Tribological Performance of Composites

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One of the most widely used wastes is their utilization as fillers or reinforcements in the metal- or polymer-based composites. The reuse of wastes for the production of tribological materials gives not only environmental benefits related to the transformation of waste into raw materials but also may improve the mechanical and tribological properties of such materials. Moreover, the use of waste reduces the production costs resulting from the lower price of filler materials and longer service life of developed products.

Keywords: waste ; composite ; polymer ; metal ; wear ; coefficient of friction ; tribology

1. Introduction

In the circular economy, responsible waste management and designing for recycling are increasingly often used slogans equated with sustainable development. Recently, the European Union has been intensively moving from linear economy to circular economy, which is assumed by keeping materials as long as possible in the loop and following the 3R approach: reduce, reuse and recycle. On 11 March 2020, the European Commission adopted a new Circular Economy Action Plan, which purpose is to “avoid waste altogether or transform it into high-quality secondary resources that benefit from a well-functioning market for secondary raw materials” [1]. Hence, a growing number of scientists pay great attention to designing this type of materials with the use of waste, such as agricultural (e.g., natural fibers), industrial (e.g., fly ash (FA), red mud (RM)) or postconsumer (e.g., polymer bags, clothes) waste materials. The properly prepared waste material may be used as a filler or reinforcement for metal or polymer-based composites aimed at use in various applications, e.g., as tribological materials directly related to the wear processes due to friction.

2. Friction

Friction is a common phenomenon in nature and technology. It can be both a desirable and undesirable factor in a given situation. Friction is a disadvantageous phenomenon, e.g., during the movement of machine elements. Then it destroys cooperating, rubbing elements. This causes, for example, axles and bearings made of valuable materials to wear off. In addition, the friction causes a loss of energy to overcome the existing resistance. On the other hand, friction can be a useful or even necessary phenomenon, e.g., in stopping the body while it is in motion. Friction is essential for the proper functioning of brake pads, clutch, belt transmissions and many other elements. There are many ways to increase or decrease friction as needed, including the use of materials with appropriate tribological properties. To determine the suitability of the tribological material for a given application, the most important factors are the observed wear of material (the lowest wear is desirable) and the coefficient of friction (COF) (both low and high can be desirable). When describing wear, it is important to distinguish between the different tribological contacts depending on the relative motion of triboelements, as they lead to different wear mechanisms (see Figure 1). For example, sliding can lead to adhesive wear, abrasive wear and fretting, whereas rolling can lead to adhesive wear, abrasive wear and fatigue. Particle or liquid impacts lead to erosive wear of studied material. When considering small particles in the contact region, one can distinguish sliding (two-body) abrasion (when particles are blocked in the surface of one of the triboelements) or rolling (three-body) abrasion (when particles roll between two sliding bodies). Abrasion can be associated with abrasive wear and fretting. Wear can be quantitatively expressed as wear rate, usually defined as volume (or mass) loss per unit distance or specific wear rate, depending additionally on the applied load. Moreover, erosive wear depends largely on the applied impingement angle, i.e., an angle at which erodent particles impact sample(s) tested in the erosion wear test.

