A Review on Cutting-Edge Utilization of UHMWPE Polymer in Industrial and Medical Applications

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Abstract
This review focuses on "ultra-high molecular weight polyethylene (UHMWPE), a high-performance polymer used in medical and industrial applications. UHMWPE shows high-performance characteristics such as high mechanical strength, excellent wear resistance, and biocompatibility. In the case of industrial applications, UHMWPE is specifically used in automotive, marine, and mining. In contrast, in the case of aerospace applications, it is used for parts like gears, bearings, ropes, cables, and conveyor belts owing to its low coefficient of friction, superior wear resistance, and high impact strength. UHMWPE composites are nowadays more promising for use in aerospace, making light parts, and protecting against bullets, which are addressed in this article. In the medical field, UHMWPE is widely accepted as an orthopedic implant for its biocompatibility and resistance to wear. It is primarily used in hip and knee arthroplasty, where it serves as an acetabular liner and tibial insert. UHMWPE has also been studied for its use in heart devices, drug delivery systems, and dental tools. Researchers are working to make UHMWPE better, and methods for improvements like cross-linking, adding tiny particles, and treating the surface. "These efforts aim to make implants work better and last longer by solving problems like wear-related bone loss or osteolysis. This paper also discusses the increasingly recognized potential of UHMWPE, leading to its growing industrial and medical applications.

Key words:
UHMWPE, industrial applications, medical applications, orthopedic implants, wear resistance, biocompatibility

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1. Introduction:

Ultra-high molecular weight polyethylene (UHMWPE) is one of the high-performing polymers that has outstanding tensile or mechanical characteristics, wear resistance, and biocompatibility [1]. In the industrial sector, UHMWPE is used in various applications in shipbuilding, the textile industry, and also in biomedical areas such as implantable devices for complete joint endoprostheses [2][3][4].There has been an impressive history of UHMWPE development over the years, from the historic gamma air-sterilized polyethylene to the new 1st and 2nd generation highly crosslinked products, all designed to improve performance [4]. In the 1990s, new methods like using irradiation in a nitrogen atmosphere and special packaging were used wherein this led to the creation of the first type of crosslinked polyethylene [2]. Recent studies have focused on solving problems related to oxidation and material damage. As a result, new types of polyethylene have been developed, including highly cross-linked polyethylene and polyethylene with vitamin E [2][5]. The significance of UHMWPE in both industrial and medical sectors is considerable. In the medical domain, it is particularly utilized in total joint arthroplasties, including acetabular liners or sockets for total hip replacements and tibial inserts for total knee replacements [6]. Their low friction, good wear resistance, and ability to resist chemicals make them useful in many industries [3]. Current research and development efforts in ultra-high-molecular-weight polyethylene (UHMWPE), particularly in the areas of processing techniques such as precipitation polymerization and additive manufacturing, are continually enhancing its potential applications and improving its performance in both industrial and medical sectors [5][6][7]. UHMWPE has improved over time, and now, third-generation materials are being made to make it stronger and more resistant to oxidation [8]. These improvements include new ways to link materials, adding antioxidants, and changing surfaces to make them last longer and lower the chance of implant failure [8][9]. As research advances, there is an increasing interest in investigating the potential of UHMWPE nanocomposites, which may offer improved mechanical strength and tribological properties for both industrial and biomedical applications [10].

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2. Fundamental Properties of UHMWPE

UHMWPE comprises long chains of simple polyethylene molecules, as shown in Figure 1, where "n" denotes the degree of polymerization, which varies from 36,000 to 110,000 [1]. Regarding the long molecular chain and the corresponding high molecular weight, the result is very strong and durable with exceptional properties [4][7]. Such properties are high mechanical properties, including high strength, excellent wear resistance, and low friction coefficient [11][12]. These properties also make it an ideal material for artificial joints and other load-bearing applications. The material has a very good resistance to chemicals and is safe for use in medical implants due to its biocompatibility [1][3]. In other words, UHMWPE is characterized by a low melting point and a high melt viscosity, which makes it challenging to process. This often necessitates specialized techniques such as powder processing and sintering [3]. For biocompatibility, UHMWPE has demonstrated exceptional performance as an artificial joint replacement, with 15-20 year durability [12]. However, ongoing research is needed to improve long-term performance due to the generation of wear debris or residual UHMWPE particles during use, which can lead to adverse interactions with the surrounding tissue [4][12]. Current research endeavors are concentrated on further enhancing these properties to prolong the lifespan of UHMWPE-based implants and improve their overall performance [1][13].

