenomena are not limited to fluid flow mechanics but that the arguments identical to those used in fluid analysis can be put forward in cases of rubbing surfaces, see Godet (1984), Colombé *et al.* (1984), Berthier *et al.* (1989, 1992), Denape *et al.* (2001).

In a general case, the load carrying mechanism depends on fluid flow. By the effective load carrying capacity, we mean that the total normal load is entirely carried by transfer particles. This, for instance, implies that a pin (in pin-on-disc test) is able to withstand normal pressure which is then developed on the top of particles present within the apparent area of contact.

If sliding surfaces are separated by an interfacial layer, then the sliding velocity difference between two sliding surfaces can be accounted for in a number of ways. The simplest case – a velocity distribution along the thickness of the interfacial layer is a linear function.

The contribution of the third body to velocity accommodation is very important. Godet suggested that the gradient of contact tangential velocity with respect to layer thickness can exist within the third body. The third body accommodates the difference in sliding velocity of parent bodies with the aid of the two following dominant modes:

(a) by interfacial sliding between the layer and parent bodies,

(b) by shearing in the bulk of the third body.

6. Role of wear debris in modifying friction and wear

The friction phenomenon is very sensitive to changes of sliding conditions. Experimental studies demonstrate that wear particles entrapped between sliding surfaces can affect frictional and wear behaviour very significantly. The presence of the debris implies modifications of the friction coefficient and the wear rate, see Kuwahara and Masumoto (1980).

Circulation of wear particles is reflected by the friction coefficient, which increases when the particles are accumulated and decreases when the particles are removed from the sliding interface. According to Suh and Sin (1980), the kinetic coefficient of friction for metals is in the neighbourhood of 0.1 to 0.2 (but mostly in the range of 0.12 to 0.17) regardless of materials tested, i.e. gold on gold, steel on steel, brass on steel, etc. Wear particles entrapped between sliding surfaces affect frictional behaviour increasing the friction coefficient to 0.5-0.7. Variations in the friction coefficient show evolution of the amount of debris in the contact; a stability of the friction coefficient indicates a constant amount of debris in the contact interface. In some experiment study, a steady value of the friction coefficient was reached when the number of newly formed wear particles was equal to the number of particles leaving the contact interface ($\mu = 0.28$ initial value, $\mu = 0.63$ steady value). The steady-state wear rate may be larger for some sliding conditions where wear particles cannot be removed from the contact and act as abrasive particles.

There is a number of reports in the literature that spherical and cylindrical wear particles roll over each other with resulting low friction. It has also been reported that, as a result of the roll formation, the coefficient of friction undergoes transition to lower values by a factor of three, and the wear decreases by several orders of magnitude. The coefficient of friction in the presence of rolls usually ranges from 0.1 to 0.4 (Zanoria *et al.*, 1995). It has been suggested that cylindrical debris can act as miniature roller bearings or "solid lubricants", so that sliding friction can be reduced.

7. Wear debris between two rough surfaces

Real engineering surfaces are rough. What happens when we put two surfaces together to form an interface? Under normal and tangential tractions, two processes occur in the interface between two sliding rough surfaces, see Hou *et al.* (1997). First, asperities are elastically and plastically deformed and flattened, resulting in closure of voids between them. Secondly, interfacial wear particles are rearranged and plastically deformed, closing many of the voids present between wear debris. Although some cavities will always remain, it is reasonable to assume that these cavities do not significantly change homogeneity of the interfacial layer. Therefore, one can assume that the interfacial layer consists of deformed asperities, wear and other debris (e.g. contaminant particles) which, under normal and tangential tractions, form a uniform layer.

The most frequently used statistical models of the surface roughness assume a symmetric Gaussian distribution for heights of surface asperities (taken with respect to a reference line or plane). The contact of two rough surfaces (that follow the Gaussian distributions) and wear particles may be modelled as contact of two smooth reference planes and an interfacial layer. Reference boundaries of bodies can be located a little inside the bodies (in comparison with real boundaries of the bodies) so that the Gaussian distribution of asperity heights of both boundary surfaces can be included (Hou *et al.*, 1997). Usually, mechanical properties of two rough surfaces in contact are characterized by compliance.

Microgeometry of sliding surfaces is not a given property but changes during the wear process. After the running-in phase, some of asperities of surfaces are deformed and other ruptured. To take into account the effect of surface finish, the wear rate and the distribution of asperity heights should be modified. Wear particles produce geometrical changes in wearing surfaces. After some number of repeated slidings, the wearing surfaces may become rougher compared with the initial surfaces. A correlation between wear debris formation and surface topography was observed by Xuan and Cheng (1992).

8. Constitutive models of wear debris

Some effort has been devoted to characterize mechanical properties of third bodies and the way they deform in rubbing contact. For these purposes, one needs some equivalent but inscrutable properties to define quasi-solid, quasi-fluid and granular-like behaviour of wear particles. However, there is a lack of constitutive laws for wear debris.

In the papers by Szefer *et al.* (1994), Szefer (1998), the interfacial layer (described with the aid of a singular surface) was assumed to be attached to contacting bodies. It might be some promise in to be able to treat wear debris as a single continuum, see Zmitrowicz (1987, 1989, 2000, 2001, 2002, 2003).

8.1. Continuum formulations

In the published literature, various continuum mechanics-based models for the third body have been proposed: (a) solid-like models, (b) fluid-like models, (c) other models (e.g. mixtures), see Elrod (1988), Berker and Van Arsdale (1992), Heshmat and Brewe (1992), Hou *et al.* (1997), Iordanoff *et al.* (2002a,b).

Advantages of the continuum approaches are following: (a) the main stages of the wear process can be considered in this approach, i.e. the formation and circulation of wear debris, and the ejection from the contact area, (b) wear debris can undergo fragmentation and/or agglomeration, (c) the third body is a thin layer, and sliding occurs at the interface between the layer and the parent bodies.

Disadvantages of the continuum models are as follows: (a) these models cannot be used of only a few wear particles are formed (a non-continuous interfacial medium), (b) difficulty to find quantitative values for physical constants, (c) discontinuity in the velocity profile, i.e. sliding velocity accommodation cannot be realized in the bulk of the third body.

8.1.1. Micropolar thermoelastic layers

A micropolar thermoelastic layer can describe solid-like behaviour of wear debris formed as rolls. Thermolastic materials with internal degrees of freedom in the form of micro-rotations were studied by Cosserat and Cosserat (1909), Aero and Kuvshinskii (1960), Aero *et al.* (1965), Gauthier and Jahsman (1975), Eringen (1975/76), Pietraszkiewicz and Badur (1983), Alts and Hutter (1988, 1989), Sansour and Bufler (1992), Blinowski (1994).

