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RESEARCH

Friction Coefficient of UHMWPE During Dry Reciprocating Sliding

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A B S T R A C T

This paper deals with the friction coefficient behaviour during dry reciprocating sliding of UHMWPE in contact with alumina (Al_2O_3), within a range of velocities typical for hip implants. Five values of normal force (100 - 1000 mN) and three values of sliding speed (4 - 12 mm/s) have been observed. Real time diagrams of the friction coefficient as a function of the sliding cycles were recorded for each test. Dynamic friction coefficient curves exhibited rather uniform behavior for all test conditions. Somewhat larger values of friction coefficient could be observed during the running-in period in case of low loads (100 - 250 mN) and the lowest velocity (4 mm/s). In case of high loads and speeds, friction coefficient reached steady state values shortly after the beginning of the test.

1. INTRODUCTION

Ultra-high molecular weight polyethylene (UHMWPE) is a unique polymer with outstanding physical and mechanical properties. Most notable are its chemical inertness, lubricity, impact resistance, and abrasion resistance. The first clinical application of UHMWPE biomaterials started in 1962 and continued with astonishing speed through the three decades of the clinical history (1962–1997), with a few clinically relevant innovations occurred beyond the removal of calcium stearate and changes in sterilization practice. Radiation crosslinked UHMWPE materials had been recently introduced to clinical practice around a year 2000. Today, second generation of radiation crosslinked materials are in clinical use, and vitamin E stabilized UHMWPE has emerged as a new, internationally standardized biomaterial.

At the November 2012 ASTM Meeting in Atlanta, GA, the UHMWPE working group considered revisions to four UHMWPE-related standards, including F648 (unfilled UHMWPE homopolymer), F2102 (FTIR analysis of oxidation), F2565 (Guide for Crosslinked UHMWPEs), and a new standard for small punch testing of medical polymers, including UHMWPE, based on F2183. The next ASTM meeting of the UHMWPE working group will be in May, 2013.

All existing data on UHMWPE indicate that for very elderly patients, artificial joints incorporating conventional UHMWPE will continue to be used. On the other hand, the more recently-introduced alternative bearing technologies, including crosslinked UHMWPE, should provide the greatest benefit to young patients (less than 60 years in age) who lead an active lifestyle and who need a total hip replacement. For patients in need of knee arthroplasty, shoulder arthroplasty, or total disc replacement, conventional UHMWPE continues to prevail as the polymeric bearing material of choice.

Polymers are large molecules synthesized from smaller molecules, called monomers. Plastics are polymers that are rigid solids at room temperature and generally contain additional additives. UHMWPE has been used as a bearing surface, in total joint prostheses, for more than 45 years.

Each year, about 2 million joint replacement procedures are performed around the world, and the majority of these joint replacements incorporate UHMWPE. Despite the success of these restorative procedures, orthopedic and spine implants have only a finite lifetime. Wear and damage of the UHMWPE components has historically been one of the factors limiting implant longevity. In the past 10 years, highly crosslinked UHMWPE biomaterials have shown dramatic reductions in wear in clinical use around the world. The orthopedic community awaits confirmation that these reductions in wear will be associated with improved long-term survival, as expected.

UHMWPE has been used for fabricating one of the bearing components in various arthroplasties, such as acetabular cups, acetabular cup liners, tibial inserts, etc. [1,2,19]. Total joints with components made of this material can function for more than twenty years if they are well designed and well implanted. Components made of UHMWPE have performed admirably in vivo. The only major concern is wear and the effect of the wear particles on the in vivo longevity of the prosthesis. Some applications of UHMWPE in biomedical area are shown in Fig. 1.

Polyethylene contains the chemical elements carbon and hydrogen. Polyethylene is created through polymerization of ethene (Fig. 2), forming an extremely long, chained molecule called generally polymer. At a molecular level, the carbon backbone of polyethylene can twist, rotate, and fold into ordered crystalline regions.

