A study of the mechanical properties of Ultra High Molecular Weight Polyethylene (UHMWPE)

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Abstract:

When looking at total-joint replacement the major concern is the wear being applied. Wear is responsible for a range of negative consequences such as fracturing of the material, ultra high molecular weight polyethylene (UHMWPE), the body reacting to debris due to wear, and possibly replacement. Therefore our objective is to study the properties of ultra high molecular weight polyethylene in order gain a better understanding of wear. There will be several different approaches taken in order to achieve our objective. One approach is to determine how the direction of wear being applied affects the strength of ultra high molecular weight polyethylene, the material used in total-joint replacement. Hypothetically, when wear is applied in the same direction as the molecular chains our material becomes stronger and wear retarded. The opposite takes place in the other directions. Another approach is to find out how well does the material resist wear when it is processed through extrusion. The intent of this research is to obtain true stress-strain curves for UHMWPE. The true stress-strain curves are used in computer simulations in order to predict wear in potential joint-replacements.

1. Introduction:

Ultra high molecular weight polyethylene is a type of polymer. A polymer is basically a molecule that consists of many (poly) parts (mer) which are linked together by covalent bonds [1]. The individual parts or segments are referred to as monomers. UHMWPE is classified as a liner homopolymer, meaning that the monomers in the material are all the same. Polyethylene, on the other hand is basically a polymer which is formed from ethylene (C2H4). Looking at UHMWPE its molecular chain can consist of as many as 200,000 repeated ethylene units. As mentioned earlier, UHMWPE is just one type out of a family of polymers. To name a few there are: low density polyethylene (LDPE), linear low density polyethylene (LLDPE), high density polyethylene (HDPE), and lastly ultra high molecular weight polyethylene (UHMWPE). Each polymer's molecular weight typically weights less than 50,000 g/mol and the arrangement of their molecular chains can be both branched and linear [1]. In the case of UHMWPE its molecular weight is 6,000,000 g/mol, while compared to HDPE's molecular weight of 200,000 g/mol.

UHMWPE must undergo three processes to obtain the state used in implants. First, the material must become polymerized from ethylene gas into UHMWPE powder. The ingredients needed in order to complete this process are ethylene, hydrogen, and titanium tetra chloride which acts as the catalyst [1]. Titanium tetra chloride is essential for producing white UHMWPE powder, which have small amounts of impurities. Below is a chart with the medical grade requirements for UHMWPE which are listed in both the ASTM F648 and ISO 5834-1 standards. The listing of each type depends upon the molecular weight and the company who manufactures them.

Table 1: Medical grade requirements of UHMPWE. [1]

Property	Requirements	
Resin Type	Types 1-2	Types 3
Trade Name	GUR 1020 & 1050	1900H
Producer	Ticona, Inc. Polyolefins (discontinued)	Basell
Ash, mg/kg, (Maximum)	150	300
Titanium, ppm, (Maximum)	40	150
Aluminum, ppm, (Maximum)	40	100
Calcium, ppm, (Maximum)	50	50
Chlorine, ppm, (Maximum)	20	90

As of January 2002 Type 3 resin is no longer manufactured. However, two major orthopedic companies have accumulated large quantities of the resin. Therefore, implants with Type 3 resin can still be manufactured.

Now that UHMWPE is in the state of resin powder, our second step is to convert our material into consolidated form. This can vary depending on what process is used for conversion. For example, one process used to change UHMWPE from resin powder is to convert it through compression molding [1]. Through this process, sheets of UHMWPE are produced by a computer controlled compression press. The produced sheets dimensions can range from 1 m by 2 m to 2 m by 4 m, while the thickness of the material can range from 30 to 80 mm. These given dimensions depend upon the size of the compression press being used. The timing of the process depends upon the dimensions

of the material, which can take up to 24 hours and sometimes even longer.

