SURFACE MICROMECHANICS OF ULTRA HIGH MOLECULAR WEIGHT POLYETHYLENE: MICROINDENTATION TESTING, CROSS LINKING, AND MATERIAL BEHAVIOR.

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Introduction

The wear behavior of ultrahigh molecular weight polyethylene (UHMWPE) is critical to the success of total joint replacements. Recent attempts to modify the wear behavior of UHMWPE by processing, in particular, cross linking UHMWPE have shown promise to increase wear resistance, but concerns continue to persist regarding other mechanical properties. It is also unclear what specific surface mechanical properties govern the wear resistance seen in these materials. The goal of this study is to demonstrate a custom-built surface mechanical test system and method that measures the micromechanical response of micromached UHMWPE surfaces to depth-sensing microindentation tests, as well as to assess the effect of depth of testing and material differences on the micromechanical responses.

Materials and Methods

A custom designed microindentation test system assessed the micromechanical behavior of three UHMWPE resins: 1. Hylamer™, 2. GUR-1020 CMS and 3. Marathon™ – a cross linked material. This instrument consists of three-axis movement stages driven by DC stage motorizers. Position in each axis is monitored by LVDTs with better than 1 µm precision. A piezoelectric actuator provides the indentation component. The motorizers, LVDTs and piezo actuator are computer-interfaced for complete control over the system. Mounted on the piezo-actuator is a combination position and load cell. This combination allows for direct measurement of the load and displacement, and compensates for the load-cell compliance for precise determination of indentation depth. All loads and displacements were calibrated prior to testing. The resolution for the system is approximately 0.2 µm for displacement and about 4.5 mN for load.

The effects of material and indentation depth were studied. Rectangular samples, approximately 3 x 3 x 5 mm were prepared by micromaching the test surface (3 mm x 5 mm surface) with a glass knife. The indentation tip consisted of a 38µm radius Al₂O₃ hemispherical tip attached to the load-displacement cell. All testing was performed using a triangular displacement waveform at 1 Hz. One hundred points per loading cycle were collected. The computer program controlling the system is capable of repeating indentations in an array of surface locations that are at fixed rectangular intervals and can, in fact, generate a surface map of mechanical property variations. Four indentations per sample and indentation depth were performed. Nine different indentation depths ranging from about 5 µm to 45 µm (piezo-actuator motion from 10 to 90 µm) were investigated for each sample. Actual sample-indentation depth, (h), was found by measuring the total motion and subtracting out the load-cell displacement. All testing was performed in air at room temperature (22 °C).

The load-deflection curve, once obtained, was subsequently analyzed using a second custom written program that takes the data and performs several calculations. From the raw load-deflection data, six different measurements were made. These are: 1. Loading slope, 2. unloading slope, 3. maximum force, 4. maximum indentation, 5. permanent indentation, 6. hysteresis energy per cycle. From these measurements subsequent surface mechanical parameters were calculated. These are: 1. surface modulus, 2. microhardness, and 3. the energy dissipation factor (hysteresis energy divided by the square of the maximum indentation depth).

The surface structural characterization was performed through a range of magnifications using a scanning electron microscope (Jeol 5600, Boston MA), and using an AFM (Digital Instruments, Nanoscope III) in the contact mode using deflection imaging. This imaging mode brings out the edge-enhanced features and is based on the error signal. Images in this mode appear to be “side lighted”.

Results

Typical load-deflection curves for the three materials are shown in figure 1. Statistically significant, as well as visible differences in each of these parameters were found for each material. Generally, Hylamer had the largest values for these parameters, followed by the GUR resin and then the Marathon. Surface modulus was independent of depth of testing and found to be 651 MPa for Marathon, 738 Mpa for GUR and 1015 MPa for Hylamer. The microhardness varied between 67 and 162 MPa depending on material and depth of testing. The materials property results are shown in table 1. Surface structural characterization shows that the micromachining process for surface preparation generated distinct surface features that varied between materials. Intermittent drawn ribbons of polymer with oriented crystals were observed in both SEM and AFM. The surface density and size of these features were characteristic of the materials with the Hylamer having the finest, but largest ribbons, followed by GUR and the Marathon.

Discussion

This study has demonstrated a microindentation instrument and method that can sensitively assess the variations in surface mechanical properties of polymeric materials in general and ultrahigh molecular weight polyethylene in particular. This system has the capability to vary the loading range, evaluate immersed samples and to develop images based on mechanical property variations on the micron scale.

Several important surface mechanical properties were assessed and the effect of indentation depth evaluated. Surface modulus, microhardness, loading slope and the energy dissipation factor were seen to be sensitive to material differences. The higher modulus of Hylamer followed by GUR and then Marathon is a similar ranking to that found in macroscopic tensile tests and are of similar magnitude. All of the surface mechanical properties described above with the exception of the microhardness were roughly independent of the indentation depth. This is useful in terms of the ability to track variations over a surface in these properties. Microhardness, however, was sensitive to indentation depth, with smaller indents yielding lower hardnesses.

The energy dissipation factor (EDF) has not been previously reported as a surface material property of interest in microindentation/nanoindentation tests. This study has demonstrated a microindentation instrument and method that can sensitively assess the variations in surface mechanical properties of polymeric materials in general and ultrahigh molecular weight polyethylene in particular. This system has the capability to vary the loading range, evaluate immersed samples and to develop images based on mechanical property variations on the micron scale.

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