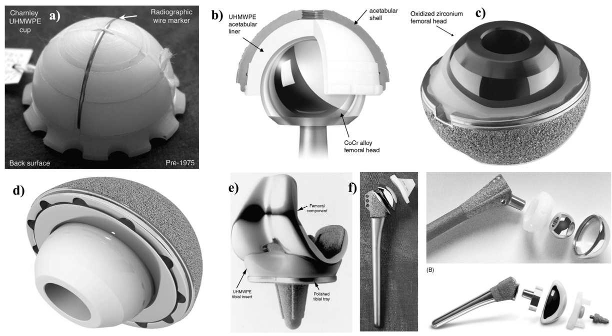


Fig. 1. Application of UHMWPE [1]: a) cup; b), c), d) liners; e) total knee components; f) shoulder prosthesis system components.

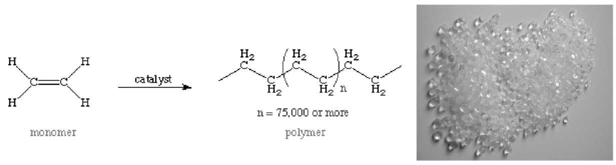


Fig. 2. Left: The repeating unit of polyethylene; Right: Granulated polyethylene.

At a supermolecular level, the UHMWPE consists of powder (also known as resin or flake) that must be consolidated at elevated temperatures and pressures to form a bulk material. Further layers of complexity are introduced by chemical changes that arise in UHMWPE due to radiation sterilization and processing.

The mechanical properties of polyethylene improve slowly with rising molecular weight of the product [20]. A dramatic change in mechanical properties, however, appears when molecular weight of the polyethylene molecule exceeds one million. This appears when more than 35000 ethylene groups are added together. Such product is called Ultra High Molecular Weight PolyEthylene. The molecular weight of the UHMWPE currently used in total joint components varies between 4 to 6 millions. Every such UHMWPE molecule is composed of 160 to 215 000 ethylene groups.

The molecular chain of UHMWPE can be visualised as a tangled string of spaghetti over a kilometer long. Because the chain is not static, but imbued with internal (thermal) energy, the molecular chain can become mobile at elevated temperatures. When cooled below the melt temperature, the molecular chain of polyethylene has the tendency to rotate about the C-C bonds and create chain folds. This chain folding, in turn, enables the molecule to form local ordered, sheetlike regions known as crystalline lamellae. These lamellae are embedded within amorphous (disordered) regions and may communicate with surrounding lamellae by tie molecules. The lamellae are on the order of 10–50 nm in thickness and 10–50 μm in length. UHMWPE has a white, opaque appearance at room temperature. At temperatures above the melt temperature of the lamellae, around 137 °C, it becomes translucent. UHMWPE exhibits the composite nature due to interconnected network of amorphous and crystalline regions.

Generally speaking, many polymers undergo three major thermal transitions: the glass transition temperature (Tg), the melt temperature (Tm), and the flow temperature (Tf). The glass transition (Tg) is the temperature below which the polymer chains behave like a brittle glass. Below Tg, the polymer chains have insufficient thermal energy to slide past one another, and the only way for the material to respond to mechanical stress is by stretching (or rupture) of the bonds constituting the molecular chain. In UHMWPE, the glass transition occurs around 120 °C.

UHMWPE shows two key features, the first one is the peak melting temperature (Tm), which occurs around 137 °C and corresponds to the point at which the majority of the crystalline regions have melted. The melt temperature reflects the thickness of the crystals as well as their perfection. Thicker and more perfect polyethylene crystals will tend to melt at a higher temperature than smaller crystals.

As the temperature of a semicrystalline polymer is raised above the melt temperature, it may undergo a flow transition and become liquid. Polyethylenes with a molecular weight of less than 500,000 g/mol can be observed to undergo such a flow transition (Tf). However, when the molecular weight of polyethylene increases above 500,000 g/mol, the entanglement of the immense polymer chains prevents it from flowing. UHMWPE does not exhibit a flow transition for this reason.

UHMWPE is a linear, low-pressure, polyethylene resin. It has both the highest abrasion resistance and highest impact strength of any plastic. Combined with abrasion resistance and toughness, the low coefficient of friction of UHMWPE yields a self-lubricating, non-stick surface. Static and dynamic coefficients are significantly lower than steel and most plastic materials. Elastic modulus of UHMWPE is approximately 0.69 GPa. ASTM F648-00 defines standard specification for Ultra-High-Molecular-Weight Polyethylene powder and fabricated form for surgical implants. To date it has proven to be the best polymer material for use in total joints.