Let us consider two contacting solids A and B and an interfacial layer S of wear debris taken as a two-dimensional continuum. Positions of particles in the layer S at time t are determined by vectors $\boldsymbol{L}$ and $\boldsymbol{l}$ in the reference and current configurations of the layer, respectively. The thermodynamical process in the interfacial layer is determined by position vectors of layer particles with respect to the reference and current configurations $\boldsymbol{x}_S(\boldsymbol{L},t)$, $\boldsymbol{X}_S(\boldsymbol{l},t)$, a tensor of micro-rotations $\boldsymbol{\chi}(\boldsymbol{L},t)$ and a function of temperature $\Theta_S(\boldsymbol{L},t)$. The tensor of micro-rotations $\boldsymbol{\chi}$ describes systematic rotations of independent layer particles, each on another, without a change of their positions. A representation of the rotation tensor in terms of an angle of rotation ψ and the unit vector of the rotation axis $\boldsymbol{k}$ is as follows

$$\begin{aligned}
&\boldsymbol{\chi} = \cos\psi \mathbf{1}_S + (1-\cos\psi)\boldsymbol{k}\otimes\boldsymbol{k} + \sin\psi \boldsymbol{k}\times\mathbf{1}_S \\
&\boldsymbol{k}\times\mathbf{1}_S = -\boldsymbol{\epsilon}_S\boldsymbol{k}
\end{aligned} \tag{8.1}$$

where $\mathbf{1}_S$ is the identity tensor for the layer, $\boldsymbol{\epsilon}_S$ is the Levi-Civita tensor for the layer S.

Gradients of deformation for the two-dimensional layer are given by

$$\mathsf{F}_S = \operatorname{Grad}_S \boldsymbol{x}_S \qquad \mathsf{F}_S^{-1} = \operatorname{grad}_S \boldsymbol{X}_S \tag{8.2}$$

As measures of deformation of the micropolar layer, we use Cosserat's deformation tensors. They are functions of displacements and micro-rotations. Cosserat's strains read: the Lagrangian surface deformation tensor

$$\boldsymbol{\Gamma} = \boldsymbol{\chi}^\top \mathsf{F}_S - \mathbf{1}_S \tag{8.3}$$

the Eulerian deformation tensor

$$\boldsymbol{\gamma}_S = \mathbf{1}_S - \boldsymbol{\chi}^\top \mathsf{F}_S^{-1} \tag{8.4}$$

the Lagrangian wryness tensor

$$\mathsf{K} = -\frac{1}{2}\boldsymbol{\epsilon}_S(\boldsymbol{\chi}^\top \operatorname{Grad}_S \boldsymbol{\chi}) \tag{8.5}$$

the Eulerian wryness tensor

$$\boldsymbol{\kappa}_S = \boldsymbol{\chi}\mathsf{K}\mathsf{F}_S^{-1} \tag{8.6}$$

We can define positions of the layer at time t by the displacement vectors given with respect to the reference and current configurations

$$\begin{aligned}
&\boldsymbol{U}_S(\boldsymbol{L},t) = \boldsymbol{x}_S(\boldsymbol{L},t) - \boldsymbol{L} \\
&\boldsymbol{u}_S(\boldsymbol{l},t) = \boldsymbol{l} - \boldsymbol{X}_S(\boldsymbol{l},t)
\end{aligned} \tag{8.7}$$

Within the linear theory, small deformations are postulated, i.e.

$$|\operatorname{Grad}_S \boldsymbol{U}_S| \ll 1 \qquad |\operatorname{grad}_S \boldsymbol{u}_S| \ll 1 \tag{8.8}$$

Furthermore, small micro-rotations within the linear theory are considered

$$\cos\psi \approx 1 \qquad \sin\psi \approx \psi \tag{8.9}$$

We introduce a vector of small micro-rotations, i.e.

$$\boldsymbol{\Psi} = \psi \boldsymbol{k} \tag{8.10}$$

with the following properties

$$\psi = |\boldsymbol{\Psi}| \qquad\qquad \boldsymbol{k} = \frac{\boldsymbol{\Psi}}{\psi} \tag{8.11}$$

For an isotropic and linearly elastic micropolar solid, the strain-displacement relations are given by

$$\boldsymbol{\gamma}_S = \operatorname{grad}_S \boldsymbol{u}_S - \boldsymbol{\epsilon}_S \boldsymbol{\Psi} \qquad\qquad \boldsymbol{\kappa}_S = \operatorname{grad}_S \boldsymbol{\Psi} \tag{8.12}$$

The symmetric part of the micropolar strain tensor is equal to the linear elastic strain tensor

$$\boldsymbol{\gamma}_S^{sym} \equiv \boldsymbol{\varepsilon}_S = \frac{1}{2}[\operatorname{grad}_S \boldsymbol{u}_S + (\operatorname{grad}_S \boldsymbol{u}_S)^\top] \tag{8.13}$$

The antisymmetric part is a relative rotation

$$\boldsymbol{\gamma}_S^{asym} = \frac{1}{2}[\operatorname{grad}_S \boldsymbol{u}_S - (\operatorname{grad}_S \boldsymbol{u}_S)^\top] - \boldsymbol{\epsilon}_S \boldsymbol{\Psi} \tag{8.14}$$

Within the linear theory it is assumed that deviations of temperature from the reference value $T_S^{(0)}$ are small

$$\Theta_S = T_S^{(0)} + T_S \qquad\qquad |T_S| \ll T_S^{(0)} \tag{8.15}$$

Two measures of stresses are assumed, i.e. a stress tensor $\boldsymbol{\sigma}_S$ and a couple stress tensor $\boldsymbol{\mu}_S$. The stress constitutive relations for the layer take the following forms

$$\begin{aligned} \boldsymbol{\sigma}_S &= -\beta T_S \mathbf{1}_S + \lambda_S \operatorname{tr}(\operatorname{grad}_S \boldsymbol{u}_S)\mathbf{1}_S + \\ &+ (\mu_S + \kappa)(\operatorname{grad}_S \boldsymbol{u}_S - \boldsymbol{\epsilon}_S \boldsymbol{\Psi}) + \mu_S(\operatorname{grad}_S \boldsymbol{u}_S - \boldsymbol{\epsilon}_S \boldsymbol{\Psi})^\top \\ \boldsymbol{\mu}_S &= \alpha_S \operatorname{tr}(\operatorname{grad}_S \boldsymbol{\Psi})\mathbf{1}_S + \beta_S \operatorname{grad}_S \boldsymbol{\Psi} + \gamma_S (\operatorname{grad}_S \boldsymbol{\Psi})^\top \end{aligned} \tag{8.16}$$

where, β is the thermal expansion, λ_S and μ_S are Lamé's constants

$$\lambda_S = \frac{E_S \nu_S}{(1+\nu_S)(1+2\nu_S)} \qquad\qquad \mu_S = \frac{E_S}{2(1+\nu_S)} \tag{8.17}$$

E_S is the Young modulus, ν_S is the Poisson number, κ, α_S, β_S, γ_S are material constants of the micropolar continuum, see Eringen (1975/76).

