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Determination of the Influence of Selected External Factors on the Physical and Structural Properties of UHMWPE

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Long-term storage of polymer materials in adverse conditions initiates the aging process. That process covers all physical and chemical conversions taking place in the structure and causing changes in the parameters of the material. This paper presents the results of the authors' own research to determine changes in the physical properties of the polymer (UHMWPE) under the influence of ionizing radiation, long-term compressive loads, temperature, the effects of the use environment (human body fluids), and polymer storage time. The in vitro degradation process of UHMWPE polymer under the influence of the above-mentioned factors was evaluated. Assumptions were made to create test conditions for the samples similar to those found in the human body. Shore D hardness tests have also been conducted, as well as differential scanning calorimetry analysis.

topics: UHMWPE (ultra-high-molecular-weight polyethylene), degradation, degree of crystallinity, physical properties

1. Introduction

Biomaterials applied in implants are influenced by the biological environment and higher stress than acceptable for that material. Many publications have raised the issue of the adverse effect of radioisotope thermoelectric generator (RTG) radiation on the properties of polyethylene [1–5].

Long-term storage of polymer materials in adverse conditions initiates the aging process, especially as far as technical and mechanical features are concerned [6, 7], and that process may be irreversible.

UHMWPE — ultra-high-molecular-weight polyethylene — used for medical purposes has a complex structural structure and consists of an amorphous phase and a crystalline phase. The quantitative ratio of these two phases determines the mechanical properties of polyethylene, and a change in this ratio can indicate the destructive processes taking place.

In the case of endoprosthesis acetabulums, the change in the degree of crystallinity of polyethylene can be caused by:

- frictional processes and prolonged pressure effects during the operation of joint endoprostheses,
- X-ray irradiation,
- processes of structure changes associated with the passage of time.

Within the framework of this study, changes in basic parameters indicating the changes that have occurred were investigated.

2. Study of changes in the degree of crystallinity of UHMWPE polymer subjected to loading

In order to determine whether a change in the degree of crystallinity could occur in the surface layer of the plastic — in this case, UHMWPE polymer — as a result of the friction process occurring within the movement node of the endoprosthesis and the associated wear, it was deemed advisable to carry out a study of changes in the degree of crystallinity, using NETZSCH's DSC 200 PC Phonox. The tests were carried out by differential scanning calorimetry (DSC), taking material samples from the polyethylene liner locations marked in Fig. 1.

Samples were taken from the area where friction processes took place and from the area that was not involved in the friction-wear processes of the polyethylene inserts. Three samples each were taken from both the loaded area and the area excluded from cooperation with the skids.

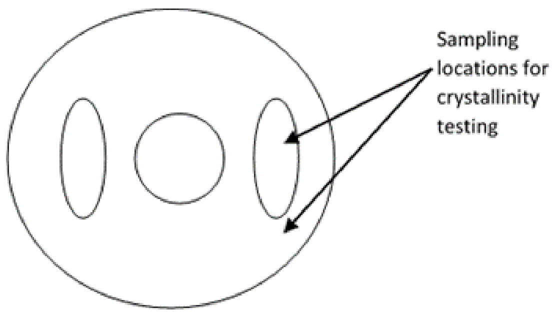

Fig. 1. Flat polyethylene insert used in research of knee endoprostheses, with marked spots where samples were taken.

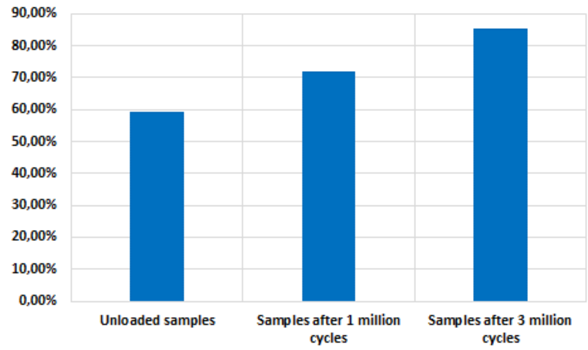

Fig. 2. Change in the degree of crystallinity of the UHMWPE as a function of the number of loading cycles.