After these sheets are produced, typically they are changed into rods or whatever shape an orthopedic manufacturer needs. The last step in processing UHMWPE is the machining of the consolidated form into whatever component is needed. Machining of the material typically consist of milling and some turning operations which is useful for both roughing and finishing UHMWPE. However, when machining the material several precautions are necessary. Several factors can be responsible for damaging UHMWPE whether through different feeding rates, cutting force of the tool, speed of the spindle, an accumulation of heat, these are just a few of the factors which must be taken into consideration [1].

UHMWPE is a polymer with practical uses in several different areas. You can find UHMWPE being used in truck and dump truck bed liners [2]. It can be found used in the food and beverage industry because of its ability to prevent the growth of fungus and bacteria. In addition, both oil and grease can be easily removed from the surface. The material can be found in the cores of golf balls, ski and snow board bottom surfaces, and it is great for noise reduction. UHMWPE also has practical uses in the medical field, in the area of interest here it is used in total-joint replacement.

When considering the use of UHMWPE in total-joint replacement, there are several advantages. First, the bulk material is biocompatible. Therefore, it can be placed inside a patient without the human body reacting experiencing a negative action. Furthermore, UHMWPE has a low coefficient of friction and a nonstick self lubricating surface. In comparison with other plastic materials, UHMPWE is found to have the highest resistance towards impact. It is proved to be very tough, allowing it to sustain

large amounts of tension and compression without fracturing or breaking. Another important advantage is its ability to resist wear, which is unmatched by any other polymer [2, 3]. Below is a graph that depicts UHMWPE's ability to resist wear compared to other resins.

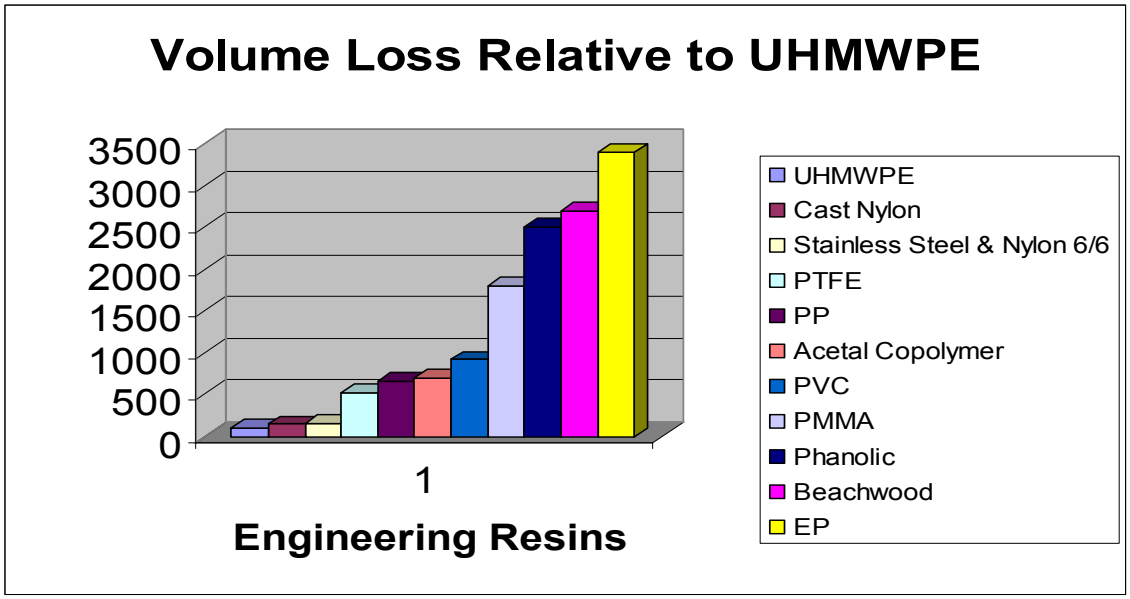

Figure 1: UHMWPE's ability to resist wear compared to other plastics. [2]