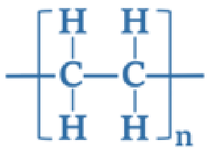

Figure 1: Molecular structure of UHMWPE

3. Industrial Applications

A. Automotive industry

As discussed above, UHMWPE is known for its high wear resistance, low friction coefficient, and excellent mechanical properties [1][12],it can be used in different industrial applications where durability and low friction are crucial. Furthermore, UHMWPE exhibits high impact resistance, which enhances its value in industrial applications.However, its processing can be challenging [14]. In contrast to the previously mentioned facts, Khalil et al. (2019) observe that UHMWPE-based products are very tough to produce by conventional methods such as injection molding and extrusion due to their ultra-high melt viscosity or almost zero flow rate at melting or higher temperatures [15][16]. This limitation may hinder the broader industrial automotive sector,which requires complex geometries or large-scale manufacturing.

B. Marine industry

In the marine industry, UHMWPE-based components are used in applications such as warps and hand ropes for large mid-water trawls in fisheries, as well as in cables and anchor ropes for net cages in large-scale mariculture [17]. Furthermore, this polymer is extensively utilized in shipbuilding due to its low coefficient of friction, superior abrasion resistance, and exceptional chemical resistance [3]. Apart from its different advantages, it has a low thermal stability and low load-bearing capacity [11], which may restrict its use in certain high-stress marine components. To address this challenge, researchers have explored the reinforcement of ultra-high-molecular-weight polyethylene (UHMWPE) with materials such as graphene nanoplatelets to improve its tribological properties and expand its applications in mechanical bearing systems [11].

C. Mining and heavy machinery

UHMWPE can be used in the manufacture of mining and heavy equipment components and accessories due to its excellent wear resistance, low coefficient of friction, and high impact strength [18][19]. And based on the aforesaid properties, UHMWPE may be suitable for conveyor belts, linings, wear plates, and chute linings in harsh mining environments. In addition, recent studies have shown that the mechanical properties and wear behavior of UHMWPE compound can be enhanced by the integration of short carbon fibers (CF) through the preparation of composites [20]. It was found that the compressive modulus and hardness increased as the fiber content increased, whereasthe friction coefficient and wear rate decreased.Furthermore, surface-treated CF with nitric acid resulted in a further improvement of the interfacial adhesion between CF and UHMWPE, resulting in superior mechanical and tribological properties. In this regard, another study has shown that glass fiber can be reinforced with UHMWPE, where glass fiber-based UHMWPE composites have been produced for use as liner sheets to protect ships, construction vehicles, and transportation equipment [21]. This study determined that the mechanical and tribological properties of the composites are highly influenced by the initial size of the powder and the length of the glass fibers.

D. Aerospace and ballistic applications

Ultra-high molecular weight polyethylene (UHMWPE) composites have shown improvement in various mechanical properties as discussed above. Moreover, the material has great potential in the aerospace sector, particularly for lightweight structural components, high strength-to-weight ratio, and ballistic protection [22]. In this context, Figure 2 presents the difference between various materials based on their density and strength.

One of the studies indicated that "UHMWPE composites exhibit superior mass efficiency compared to conventional metallic and composite armor materials in resisting fragments simulating projectiles [23]. In the case of ballistic protection, UHMWPE fabrics integrated with Energy Absorption Materials and Structures (EAMS) have been shown to reduce backface signature values by 6-17% compared to pure UHMWPE panels with equivalent areal density [24].Compared to other laminate structures, unidirectional UHMWPE composite laminates exhibit superior ballistic velocity and energy absorption per unit