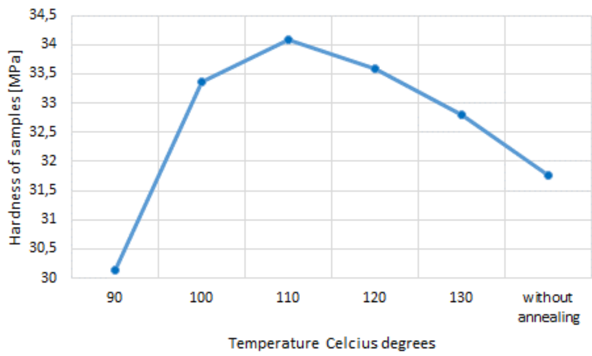

Fig. 3. Samples' hardness change under the influence of annealing temperature.

From the measurements, it can be concluded that subjecting the polyethylene insert to loading during testing of the endoprosthesis on the knee joint simulator results in an increase in the degree of crystallinity of the plastic. The average increase in the degree of crystallinity of the polyethylene used for testing is between 10 and 12% after 1 million cycles, and about a 13% increase from the previous state is recorded in the case of 3 million load cycles. Observing these changes, it can be concluded that as the number of load cycles to which the polyethylene inserts have been subjected increases, the embrittlement of the plastic within the friction node increases.

Figure 2 shows how the degree of crystallinity of UHMWPE polymer changes as a function of the number of load cycles transferred.

An important influence on friction is the size of the spherulites. A more fine-grained and homogeneous structure ensures that smaller friction coefficient values are obtained. Achieving homogeneity of the supramolecular structure throughout the sample material is impossible. This effect is probably due to the inhomogeneity of the surface condition caused by the complexity of the formation of supramolecular structures during the crystallization period [8, 9].

3. The influence of UHMWPE thermal treatment on hardness and crystallinity degree change

Thermal treatment is one of the methods enabling modifications of properties of plastics — including polyethylene.

Based on literature data [9, 10], we can say that annealing increases crystallinity phase action and causes the growth of crystallites' average dimensions. Changing mechanical properties makes the material more wear-resistant.

The main aim of the below tests was to determine the influence of annealing temperature on hardness and mass change of a tested sample.

The annealed samples were made of medical polyethylene called Chirulen® (UHMWPE acc. ISO 5834-2) immersed in vaseline oil. The annealing time was 3 h. The process was carried out in a dryer with a thermostat. The samples were put into a copper crucible filled with vaseline oil.

Figure 3 presents an influence of the above annealing temperature on UHMWPE samples' hardness.

According to the carried out tests, we can say that up to 90°C, the samples' hardness slightly grows. In higher temperatures, it grows clearly. Above 110°C, the hardness decreases back. That is why we can consider 110°C as an optimal temperature of annealing.

To assess the influence of annealing temperature on the structure of plastics and to designate crystallinity degree, the differentiate scanning calorimetry method of DSC was used for tests. The samples for the tests were taken out of the surface layer of modified samples by means of microtome. The analysis helped to define the ratio between the crystallinity phase and the amorphous one in the tested samples.

According to the above analysis, we can claim that the difference in crystallinity degree between samples annealed at 90°C (the lowest) and the ones

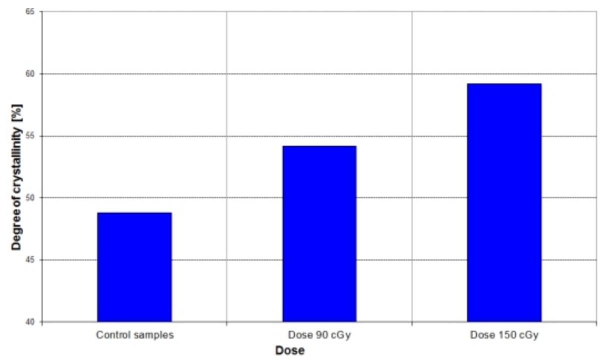

Fig. 4. Degree of crystallinity of the samples tested.

