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Analysis of Ultra-High Molecular Weight Polyethylene Reinforced with Zeolite Composite for Human Implant

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Abstract

Ultra-high molecular weight polyethylene reinforced with different loadings of zeolite particles were prepared using hot compression molding. The effects of zeolite particles on the mechanical and tribological properties of the ultra-high molecular weight polyethylene composites were studied. the tribological properties were investigated using a ducom tr-20 pin-on-disc tester under different sliding speeds of 0.209 m/s, 0.419 m/s and 0.838 m/s with various applied loads of 10, 20, and 30 n. the worn surfaces and transfer films of the zeolite ultra-high molecular weight polyethylene composites were observed under the scanning electron microscope. The results showed that the addition of zeolite into ultra-high molecular weight polyethylene matrix has reduced the tensile strength and elongation at break, but increased the modulus. The 10 wt. % zeolite ultra-high molecular weight polyethylene composites showed an increase of ~25% in impact strength as compared to pure ultra-high molecular weight polyethylene. The 20 wt. % zeolite ultra-high molecular weight polyethylene composite exhibited lowest wear volume loss as compared to 10 wt. % zeolite/ultra-high molecular weight polyethylene and pure ultra-high molecular weight polyethylene. In addition, the average coefficient of friction was also found to decrease with the addition of zeolite. The lowest average coefficient of friction was also obtained with the 20 wt. % zeolite/ultra-high molecular weight polyethylene composite. The wear volume loss was found to increase with increasing applied loads for all samples. Meanwhile, the average coefficient of friction values have decreased with increasing applied loads. Furthermore, shallower wear grooves and smoother worn surfaces were observed for zeolite/ultra-high molecular weight polyethylene composites as compared to pure ultra-high molecular weight polyethylene. In terms of the transfer film observation, the counter face of pure ultra-high molecular weight polyethylene was partially covered, rough, and discontinuous. On the other hand, counter faces of zeolite/ultra-high molecular weight polyethylene composites were fully covered, smooth, and continuous. Overall, the tribological properties showed significant improvement with the reinforcement of zeolite in ultra-high molecular weight polyethylene.

I. Introduction

Bone fracture and bone tissue injury are big medical problems. An estimated 20 million bone fractures occur annually in the India. Bone defect caused by injury, infection, tumor and congenital diseases is one of the most common diseases in clinical orthopaedics; sometimes injury is so severe that bone grafting has to be performed for further prevention. Preparation of ideal bone substitutes with good biocompatibility and biodegradability to repair bone defects has become the prime focus. So far artificial materials used in hard tissue repair and reconstruction most notably are metals and their alloys, then the ceramic materials and their composite materials. The elastic modulus of human bone is between 4.6 to 20GPa[2]. According to the structure, bone is divided into cortical bone and cancellous bone. Mechanical properties of cortical bone are: elastic modulus of 16—20GPa, and ultimate strength of 30—211MPa. Mechanical properties of cancellous bone are: elastic modulus of 4.6—15GPa, and ultimate strength of 51—193MPa. The density of cortical bone is about 1 990 kg/m3 and cancellous bone is lower than it but more elastic. Ceramic is preferred over metal because the elastic modulus of ceramic is more close to the natural bone and scientists are focusing to improve its brittleness for clinical use. Therefore, development of materials of proper mechanical properties without affecting biological compatibility has become a significant subject. One of the applications include internal fixation of fractures by bone plates, nails or intermedullary rods. Many of the composites are made of only two components. The biggest advantage of composites is that they are strong as well as light. The two individual components are mixed in which one is the binder and other is the matrix. It binds and surrounds together the fiber and fragments of different materials known as reinforcements. A new material can be made to fulfill the application needed.

II. Material Preparation

Ultra-high molecular weight polyethylene is an engineering thermoplastic that is widely employed in advanced engineering application due to its outstanding properties such as high impact resistance, self-lubricating, chemical inertness and the highest wear resistance as compared to other thermoplastics. Its wide range of applications includes artificial joint replacement component, lining for dump trucks, bumpers and siding for ships, sewage and gas pipes and etc. for decades, the increasing demand of artificial joint implant from the global market has made ultra-high molecular weight polyethylene to become one of the major research interests among researchers and industries. It is an established material for many years to be applied as artificial joint replacement components; prosthetic joints that are able to replace degraded human joints caused by severe arthritis or injuries. Despite its exceptional properties, the long term wear problem occurs after certain service period still remained as the challenge. The production of wear debris will cause adverse effects to human body system which subsequently leads to osteolysis and aseptic loosening of the implant.