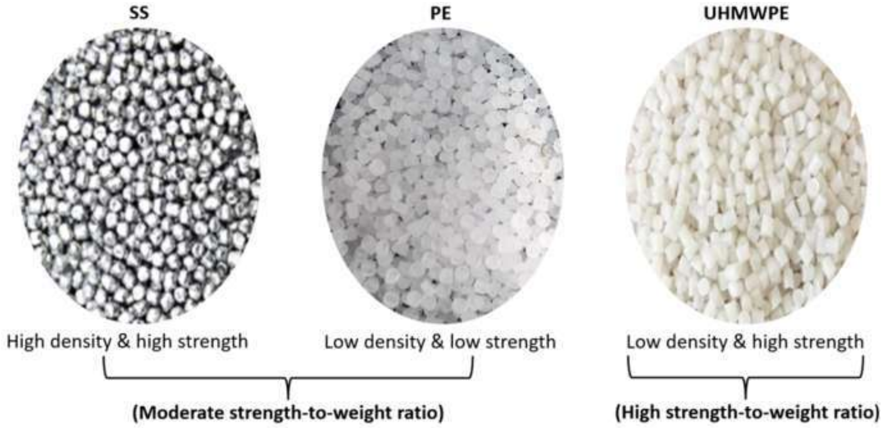

Figure 2: Various materials showing strength-to-weight ratio based on density and strength

weight [25].Here, it is better to say the entire composite can be affected by fiber type, fabric structure, and orientation of fabric layers.

4. Medical Applications

A. Orthopedic implants

Ultra-high molecular weight polyethylene (UHMWPE) is extensively utilized in orthopedic implants, particularly in hip and knee replacements, owing to its superior properties, including high wear resistance, biocompatibility, and chemical stability [1][6]. In total hip arthroplasty, ultra-high-molecular-weight polyethylene (UHMWPE) is frequently employed as acetabular liners or sockets, whereas in total knee arthroplasty, it functions as tibial inserts [6]. UHMWPE's performance in hip implants depends on the chemical and mechanical conditions in the implant environment that may change its properties over time. For example, UHMWPE hip cups may experience density increase and oxidative chain degradation [26]. In this context, the material for the selection of the femoral head plays a crucial role in determining wear rates. Conventional UHMWPE can be combined with ceramic heads consisting of alumina or cobalt chromium, and alumina-based heads effectively reduce wear rates more than cobalt chromium [27][28]. Several modifications have been investigated to improve the performance of UHMWPE in orthopedic applications. Among these, irradiation crosslinking has shown much lower wear rates than conventional UHMWPE [28]. UHMWPE may also be enhanced with nanoparticles, including zirconium oxide, to increase both mechanical and biological attributes [29]. In addition, the surface hardness can be improved by surface modification, including nitrogen plasma immersion ion implantation [30]. These improvements were designed to address UHMWPE implant challenges, such as wear-related osteolysis, and to improve overall implant durability and lifetime.

B. Cardiovascular devices, drug delivery systems and dental applications

Ultra-high-molecular-weight polyethylene is used in many heart devices, like parts of the heart valves and vascular grafts, or blood vessel replacements. It is also used in systems that deliver medicine, or as a drug delivery system, and in dental applications. In cardiovascular applications, UHMWPE tissue-engineered cardiovascular grafts (TECVG) have demonstrated potential as a viable alternative to conventional prosthetic grafts. These TECVGs show promising results for growth, longevity, and infection resistance, with no indication of rejection problems [31]. UHMWPE is also being used as a platform for cardiovascular drug delivery systems, where researchers have developed scaffolds integrated with growth factors, cytokines, and drugs to facilitate the targeted and local delivery of drug molecules [31]. Although UHMWPE is widely used in orthopedic applications, its use in cardiovascular devices has rarely been documented in the available literature. However, the ability to deliver vascular endothelial growth factor (VEGF) to UHMWPE surfaces using silk fibroin coating has shown improved bone-to-implant integration, with potential cardiovascular applications [32].

5. Conclusions

This work effectively discussed the high-performance polymer, ultrahigh molecular weight polyethylene, with applications in both the industrial and medical domains. The characteristics of UHMWPE, such as its tensile or mechanical properties, biocompatibility, and resistance to various chemicals, are well discussed in this paper. It is utilized in various industrial sectors, including the automotive, marine, mining, and aerospace industries. Its suitability for components like gears, bearings, ropes, cables, and conveyor belts owing its low friction coefficient, excellent wear resistance, and strong impact strength. In the aerospace industry, UHMWPE composites have demonstrated potential for use in lightweight structural parts and ballistic protection. UHMWPE has been particularly advantageous in the medical sector, notably in orthopedic implants such as hip and knee replacements. Due to its biocompatibility and wear resistance, this material is preferred for use in acetabular liners and tibial inserts.

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