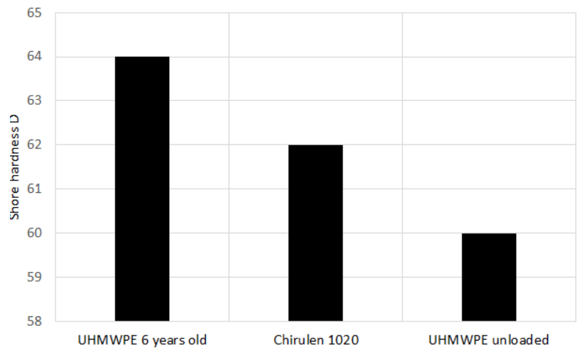

Fig. 5. Hardness of polyethylene samples.

annealed at 130°C (the highest) equals only 5%. However, the difference between the sample not subjected to any modifications and the one annealed at 130°C equals about 6%. The differences between the results for individual samples annealed duly at 100°C, 110°C, and 120°C equal about 1%. This result proves that the growth in the temperature of annealing is accompanied by the increase in crystallinity degree of the plastic.

4. Change in the degree of crystallinity of exposed samples

According to literature sources [10–12], UHMWPE cross-linking caused by radiation usually occurs in amorphous areas. In the crystalline areas, radicals migrate to the surface of the crystallites and merge there to form a cross-linked structure.

For the samples exposed to X-ray radiation, the change in the degree of crystallinity of irradiated UHMWPE samples was also examined. The differential scanning calorimetry (DSC) method was used to evaluate the degree of crystallinity.

The degree of crystallinity for each test was:

- 54.2% — for the sample with a dose of 90 cGy,
- 59.2% — for the sample with a dose of 150 cGy,
- 48.8% — for an unexposed sample.

The difference in the degree of crystallinity for the test samples is illustrated in Fig. 4.

It can be concluded based on the tests performed in the study that the difference between the degree of crystallinity of the sample with the absorbed dose of 90 cGy (the lowest dose) and the sample with the dose of 150 cGy (the highest dose) is $\approx$ 5%. A similar difference in the degree of crystallinity (5.4%) was observed between the non-exposed and the 90 cGy samples.

Based on these observations, it can be stated that with the increase in the absorbed dose, the degree of crystallinity of UHMWPE increases. This increase was ca. 5% for every 60 cGy of the dose absorbed.

5. UHMWPE hardness testing

Long-term storage of polymer materials in adverse conditions initiates the aging process, especially as far as technical and mechanical features are concerned [11, 12], and that process may be irreversible. The tests were performed on samples made of UHMWPE (Chirulen® 1020).

The tests on polyethylene samples were conducted a few weeks after the polymer was produced and 6 years after their purchase and preparation. All this time the samples were stored in a closed container with no exposure to light.

The determination of hardness by Shore's method was conducted according to the norm PN–EN ISO 868, type D. The tested polyethylene samples were previously subjected to wear–friction tests on simulator T-05. According to directives, the taken result was an arithmetic average of all measurements, rounded to the unit. Figure 5 shows the hardness of polyethylene samples.

Analyzing the obtained results, one can notice that the loaded and aged UHMWPE changes its hardness. The hardest was UHMWPE stored for 6 years, subjected to long-term load when tested on simulator T-05. The hardness of samples made of Chirulen® 1020, subjected to load, was two units higher than of the sample made of the same material but not subjected to any factors.

6. Conclusions

(i) Polyethylene components are exposed to many physical parameters, which may result in a much shorter life of these components. The results of the research conducted allow us to indicate the parameters that may significantly shorten the time of their proper functioning.

(ii) It can be concluded that subjecting UHMWPE to load and aging affects its hardness. Long-term subjection of UHMWPE to load and aging causes an increase in crystallinity chase input.

(iii) Long-term storage of UHMWPE causes changes in its tenacity and tribological features. Conducted tests proved increased wear of that material.

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