The several advantages discussed above contribute to the wide use of UHMWPE. In light of the several advantages of the material there are some drawbacks. As stated above one advantage of UHMWPE is its ability to resist wear. Unfortunately, there are some serious consequences when dealing with wear. Wear can lead to both mechanical failure and most importantly biological failure [4]. The bulk of the material is biocompatible with the human body, but particle debris due to wear are not. The debris that breaks off can react with the tissue surrounding the bone. This reaction can lead to loosening of the prosthesis and eventually replacement. On an average, total-joint replacements have a life span of ten years. However, each addition replacement has the

half-life of the previous replacement. When considering older patients this may not pose a problem due to their limited life span. While a prosthesis being implanted into younger more active patients becomes a serious problem because of the longer anticipated life.

2. Experiment:

2.1 Theories:

The main purpose of our research is to determine the affects of wear upon UHMWPE in total-joint replacement. Essentially, we want to try to understand and how to slow down the wear process. Thus, allowing us to develop both longer lasting and more efficient total-joint replacements. Looking at an initial block of UHMWPE the molecular chains are entangled, just imagine the molecular chains as a big plate of spaghetti. Now when sliding loads are applied to a specimen of UHMWPE, the molecular chains begin to straighten and untangle. Typically, the molecular chains align in the same direction of the applied load. In addition to the molecular chains aligning in this direction, the strength tends to increase in this direction. Small amounts of wear are likely to occur in this direction. Looking at other directions the material tends to become weak and wear is most likely to occur in these directions.

One approach is to determine the relationship between the molecular chain alignment and the direction of wear being applied. Theoretically, molecular alignment can aid in the strength of the material. When a load is applied in the same direction in which the molecular chains are aligned, strain-hardening occurs. Simply stated, that our specimen is strong in this direction and wear is least likely to occur. On the other hand, if loads are applied in another direction other than that of the aligned molecular chains, strain-softening occurs. In this direction the material can undergo increased wear and is

essentially weaker in this direction. Therefore, we intend to verify this hypothesis with our own specimens.

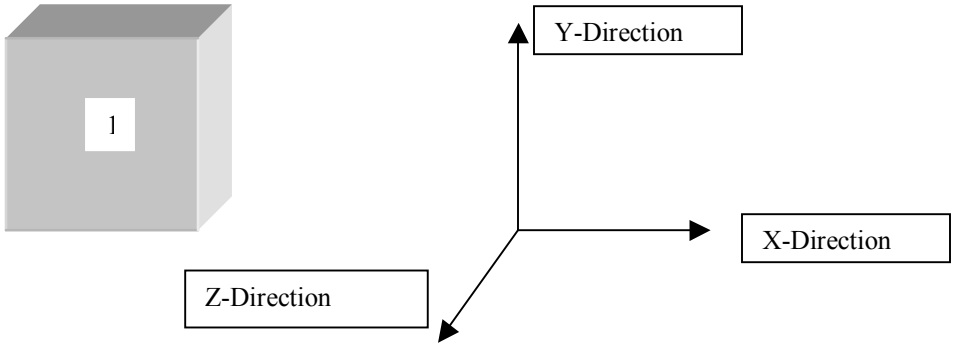

Figure 2: A representation of our axis used.

The above approach is also essential in achieving our second goal, which is to determine whether our material is processed through extrusion. Figure 2 is a representation of our initial block of UHMWPE. Hypothetically, our initial specimen was processed through extrusion, meaning that the molecular chains have already been orientated. It is assumed that the molecular chains are already aligned in the y-direction. From the initial specimen, three small specimens were cut. The first specimen was cut in the y-direction from surface 1 or the surface facing you. The second specimen was cut from the same surface however in the z-direction. Last, the third specimen was cut from surface 2 the top surface, in the x-direction. Four different loading speeds will be applied to each specimen, which are shown in the results section. If the stress-strain curves are similar, then it is believed that the material is isotropic. A material is isotropic when it has the same material properties in all directions. If the stress-strain curves do not match, then it can be deduced that the initial block of UHMWPE was not processed through extrusion which results in anisotropic properties.

