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TECHNOLOGICAL FUNDAMENTALS OF POLYMER MATERIALS PROCESSING: MODERN FORMING AND RECYCLING METHODS

This article examines the fundamental physicochemical principles underlying polymer materials processing, the specific features of thermoplastic, thermosetting polymer, and elastomer forming, and the prospects for the reuse of polymer waste. The importance of rheological properties and processing parameters in ensuring product quality and improving resource efficiency in manufacturing is highlighted.

Keywords: *polymer materials, polymer processing, thermoplastics, thermosetting polymers, elastomers, recycling, processing parameters.*

У статті розглянуто основні фізико-хімічні закономірності перероблення полімерних матеріалів, особливості формування термопластів, реактопластів та еластомерів, а також перспективи повторного використання полімерних відходів. Висвітлено значення реологічних властивостей і технологічних параметрів для забезпечення якості виробів та підвищення ресурсоефективності виробництва.

Ключові слова: *полімерні матеріали, перероблення полімерів, термопласти, реактопласти, еластомери, рециклінг, технологічні параметри.*

Polymer materials play an important role in modern industrial manufacturing because they combine low density, mechanical strength, chemical resistance, and ease of processing [6]. Their wide range of applications requires continuous improvement in processing technologies to produce items with various shapes, dimensions, and functions [7]. The relevance of this study is also associated with the growing volume of polymer waste and the need for the rational use of material resources. Selecting an effective processing method makes it possible not only to ensure the required product quality but also to reduce raw material and energy consumption.

The aim of the article is to summarize the technological fundamentals of polymer materials processing, characterize the main forming methods, and identify prospects for polymer waste recycling.

Fundamental Physicochemical Principles of Polymer Processing. Polymers are high-molecular-weight compounds whose macromolecules consist of repeating structural units. Based on their origin, they are classified as natural, artificial, or synthetic. Differences in chemical structure, molecular weight, degree of crystallinity, and intermolecular interactions determine the physicomechanical characteristics of polymer materials and the specific requirements for their processing [6]. The main stages in thermoplastic polymer processing include heating, softening or melting, forming, cooling, and solidification. For amorphous polymers, the glass transition temperature is an important parameter, as segmental mobility of the macromolecules increases above this temperature. In semicrystalline materials, the melting temperature of the crystalline regions is particularly significant. After forming, cooling enables the product to retain its required shape and achieve mechanical stability [7].

The rheological behavior of polymer melts is another important characteristic. Viscosity determines a materia’s resistance to flow and depends on temperature, molecular weight, deformation rate, and the composition of the polymer formulation. Polymers are also characterized by viscoelasticity, which involves a combination of the properties of viscous liquids and elastic solids [1]. Inadequate control of these characteristics may result in uneven mold filling, product

deformation, internal stresses, or dimensional instability. Therefore, optimizing temperature, pressure, flow rate, and cooling conditions is essential for maintaining a stable processing operation.

Processing Characteristics of Different Classes of Polymers. Depending on their behavior when heated, polymer materials are classified as thermoplastics, thermosetting polymers, and elastomers. Thermoplastics soften or melt when heated and solidify again upon cooling. Under appropriate conditions, this cycle can be repeated, providing opportunities for mechanical recycling [5]. Common thermoplastics include polyethylene, polypropylene, polystyrene, and polyethylene terephthalate [6].

One of the most important methods for processing thermoplastics is extrusion. During this process, the polymer material is conveyed by a screw along a heated barrel, where it melts and becomes homogenized before passing through a forming die. This method is used to manufacture pipes, profiles, films, and sheets. Product quality depends on the temperature profile, screw rotational speed, melt pressure, and cooling efficiency [7].

Another widely used method is injection molding, which involves injecting molten polymer into a closed mold, followed by cooling. This technology offers high productivity and enables the manufacture of products with complex geometries. Key process parameters include melt temperature, mold temperature, injection pressure, holding time under pressure, and cooling time.

Thermosetting polymers differ from thermoplastics in that they form a three-dimensional cross-linked structure during curing. Once the chemical curing process is complete, they cannot be remelted in the same way as thermoplastics. Compression molding and the molding of reactive polymer compounds are used to manufacture products from these materials. During compression molding, the material is placed in a mold, heated, and maintained under pressure until the required degree of curing is achieved. The processing conditions must ensure that the chemical reaction proceeds appropriately and prevent the formation of defects [10].