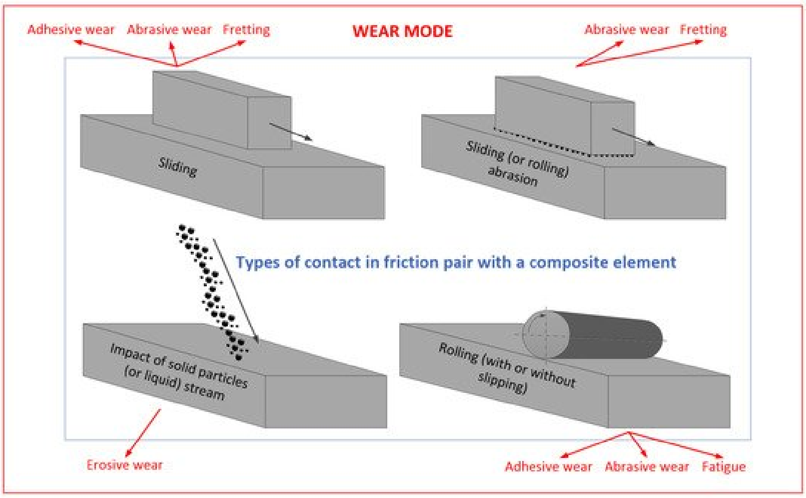

Figure 1. Types of contact between triboelements and the resulting wear modes.

Materials for tribological applications can generally be divided into metals (and their alloys), ceramics, polymers and others. Among various metal materials used for tribological applications, aluminum and its alloys are one of the most commonly studied. However, these types of materials are characterized by low hardness and limited tribological properties, which, in turn, limit the possibilities of their application [2]. The most popular way to increase the strength of aluminum and its alloys is to add insoluble reinforcement to create a metal matrix composite. Both monolithic (single reinforcement) and hybrid (more than one reinforcement in composite) composites are developed, and in both cases, satisfactory results can be obtained in terms of tribological performance. In aluminum metal matrix composites, ceramic particles like carbides (e.g., SiC, B_4C, TiC), oxides (e.g., Al_2O_3, MgO, $ZrSiO_4$, ZrO_2), borides (e.g., TiB_2, AlB_2) and nitrides (e.g., BN, AlN) are most often used as reinforcements. The addition of at least two reinforcements and thus the production of a hybrid composite is intended to enhance the mechanical and tribological properties compared to the materials reinforced with a single type of filler. The main disadvantage of this type of composites is often a reduction in ductility and an increase in brittleness of the composite [3]. On the other hand, many researchers primarily use polymer matrices to create composites reinforced with waste materials. Among these composites, one of the most commonly used is epoxy resin. Epoxy resin is resistant to many chemical agents (oils, greases), has high strength and good adhesion to the substrate, and exhibits higher resistance to cracking, environmental degradation and thermal decomposition compared to other thermosetting polymers [4]. However, there are also some obvious disadvantages of epoxy, such as its price, low impact and fracture resistance, as well as relatively high wear rate. Thus, to improve the mechanical performance and tribological properties, different fillers and reinforcements (e.g., nanotubes, SiO_2, ZnS, MoS_2, C-BN, H-BN, fullerene, graphite and graphene oxide) have been incorporated into epoxy in several investigations [5]. Hence, new reinforcements are sought to eliminate these drawbacks, e.g., waste-derived reinforcements (see Figure 2).

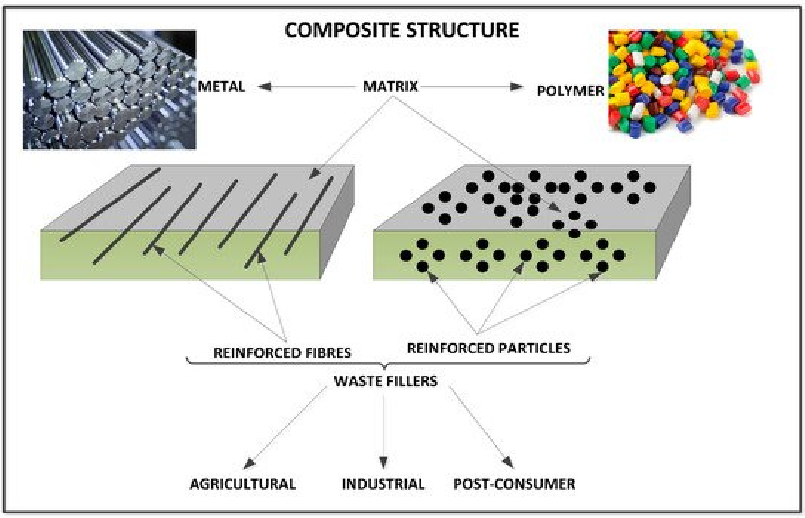

Figure 2. The general structure of metal- and polymer–matrix composites filled with various waste materials.