Two equations of motion define unknown displacements and microrotations in the layer, see Zmitrowicz (1987, 1989). The equations of motion of the micropolar thermoelastic layer with friction and wear effects included are as follows

$$\begin{gathered}\rho_S \frac{\partial^2 \boldsymbol{u}_S}{\partial t^2} + \beta \operatorname{grad}_S T_S - (\lambda_S + 2\mu_S + \kappa) \operatorname{grad}_S \operatorname{div}_S \boldsymbol{u}_S + \\ +(\mu_S + \kappa) \operatorname{curl}_S \operatorname{curl}_S \boldsymbol{u}_S + \kappa \operatorname{curl}_S \boldsymbol{\Psi} - \boldsymbol{t}_{AS} - \boldsymbol{t}_{BS} - m_A \boldsymbol{V}_{AS} - m_B \boldsymbol{V}_{BS} = \boldsymbol{0} \\ \rho_S \boldsymbol{j}_0 \frac{\partial^2 \boldsymbol{\Psi}}{\partial t^2} - (\alpha_S + \beta_S + \gamma_S) \operatorname{grad}_S \operatorname{div}_S \boldsymbol{\Psi} + \gamma_S \operatorname{curl}_S \operatorname{curl}_S \boldsymbol{\Psi} - \kappa \operatorname{curl}_S \boldsymbol{u}_S + \\ +2\kappa \boldsymbol{\Psi} - \boldsymbol{c} + (m_A + m_B) \boldsymbol{j}_0 \frac{\partial \boldsymbol{\Psi}}{\partial t} = \boldsymbol{0}\end{gathered} \tag{8.18}$$

where $\boldsymbol{t}_{AS}$, $\boldsymbol{t}_{BS}$ are friction forces between the layer S and the bodies A and B. $\boldsymbol{V}_{AS}$, $\boldsymbol{V}_{BS}$ are sliding velocities between the layer S and the bodies A and B. m_A, m_B are masses supplied to the layer from the bodies A and B during the wear process, $\boldsymbol{j}_0$ is the microinertia tensor of wear debris, $\boldsymbol{c}$ is the couple of friction forces in the layer.

8.1.2. Micropolar fluid films

Micropolar fluid films can describe fluid-like behaviour of cylindrical or spherical wear debris. Micropolar fluids were studied by Więckowski (1955), Stokes (1966), Eringen (1975/76), Leslie (1979), Eringen (1980), Kirwan (1986), Lin (1997), Walicka (2000).

The absolute velocity of a layer particle is defined by

$$\boldsymbol{v}_S = \frac{D\boldsymbol{x}_S}{Dt} \equiv v^\alpha \boldsymbol{a}_\alpha + z_n \boldsymbol{n} \qquad \alpha = 1, 2 \tag{8.19}$$

where, $\{\boldsymbol{a}_\alpha, \boldsymbol{n}\}$ are the unit vectors of the layer, v^α, z_n are tangential and normal components of the velocity. It is seen that the velocity of the layer particle is a sum of the superficial velocity $v^\alpha \boldsymbol{a}_\alpha$ and the velocity $z_n \boldsymbol{n}$ along a trajectory normal to the layer. The vector of the angular velocity about an instantaneous axis of rotation is defined by

$$\boldsymbol{\omega} = \dot{\psi} \boldsymbol{k} + \sin\psi \dot{\boldsymbol{k}} + (1 - \cos\psi) \boldsymbol{k} \times \dot{\boldsymbol{k}} \tag{8.20}$$

Two deformation rate measures are introduced using the vectors of translational and rotational velocity. The following deformation rate measures are assumed in the case of the micropolar fluid layer

$$\mathsf{A} = \operatorname{grad}_S \boldsymbol{v}_S - \boldsymbol{\epsilon}_S \boldsymbol{\omega} \qquad\qquad \mathsf{B} = \operatorname{grad}_S \boldsymbol{\omega} \tag{8.21}$$

Let us decompose the stress tensor as follows

$$\mathbf{T}_S = \pi \mathbf{1}_S + \mathbf{T}_S^{(d)} \tag{8.22}$$

where π is the thermodynamic pressure in the fluid, $\mathbf{T}_S^{(d)}$ is the dissipative part of the stress tensor. The following constitutive relations are used for the stress tensor $\mathbf{T}_S^{(d)}$ and the couple stress tensor $\mathbf{M}$

$$\begin{aligned} \mathbf{T}_S^{(d)} &= \lambda_v(\operatorname{tr}\mathbf{A})\mathbf{1}_S + (\mu_v + \kappa_v)\mathbf{A} + \mu_v \mathbf{A}^\top \\ \mathbf{M} &= \alpha \boldsymbol{\epsilon}_S \operatorname{grad}_S \Theta_S + \alpha_v(\operatorname{tr}\mathbf{B})\mathbf{1}_S + \beta_v \mathbf{B} + \gamma_v \mathbf{B}^\top \end{aligned} \tag{8.23}$$

where λ_v, α_v, μ_v, κ_v, α, α_v, β_v, γ_v are material constants, see Eringen (1975/76), Eringen (1980).

Two governing equations define the unknown translational and rotational velocities in the layer, see Zmitrowicz (1987, 1989). The equations of motion for the micropolar fluid layer are as follows

$$\begin{aligned} &\rho_S \frac{D\boldsymbol{v}_S}{Dt} + \operatorname{grad}_S \pi - (\lambda_v + 2\mu_v + \kappa_v) \operatorname{grad}_S \operatorname{div}_S \boldsymbol{v}_S + \\ &+(\mu_v + \kappa_v) \operatorname{curl}_S \operatorname{curl}_S \boldsymbol{v}_S - \kappa_v \operatorname{curl}_S \boldsymbol{\omega} - \boldsymbol{t}_{SA} - \boldsymbol{t}_{SB} - \\ &-m_A \boldsymbol{V}_{AS} - m_B \boldsymbol{V}_{BS} = \mathbf{0} \\ &\rho_S \boldsymbol{j}_0 \frac{D\boldsymbol{\omega}}{Dt} - (\alpha_v + \beta_v + \gamma_v) \operatorname{grad}_S \operatorname{div}_S \boldsymbol{\omega} + \gamma_v \operatorname{curl}_S \operatorname{curl}_S \boldsymbol{\omega} - \kappa_v \operatorname{curl}_S \boldsymbol{v}_S + \\ &+2\kappa_v \boldsymbol{\omega} - \boldsymbol{c} + (m_A + m_B)\boldsymbol{j}_0 \boldsymbol{\omega} = \mathbf{0} \end{aligned} \tag{8.24}$$

In the equations of motion, the following effects are included: friction forces, friction couple and the supply of wear debris to the interfacial layer S.

8.1.3. Thermo-viscous fluid films

As an example, we consider a non-polar fluid. To this end, it is assumed that the rotational velocity $\boldsymbol{\omega}$ and the couple stress tensor $\mathbf{M}$ as well as the friction couple $\boldsymbol{c}$ are equal to zero.

