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HIGH FRICTION COEFFICIENT MATERIALS

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Abstract: *This paper presents some insights into the materials characterised by the high friction coefficient. Friction coefficient is one of the essential parameters for evaluation of the contact development, but it still needs further investigations, especially from nano and micro aspects. There are several approaches to the determination and quantification of the static and dynamic coefficients, whereas methodology involving energy dissipation has gained attention for the nano and micro contacts. High friction is applied in systems where good adhesion is needed, such as breaks or in the case of dry adhesives – fitting of the elements together. Material combinations are reviewed, that exhibit high friction coefficients during contact. Two types of materials are presented from friction aspects: Ti-based alloys for medical implants where high friction is a negative property and Al-based alloys for which this feature has been used in various friction welding applications. In the case of Ti-based alloys, many approaches have been tried to overcome high friction and associated high detrimental wear, but it is still the evident problem. For aluminium alloys, it is used for joining two parts in different systems, such as car body, ship elements, or various rail wagon related elements.*

Keywords: *friction coefficient, adhesion, Ti alloys, Al alloys, contact.*

1. INTRODUCTION

Friction coefficient was introduced a very long time ago, by Leonardo Da Vinci, who defined it as the ratio of frictional force and normal component [1]. Friction coefficient is very commonly taken as the parameter which is either a known value for the system under observation from the tables in the literature (as in the case of many modeling methods), or it is experimentally determined in scope of tribological testing [2-7]. However, fundamental understanding of the governing influences on the value variations is still rather ambiguous, what is even more odd, considering the fact that friction coefficient is one the essential parameters in numerous calculations and system definitions. On the other hand, if the two relative surfaces in contact are observed, it is quite obvious that many influential factors determine the contact behaviour and from this point of view, friction coefficient is no more a simple parameter because it reflects all of these influences. In most of the engineering cases, only macro behaviour of the contact zone is satisfying enough for the system description and maintenance. However, if the scale is lowered down to micro and especially to nano levels, many factors become interlinked and under debate, thus making a question of friction coefficient very complex one.

In general, friction coefficient depends on the materials in contact, their geometry, surface roughness, environment and temperature. Static or dynamic friction coefficient can be studied as: static to reflect the start of the motion, and dynamic or kinetic one, related to the maintenance of the motion. Difference between static and dynamic friction coefficient was noticed by ancient Greeks. They recognized that it is easier for the object to continue its movement than to start it from the inaction. The classical law of friction was first defined by Leonardo Da Vinci, who is sometimes considered to be the pioneer of tribology, whose work was documented in notes but not published at that time (year of 1493). These principals were discovered and first time published by Amontons in 1699 who defined friction force and dependence on applied load and independence of the contact area. In general, 1st and 2nd Amontons' laws of friction are still valid in cases of dry friction. In 1750, Belidor and Euler introduced the difference between static and dynamic friction. The first comprehensive study of the friction was realised by Coulomb in 1785 who studied the various influences originating from the materials in contact, contact geometry, external loading, velocities, time in contact, temperature, humidity. Coulomb stated that kinetic friction is independent of the sliding velocity. It was not until 1950 that surface roughness was essentially recognised as the highly influential factor, when Bowden and Tabor showed that contact surfaces on micro level are very small and introduced the term 'real contact surface', whereas the real contact surface is significantly smaller than previously considered the macro contacts.

For a very long time, common understanding has been that the friction coefficient can only have a value between 0 and 1 and also that static coefficient is higher than its dynamic value. Frictional energy, created during the motion of the two surfaces in relative contact, is partially transformed into heat, deformation and wear of the surfaces. At micro and nano scale, thermodynamics, as well as several other influences (chemistry, micro/nano roughness, etc.) start to govern the process. Work created due to friction can be transformed into deformations and heat can affect surface properties which can be used in polishing process. Work induced with friction can be used in material mixing and merging in frictional welding [11].

