A comparison between mechanical properties of UHMWPE from ram extrusion process and UHMWPE from compression molding process for a hip joint liner

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Abstract. The compression molding (CM) forms the liner from UHMWPE powder into solid form whereas the machining process forms the liner from a bar of UHMWPE made from ram extrusion (RE) process. Our research goal is to determine and compare the mechanical properties of UHMWPE resulting from compression molding process and ram extrusion. The compression molding is experimentally proceed in UNDIP laboratory whereas the UHMWPE from ram extrusion (RE) process is imported from an European country. The mechanical properties test consists of tensile test and hardness test. The final test results of the tensile strength: CM and RE have yield strength value of 23.66 MPa and 25.25 MPa, respectively. Ultimate tensile strength of CM and RE are 35.36 MPa and 29.70 MPa, respectively. The elongation of CM is 214.75% whereas RE is 120.45%. The material hardness is 15.1 V HN for CM and 8.9 VHN for RE. The results in this study show that the CM specimens have better ultimate tensile strength, elongation, and hardness than RE specimens.

1. Introduction

Ultra-high molecular weight polyethylene (UHMWPE) has been extensively used as a successful load bearing material in orthopedic applications due in part to its superior properties of biocompatibility, good wear resistance, chemical stability, and lubricity which fit the biological and mechanical requirements [1]. Despite the recognized success and worldwide acceptance of total joint arthroplasty, wear is a major obstacle limiting the longevity of implanted UHMWPE components. Increased attention has been devoted to the understanding of factors influencing the mechanical behavior of UHMWPE. As with any semicrystalline polymer, the mechanical properties of UHMWPE are inextricably linked to its chemical structure, molecular weight, crystalline organization, and thermal history. All of these factors, in turn, affect the morphological, chemical, and mechanical processes which may influence [2]. To meet the technical requirements of UHMWPE before being used as an acetabular liner in the artificial hip joint component, the UHMWPE processing technique becomes an important matter to be considered and studied. UHMWPE manufacturing methods commonly used today are compression molding and ram extrusion. Many researchers have conducted studies on the development of compression molding
and ram extrusion in order to continuously improve the mechanical and tribological properties of UHMWPE.

In compression molding process, high melting temperature of consolidated UHMWPE was effective in improving its toughness by using properly selected melting temperatures and durations. The chain scissioning and improved chain entanglements through granule boundaries were two major causes for the improvement of the mechanical properties. The improved plasticity and ductility by high temperature melting did not significantly compromise the wear rates [3]. To improve wear resistance, many researchers have conducted the crosslinking method against UHMWPE, but cross-linking also restricts relative chain movement in the amorphous regions and hence decreases toughness [4-7].

In parallel, equal channel angular extrusion (ECAE) method produces a highly entangled material with better mechanical properties than radiation cross-linked material. Entanglement density in ECAE processed UHMWPE was significantly greater than in control materials, although there was no significant relationship found between entanglement density and processing conditions. Still, mechanical properties in ECAE processed materials were found to vary with processing conditions, suggesting underlying material structure changes [8].

To meet the high demand for enhanced tribological and mechanical properties of ultra-high molecular weight polyethylene (UHMWPE), the incorporation of nano-reinforcements has generally been applied. UHMWPE nanocomposites reinforced with graphite nanoplatelets (GNPs). The modification of GNP surfaces with organosilane was found to effectively disperse the GNP in the polymer matrix and to improve interfacial interactions between phases. As a result, simultaneous improvements in wear resistance and storage modulus have been realized for the UHMWPE nanocomposites with silanized GNPs, up to 980% and 170%, respectively [9].

Some of the aforementioned studies are the development of compression molding and ram extrusion methods. Both of these methods continue to grow due to the demands of UHMWPE production requirements with good mechanical and tribological properties. However, there is no recent study that discusses compression molding and ram extrusion comparisons in terms of the mechanical properties of the products produced. In this study, both methods are re-analyzed. The latest side of the study is no longer using conventional compression molding methods, but has used direct compression molding (DCM) methods for the manufacture of test specimens. The advantage of this DCM method is that it can directly convert UHMWPE powder into acetabular liner product. This cannot be done by the method of ram extrusion.