The surface gradient operator of the layer velocity is decomposed into symmetric and antisymmetric parts

$$\operatorname{grad}_S \boldsymbol{v}_S = \mathbf{D}_S + \mathbf{W}_S \tag{8.25}$$

where

$$\begin{aligned}\mathbf{D}_S &= \frac{1}{2}[\,\mathrm{grad}_S\boldsymbol{v}_S + (\,\mathrm{grad}_S\boldsymbol{v}_S)^\top]\\ \mathbf{W}_S &= \frac{1}{2}[\,\mathrm{grad}_S\boldsymbol{v}_S - (\,\mathrm{grad}_S\boldsymbol{v}_S)^\top]\end{aligned} \tag{8.26}$$

In classical fluid mechanics of viscous flow, the deformation rates are completely measured by $\mathbf{D}_S$. The thermodynamic pressure can be introduced similar as in the case of the micropolar fluid. The dissipative part of the stress tensor is of the form

$$\mathbf{T}_S^{(d)} = \mathbf{T}_S^{(d)}(\mathbf{D}_S) \tag{8.27}$$

The constitutive equations for the stress tensor take the form typical for Newtonian fluids, i.e.

$$\mathbf{T}_S = \pi\mathbf{1}_S + \lambda(\,\mathrm{tr}\,\mathbf{D}_S)\mathbf{1}_S + 2\mu\mathbf{D}_S \tag{8.28}$$

where, λ and μ are viscosity constants. In the subject literature, exceptionally non-Newtonian models of lubricant fluids are proposed, e.g. viscoelastic of Rivlin-Ericksen, pseudoplastic of Reiner-Rivlin, etc.

The governing equations of motion of the layer given in the component notation, $\alpha,\beta,\varepsilon = 1,2$ and $n \equiv 3$, are as follows

$$\begin{aligned}&\rho_S\Big(\frac{\partial v_\alpha}{\partial t} + v_{\alpha|\beta}v^\beta - 2z_n b_{\alpha\beta}v^\beta - z_n z_{n,\alpha}\Big) + \pi_{,\alpha} - (\lambda+\mu)(v^\beta|_{\beta\alpha} - 2K_m z_{n,\alpha}) -\\ &-\mu v_\alpha|_\beta^\beta + \mu v^\varepsilon b_{\varepsilon\beta}(b_\alpha^\beta + 2K_m a_\alpha^\beta) + 3\mu z_{n,\beta}b_\alpha^\beta - t_{(SA)\alpha} -\\ &-t_{(SB)\alpha} - m_A V_{(AS)\alpha} - m_B V_{(BS)\alpha} = 0\\ &\rho_S\Big(\frac{\partial z_n}{\partial t} + 2z_{n,\alpha}v^\alpha + v^\alpha b_{\alpha\beta}v^\beta\Big) - z_{n,\alpha\beta}a^{\beta\alpha} - 2K_m(\lambda v^\alpha|_\alpha - \pi - 2\lambda K_m z_n) -\\ &-\mu b^{\alpha\beta}(2v_{\alpha|\beta} + v_{\beta|\alpha} - 2z_n b_{\alpha\beta}) - t_{(SA)n} - t_{(SB)n} = 0\end{aligned} \tag{8.29}$$

where, K_m is the mean curvature of the layer, $a^{\alpha\beta}$ is the metric tensor, $b^{\alpha\beta}$ is the curvature tensor, see Zmitrowicz (1987, 1989).

8.1.4. Mixtures

Solid-liquid and solid-gas mixtures as constitutive models of wear debris were proposed by Berker and Van Arsdale (1992). Heshmat and Brewe (1992) investigated a solid powder lubricant film between sliding surfaces. They postulated that a powder lubricant exhibits some of the basic features of hydrodynamic lubrication, and they proposed a semi-empirical rheological model of the powder film.

Hou *et al.* (1997) investigated rheological behaviour of the interfacial layer which forms the third body in rolling-sliding contacts and consists of wear debris and contaminants. It was assumed that the wear and other debris, under traction and extreme pressure, form a uniform, solid, incompressible layer. Hou *et al.* (1997) suggested an elastic-plastic rheological model for the compressed layer.

8.2. Discrete formulations

Some authors assumed that equations of continuum mechanics cannot be used in the case of the third body. They postulated that the third body is discontinuous, heterogeneous and anisotropic. For example, wear of steel can lead to a situation in which there is a layer of a granular material separating sliding bodies. In that case, mechanics of granular media should be applicable to define mechanical properties of the third body. That is why the discrete approach has been applied to the study of the third body.

Advantages of the granular material model are following: (a) it is possible to simulate a non-continuous interfacial medium, (b) it is well known that the granular media can exhibit both solid-like and fluid-like behaviour, (c) the velocity accommodation takes place in the bulk of the third body by shearing.

Disadvantages of the granular model: (a) a number of particles in the layer is constant; formation of new particles and ejection of the particles from the contact region cannot be considered, (b) a choice of inter-particle forces is arbitrary, (c) the layer has a finite thickness, and the size and shape of the particles have to be assumed.

8.2.1. Granular material models

Granular material models have been used to describe quasi-granular behaviour of wear debris, see Ikramov (1983), Berker and Van Arsdale (1992), Iordanoff *et al.* (2002a,b), Iordanoff and Khonsari (2004). Almost all classical theories of the granular flow involve an assumption that particles are spherical in shape, similar in size and non-cohesive. An incompressible granular medium is commonly supposed. Motion in a granular medium is attributed to boundary conditions and to interactions between particles at points of contact. Interaction forces between the particles can be defined in the frame of the Hertzian contact theory (see e.g. Kantani, 1981). They can include friction, adhesion and impact (with the restitution coefficient). Elrod (1988) assumed that the interactions between the particles transport normal and tangential contact forces which depend on the shape and roughness of a particle. The granular medium theory has been intensively studied by Hutter *et al.* (1996). Some generalizations of the rigid body were done by Więckowski (1973), who took into account polar effects.

In order to extend and specialize mechanics of granular media to the third body, it was assumed that the interfacial layer occurs as a discontinuous medium consisting of isolated discrete particles. For a given type of particles, it is reasonable to assume that all particles have the same shape. Therefore, particles of the third body are modelled by assemblies of elastic spheres (or cylinders). The particles are of micrometer size, and the assembly has a finite thickness. Motion of the particles through the contact interface takes place. Then, equations of motion are applied to each particle considered as an isolated solid body.

