Impact compaction of ultra high molecular weight polyethylene

B S Zlobin, A A Shtertser, V V Kiselev and S D Shemelin

Design and Technology Branch, Lavrentyev Institute of Hydrodynamics, Novosibirsk, 630090, Russia

E-mail: asterzer@mail.ru

Abstract. Ultra high molecular weight polyethylene (UHMWPE) is a partially crystalline polymer with unique physical and mechanical characteristics. Therefore it finds a wide use in present-day mechanical engineering. Experiments on impact compaction of UHMWPE granules were performed on the special facility designed for consolidation of powders. Bulk samples were made out of GUR 4150 powder with molecular weight of $9.2 \times 10^6$ g/mol. The method of impact compaction permits to make not only pure UHMWPE compacts, but material with micro- and nano-sized additions as well, and produce composites with reinforcing metal structures.

1. Introduction

Ultra high molecular weight polyethylene (UHMWPE) is unique material with high toughness and wear resistance, high shock resistance, low friction, and many other remarkable properties. Bulk material is made out of UHMWPE powder by different methods, mostly by the hot molding technique. Having a great molecular weight (millions of g/mol), this material does not pass into the viscous-flow state even at high temperatures up to its melting point, besides, UHMWPE has high viscosity in the liquid state. These properties hinder producing of bulk material by forming operation. That’s why the existing industrial technologies (hot molding, ram extrusion, sintering, etc.) are expensive and complicated. In this connection, dynamic loading methods are of interest, as they possibly can simplify the process of powder consolidation. The first encouraging results were obtained in [1] where the method of cyclic high-velocity forming was used. In present studies the impact compaction technique, consisting in sequence of blows affecting the powder portion, was employed. Bulk samples of pure UHMWPE and of UHMWPE with micro- and nanosized additives were made. Besides, composite samples with reinforcing metal structure were produced by the said technique.

2. Experiments on UHMWPE compaction

The first stage experiments on the impulse compaction of the UHMWPE powder performed in Lavrentyev Institute of Hydrodynamics are described in [2]. In present study we have used the same experimental facility (hydro-pneumatic apparatus) providing the impact rate up to 9 blows per second. The supposed method was designated in [2] as cyclic impact compaction (CIC). Bulk samples were made out of the commercial GUR 4150 powder with molar mass of $9.2 \times 10^6$ g/mol. A peculiarity of CIC method is that material remains in the solid state during the treatment, hence the starting content of crystal phase (about 66%) remains in the compact. The tensile strength of the produced material
reaches 45.3 MPa and elongation can be as much as 370%. The CIC method is the promising one for the production of small articles, similar to those shown in figure 1. The obtained compacts require minimal after-treatment, like those produced by closed-die forming technique. But in contrast to this technology CIC permits to make parts directly from the starting powder material.

Presently, there are the works addressed to the production and characterization of polymer composites on the base of UHMWPE with different additives [3, 4]. This direction in development of new materials with enhanced properties is considered as having of good prospects. Positive results of CIC application for pure UHMWPE powder enabled us to make experiments with UHMWPE powder modified by micro- and nano-sized TiO₂, SiO₂ and SiC additives at the amount of 2 wt.% The procedure of powder modification is described in detail in [2]. The obtained compacts with the density of 0.94 – 0.95 g/cm³ are shown in figure 1.

3. Properties of compacts made by CIC

Cylindrical samples for tensile tests were made out of the compacts containing micro- and nano-additives (figure 3a). The sample deformable length was 10 mm, diameter 6 mm. The tests were carried out on the testing machine ZDM-5 at the elongation velocity of 6.5 mm/min. The tested samples were fixed in the special holders, since the design of ZDM-5 does not permit testing of small-size specimens. The outlook of samples after the tests is presented in figure 3b. It should be noted that after unloading specimens shrink so that their length decreases by about 30%. The test results are the following: tensile strength σ = 23.1, 31.4 and 27.7 MPa for specimens with SiC, TiO₂ and SiO₂ additives, respectively; elongation δ = 250, 290 and 300% for specimens with SiC, TiO₂ and SiO₂ additives, respectively.