Definition of the factors that influence friction on micro and nano scale still represents a complex issue and several approaches has been proposed. There are many proposed friction models in the literature, that consider geometry (roughness), mechanical properties (stress, strain), fluid dynamics, electrostatic forces between surface atoms, chemical compatibility, shear strength of the adhesive junctions and other. Methodologies considering energy dissipation modes are considered to be the promising ones to provide general friction theory at micro/nano scale [8-10]. In different tribosystems, energy due to the work of friction is distributed in different ways, from the heat that simply increase internal energy of the materials in contact, or forming of new surfaces and wear debris by forming and breaking the micro-welded zones, and deformation of the contact films. The relationship between friction and wear is evident and yet there is no direct general theory to quantify it, except experimental dependences within separate tribo testing.

Energy transformed as friction effect can be stored inside the tribosystem or distributed in several ways, as per eq. 1.

$$E_f = E_{out} + E_{st} \quad (1)$$

where: Ef - total energy resulting from friction; Eout – energy that left the system; Est – energy stored within the system.

For example, energy created by mechanical sliding can be transformed into heat, vibrational energy (sound), material deformation, or wear. Therefore, energy can be stored within a material, in a form of microstructural defects. Accordingly, two materials with the same value of the friction coefficient can experience different levels of wear because of different energy distribution between and inside materials. Relationship between friction and wear can change over time within one system and usually is changing, thus additionally introducing complexity in investigation of friction and wear.

Recent investigations, both theoretical and experimental, indicate that from simple energy approach, friction is related to 1) adhesion of the micro-contacts leading to material damage after breaking of those bonds and 2) plastic deformation of surface asperities [10]. However, energy dissipation in atomic-scale friction is much more complex than this approach [8, 9].

Frictional energy dissipates during microscopic deformations of surface asperities and converts into heat. Down to micro and nano scale, frictional force depends of interactive physical and chemical properties, loads, relative velocity, and temperature within small contact zones of surface asperities. As the direct consequence, generated heat is not equally distributed between the two surfaces in contact. Heat distribution level depends of heat conductivity, heat capacity, relative velocity, interspace and many other factors. Localized plastic deformation can significantly change heat distribution, because part of the energy is retained within a material microstructures (e.g. uniaxial strain test always store some energy in the microstructure in a form of residual stresses) and it can be as much as 80 - 100% of the total energy input.

Perceived knowledge on the friction coefficient has changed during last decades and values of the coefficient higher than 1 are proven from many experimental results. Consequently, materials that can exhibit these high friction coefficients has been studied and several practical applications have been recognised.

2. REVIEW OF THE MATERIALS WITH HIGH FRICTION COEFFICIENT

Static coefficient of friction is related to the initiation of motion, whereas dynamic friction coefficient pertains to the maintaining of the motion. Two opposite areas can be observed related to the friction coefficient exhibited in the process: low and high friction coefficient levels. Low friction coefficient is desired property in the cases when smooth rolling or sliding is requested during the contact between two different elements. Opposite to this approach, very high friction coefficients are studied for development of specific applications such as brake systems, or locking the elements together during assembly of some systems (zero slip), or cold welding, and others. High friction materials were mainly focused on brake materials earlier and did not have that much attention until last decades, and especially with advent of nanotechnologies they became interesting subject of research. Well known gecko feet effect [12] provoked very interesting investigations to mimic such materials and surface structures to enable high friction and low adhesion for many new nano/micro-related applications. The extraordinary natural surface design of the gecko feet lies within the set of arrays with hundreds of flexible fibers thus providing very high adhesion and friction on the opposite surface, for all surfaces, from rough to smooth or hydrophobic and hydrophilic surfaces, by using only weak van der Waals forces. This principle has been studied for application in dry adhesives.

It is usually considered that static coefficient of friction is always higher than the dynamic values. It is most often so, but there are numerous cases when dynamic values can be dramatically higher than static ones (even 40-50% higher), because it strongly depends on the materials in contact, as well as the contact conditions (surface roughness, load or pressure, velocity, environment and especially the temperature).

Table 1 presents several common combinations of materials in contact that result in high friction coefficients, with average values under ambient temperature. Comparison of changes in material combinations related to the friction coefficients is given in Table 2. It is obvious that materials in contact have major influence on the frictional values, but also the environment can result in significant changes. For example, car tires are significantly easier to start moving on the asphalt than on the grass (or in the case of the rubber - wet asphalt/concrete/road vs. rubber - dry asphalt/concrete/road), which is commonly known fact in life, really nicely represented by the frictional values in Table 2. It can also be seen that even changes within the material compositions or structures, can decrease by half the frictional values (e.g. copper – cast iron vs copper – mild steel). Also, environment can have major influence, like in the case of graphite –graphite contact (in vacuum 0.5-0.8 down to 0.1 without the vacuum).