3. Development

Recently, researchers have paid increasing attention to the use of waste materials as fillers/reinforcements for metal or polymer matrices to obtain composites exhibiting desirable tribological properties that would become an alternative to the traditionally used fillers. Such reuse of waste for tribological applications has several advantages: (i) environmental benefits by the transformation of waste into raw materials; (ii) an improvement of mechanical and tribological properties, as some researchers suggest treating such properly prepared materials as biosolid lubricants [6], (iii) economic benefits due to lower material production costs and longer service life (reduced wear rate); (iv) a reduction of the overall weight of the material, which is especially important in the case of metal materials used for tribological applications.

Literature reports indicate a relationship between tribological properties and mechanical properties. Therefore, the majority of publications investigate both of them. Taking into account the limited space of the article, this review focuses on the description of tribological properties without considering the mechanical properties. Experimental data were collected from scientific reports available until December 2020.

To the best of our knowledge, there is no review evaluating the tribological performance of metal and polymer-based composites reinforced with various agricultural, industrial and postconsumer wastes. In this article, a detailed review of polymer and metal–matrix composites filled with industrial, agricultural and postconsumer wastes is presented. This paper, containing four sections, is organized as follows: the first section deals with the agricultural waste materials used in metal and polymer matrix, the second section deals with the industrial waste materials used in metal and polymer matrix, the third section deals with postconsumer waste materials and the fourth section elaborate on the conclusions and the future scope of research.

4. Future Perspectives

This entry indicated that industrial and agricultural wastes are mainly used for tribological applications. Among the agricultural wastes, the most frequently described wastes are various natural fibers of plant origin (in a polymer matrix) and RHA (in the metal matrix), whereas among industrial wastes, FA, RM, and various slags and sludges, are the most commonly used. It seems that at least some of them have a high potential to reduce frictional resistance and wear.

Aluminum alloy metal matrix composites can be a good example here. The specific configuration of their properties, such as high mechanical strength and corrosion resistance with low weight, predispose them as a hypothetical material for manufacturing of many frictionally working parts like pistons, plane bearings, sliders, brake rotors, etc. Unfortunately, the problem is often the high production costs of parts based on such composites. That is why low-cost materials with comparable characteristics are in demand. In our review, we indicate applications in which the use of RHA as a reinforcing filler for a composite with an AlSi10Mg alloy matrix significantly improved its wear resistance [7]. Another example would be the use of RHA as a filler for the composite with the AA6351 matrix. In this case, only a slight decrease in wear resistance was observed compared to the reference material. Therefore, it is possible to use agricultural waste fillers for composites with an aluminum matrix without adversely affecting their tribological properties.

Even greater possibilities apply to composites with typically plastic matrixes. There are also great possibilities in the application of waste fillers to compose the structure of composites with typically polymer matrixes. The results of the scratch tests presented in Ariharan et al. [8] indicate that the resistance to wear of an RHA-reinforced PP composite exhibits the same wear resistance as the reference material (PP composite without RHA). Therefore, it can be assumed that PP-RHA composites will be suitable for tribological applications of classic PP composites. In practice, these can be parts operating under light to medium-heavy sliding friction conditions, e.g., plain bearings or gaskets and inner and outer races of rolling bearings (balls and rollers are steel or glass). Another example would be the use of snail shells (as a filler) in PE matrix composites. In this case, it was observed that the addition of waste filler increased the hardness and wear resistance compared to the reference composite (PE composite without snail shells) [9]. PE composites are widely used in modern technics. Therefore, their versions with waste fillers may prove to be an interesting alternative for less responsible applications, e.g., low-speed bearings, runners for bottling in filling lines, chain guides in plate conveyors, etc. The responsible application of these composites as camshafts in engines, valve trains, or biomedical bearing material (joint prostheses) can also be considered. PA composites are another widely used group of polymeric materials in which waste fillers can be used. Biocarbon obtained from the pyrolysis of polymer wastes can be an example of it. In the investigation carried out in Myalski et al., the wear of the PA composite with this filler was characterized by much lower wear in the sliding test on cast iron than standard PA6 and other PA composites [10]. This “paves the way” for PA composites with waste fillers for the production of plain bearings as well as gears. Recycled carbon fibers can also be used as a filler for PEEK-based composites. According to Lin and Schlarb, this type of composite is characterized by excellent friction and wear performance [11]. PEEK is one of the polymers with the best tribological properties, including high operating temperature, resistance to most chemical reagents, and suitability for work under high contact stresses. The disadvantage is the high production cost. Therefore, the use of waste filler can be economically advantageous without losing strength properties. The application of such composites can be wide—from the previously mentioned bearings and gears to friction pairs in aviation and aerospace, working at temperatures exceeding even 200 °C.