Let us consider a thick interfacial layer in the reference system Oxz. The particles can displace along the axes Ox and Oz, and they can rotate along the axis Oy normal to the plane Oxz. Equations of translational and rotational motions are as follows

$$\begin{aligned} m_i\ddot{\boldsymbol{u}}_i &= \sum_{j=1}^{k} \boldsymbol{F}_{(ij)} \qquad & I_i\ddot{\psi}_i &= \sum_{j=1}^{k} M_{y(ij)} \\ \boldsymbol{u}_i^t &= [x_i^t, z_i^t]^\top & \boldsymbol{F}_{(ij)} &= [F_{x(ij)}, F_{z(ij)}]^\top \end{aligned} \tag{8.30}$$

where, x_i^t, z_i^t, ψ_i^t define the position of the particle i at time t, $F_{x(ij)}$, $F_{z(ij)}$ are the inter-particle forces on the particle i due to particle j, $M_{y(ij)}$ is the inter-particle moment on the particle i due to particle j, m_i is the mass and I_i is the inertia moment of the particle i. Notice that displacements and rotations of the particles are finite in this formulation.

Algorithms of calculations are based on approaches used in Molecular Dynamics. The algorithm of discrete elements was formulated at first by Cundall (1971) and Cundall and Strack (1979). Steps of calculation are as follows:

— Accelerations of particles are computed using equations of motion $(8.30)_{1,2}$, i.e.

$$\ddot{\boldsymbol{u}}_i^{t+\Delta t} = \sum_{j=1}^{k} \frac{\boldsymbol{F}_{(ij)}}{m_i} \qquad \ddot{\psi}_i^{t+\Delta t} = \sum_{j=1}^{k} \frac{M_{y(ij)}}{I_i} \tag{8.31}$$

where, Δt is a small time step.

— New velocities of the particles are calculated by a numerical integration procedure

$$\dot{\boldsymbol{u}}_i^{t+\Delta t} = \dot{\boldsymbol{u}}_i^t + \frac{\ddot{\boldsymbol{u}}_i^t + \ddot{\boldsymbol{u}}_i^{t+\Delta t}}{2}\Delta t$$
$$\dot{\psi}_i^{t+\Delta t} = \dot{\psi}_i^t + \frac{\ddot{\psi}_i^t + \ddot{\psi}_i^{t+\Delta t}}{2}\Delta t \tag{8.32}$$

— New positions of the particles are computed as follows

$$\boldsymbol{u}_i^{t+\Delta t} = \boldsymbol{u}_i^t + \dot{\boldsymbol{u}}_i^{t+\Delta t}\Delta t + \ddot{\boldsymbol{u}}_i^{t+\Delta t}\frac{(\Delta t)^2}{2}$$
$$\psi_i^{t+\Delta t} = \psi_i^t + \dot{\psi}_i^{t+\Delta t}\Delta t + \ddot{\psi}_i^{t+\Delta t}\frac{(\Delta t)^2}{2} \tag{8.33}$$

The contact force $\boldsymbol{F}_{ij}$ can be decomopsed into normal $\boldsymbol{F}_n$ and tangential $\boldsymbol{F}_t$ components. The normal component can have an elastic term (a penetration function) and a damping term (e.g. viscous damping). The tangential component is friction.

Boundary conditions for the upper and lower walls must be defined, e.g. they can move or be fixed horizontally or vertically. The accommodation of the sliding velocity between the upper and lower walls can be realized by shearing in the layer of granular particles.

9. Conclusions

Our main results are as follows:

- Wear particles are of small sizes and different shapes.
- Wear debris can be "rolled over" into cylindrical, spherical and needle-like particles.
- Wear particles transmit translational and rotational displacements at the contact interface.
- Wear particles transmit forces and moments at the interface.
- The presence of wear debris implies modifications of the friction coefficient, wear rate and surface roughness.

- Various constitutive models can characterize quasi-solid, quasi-fluid and granular-like behaviour of wear particles. Both continuum based models and granular material models are discussed in this study.

- The practical importance of wear particles depends on a sliding system. It is extremely important in contacts where formation of loose particles is permanent, since they control the friction process. For example, in bearings, in fretting processes and in prostheses of human joints, wear particles are always present inside the contact region. Wear debris in the prostheses of human joints may be responsible serious illnesses (Podsiadlo *et al.*, 1997, 1998; Tipper *et al.*, 2001).

- Analysis of wear debris is an important indicator in fault diagnosis of machines and mechanisms.

Acknowledgements

The financial support was provided by the State Committee for Scientific Research, grant No. 8 T07A 034 20.

References

1. Aero E.L., Bulganin A.N., Kuvshinskii E.V., 1965, Nonsymmetric hydrodynamics, *Prikl. Mat. Mekh.*, **29**, 297, in Russian
2. Aero E.L., Kuvshinskii E.V., 1960, Fundamental equations of the theory of elastic media with rotationally interacting particles, *Fizika Tverdogo Tela*, **II**, 1399-1409, in Russian; *Trans. Soviet Physics Solid State*, **II**, 1272-1281, 1961, in English
3. Alts T., Hutter K., 1988, 1989, Continuum description of the dynamics and thermodynamics of phase boundaries between ice and water, Part I-IV, *J. Non-Equilib. Thermodyn.*, **13**, 3, 1988, 221-257, 259-280, **13**, 4, 1988, 301-329, **14**, 1, 1989, 1-22
4. Anderson D.P., 1982, *Wear Particle Atlas*, Telus Inc., Naval Air Engineering Center, Technical Report NAEC-92-163, revised edn.
5. Archard J.F., 1953, Contact and rubbing of flat surfaces, *J. Appl. Phys.*, **24**, 8, 981-988
6. Barwell F.T., 1983, The contribution of particle analysis to the study of wear of metals, *Wear*, **90**, 1, 167-181

7. Berker A., Van Arsdale W.E., 1992, Phenomenological models of third body rheology, [in:] *Wear Particles: From the Cradle to the Grave*, D. Dowson *et al.* (Edit.), Elsevier, Amsterdam, 337-346

8. Berthier Y., Godet M., Brendle M., 1989, Velocity accomodation in friction, *Tribology Transactions*, **32**, 4, 490-496

9. Berthier Y., Vincent L., Godet M., 1992, Velocity accommodation sites and modes in tribology, *Eur. J. Mech., A/Solids*, **11**, 1, 35-47

10. Berthier Y., Wehbei D., Wack J., Roques-Carmes C., Godet M., 1988, Fractals: a method of characterisation of third body morphology, [in:] *Interface Dynamics*, Proceedings of the 14th Leeds-Lyon Symposium on Tribology Held at the INSA, Lyon 1987, D. Dowson *et al.* (Edit.), Elsevier, Amsterdam, 105-108

11. Blinowski A., 1994, Revolutions of deformable bodies. Part 1 – Geometry and kinematics, *Prace IPPT*, **7**, Warszawa, 1-112, in Polish

12. Bowen E.R., Westcott V.C., 1976, *Wear Particle Atlas*, Foxboro Analytical/Tranonics Inc., Burlington Mass. USA

13. Cheng J., Yang Z.Y., 1998, Fuzzy synthetic decision-making system in ferrographic analysis, *Wear*, **222**, 1, 1-20

14. Cho U., Tichy J.A., 2000, A study of two-dimensional binary images of wear debris as an indicator of distinct wear conditions, *J. of Tribology*, **44**, 1, 132-136