Along with the extensive application of UHMWPE, the understanding of polymer tribology is becoming increasingly important. Many authors have investigated different aspects of tribological performance of UHMPWE [2-7]. The structural factors associated with surface mechanical properties (crosslinking, oxidation state, local orientation of polymer, crystallinity, etc.) can be highly variable and localized and may vary on micron spatial scales or smaller [8]. The relationship between UHMWPE mechanical properties and the in-vivo performance of a fabricated form has not been determined. While trends are apparent, specific property-polymer structure relationships are not well understood. The mechanical properties are subject to variation as the fabrication process variables (such as temperature, pressure, and time) are changed. [ASTM F-648 (2000)].

Reciprocating sliding at different test devices and from different aspects has been a subject of investigations [9-11]. Different approaches for improvement of existing UHMWPE materials have been tried. [10] investigated effects of nitrogen ion irradiation on tribological properties. [9] investigated friction and wear behavior of ultra-high molecular weight polyethylene as a function of polymer crystallinity. [2,7-8,13-15] investigated crosslinking and material behaviour with different approaches to crosslinking.

This paper deals with friction coefficient behaviour during dry reciprocating sliding of UHMWPE in contact with alumina (Al_2O_3), within a range of velocities typical for hip implants. Five values of normal force and three values of sliding speed have been observed.

2. MATERIALS AND TRIBOLOGICAL TEST

Polished rectangular flat UHMWPE samples were used for tests, supplied by the company Narcissus Ada, Serbia. Sliding tests were done at ball-on-flat configuration of CSM Nanotribometer in dry conditions. Alumina was used as a ball material (diameter, 1.5 mm), since it is extremely hard and chemically inert. Alumina is frequently used in combination with UHMWPE in artificial hip joints. Duration of each test was 3000 cycles (1 cycle, 1.6 mm), which is enough to reach stabile steady state of friction coefficient. During the test, the dynamic friction coefficients were recorded in real time, using the built-in TriboX 2.9.0 software. Five values of normal force (100 - 1000 mN) and three values of sliding speed (4 - 12 mm/s) have been tested. Maximum elastic contact stress (according to applied normal loads) were calculated by Hertz method and compared to test conditions. Characteristics of conducted tribological tests are given in Table 1.

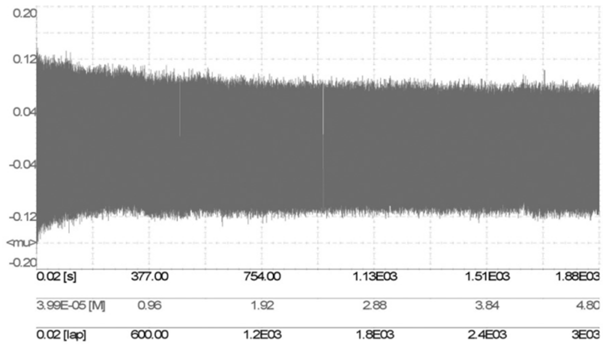
Table 1. Tribological parameters.

Normal load values, F_n	100 mN, 250 mN, 500 mN, 750 mN, 1000 mN
Maximum elastic contact stress (according to applied normal loads)	28.5 MPa, 38.6 MPa, 48.7 MPa, 55.7 MPa, 61.3 MPa
Maximum linear speed values, v	4 mm/s; 8 mm/s; 12 mm/s

3. RESULTS AND DISCUSSION

Real time diagrams of the friction coefficient as a function of the sliding cycles (sliding distance) were recorded for each test. Friction coefficient curve is of sinusoid shape, whereat the opposite directions are marked with + and - sign, denoting coefficient of friction in two different directions of sample moving. Good agreement with reported values of friction coefficient was obtained [6,16-18].