2. Experimental method

2.1. Compression molding
Historically, the UHMWPE powder has been converted by compression molding since the 1950s because the industries in the area around Ruhrchemie already had experience with this processing technique. At first, the semifinished material was distributed under the trade name RCH-1000/ Hostalen GUR 412. During the 1970s, the compression molded UHMWPE was manufactured and distributed by Ruhrchemie/Hoechst and later distributed by the company Europlast specifically for orthopedic applications under the trade name CHIRULEN, which denoted that the material was produced in Germany by a dedicated press using established processing parameters. Thus, references in the orthopedic literature to RCH-1000 and CHIRULEN apply to compression molded UHMWPE, which was similar to contemporary GUR 1020. Note, however, that GUR 412 would have contained calcium stearate, whereas GUR 1020 does not [1].

An example of a compression molding press, currently installed at MediTECH in Vreden, Germany, is shown in Figure 1. This particular press, originally designed by Hoechst in the 1970s for production of CHIRULEN, molds two 1 m by 2 m sheets in a single press cycle. One UHMWPE sheet is pressed between the upper and middle platens, and the second is produced between the middle and lower platen. The platens are oil heated and hydraulically actuated from below. The heating and load- ing systems are
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Figure 1. Compression molding press (along with the author, for scale) for production of 1 m by 2 m sheets of UHMWPE [1].

all computer controlled. Finally, the entire press is contained in a clean room to reduce the introduction of extraneous matter into the sheet. Due to the relatively low thermal conductivity of UHMWPE, the duration of the molding cycle will depend upon the particular geometry of the press and the size of the sheet to be produced, but the processing time can last up to 24 h. The long molding times are necessary to maintain the slow, uniform heating and cooling rates throughout the entire sheet during the molding process [1].

2.2. Ram extrusion
In contrast with compression molding, which originated in Germany in the 1950s, ram extrusion of UHMWPE was developed by converters in the United States during the 1970s. Historically, a wide range of UHMWPE resins have been extruded over the past three decades. From the early 1970s to early 1980s, ram-extruded Hi-Fax 1900 resin from Hercules Powder Company (Wilmington, Delaware, USA) was commonly supplied to bulk form converters. In the early 1960s Hoechst’s GUR 412 resin was made available to converters. Although GUR 412 tended to have a lower extraneous particle count than 1900, it was also more difficult to process using ram extrusion due to its lower average molecular weight and lower melt viscosity. In the mid 1980s, converters began ram extruding using the higher average molecular weight Hoechst GUR 415 resin, which also had a lower extraneous particle count relative to 1900 and was easier to extrude than GUR 412.

Figure 2. Schematic of a ram extruder [1].
During the 1980s and early 1990s, extruded rods of GUR 412, 415, and (more rarely) 1900 CM (a calcium stearate containing grade of 1900 resin) were all used in orthopedics. Thus, it is difficult to generalize about the resin types used in implants without tracing the lot numbers used by a particular manufacturer. The generic schematic of a ram extruder is illustrated in Figure 2. UHMWPE powder is fed continuously into an extruder. The extruder itself consists essentially of a hopper that allows powder to enter a heated receiving chamber, a horizontal reciprocating ram, a heated die, and an outlet. Within the extruder, the UHMWPE is maintained under pressure by the ram, as well as by the back pressure of the molten UHMWPE. The back pressure is caused by frictional forces of the molten resin against the heated die wall surface as it is forced horizontally through the outlet. Beyond the outlet, the rod of UHMWPE is slowly cooled in a series of electric heating mantles [1].