UHMWPE is a complicated material, meaning that several factors can be responsible for wear. The temperature or loading speed is just a few examples of factors that can contribute to wear. In our case, the speed of the applied load is the focus. Different loading speeds can result in different material properties. Stress-strain curves will be obtained, thus allowing us to compute the Young's Modulus for each specimen and compare them.

2.2 Experimental Setup

Our research requires us to apply tension to specimens of specific dimensions. Before the experiment is conducted the specimens must be machined. The dimensions of the specimen are found in the Standard Test Method for Tensile Properties of Plastics [6]. Below are specimen dimensions that can be found in the standard for testing the tensile properties of plastics.

Table 2: Dimension specs for tensile test. [6]

Dimensions		7 (0.28) or under			Over 7 to 14 (0.28 to 0.55), incl		4 (0.16) or under	
		Type I	Type II		Type III		Type IV	Type V
W--Width of narrow section		13 (0.50)	6 (0.25)		19 (0.75)		6 (0.25)	3.18 (0.125)
L--Length of narrow section		57 (2.25)	57 (2.25)		57 (2.25)		33 (1.30)	9.53 (0.375)
WO—Width overall, min		19 (0.75)	19 (0.75)		29 (1.13)		19 (0.75)	
WO—Width overall, min								9.53 (0.375)
LO—Length overall, min		165 (6.5)	183 (7.2)		246 (9.7)		115 (4.5)	63.5 (2.5)
G--Gage Length		50 (2.00)	50 (2.00)		50 (2.00)			7.62 (0.300)
G--Gage Length							25 (1.00)	
D—Distance between grips		115 (4.5)	135 (5.3)		115 (4.5)		65 (2.5)	25.4 (1.0)
R--Radius of fillet		76 (3.00)	76 (3.00)		76 (3.00)		14 (0.56)	12.7 (0.5)
RO--Outer radius (Type IV)							25 (1.00)	

Dimensions for Thickness, T, mm (in.)

The reason for these specifications is to allow a comparison between the obtained data and previous data from other research experiments. These standards are used by various different researchers and are the standards used in most articles and journals. Figure 3 shows the specimen after being machined.

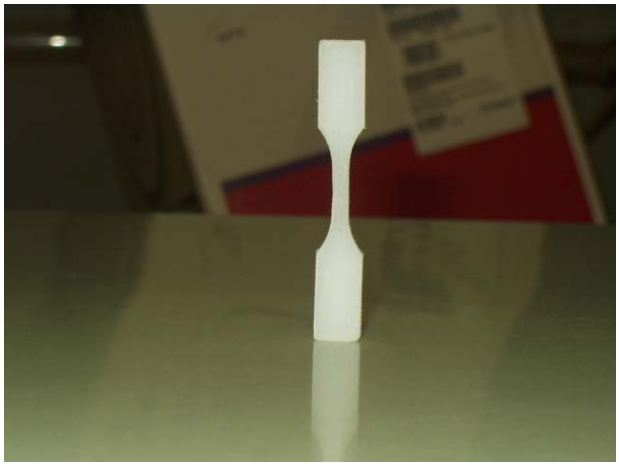

Figure 3: Example of specimen in dog bone shape.

Figure 4 is another picture of the specimens being used. The difference between figure 4 and 3 is shading of the specimen. The specimen in figure 4 is painted for measurement purposes, it allows us to place scribe marks onto the specimen. The scribe marks placed upon the specimen are set at the gage length given from the tensile testing standard. The purpose is to help determine the change in distance between the scribe marks after the test is conducted.