15. Colombié CH., Berthier Y., Floquet A., Vincent L., Godet M., 1984, Fretting: load carrying capacity of wear debris, *J. of Tribology*, **106**, 2, 194-201

16. Cosserat E., Cosserat F., 1909, *Théorie des Corps Déformable*, A. Hermann et Fils, Paris

17. Crone W.C., 1967, *The Particle Atlas*, Ann Arbor Science Publishers

18. Cundall P.A., 1971, A computer model for simulating progressive large scale movements of blocky rock systems, [in:] *Proc. of the Symposium of the Int. Society of Rock Mechanics*, Nancy, **1**, 132-150

19. Cundall P.A., Strack O.D.L., 1979, A discrete numerical method for granular assemblies, *Géotechnique*, **2**, 47-65

20. Davies J.E., 1986, Spherical debris particles in engine oil, *Wear*, **107**, 2, 189

21. Denape J., Berthier Y., Vincent L., 2001, Wear particle life in a sliding contact dry conditions: third body approach, [in:] *Fundamentals of Tribology and Bridging the Gap Between the Macro- and Micro/Nanoscales, Proceedings of the NATO Advances Study Institute*, B. Bushan (Edit.), Kluwer Academic Publishers, Dordrecht, 393-411

22. Descartes S., Berthier Y., 2002, Rheology and flows of solid third bodies: background and application to an $MoS_{1.6}$ coating, *Wear*, **252**, 7-8, 546-556

23. DON J., RIGNEY D.A., 1985, Prediction of debris flake thickness, *Wear*, **105**, 1, 63-72

24. DOWSON D. ET AL. (EDIT.), 1992, Wear particles: from the cradle to the grave, *Proceedings of the 18th Leeds-Lyon Symposium on Tribology held at the INSA*, Lyon 1991, Elsevier, Amsterdam

25. DOWSON D. ET AL. (EDIT.), 1996, The third body concept: interpretation of tribological phenomena, *Proceedings of the 22nd Leeds-Lyon Symposium on Tribology*, Lyon 1995, Elsevier, Amsterdam

26. ELROD H.G., 1988, Granular flow as a tribological mechanism – a first look, [in:] *Interface Dynamics*, D. Dowson *et al.* (Edit.), Elsevier, Amsterdam, 75-88

27. ERINGEN C., 1975/76, *Continuum Physics*, **1-4**, Academic Press, New York

28. ERINGEN C., 1980, Theory of anisotropic micropolar fluids, *Int. J. Engng. Sci.*, **18**, 5-17

29. FINKIN E.F., 1964, The wear of copper, aluminum, mild steel and zinc, and their particle shape factors, *ASLE Transactions*, **7**, 377-382

30. GAUTHIER R.D., JAHSMAN W.E., 1975, A quest for micropolar elastic constants, *J. Appl. Mech.*, **42**, 369-374

31. GEORGES J.-M., MEILLE G., 1985, Microscopical behaviour of the third body in dry friction or boundary lubrication, *Proc. of the JSLE Int. Tribology Conference*, Tokyo 1985, Part I, 885-890

32. GODET M., 1984, The third-body approach: a mechanical view of wear, *Wear*, **100**, 437-452

33. GODET M., 1988, Modeling of friction and wear phenomena, [in:] *Approaches to Modeling Wear*, F.F. Ling and C.H.T. Pian (Edit.), Springer, Berlin, 12-36

34. GODET M., 1989, Third bodies in tribology, *Proc. 5th Int. Congress on Tribology, Eurotrib 89*, Helisinki 1989, **I**, 1-15

35. GODET M., BERTHIER Y., LANCASTER J., VINCENT L., 1991, Wear modelling: using fundamental understanding or practical experience?, *Wear*, **149**, 1-2, 325-340

36. GODET M., PLAY D., 1975, Third-body formation and elimination on carbon-fibre/epoxy composite, [in:] *Space Tribology*, H.M. Briscoe (Edit.), European Space Agency, Neuilly, 165-174

37. HATCHETT C., 1803, Experiments and observations on the various alloys, on specific gravity, and on comparative wear of gold. Being the substance of a report made to the Right Honourable the Lord of the Committee of Privy Council, appointed to take into consideration the state of the coins of the Kingdom, and the present, establishment and Constitution of his Majesty's Mint, *Phil. Trans. R. Soc. London*, for the year MDCCIII, Part I, 43-194

38. Hawthorne H.M., 1991, On the role of interfacial debris morphology in conforming contact tribosystem, *Wear*, **149**, 1-2, 169-185

39. Heshmat H., Brewe D.E., 1992, On some rheological aspects of tribo particulates, [in:] *Wear Particles: From the Cradle to the Grave*, D. Dowson *et al.* (Edit.), Elsevier, Amsterdam, 356-367

40. Hou K., Kalousek J., Magel E., 1997, Rheological model of solid layer in rolling contact, *Wear*, **211**, 1, 134-140

41. Hunt T.M., 1993, *Handbook of Wear Debris Analysis and Particle Detection in Liquids*, Elsevier Applied Science

42. Hutter K., Svendsen B., Rickenmann D., 1996, Debris flow modeling: A review, *Continuum Mechanics and Thermodynamics*, **8**, 1, 1-35

43. Hwang D.H., Kim D.E., Lee S.J., 1999, Influence of wear particle interaction in the sliding interface on friction of metals, *Wear*, **225-229**, Part I, 427-439

44. Ikramov U., 1983, Kinematics of abrasive particle interaction with friction surfaces, *Zagadnienia Eksploatacji Maszyn*, **55**, 3, 271-282

45. Iordanoff I., Berthier Y., Descartes S., Heshmat H., 2002a, A review of recent approaches for modelling solid third bodies, *J. of Tribology*, **124**, 4, 725-735

46. Iordanoff I., Khonsari M.M., 2004, Granular lubrication: toward an understanding of the transition between kinetic and quasi-fluid regime, *J. of Tribology*, **126**, 1, 137-145

47. Iordanoff I., Seve B., Berthier Y., 2002b, Solid third body analysis using a discrete approach: influence of adhesion and particle size on macroscopic properties, *J. of Tribology*, **124**, 3, 530-538

48. Jiang J., Stott F.H., Stack, M.M., 1998, The role of triboparticulates in dry sliding friction, *Tribology International*, **31**, 5, 245-256

49. Jin Y., Wang C., 1989, Spherical particles generated during the running-in period of a diesel engine, *Wear*, **131**, 2, 315-328

50. Kantani K., 1981, A theory of contact force distribution in granular materials, *Powder Technology*, **28**, 2, 167-172

51. Kato K., 1990, Tribology of ceramics, *Wear*, **136**, 1, 117-133

52. Kirk T.B., Panzera D., Anamalay R.V., Xu Z.L., 1995, Computer image analysis of wear debris for machine condition monitoring and fault diagnosis, *Wear*, **181-183**, II, 717-722