A wide range of rod diameters is achievable (up to 12 inches in diameter) using extrusion, but the rate of production depends on the rod size due to the increased cooling times needed with the larger rod diameters. Rod sizes ranging from 20 to 80 mm in diameter are most often used in orthopedic applications. Typical production rates are on the order of mm/minute [1].

2.3. Materials
For UHMWPE material from Ram Extrusion (RE) result, obtained by buying from Europe and already in the form of solid cylinder. Images of UHMWPE from Ram Extrusion process can be seen in Figure 3.

![Figure 3. UHMWPE from ram extrusion process.](image)

For UHMWPE material of Compression Molding (CM) result, obtained by compression molding process of UHMWPE powder using compression molding machine at Laboratory for Engineering Design and Tribology, Diponegoro University. The physical form of the compression molding machine facilities contained in the Laboratory for Engineering Design and Tribology, Diponegoro University can be seen in Figure 4.

![Figure 4. Compression molding machine at Laboratory for Engineering Design and Tribology, Diponegoro University.](image)

2.4. Method

2.4.1. Tensile test preparation. For UHMWPE material from Ram Extrusion (RE) result, a tensile test specimen is made using a machining process with a specimen dimension in accordance with JIS K-7113 standard. The number of test specimens used was 2 specimens. Tensile test specimens for RE product can be seen in Figure 5.
Figure 5. Tensile test specimen for RE product.

For UHMWPE material from Compression Molding (CM) result, tensile specimens were made using compression molding process with dimension according to ASTM D-638 Type IV standard. The compression molding process takes place at a certain pressure. Figure 6 shows the compression molding process. This process is to convert UHMWPE powder form to UHMWPE solid form. The orange color line in Figure 6 represents the compressive force variation (kgf) given during the compression molding process. While the blue color line represents the amount of temperature (°C) used in the compression molding process. In this cycle, there are two special treatments in the melting phase and in the recrystallization phase. This treatment is done by holding the compressive force and temperature at specified temperature as determined in Figure 6. The compression molding machine made by Laboratory for Engineering Design and Tribology, Diponegoro University has been equipped with special software that allows the machine to operate automatically and which one could easily monitor.

Figure 6. The parameter of compression molding process.

Figure 7. Tensile test specimen for CM product.

The results of the compression molding process in Figure 6 will produce UHMWPE in the form shown in Figure 7. This UHMWPE product will be used as a tensile test specimen with dimensions in accordance with ASTM D-638 Type IV standard. The number of specimens used for the tensile test process is the number of two test specimens.

Although using different test specimen standards between JIS-7113 on RE specimens and ASTM D-638 Type IV on CM specimens. However, the tensile test results can still be scientifically justified because JIS 7113 and ASTM D-638 Type IV standards have the same function as standard tensile testing.
for plastic materials, which in this case are UHMWPE materials. Differences in the use of test standards are intended to enrich the reference of researchers to not only fix on one standard test alone.

2.4.2. Micro hardness test preparation. This hardness testing process aims to determine the UHMWPE material hardness character. In this test, micro-hardness measurement method is used. For micro hardness test specimens, each RE product or CM, tested three specimens. Of the three test specimens it is expected to represent the value of micro hardness in the RE product or CM product which will be used to analyze the UHMWPE mechanical properties further.

3. Result and discussion

3.1. Tensile test
To find out the result of tensile test of CM product and RE product, we can see it in Figure 8. The result of tensile test consist of three values, i.e., value of yield strength, ultimate tensile strength, and elongation value. The value shown in Figure 8 are the average values of two specimens in each product. The RE product has a higher yield strength than the CM product. That is 25.25 MPa for RE product and 23.67 MPa for CM product. Contrariwise, the CM product has a higher ultimate tensile strength than the RE product at 35.36 MPa for the CM product and 29.70 MPa for the RE product. The last parameter of this tensile test is the elongation value. It appears that CM products have greater elongation values than RE products at 214.75% for CM products and 120.45% for RE products.