Dynamic friction coefficient curves exhibited rather uniform behavior for all test conditions (Fig. 3). Somewhat larger values of friction coefficient could be observed during the running-in period in case of low loads (100-250 mN) and the lowest velocity (4 mm/s), as shown in Fig. 3a. In case of high loads and speeds, friction coefficient reached steady state values shortly after the beginning of the test. Maximum contact pressures in these tests were approximately from 30 - 60 MPa, representing high contact stresses exhibited in hip/knee implants. Especially extreme loading conditions are present in the knee implant system. Similar behaviour (short running-in phase for the friction coefficient) was also reported by other authors [18].



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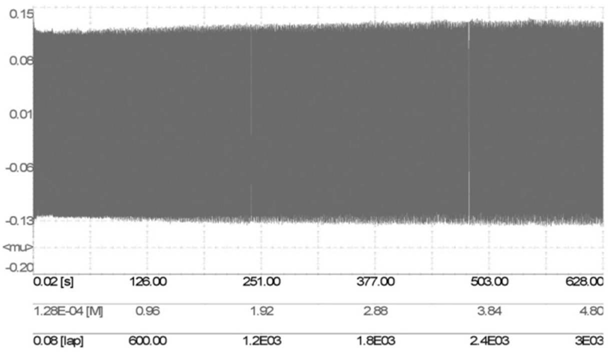
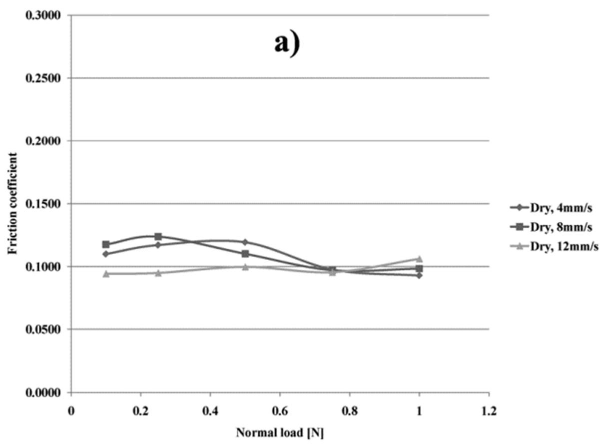


b

Fig. 3. Dynamic friction coefficient curve during dry sliding: a) v=4 mm/s, F_N=100 mN; b) v=12 mm/s, F_N=1000 mN.



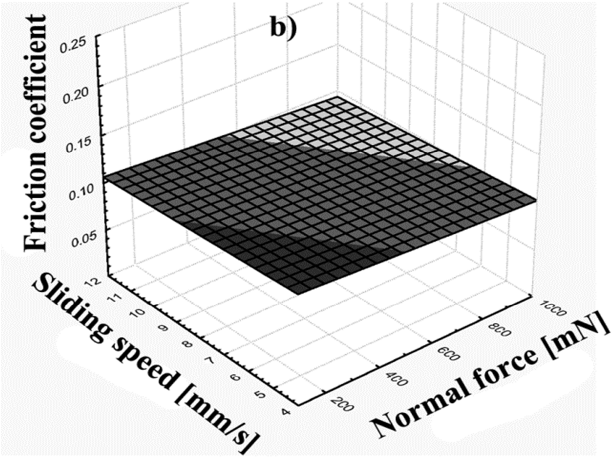


Fig. 4. a) Friction coefficient as a function of the normal load; b) Friction coefficient as a function of the normal load and sliding speed.

An average value of the dynamic coefficient of friction (denoted by 'friction coefficient' further in the text) was calculated, for all test conditions, for a steady state period of friction, as the root mean square function using the raw data obtained by the nanotribometer. Comparative diagrams of variation of the average values of the dynamic friction coefficient, with load and sliding speed, are given in Fig. 4. It can be seen from presented diagrams that the sliding speed exhibited no significant influence on the friction coefficient. Load increase produced very slight decrease of the friction coefficient, for all tested conditions.

4. CONCLUSION

This research showed that UHMWPE exhibits low dynamic friction coefficient (average value around 0.1 for all tests) under dry conditions, in contact with alumina. It also showed that low loads leaded to a bit longer running-in time, but for all tests steady friction state was achieved and maintained throughout the test with very short running-in periods. Sliding speed change showed no influence on the dynamic friction coefficient.

Acknowledgments

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