53. Kirk T.B., Stachowiak G.W., Batchelor A.W., 1991, Fractal parameters and computer image analysis applied to wear particles isolated by ferrography, *Wear*, **145**, 2, 347-365

54. Kirwan A.D., 1986, Boundary conditions for micropolar fluids, *Int. J. Engng. Sci.*, **24**, 7, 1237-1242

55. Kohen I., Play D., Godet M., 1980, Effect of machine rigidity or degrees of freedom on the load-carrying capacity of wear debris, *Wear*, **61**, 2, 381-384

56. Kuwahara K., Masumoto H., 1980, Influence of wear particles on the friction and wear between copper disk and pin of various kinds of metal, *Lubrication Engineering*, **36**, 6, 362

57. Larsen-Badse J., 1968, Influence of girt diameter and specimen size on wear during sliding abrasion, *Wear*, **12**, 35-53

58. Leslie F.M., 1979, On the thermodynamics of polar fluids, *Archive for Rational Mechanics and Analysis*, **70**, 2, 189-202

59. Lin J.-J., Chen Y., Cheng Y.-Q., 1992, The generation of wear debris of different morphology in the running-in process of iron and steels, *Wear*, **154**, 2, 259-267

60. Lin J.R., 1997, Effects od couple stresses on the lubrication of finite journal bearings, *Wear*, **206**, 1-2, 171-178

61. Lu L., Farris T.N., Chandrasekar S., 1992, Sliding microidentation wear particles: spheres in grinding swarf, [in:] *Wear Particles: From the Cradle to the Grave*, D. Dowson *et al.* (Edit.), Elsevier, Amsterdam, 257-263

62. Mizumoto M., Kato K., 1992, Size distribution and number of wear particles generated by the abrasive sliding of a model asperity in the SEM-Tribosytem, [in:] *Wear Particles: From the Cradle to the Grave*, D. Dowson *et al.* (Edit.), Elsevier, Amsterdam, 523-530

63. Murti V.S., Philip P.K., 1987, An analysis of the debris in ultrasonic-assisted electrical discharge machining, *Wear*, **117**, 2, 241-250

64. Myshkin N.K., Kong H., Grigoriev A.Ya., Yoon E.-S., 2001, The use of colour in wear debris analysis, *Wear*, **250-251**, Part 2, 1218-1226

65. Nikas G.K., Sayles R.S., Ioannides E., 1998, Effects of debris particles in sliding/rolling elastohydrodynamic contacts, *J. Eng. Trib., Proc. Inst. Mech. Eng.*, **212**, J5, 333-343

66. Peng Z., Kirk T.B., 1997, Two-dimensional fast Fourier transform and power spectrum for wear particle analysis, *Tribology International*, **30**, 8, 583-590

67. Peng Z., Kirk T.B., 1998, Computer image analysis of wear particles in three-dimensions for machine condition monitoring, *Wear*, **223**, 1-2, 157-166

68. Peng Z., Kirk T.B., 1999a, The study of three-dimensional analysis techniques and automatic classification systems for wear particles, *J. of Tribology*, **121**, 1, 169-176

69. Peng Z., Kirk T.B., 1999b, Wear particle classification in a fuzzy grey system, *Wear*, **225-229**, Part II, 1238-1247

70. Peng Z., Kirk T.B., Xu Z.L., 1997, The development of three-dimensional imaging techniques of wear particle analysis, *Wear*, **203-204**, 418-424

71. Pietraszkiewicz W., Badur J., 1983, Finite rotations in the description of continuum deformation, *Int. J. Engng. Sci.*, **21**, 9, 1097-1115

72. Podsiadlo P., Kuster M., Stachowiak G.W., 1997, Numerical analysis of wear particles from non-arthritic and osteoarthritic human knee joints, *Wear*, **210**, 1-2, 318-325

73. Podsiadlo P., Stachowiak G.W., 1998, Evaluation of boundary fractal methods for the characterization of wear particles, *Wear*, **217**, 1, 24-34

74. Podsiadlo P., Stachowiak G.W., 1999a, 3-D imaging of surface topography of wear particles found in synovial joints, *Wear*, **230**, 2, 184-193

75. Podsiadlo P., Stachowiak G.W., 1999b, Applications of Hurst orientation transform to the characterization of surface anisotropy, *Tribology International*, **32**, 7, 387-392

76. Podsiadlo P., Stachowiak G.W., 2000, Scale-invariant analysis of wear particle surface morphology I: Theoretical background computer implementation and technique testing; II: Fractal dimension; III: Pattern recognition, *Wear*, **242**, 1-2, 160-179, 180-188, 189-201

77. Rabinowicz E., 1977, The formation of spherical wear particles, *Wear*, **42**, 1, 149-156

78. Rabinowicz E., 1995, *Friction and Wear of Materials*, J.Wiley, N.Y., 2nd ed.

79. Reda A.A., Bowen R., Westcott V.C., 1975, Characteristics of particles generated at the interface between sliding steel surfaces, *Wear*, **34**, 3, 261-273

80. Rennie G., 1829, Experiments on the friction and abrasion of the surface of solids, *Phil. Trans. R. Soc. London*, **34**, Prt I, 143-170

81. Roylance B.J., Raadnui S., 1994, The morphological attributes of wear particles-their role in identifying wear mechanisms, *Wear*, **175**, 1-2, 115-121

82. Roylance B.J., Wang G., Bovington C.H., 1992, The determination of particle morphological parameters to assist in elucidation of wear process, [in:] *Wear Particles: From the Cradle to the Grave*, D. Dowson *et al.* (Edit.), Elsevier, Amsterdam, 75-79

83. Roylance B.J., Williams J.A., Dwyer-Joyce R., 2000, Wear debris and associated wear phenomena-fundamental research and practice, *J. Eng. Tribology, Proc. Inst. Mech. Eng.*, **214**, J1, 79-105

84. SAMUELS L.E., DOYLE E.D., TURLEY D.M., 1980, Sliding wear mechanisms, [in:] *Fundamentals of Friction and Wear of Materials*, D.A. Rigney (Edit.), American Society for Metals, Pittsburgh, 13-41

85. SANSOUR C., BUFLER H., 1992, Exact finite rotation shell theory, its mixed variational formulation and its finite element implementation, *Int. J. Num. Meth. Engrg.*, **34**, 1, 73-115

86. SANTANAM N., 1983, Effect of wear debris on wear in rolling-sliding motion, *Wear*, **90**, 2, 261-267

87. SCOTT D., SEIFERT W.W., WESTCOTT V.C., 1974, The particles of wear, *Scientific American*, **230**, 5, 88-97

88. SHEASBY J.S., 1983, Direct observation of dry wear, *Wear*, **89**, 2, 173-183

89. SHERRINGTON I., HAYHURST P., 2001, Simultaneous observation of the evolution of debris density and friction coefficient in dry sliding steel contacts, *Wear*, **249**, 3-4, 182-187