Table 1. Material combinations that result in high friction coefficient [13]

Material combinations		Static coefficient of friction		Dynamic coefficient of friction	
		Dry contact, Clean surfaces	Lubricated	Dry contact, Clean surfaces	Dry contact, Clean surfaces
Aluminum	**Aluminum**	**1.05 - 1.35**	**0.3**		
Aluminum	Mild Steel	0.61			
Cast Iron	**Cast Iron**	**1.1**		**0.15**	**0.07**
Car tire	Asphalt	0.72			
Copper	Copper	1	0.08		
Copper	Cast Iron	1.05		0.29	
Glass	Glass	0.9 - 1.0	0.1 - 0.6	0.4	0.09 - 0.12
Glass	Nickel	0.78	0.56		
Graphite	Graphite (in vacuum)	0.5 - 0.8			
Ice	Steel	0.03			
Iron	Iron	1.0	0.15 - 0.20		
Nickel	Nickel	0.7 - 1.1	0.28	0.53	0.12
Nickel	Mild Steel			0.64	0.178
Platinum	**Platinum**	**1.2**	**0.25**		
Rubber	**Rubber**	**1.16**			
Rubber	Dry Asphalt	0.9		0.5 - 0.8	
Rubber	Dry Concrete			0.6 - 0.85	
Silver	**Silver**	**1.4**	**0.55**		
Skin	Metals	0.8 - 1.0			
Steel	Steel	0.5 - 0.8	0.16		
Tungsten Carbide	Iron	0.8			
Tire, dry	Road, dry	1			
Zinc	Cast Iron	0.85		0.21	
Zinc	Zinc	0.6	0.04		

Table 2. Comparison of changes in material combinations that result in significant changes in friction coefficient values

Material combinations		Static coefficient of friction		Dynamic coefficient of friction	
		Dry contact, Clean surfaces	Lubricated	Dry contact, Clean surfaces	Dry contact, Clean surfaces
Car tire	**Asphalt**	**0.72**			
Car tire	Grass	0.35			
Copper	**Cast Iron**	**1.05**		0.29	
Copper	Mild Steel	0.53		0.36	0.18
Graphite	**Graphite (in vacuum)**	**0.5 - 0.8**			

Graphite	Graphite	0.1	0.1		
Rubber	**Dry Asphalt**	**0.9**		**0.5 - 0.8**	
Rubber	Wet Asphalt			0.25 - 0.75	
Rubber	**Dry Concrete**			**0.6 - 0.85**	
Rubber	Wet Concrete			0.45 - 0.75	
Tire, dry	**Road, dry**	**1**			
Tire, wet	Road, wet	0.2			