Although the heavy industry is the largest producer of potentially hazardous waste material, the agricultural byproducts seem to be an interesting alternative since they can deliver various materials and substances that can be reused. For example, the total production value of food waste in the world is estimated at $1 trillion, whereas about one-third of food is wasted globally [12]. Fruit seeds seem a unique waste material that cannot only be used to produce bioactive compounds [13][14] but also offers a potentially valuable fiber. Although there are some studies dealing with the disposal of fruit seeds (e.g., from *Jatropha curcas* L. or *Phoenix dactylifera* L.) for tribological applications [15][16], the highest seeds waste is generated from other, more popular fruits [13]. Poland is one of the biggest fruit producers in Europe (behind Spain, Italy, France and Greece), and at the same time is the second biggest sour cherry producer in the world [17]. As sour cherries are mostly being processed and not consumed fresh, there is a high need to utilize the generated seeds for various applications, e.g., for tribological materials.

Postconsumer wastes seem to also be promising, albeit still not so popular, filler materials. Although this review indicates the potential possibilities of their use in tribological materials, it is still a research area to be expanded, especially regarding the fact that the disposal of textile products or plastics at the end of their life is a huge environmental problem. The global market of composites made from polymers and textile fibers is expected to increase by 40% from 2014 to 2020, which results from many desirable properties, such as high-strength values and corrosion resistance [18]. However, these types of materials require a special pretreatment, including the process of recovery of fibers from textile materials by mechanical, chemical, or biochemical methods. These methods should also be optimized to be as eco-friendly and material-efficient as possible. To gain a maximal environmental effect, there is still a need for the development and selection of the optimal treatment methods for all types of wastes. However, to select the best waste material for a particular application and the best methods of its treatment, various environmental tools, such as Life Cycle Assessment, should be used. It is also crucial to utilize the most abundant materials in the first place (e.g., FA) still considering their possible migration from the composite (and possible toxic or ecotoxic effect), but also to reuse wastes available locally (e.g., sour cherries seeds in Poland) to avoid transport-related emissions. Only taking these parameters into account will allow for the production of truly green materials exhibiting desirable tribological properties.

5. Conclusions

- This entry has shown that agricultural, industrial and postconsumer waste is a promising filler material for composites based on both polymer and metal matrices;
- Its use as reinforcement for composites exhibiting desirable tribological properties only gained in popularity in recent years (especially after 2015);
- The reuse of wastes for tribological applications has advantages, such as environmental and economic benefits, an improvement of mechanical and tribological properties and a reduction in the overall weight of the material;
- Wherever the wear of the produced composites is not worse than the reference materials, their application should be considered for ecological and economic reasons;
- There is a great need to find further wastes that can potentially be useful in improving the tribological properties of the currently used materials;
- Future research should focus not only on the waste that is generated in large quantities but also on that available locally to minimize the environmental impact related to the life cycle of tribological materials.

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