The presence of fine ceramic particles in the polymer volume usually increases its wear resistance. To compare the wear resistance of samples obtained by CIC and those made of PTFE and commercial UHMWPE, the experiments were made on dry friction of said polymers against the hardened steel counterpart with the surface ground to the roughness of grade 8 (0.438 μm). Four cylindrical samples were prepared for the tests: the first one was made of pure UHMWPE by CIC, the second one was made of UHMWPE + 2 wt% SiO₂ by CIC, the third one was made of commercial UHMWPE, and the forth one was made of PTFE (figure 4). Friction of polymer samples against steel counter face was organized in the forth – and – back movement with an amplitude of 100 mm. Total friction path amounted to 4,000 m for samples made of UHMWPE and 200 m for that made of PTFE, the pressing force was 151.8 N. The wear of samples was characterized by their mass loss after the tests. The precision laboratory balance LV 210-A was used for sample weighing. The tests were made on BiSS UTM servo-hydraulic testing machine in the Laboratory of Mechanical and Climatic Testing in the
Industrial Park of Novosibirsk Academic Township (Akademgorodok). Because of the limited test time we failed to compare the wear resistance of UHMWPE samples, since their mass loss was close to the balance limit of accuracy. Tests have shown the mass loss of 0.5, 0.5, 0.3 and 15 mg for the first, second, third and forth sample, respectively. So, taking into account the mass loss and friction path, we can conclude that UHMWPE material made by CIC has the wear resistance at least 600 times as much as that of PTFE.

**Figure 3.** Samples from the UHMWPE modified by additives of SiC, TiO₂, and SiO₂ (2 mass %): a – before the tensile tests; b – after the tests.

Composite materials on the base of UHMWPE with metal reinforcement are of great interest. Since polymers chemically not interact with different other materials, including metals, there are difficulties in manufacturing of such composites. In engineering practice the polymer-metal joining is provided by different design solutions based on mechanical locking of composite components. To make polymer – metal composite, on the first stage the discs with the thickness of 2 – 4 mm were produced by CIC, then, on the second stage CIC was used for stamping the multilayered item consisting of alternate layers of polymer and perforated titanium bands with the thickness of 0.5 mm. Figure 5a presents the 5-layered compact produced by the described technological route. Analysis of the compact macrostructure shows that it is dense all over the volume and there are no cavities in the polymer – metal interface and in perforation areas (figure 5b). Figure 5c shows the specimen for tensile test cut out of the composite compact.

Figure 6a presents the tensile diagram of pure UHMWPE bulk material made by CIC, this is a typical polymer elongation diagram [2]. Figure 6b presents the tensile diagram for the specimen shown in figure 5c. This diagram was obtained on the Zwick Z100 testing machine at elongation velocity of 1 mm/min.
Figure 5. Polymer-metal composite: а – five-layer compact; б – compact structure; в – specimen for the tensile test.

Figure 6. Tensile diagrams of specimens: а – pure UHMWPE [2]; б – five-layer composite.

It is evident that diagrams shown in figures 6а and 6б differ dramatically. Deformation curve of the composite specimen is somehow similar by character to tensile curves of metals. The maximal load value in figure 6б indicates that metal and polymer layers behave as a single whole.

The impact toughness of composite material was detected on the ram impact machine KM-30. The sample sizes followed the recommendations of the Russian standard GOST 4647-80 (figure 7а). The tests demonstrated that composite samples, made by CIC method, do not fail completely. This is also typical for the samples made of pure UHMWPE [2]. Therefore it is difficult to estimate the impact toughness of obtained compacts quantitatively. However, we can suppose that UHMWPE compacts, especially reinforced with metal layers, can successfully sustain the impact loading and possibly the action of piercing projectiles.
Besides the above-mentioned composite samples with flat metal reinforcing inserts, the experiments were carried out on CIC treatment of UHMWPE powder with the cylindrical steel element inserted into the powder volume. After compaction the steel element inside the compact was joined to the steel rod as is shown in figure 8a. Then the steel rod and UHMWPE compact were fixed in holders of the ZDM-5 testing machine (UHMWPE via special transition device) and tensile test was done. Figure 8b shows the sample after the test. It is evident, that steel rod with diameter of 5 mm was broken at the force of 8212 N and cylindrical element was not pulled out of the compact. This is another demonstration of CIC capability to induce the strong joining between composite components.

4. Conclusion
The results of present studies show that the method of cyclic impact compaction has a significant potential in manufacturing of composites on the base of ultra high molecular weight polyethylene. These composites can contain either micro- and nano-additives or metal reinforcing structures.

References
[1] Jaufres D, Lame O, Vigier G and Dore F 2007 Polymer 48 6374-6383
[2] Zlobin B S, Shtertser A A, Kiselev V V, Shemelin S D, Poluboyarov V A and Zhdanok A A 2017 J. Appl. Mech. Tech. Phys. 58 435-442
[3] Selyutin G E, Gavrilov V V, Voskresenskaya E N, Zakharov V A, Nikitin V E and Poluboyarov V A 2010 Chem. Sustain. Develop. 18 301-314
[4] Gogoleva O V, Petrova P N, Popov S N and Okhlopkova A A 2015 J. Frict. Wear 36 301-305