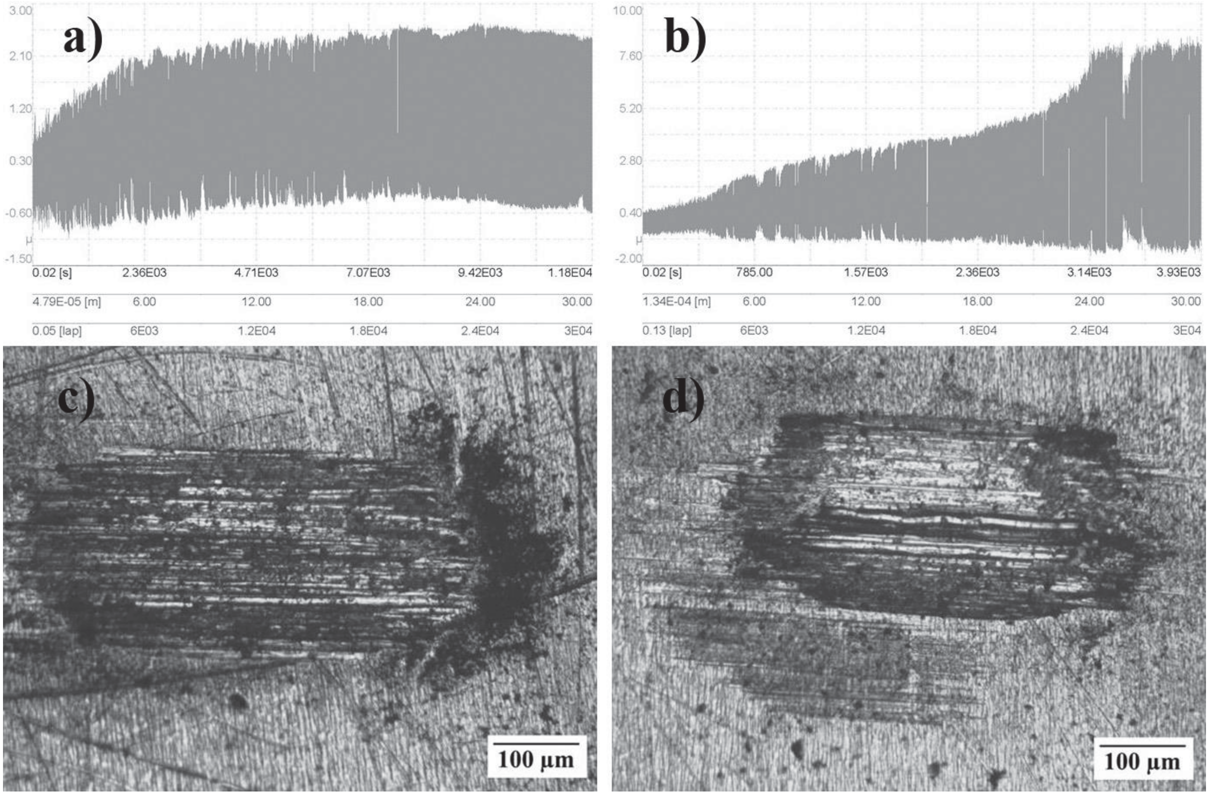

Figure 1. Sample 2: Diagrams of friction coefficient and optical micrograph showing wear track on Ti6Al4V sample: a), c) Ringer, v=4 mm/s; FN=100mN; b), d) Ringer, v=12 mm/s; b FN=100mN

The influence of the temperature is also very significant. Moving surfaces in relative contact to each other always results in frictional heating, thus the contact zone temperature is always higher than ambient temperature, even in the cases when contact is maintained without externally elevated temperatures. On the other hand, the increase of the temperature within the contact zone is strongly influenced by the material types in contact, velocities and loading, as well as the environment. So called flash temperatures and especially at micro/nano scale represents complex problem, still with many debates related to its origin and its influence on the development of motion.

Some materials are especially prone to detrimental effects of the frictional heating, inducing such high frictional coefficients thus resulting in micro galling and micro-welding. For example, some α-β microstructures of medical grade Ti alloys (e.g. Ti6Al4V) can exhibit dynamic friction coefficients significantly higher than 1, as given in Fig. 1, sample 2 selected from 4 types of Ti6Al4V in contact with alumina ball (ball-on-flat).

This particular contact resulted in detrimental abrasive and adhesive wear with very high flash temperatures that can be concluded even without measuring the temperatures, due to the black burnt wear debris widely spread all around the contact zone (Fig. 1 c, d). This is commonly recognised problem with these Ti alloys and many new approaches have been studied to overcome it in order to use these alloys in medical implants.

Table 3. Chemical Composition of Al based element widely employed in friction stir welding process