Figure 1: Ultra-high molecular weight polyethylene

Therefore, the modifications of UHWMPE to enhance its mechanical and tribological properties are currently a trending research topic. The regularly applied approach is the incorporation of reinforcement filler into the ultra-high molecular weight polyethylene matrix. In literature, many studies used various reinforcements incorporated into ultra-high molecular weight polyethylene matrix in order to enhance its wear performance. This includes the addition of kaolin, carbon fiber, carbon nanotube, zirconium particles, hydroxyapatite, alumina, zno and others. The incorporation of particulate or fiber reinforcement into polymer would improve its mechanical properties and hence, alter the wear mechanism. High strength filler reinforcement may increase the surface micro-hardness and leads to improvement in abrasion resistance of the ultra-high molecular weight polyethylene. In recent years, inorganic mineral has attracted significant research interest as polymer filler due to their excellent mechanical properties, ability to induce electrical, low cost and their role as anti-blocking agent and nucleating agent in polymer. Zeolite is an inorganic material based on tetrahedral alo4 and sio4aluminosilicate with micro-porous structure. Reinforced of zeolite into polymer composite has been found to be a capable method in improving the mechanical properties and crystallinity behaviour of polymer. Zeolite-filled epoxy composites resulted significant improvements on the mechanical properties.

Figure 2: Zeolite

Zeolite is a ceramic-based material consists of silica and alumina elements. Therefore, it has the potential as ultra-high molecular weight polyethylene reinforcement for wear resistance enhancement. Investigated the wear resistance coating of zeolite as compared to commercial chrome and cadmium coatings, the results Although several materials, absorbable or non-absorbable, and biologic or synthetic, have been used to repair CDH, the ideal material has yet to be established. Historically, expanded poly tetrafluoroethylene has been the product of choice for a non-absorbable diaphragmatic implant by paediatric surgeons. However, this product does not incorporate into surrounding tissues compared to other materials, theoretically increasing a patients' risk for recurrence. Polyester/collagen composite meshes have been used for decades in adults undergoing complex groin, incisional, and ventral hernia repairs with excellent results. Here we present two cases of CDH recurrence successfully treated with parietex™ composite mesh. Ultra-High Molecular Weight Polyethylene in powdered form with an average molecular weight of 5 x 106 g/mol and density of 0.93 g/cm^3 was taken for analysis. Commercial zeolite powder of less than 45 μm in particle size was used for composite making. The composites were produced by compression molding machine with the pressure of 1000 psi. Different filler loadings of zeolite were mixed homogeneously with ultra-high molecular weight polyethylene using a dry mechanical ball mill. The mixing process took 4 h to complete with the rotation speed of 30 Hz. After mixing, the compound was pre-heated at a temperature of 160°C for 10 min and hot pressed for 7 min. The composite sheet was obtained after cool pressing at 15ºC for 5 min.

III. Properties of composites

Tensile properties were evaluated using a universal testing machine according to ASTM D638 standard with a crosshead speed of 20 mm/min on dumbbell-shaped samples of gauge length of 50 mm and sample thickness of 1 mm. Five specimens were tested for each sample; the average reading and standard deviations were later calculated. Tensile strength, Young's modulus and elongation at break were determined from the stress-strain curve. The impact energy absorbed were measured using Charpy standard pendulum impact tester according to ASTM D6110-04. The test was carried out on 2 mm depth single edge Vshape notched samples with 50.0J pendulum energy. The impact strength was calculated by dividing the impact energy absorbed with the cross-section area of the sample. All the data were calculated from the average of five specimens. The wear and frictional properties of the zeolite /ultra-high molecular weight polyethylene composites were performed using Ducom TR-20 pin-on-disc tester under dry sliding conditions. The test samples were cut into dimensions of 9 x 9 x 30 mm. The weight loss was then changed to volume loss by dividing it with the specific composites density. The worn surfaces and transfer films of the composites were observed under the Hitachi TM-3000 Table top Scanning Electron Microscope. All the surfaces of the test samples were coated with gold/palladium (Au-Pd) layer by using a vacuum sputter chamber before scanning.