![Figure 8. Tensile test result.](image)

![Figure 9. Hardness test result.](image)
3.2. Hardness test
To find out the results of the CM product hardness test and the RE product, we can see it in Figure 9. This figure provides information to us about the value of each material hardness test. The CM product specimens have hardness values of 14.5 VHN; 15.9 VHN and 14.9 VHN. Whereas the RE product specimens have hardness values of 9.1 VHN; 8.8 VHN and 8.8 VHN. The pattern that can be seen for the whole test was that on all specimens for hardness testing, CM products are superior to RE products. The mean hardness values for these two products are 15.1 VHN for CM products and 8.9 VHN for RE products.

3.3. Discussion
Our research goal is to find out and compare the mechanical properties of UHMWPE resulting from compression molding process and ram extrusion. We can see in Figure 8 of the test results of RE and CM specimens. The value of yield strength, there is a difference but not significant. While the significant difference occurs in the ultimate value of tensile strength and elongation. It is known that a higher crystalline quantity can inhibit crack initiation and slow down crack propagation by encouraging crack deflection around lamellae structures [10]. The property of preventing crack and its propagation is one result of the higher value of ultimate tensile strength and elongation of a material. Therefore, the significant difference between the ultimate tensile strength and elongation values of CM and RE specimens can be due to the crystallinity value of the CM specimen larger than the RE specimen. Different results are also seen from the values of hardness of specimens CM and RE. The CM specimen has an average hardness value of 70% greater than the RE specimens. This is closely related to the difference in microstructural properties of both CM and RE specimens. Although this study showed better mechanical properties of CM specimens than RE specimens, it can not be generalized that the product of the compression molding (CM) process will always be better in mechanical properties compared to the ram extrusion product (RE). Differences in mechanical properties occur due to many factors that affect both resin types, manufacturing methods and UHMWPE sterilization processes.

The processing of UHMWPE has evolved considerably over the last half century and is uniquely tied to changes in the microstructural features of this polymer. Such evolution manifests as trade-offs in the clinical performance of this material. Crosslinking improves the wear resistance of UHMWPE but with a compromise in fatigue fracture resistance along with susceptibility to oxidation and fatigue wear in vivo. Annealing crosslinked materials above and below the melt can retain wear resistance and improve oxidative resistance, but influence crystalline quality and quantity that drives down fatigue crack propagation resistance. Enhancing crystalline quantity can restore this fatigue resistance, but increases the modulus and accompanying contact stresses that can render an implant more susceptible to delamination and pitting in vivo. Future iterations of this polymer should consider all aspects of microstructural changes, especially those that affect fatigue wear and fracture, to promote UHMWPE durability under greater and longer-lasting loading cycles and extend the lifetime of modern TJRs [10].

In direct compression molding (DCM), sometimes also called net shape compression molding, the manufacturer of the polyethylene insert effectively converts the resin to a finished or semifinished part using individual molds. One advantage of DCM is the extremely smooth surface finish obtained with a complete absence of machining marks at the articulating surface. In addition, higher processing pressures may be attained, if desired, because the projected surface area of each individual part mold is relatively small compared to the area of large molds used to compression mold sheets [1]. Starting from this study we will continue to develop the method of manufacturing compression molding or more precisely direct compression molding machine to convert UHMWPE powder into acetabular liner, without going through the process of milling or machining. Certainly still guided against the research that has been done by many researchers.

4. Conclusion
This study shows that the mechanical property of the CM specimens are better than the RE Specimens, especially in terms of ultimate tensile strength, elongation and micro hardness. Although
this study showed better mechanical properties of CM specimens than RE specimens, it can not be
generalized that the product of the compression molding (CM) process will always be better in
mechanical properties compared to the ram extrusion product (RE). Differences in mechanical
properties occur due to many factors that affect both resin types, manufacturing methods and UHMWPE
sterilization processes. Direct compression molding (DCM) becomes the right solution for the moment
in terms of time and cost efficiency in manufacturing acetabular liner components.

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