(wt. %) of 5083 – O Thin Plate [13]									
Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	V	Al
0.35	0.29	0.08	0.67	4.32	0.12	0.18	0.07	-	Bal.
(wt %) of aluminum alloy 2024 – T4 (wt %) [14]									
Si	Fe	Cu	Mn	Mg	Zn	Ti	Others		Al
0.5	0.5	3.8 – 4.9	0.3 – 0.9	1.2 – 1.8	0.3	0.15	Ni: 0.1, Fe + Ni:0.5		Bal.
(wt %) of AA1050 [15]									
Si	Fe	Cu	Mn	Mg	Zn	Ti	Cr		Al
0.08	0.27	0.02	0.01	0.01	0.02	0.02	-		Bal.
(wt %) of AA 5754 [15]									
Si	Fe	Cu	Mn	Mg	Zn	Ti	Cr		Al
0.4	0.4	0.1	0.5	2.6 -3.2	0.2	0.15	0.3		Bal.
(wt %) of 7075 – T6 [16,28]									
Si	Fe	Cu	Mn	Mg	Zn	Ti	Cr		Al
0.58	0.35	1.2	0.12	2.1	5.1	-	-		Bal.
(wt %) of AA6061 - T6 [17,29]									
Si	Fe	Cu	Mn	Mg	Zn	Ti	Cr		Al
0.4 - 0.8	0.7 (max)	0.15 – 0.4	0.15 (max)	0.8 – 1.2	0.25 (max)	0.15 (max)	0.04 – 0.35		95.85 – 98.56
Others (0.05 each – max) – total 0.15									
(wt %) of AA 7020 [18]									
Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Others	Al
-	0.35	0.10	0.24	1.30	0.14	4.70	0.08	7.65	85.44
(wt %) of A 6082 [19]									
Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Others	Al
1.0	0.15	0.02	0.7	1.15	0.15	0.02	0.1	-	Bal.
(wt %) of 6061 Al [20]									
Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Others	Al
0.6	0.7	0.2	0.15	0.9	0.1	0.25	-	-	Bal.
(wt %) of AA 2024 – T351 [21]									
Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Others	Al
0.06	0.15	1.3	0.02	2.4	0.19	5.8	0.07	-	Bal.
(wt %) of AA 5052 – [22]									
Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Others	Al
0.25	0.4	0.1	0.15-0.35	2.2 – 2.8	0.1	-	-	-	Bal.
(wt %) of 2A70 [23]									
Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Ni	Al
0.35	1.1	2.01	0.20	1.57	-	0.30	0.03	0.95	85.44
(wt %) of 2219 T87 [24]									
Si	Fe	Cu	Mn	Mg	Zr	Zn	Ti	Ni	Al
0.08	0.18	6.38	0.32	-	0.18	-	0.06	0.03	Bal.
(wt %) of AA5010 [25]									
Si	Fe	Cu	Mn	Mg	Zr	Zn	Ti	Ni	Al
0.62	0.33	0.28	0.06	0.9	-	0.02	0.02	-	Bal.
(wt %) of AA 2219 [26]									
Si	Fe	Cu	Mn	Mg	Zr	Zn	Ti	V	Al
0.49	0.23	6.48	0.32	-	0.2	0.04	0.06	0.08	92.1
(wt %) of A6111 [27]									
Si	Fe	Cu	Mn	Mg	Zr	Zn	Ti	V	Al
1.041	0.036	0.803	0.066	0.592	-	-	-	-	Bal.
(wt %) of A5023 [27]									
Si	Fe	Cu	Mn	Mg	Zr	Zn	Ti	V	Al
0.110	0.090	0.200	0.005	5.680	-	-	0.090	-	Bal.

Accordingly, Ti alloys are avoided to use in implant elements where there is any type of motion.

One of the materials that exhibit very high friction coefficients when mated to itself is aluminium (Al), hence very suitable for frictional welding applications. It is commonly used for frictional welding in different combinations of devices, technologies and working regimes [11, 13-27]. Chemical compositions of Al-based alloys used for frictional welding are given in Table 3.

General application is in sheet metal industry and light weight engineering applications, and especially in transportation industry (shipbuilding industry, rail and automotive industry). However, these technologies, as well as material properties are further studied for improvements, most often by using simulation and modeling approaches, such as stress – strain localization models, thermo-mechanical finite element (FE) modeling and analysis. Usual demands upon joints formed in such way are certain level of loading (including shear stress), usually also with reversals during the lifetime, during which it must not exhibit wear, creep or micro cracking and other forms of failure.

3. CONCLUSION

The role of the friction used in some practical applications where high friction coefficients of the materials are used, can be observed in several ways: to lock elements together during the assembly procedure; to provide very strong joining (solid state welding); or to provide better adhesion of elements also under conditions of dry contact. Several existing material combinations presented in this paper are those already commonly used but many more are yet to appear, especially if joining of two different materials are further considered.

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