IV. Results and discussion

The tensile strength of ultra-high molecular weight polyethylene composites decreases with the increase of zeolite loadings. This indicates the poor interaction between zeolite and ultra-high molecular weight polyethylene matrix. The modulus of the ultra-high molecular weight polyethylene composites increases with the increasing zeolite loadings. This may be due to the incorporation of the rigid particle filler into the polymer matrix. The elongation at break showed decrease with the increasing of zeolite loadings. This may be due to the interruption of the polymer chain mobility of the ultra-high molecular weight polyethylene matrix by the zeolite filler in the composite system which leads to the decrease in the plastic deformation. Upon the reinforcement of zeolite, the increased in impact strength was observed for 10 wt. % zeolite/ultra-high molecular weight polyethylene composites. The impact strength was found to increase to 144.46 kj/m^2 for the ultra-high molecular weight polyethylene composites containing 10 wt. % zeolite as compared to 115.70 kj/m2 for pure ultra-high molecular weight polyethylene. It shows ~25% increment as compared to pure ultra-high molecular weight polyethylene. However, the impact strength shows a reduction for 20 wt. % zeolite/ ultra-high molecular weight polyethylene composite. This suggests that adding the optimum amount of zeolite loadings could improve the impact resistance of ultra-high molecular weight polyethylene. High loadings of zeolite would tend to cause agglomeration and act as stress concentration in the composites system. As a result, low impact strength was observed for 20 wt. % zeolite/ultra-high molecular weight polyethylene composite. The volume loss shows significant reduction after the reinforcement of zeolite into ultra-high molecular weight polyethylene for the three sliding speeds. 20 wt. % zeolite loading shows the lowest volume loss as compared to pure ultra-high molecular weight polyethylene and 10 wt. % zeolite/ultra-high molecular weight polyethylene composite. During the sliding wear test, the samples were subjected to micro-cutting and micro-ploughing of the counterface asperities. This will subsequently cause the removal of surface materials from the main body of the sample. The reduction of the volume loss for zeolite/ultra-high molecular weight polyethylene composites indicates that zeolite has the ability in increasing the load-carrying capacity and prevents the removal of the contacting surface materials. The presence of zeolite in the composite would protect the soft polymer matrix from easy removal from the bulk body and reduce the stress exerted by the counter face. Therefore, the wear resistance of the ultra-high molecular weight polyethylene composites was increased. It can be seen that the volume loss increased with the increase of applied loads. This may be due to the increase of the penetration depth between the counter face asperities and sample contacting surfaces. The increase of penetration depth will increase the real contact area and leads to increase in volume loss of the samples. Therefore, the volume loss increased with the increasing applied loads. In general, it can be seen that the average coefficient of friction was reduced after the reinforcement of the zeolite particles. The 20 wt. % zeolite/ultra-high molecular weight polyethylene composites exhibited lowest average coefficient of friction as compared to pure ultra-high molecular weight polyethylene and 10 wt. % zeolite/ultra-high molecular weight polyethylene composites. The average coefficient of friction was found to be reduced with the increasing applied loads. The wear grooves and furrow marks caused by the micro-cutting and micro-ploughing of the counter face asperities were observed for all the samples. For ultra-high molecular weight polyethylene, deep wear grooves and rough surfaces were observed. The severity of wear grooves on the worn surface of ultra-high molecular weight polyethylene was reduced with the reinforcement of zeolite. Shallower wear grooves and smoother surfaces were observed for both 10 wt. % zeolite/ultra-high molecular weight polyethylene and 20 wt. % zeolite/ultra-high molecular weight polyethylene as compared to pure ultra-high molecular weight polyethylene. this shows that the reinforcement of zeolite particles into ultra-high molecular weight polyethylene increase the micro-cutting and micro-ploughing resistance. The increase in load carrying-capacity of the zeolite/ultra-high molecular weight polyethylene composites also contributed to the reduction of the severity from rough worn surface to mild worn surface. The tribological properties of the polymer composites depend greatly on the formation of the transfer films. A good transfer film would effectively cushion the counter face asperities from being direct contact with the sample surfaces as well as reduce the friction coefficient and wear volume loss of the materials.

V. Conclusion

The tensile strength and elongation at break of ultra-high molecular weight polyethylene have decreased, while the modulus increased with the addition of zeolite loadings. the impact strength increased by ~25% for 10 wt.% zeolite-reinforced ultra-high molecular weight polyethylene as compared to pure ultra-high molecular weight polyethylene. the 20 wt.% zeolite /ultra-high molecular weight polyethylene composite showed lowest wear volume loss and lowest average coefficient of friction as compared to 10 wt.% zeolite /ultra-high molecular weight polyethylene and pure ultra-high molecular weight polyethylene. The worn surface showed reduced wear severity upon reinforcement of zeolite. Pure ultra-high molecular weight polyethylene exhibited rough, discontinuous and was partially covered on the counter face. On the other hand, the counter face of zeolite /ultra-high molecular weight polyethylene composites was fully covered, smooth, and continuous. From the results obtained, zeolite-reinforced ultra-high molecular weight polyethylene composites are capable to be implemented in joint implant applications of which wear and friction issues can be reduced. Overall, the reinforcement of zeolite particles into ultra-high molecular weight polyethylene matrix significantly improved the tribological properties of ultra-high molecular weight polyethylene.

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