Elastomers, including rubbers, are characterized by their ability to undergo substantial reversible deformation. Vulcanization, the formation of cross-links between polymer chains, is used to impart the required performance properties to rubber products. Rubber articles are manufactured using compression molding, injection molding, and extrusion [6]. The choice of technology depends on the rubber compound formulation, product geometry, and requirements for strength, elasticity, and wear resistance [7].

Polymer Waste Recycling and Resource Efficiency. The increasing consumption of polymer products is accompanied by a growing volume of waste, a significant proportion of which consists of packaging materials. The potential for their reuse depends on their chemical composition, degree of contamination, presence of additives, and compatibility of their components. Thermoplastic waste is of particular interest because it can be softened and formed again [10].

Mechanical recycling generally involves sorting, shredding, cleaning, drying, and remelting waste materials, followed by pelletization [4]. The resulting recycled raw material can be used to manufacture new products if its properties meet the established requirements. However, repeated heating may cause thermo-oxidative degradation, changes in molecular weight, and deterioration of mechanical properties [8]. Therefore, processing conditions must be controlled, and the quality of the recycled material must be evaluated.

The use of recycled polymers to manufacture filaments for additive manufacturing is a promising area of development [2]. For this purpose, waste materials are sorted, shredded, and, where necessary, cleaned before being processed in an extruder into a filament with a controlled diameter [3]. This approach expands the possibilities for reusing raw materials, although it requires consistent material composition and properties [9]. Polymer technologies are also used in the manufacture of membranes and filtration materials for water treatment, wear-resistant machine components, and household products. Incorporating recycled raw materials into such products can help reduce the consumption of virgin resources [4].

In conclusion, polymer processing involves softening, melting, flow, forming, and solidification. The choice of technology depends on polymer type, rheological properties, and product requirements. Optimizing processing conditions, improving product quality, and expanding polymer recycling are essential for enhancing resource efficiency and promoting sustainable polymer manufacturing.

REFERENCES

1. Banerjee R., Ray S. S. Role of Rheology in Morphology Development and Advanced Processing of Thermoplastic Polymer Materials: A Review. *ACS Omega*. 2023. Vol. 8, № 31. P. 27969–28001. https://doi.org/10.1021/acsomega.3c03310

2. Fico D., Rizzo D., Casciaro R., Esposito Corcione C. A Review of Polymer-Based Materials for Fused Filament Fabrication (FFF): Focus on Sustainability and Recycled Materials. *Polymers*. 2022. Vol. 14, № 3. Article 465. https://doi.org/10.3390/polym14030465

3. Mikula K., Skrzypczak D., Izydorczyk G., Warchoł J., Moustakas K., Chojnacka K., Witek-Krowiak A. 3D printing filament as a second life of waste plastics – a review. *Environmental Science and Pollution Research*. 2021. Vol. 28. P. 12321–12333. https://doi.org/10.1007/s11356-020-10657-8

4. Ragaert K., Delva L., Van Geem K. Mechanical and chemical recycling of solid plastic waste. *Waste Management*. 2017. Vol. 69. P. 24–58. https://doi.org/10.1016/j.wasman.2017.07.044

5. Schyns Z. O. G., Shaver M. P. Mechanical Recycling of Packaging Plastics: A Review. *Macromolecular Rapid Communications*. 2021. Vol. 42, № 3. Article 2000415. https://doi.org/10.1002/marc.202000415

6. Vlachopoulos J., Strutt D. Polymer processing. *Materials Science and Technology*. 2003. Vol. 19, № 9. https://doi.org/10.1179/026708303225004738

7. Zheng W., Kramschuster A., Jordan A. Polymer Processing – An Introduction. *Characterization and Failure Analysis of Plastics*. Vol. 11B. Materials Park, OH: ASM International, 2022. P. 1–30. https://doi.org/10.31399/asm.hb.v11B.a0006864

8. Zhou J., Hsu T.-G., Wang J. Mechanochemical Degradation and Recycling of Synthetic Polymers. *Angewandte Chemie International Edition*. 2023. Vol. 62, № 27. Article e202300768. https://doi.org/10.1002/anie.202300768

9. Cruz Sanchez F. A., Boudaoud H., Camargo M., Pearce J. M. Plastic recycling in additive manufacturing: A systematic literature review and opportunities for the circular economy. *Journal of Cleaner Production*. 2020. Vol. 264. Article 121602. https://doi.org/10.1016/j.jclepro.2020.121602

10. Zong H., Hadi R. P., Zecher-Freeman N., Bu F., Zhang M., Arsnow G., Wang C. End-of-Life Plastics Management: A Review. *Johnson Matthey Technology Review*. 2024. Vol. 68, №3. P. 322–334. https://doi.org/10.1595/205651324X17001378211164