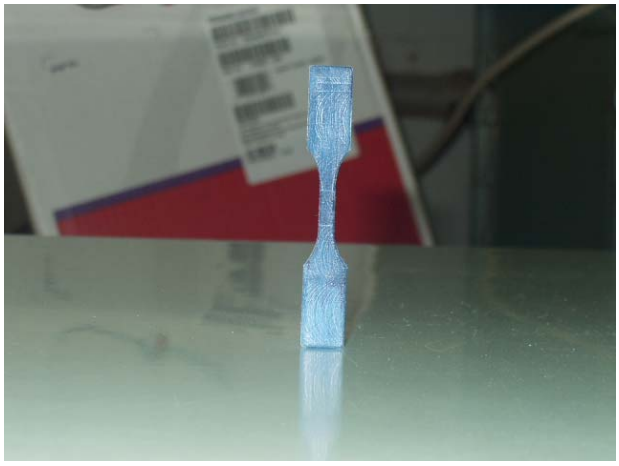

Figure 4: Dog bone specimen was painted and marked in order to allow us to take initial and final measurements.

Figure 5 shows the machine used to conduct tensile test. As depicted there is both a lower and higher grip where the specimen of UHMWPE is placed. The bottom or lower grip remains stationary, while the top or upper grip moves according to the given loading speed. Not seen in the picture is the computer through which the tensile data is collected.

Figure 5: Our machine used for tension test.

The machine can be operated either under manual control or by computer control. Figure 6, is a picture of the grips being used during the testing.

Figure 6: A closer look at the grips used for our test.

2.3 Data

In order to obtain the stress and strains for each point in time, there are a few measurements needed. Below, table 3 shows the information needed to calculate each value. To calculate the stress you must take the load and divide it by the area. The strain is calculated by dividing the distance the crosshead has moved by the initial gauge length.

Table 3: These measurements are essential to calculating stress and strain.

Width of Narrow Sect. (mm):	3.18
Thickness of Narrow Sect. (mm):	4
Area (mm^2):	12.72
Gauge Length (mm):	8.00

The data below are comparisons of different loading speeds on each specimen. Four different loading speeds were applied to in order to gain an insight on how loading speed affects the yielding point.