90. STACHOWIAK G.W., 1998, Numerical characterization of wear particles morphology and angularity of particles and surfaces, *Tribology International*, **31**, 1-3, 139-157

91. STACHOWIAK G.W., PODSIADLO P., 1999, Surface characterization of wear particles, *Wear*, **225-229**, Part II, 1171-1185

92. STOKES V.K., 1966, Couple stresses in fluids, *Phys. Fluids*, **9**, 1709-1715

93. SUH N.P., SIN H.-C., 1980, On the genesis of friction and its effect on wear, [in:] *Solid Contact and Lubrication*, H.S. Cheng and L.M. Keer (Edit.), AMD-vol. 39, 167-183

94. SWANSON P.A., VETTER A.F., 1985, The measurement of abrasive particle shape and its effect on wear, *ASLE Transactions*, **28**, 2, 225-230

95. SZEFER G., 1998, Contact problems in terms of large deformations, *Z. Angew. Math. Mech.*, **78**, 8, 523-533

96. SZEFER G., JASIŃSKA D., SALAMON J.W., 1994, Concept of a singular surface in contact mechanics, *Arch. Mechanics*, **46**, 4, 581-603

97. TIPPER J.L., FIRKINS P.J., BESONG A.A., BARBOUR P.S.M., NEVELOS J., STONE M.H., INGHAM E., FISHER J., 2001, Characterization of wear debris from UHMWPE on zirconia ceramic, metal-on-metal and alumina ceramic-on-ceramic hip prostheses generated in a physiological anatomical hip joint simulator, *Wear*, **250-251**, Part I, 120-128

98. UMEDA A., SUGIMURA J., YAMAMOTO Y., 1998, Characterization of wear particles and their relations with sliding conditions, *Wear*, **216**, 2, 220-228

99. Unchung Cho, Tichy J.A., 2000, Quantitative correlation of wear debris morphology: grouping and classification, *Tribology International*, **33**, 7, 461-467

100. Walicka A., 2000, Pressurized flows of a micropolar fluid between surfaces of revolution: The fixed one and the rotating one, *Inż. Chem. Procesowa*, **21**, 1, 57-74

101. Wang Y., Cao C., Wang D., 1986, A study of the formative mechanism of spherical wear particles, *Wear*, **108**, 3, 285-294

102. Więckowski J., 1955, On motion equations of real fluids, *Arch. Hydrotechniki*, **2**, 3, 191-208, in Polish

103. Więckowski J., 1973, Elements of rigid body mechanics in absolute notation and some generalizations, *Biuletyn IMP PAN*, Nr. 72/736/1973, Gdańsk, 1-46, in Polish

104. Wilson F., Eyre T.S., 1969, The generation of hard particles during sliding wear, *Wear*, **14**, 285-288

105. Wirth A., Eggleston D., Whitaker R., 1994, A fundamental tribochemical study of the third body layer formed during automotive friction braking, *Wear*, **179**, 1-2, 75-81

106. Wrona M., 2003, Applications of fractal methods in wear debris analysis, *Tribologia*, **189**, 3, 103-117, in Polish

107. Wuttkowski J.G., Ioannides E., 1992, The effect of contaminants on bearing life, *SKF, Ball Bearing Journal*, **239**, 9-11

108. Xu K., Luxmoore A.R., 1997, An integrated system for automatic wear particle analysis, *Wear*, **208**, 1-2, 184-193

109. Xuan J.L., Cheng H.S., 1992, Microscopic wear debris generation and surface topography, [in:] *Wear Particles: From the Cradle to the Grave*, D. Dowson *et al.* (Edit.), Elsevier, Amsterdam, 247-256

110. Zanoria E.S., Danyluk S., McNallan M.J., 1995, Formation of cylindrical sliding-wear debris on silicon in humid conditions and elevated temperatures, *Tribology Transactions*, **38**, 3, 721-727

111. Zhang M.Q., Lu Z.P., Friedrich K., 1997, On the wear debris polyetheretherketone: fractal dimensions in relation to wear mechanism, *Tribology International*, **30**, 2, 87-102

112. Zmitrowicz A., 1987, A thermodynamical model of contact, friction and wear: II constitutive equations for materials and linearized theories, *Wear*, **114**, 2, 169-197

113. Zmitrowicz A., 1989, On the thermodynamics of contact, friction and wear, *Zeszyty Naukowe IMP PAN*, No. 287/1212/89, Gdańsk, 1-190

114. ZMITROWICZ A., 2000, Variational approach to contact, friction and wear problems, *Z. Angew. Math. Mech.*, **80**, S2, S463-S464

115. ZMITROWICZ A., 2001, Variational descriptions of wearing out solids and wear particles in contact mechanics, *J. Theoretical and Applied Mechanics*, **39**, 3, 791-808

116. ZMITROWICZ A., 2002, Wear profiles and wear debris taken into account in variational approaches to contact mechanics, [in:] *Proceedings of the Fifth World Congress on Computational Mechanics*, H.A. Mang, F.G. Rammerstorfer, J. Eberhardsteiner (Edit.), Vienna University of Technology, http://wccm.tuwien.ac.at, 1-10

117. ZMITROWICZ A., 2003, Solution algorithms of contact problems with wear debris between sliding surfaces, [in:] CD-ROM *Proceedings of the 15th Int. Conference on Computer Methods in Mechanics*, T. Burczyński, P. Fedeliński, E. Majchrzak (Edit.), Silesian Technical University, Gliwice/Wisła, 1-10

Cząstki zużycia: przegląd własności i modeli konstytutywnych

Streszczenie

Zużycie jest to stopniowe usuwanie materiału ze stykających i trących się powierzchni ciał stałych podczas ich względnego poślizgu. Mechanizm zużycia powoduje tworzenie cząstek zużycia. Cząstki są o małych wymiarach i różnych kształtach. Cząstki zużycia mogą być „zrolowane” w walce, kule lub igiełki. Cząstki oddzielone od trących się powierzchni tworzą prawie ciągłą warstwę pośrednią. Przekazują one siły, momenty i przemieszczenia (translacyjne i obrotowe) w obszarze styku. Obecność cząstek zużycia między ślizgającymi się powierzchniami oddziaływuje w sposób istotny na zjawiska tarcia i zużycia. Relacje konstytutywne charakteryzują własności cząstek zużycia typu quasi-ciało stałe, quasi-płyn i ośrodek granulowany. W pracy rozpatrzono dwa modele konstytutywne cząstek zużycia: (a) model ośrodka ciągłego, (b) model ośrodka granulowanego. Modele typu ośrodka ciągłego zostały sformułowane dla mikropolarnego materiału termosprężystego, płynu mikropolarnego i płynu termo-lepkiego.

Manuscript received March 9, 2004; accepted for print July 14, 2004