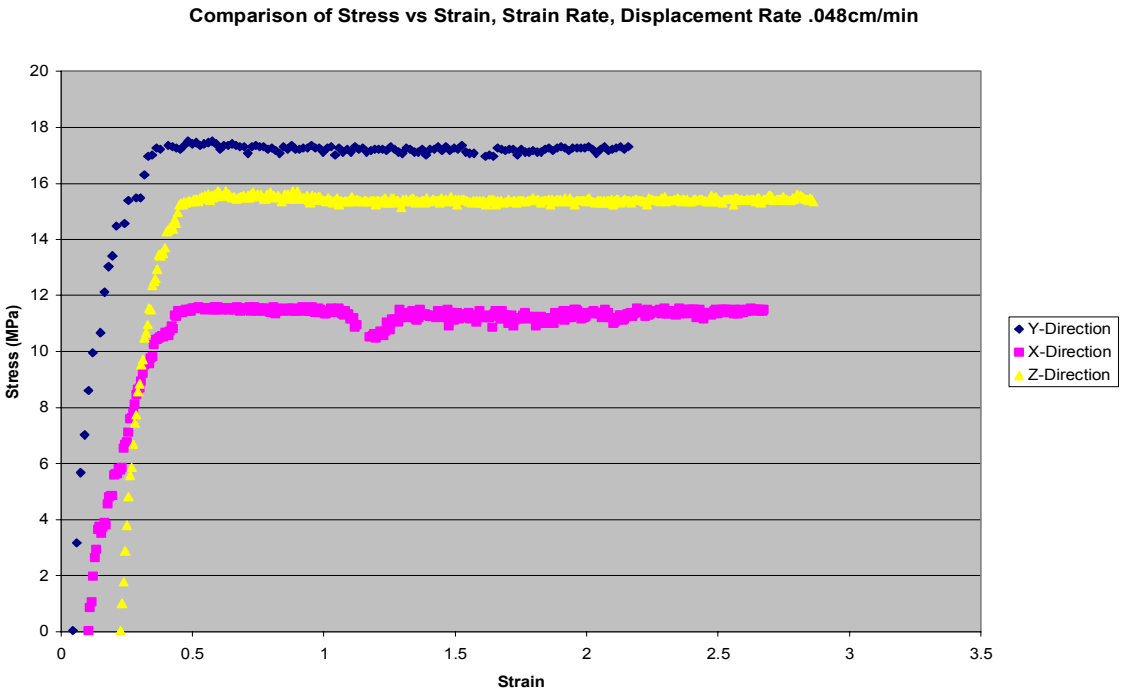

Figure 7: Comparison between stress versus strain curves at .048cm/min displacement rate.

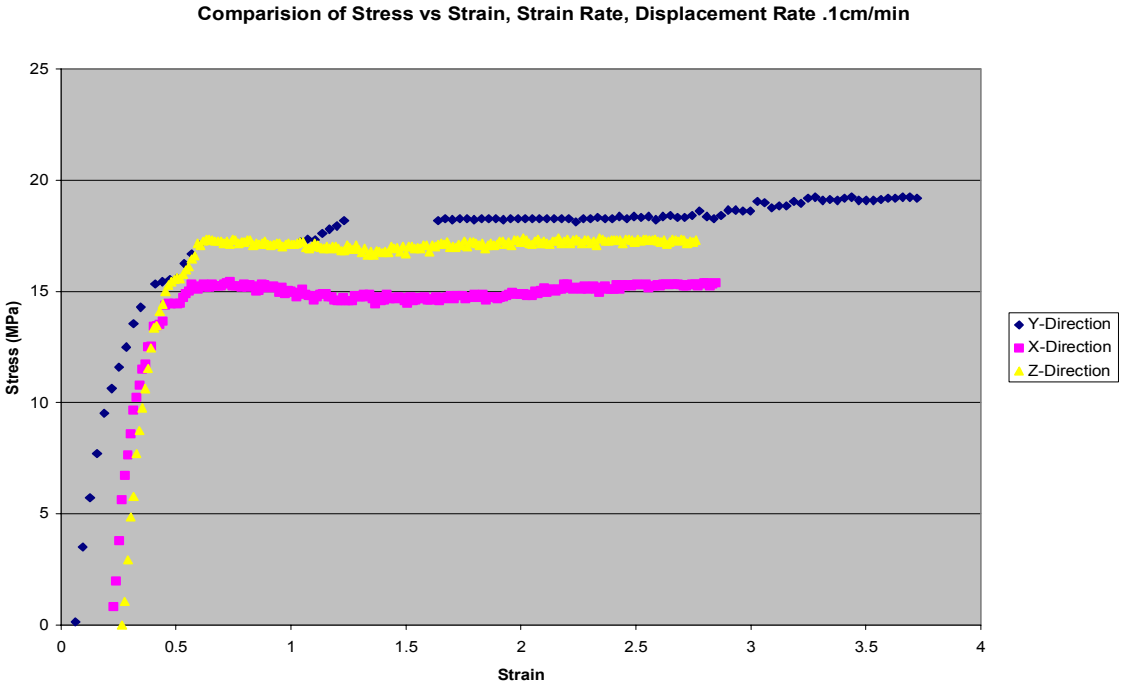

Figure 8: Comparison between stress versus strain curves at .1cm/min displacement rate.

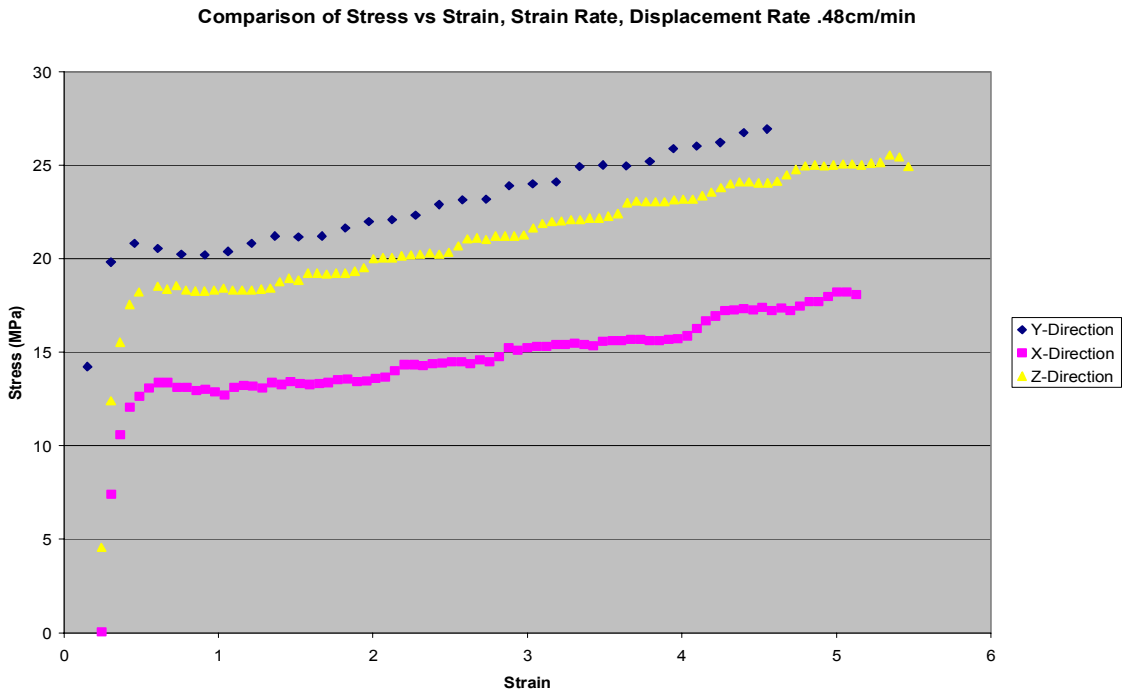

Figure 9: Comparison between stress versus strain curves at .48cm/min displacement rate.

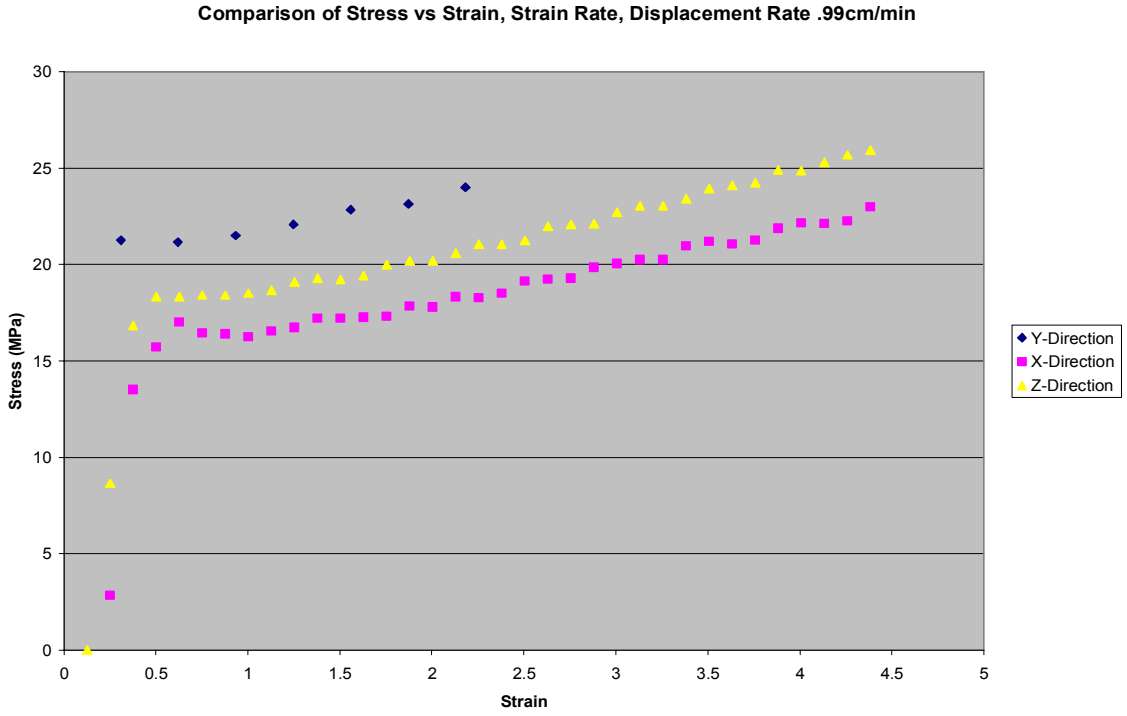

Figure 10: Comparison between stress versus strain curves at .99cm/min displacement rate.

2.4 Discussion

As stated in the theories portion of this paper, the main purpose of our experiments is to determine the effects of wear upon a specimen of UHMWPE. In doing so the main focus was to determine the effects of wear in multiple directions. In addition, these tests will also prove whether the given specimen was initially processed through extrusion. In order for our initial specimen to not be processed through extrusion, we would have to show that our specimen is isotropic. The stress-strain curves would be exact for each specimen, thus meaning that our initial block of UHMWPE would have the same material properties in every direction. Referring to any one of the above stress-strain curve comparisons, it is clear that both the stress-strain curves and load versus displacement curves vary in different directions. Ultimately, it is safe for us to say that our initial block of UHMWPE was in fact processed by extrusion and the molecular chains have orientated in some fashion.

In addition, we have found additional data to give evidence in favor of the direction of orientation. Initially, it was believed that the molecular chains were orientated in the y-direction of our specimen. As mentioned previously, when tension is applied to a specimen whose molecular chains are aligned in the same direction as the applied load, strain hardening occurs. Essentially, that material would be most like to have the highest resistance towards the applied load, making it harder to stretch the material. Furthermore, it would take a longer period of time to gain plastic deformation. In order to verify this assumption, the focal point will be the yielding point of each specimen. The higher the yielding point, the longer it will take for the specimen to reach plastic deformation. When looking at each of the above stress-strain curves, the yielding

point for the y-direction curve is higher than both x-direction and z-direction. Thus, the specimen cut in the y-direction under the applied tension takes longer to reach plastic deformation. It also safe to say that the specimen of UHMWPE cut from this direction is tough and less likely to experience wear. Thus, the molecular chains are most likely to be orientated in this direction. With this information, it can also be said that molecular orientation can have an effect in the retardation of wear.

Furthermore, from the above data it can be deduced that different loading rates also have an effect upon UHMPWE. When referring to figures 7 – 10 as the loading rate increases, the yielding point increases too. According to the above data, when we applied a load of .99 cm/min, the yielding point in all three directions was the highest. While looking at the loading speed of .048 cm/min, the yielding point is significantly lower than that of .99 cm/min load. What this means is that when applying small amounts of load, our specimens will undergo plastic deformation earlier than those of higher loading speeds. The higher the loading speed, the specimen will spend more time in the elastic deformation stage.

3. Conclusion

We have demonstrated the effects of multi-directional loading upon the strength of UHMWPE. Depending upon material processing, the strength of the material can vary in different directions. By a series of tension test upon specimens cut in different directions, stress-strain curves were obtained for each specimen under a series of different loading rates. Looking at the yielding point for each specimen under each loading rate we were able to verify that our specimen was in fact extruded. In addition, the direction of the molecular alignment was also concluded through the obtained results.

Even though the above results have verified our previous hypothesis, we are still unable to absolutely predict the behavior of UHMWPE. What is expected to come in the future is to determine the effects of wear upon a specimen that experiences multiple loads.

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