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POLISHCHUK ANDRII
Khmelnytskyi National University
https://orcid.org/0000-0001-7887-7169
e- mail: andrepol 215@gmail.com
BOBUKH SERHII
Khmelnytskyi National University
https://orcid.org/0009-0002-0026-0753
e-mail: bobukhs@gmail.com
ZAHUROVSKYI MAKSYM
Khmelnytskyi National University
https://orcid.org/0009-0007-8839-2422
e-mail: blonskiy123@ukr.net
BONEK MIROSLAW
Silesian University of Technology
https://orcid.org/0000-0002-0321-7737
e- mail: miroslaw.bonek@polsl.pl

DESIGN FEATURES OF A SINGLE-SCREW EXTRUDER FOR MANUFACTURING COMPOSITE FILAMENT BASED ON ABS THERMOPLASTIC REINFORCED WITH CARBON AND KEVLAR FIBERS

This article discusses the design features of a single-screw extruder for producing composite filament based on an ABS thermoplastic matrix reinforced with short carbon and Kevlar fibers. Such a composite is characterized by increased impact toughness, tensile strength, and elastic modulus compared to pure ABS. Kevlar fibers provide high impact energy absorption capacity due to their microfibrillar structure, preventing crack propagation, while carbon fibers increase stiffness. The composites are compatible with FDM printing, improve interlayer adhesion, and reduce the coefficient of friction, making them promising for friction parts, robotics, and mechanical engineering. Producing standard-diameter filament requires specialized equipment. Screw extrusion is optimal because it provides heating, mixing, melting, and extrusion of the mixture. The screw generates shear heating, supplemented by heaters. The screw consists of feed, compression, and metering zones with an optimal compression ratio that accounts for the thermal sensitivity of the matrix and the abrasiveness of the fillers. The clearance between the screw and the barrel prevents backflow. The temperature profile creates a gradient from the feed zone to the metering zone for controlled melting without degradation. Gravimetric feeding, the absence of filters, pre-drying of ABS, cooling, and laser diameter control ensure process stability. The system includes a feed hopper, forming head, cooling system, diameter sensor, and winding unit. Analysis confirmed the design's effectiveness for producing reinforced filaments with predictable mechanical properties. The results are applicable to the additive manufacturing of high-reliability, impact-resistant structural elements in industries where lightness, strength, and resistance to dynamic loads are critical.

Keywords: *single-screw extruder; composite filament; Kevlar and carbon fiber; ABS plastic; 3D printing.*

ПОЛІЩУК АНДРІЙ, БОБУХ СЕРГІЙ, ЗАГУРОВСЬКИЙ МАКСИМ
Хмельницький національний університет
БОНЕК МИРОСЛАВ
Сілезький технологічний університет

КОНСТРУКТИВНІ ОСОБЛИВОСТІ ОДНОШНЕВОГО ЕКСТРУДЕРА ДЛЯ ВИГОТОВЛЕННЯ КОМПОЗИТНОГО ФІЛАМЕНТУ НА ОСНОВІ ТЕРМОПЛАСТИКУ ABS, АРМОВАНОГО ВУГЛЕЦЕВИМИ ТА КЕВЛАРОВИМИ ВОЛОКНАМИ

Стаття присвячена конструктивним особливостям одношнекового екструдера для виробництва композитного філаменту на основі термопластичної матриці ABS, армованої короткими волокнами вуглецю та кевлару. Такий композит характеризується підвищеною ударною в'язкістю, міцністю на розтяг та модулем пружності порівняно з чистим ABS. Кевларові волокна забезпечують високу поглинальну здатність енергії удару завдяки мікрофібрильній структурі, запобігаючи поширенню тріщин, тоді як вуглецеві волокна підвищують жорсткість. Композити сумісні з FDM-друком, покращують адгезію між шарами та знижують коефіцієнт тертя, що робить їх перспективними для деталей тертя, робототехніки та машинобудування. Виробництво філаменту стандартного діаметра вимагає спеціалізованого обладнання. Шнекова екструзія оптимальна, оскільки забезпечує нагрівання, перемішування, плавлення та видавлювання суміші. Шнек створює зсувне нагрівання, доповнюване нагрівачами. Шнек складається із зон подачі, компресії та дозування з оптимальним співвідношенням компресії, що враховує термочутливість матриці та абразивність наповнювачів. очний зазор шнек-циліндр запобігає зворотному потоку. Температурний профіль створює градієнт від зони подачі до дозування для контрольованого плавлення без деградації. Гравіметрична подача, відсутність фільтрів, попередня сушка ABS, охолодження та лазерний контроль діаметра гарантують стабільність процесу. Комплекс включає бункер подачі, формуючу головку, систему охолодження, датчик діаметра та намотку. Аналіз підтвердив ефективність конструкції для виробництва армованої нитки з прогнозованими механічними властивостями. Результати придатні для адитивного виробництва ударостійких конструкційних елементів підвищеної надійності в галузях, де важливі легкість, міцність та стійкість до динамічних навантажень.

Ключові слова: *одношнековий екструдер; композитний філамент; кевларове та вуглецеве волокно, ABS пластик; 3D друк.*

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Introduction

The development of additive manufacturing (3D printing) technologies is accompanied by a demand for functional materials with improved mechanical properties, which is achieved by creating composite filaments based on thermoplastic matrices reinforced with high-strength fibers. In particular, the introduction of carbon fibers (CF) and Kevlar (aramid fibers) into an ABS matrix allows for a tensile strength of 50–80 MPa (compared to 30–40 MPa for pure ABS) and a modulus of elasticity of 4–6 GPa, making such composites suitable for structural components in the aerospace, automotive, and robotics industries [1].

The production of 1.75-mm-diameter filaments requires specialized screw extruders capable of ensuring uniform distribution of reinforcing fibers (3–12 mm in length, 10–20% by mass), stable filament geometry (±0.05 mm), and preservation of the mechanical properties of the fillers. The main challenges include abrasive wear of the screws caused by CF, degradation of ABS at temperatures above 250°C, deterioration of fiber-matrix adhesion, and instability in the viscosity of the composite [2].

The aim of this work is to analyze the design features of a single-screw extruder for the production of composite filaments based on ABS thermoplastic reinforced with carbon and Kevlar fibers, including the optimization of screw parameters, a detailed description of the main components, operating conditions, and recommendations for counteracting the abrasive wear of working parts. The results are based on a systematization of the principles of screw extrusion and practical data on the processing of reinforced thermoplastics [3].

Research Object and Methods

The subject of the study is the design features of a single-screw extruder for the production of ABS filament reinforced with carbon and Kevlar fibers. The methods include an analysis of the principles of screw extrusion, an evaluation of the screw and barrel parameters, temperature regimes, and composite processing technology.

Problem Statement

The objective of this work is to analyze the design features of a single-screw extruder for the production of composite filament based on ABS thermoplastic, reinforced with carbon and Kevlar fibers, with optimization of the screw parameters and temperature regime.

Results and Discussion

One of the most effective ways to improve the mechanical and operational properties of polymeric materials is the introduction of reinforcing fibers, which significantly alter the matrix structure and form a composite with specified parameters of strength, stiffness, and durability (Fig. 1) [4].

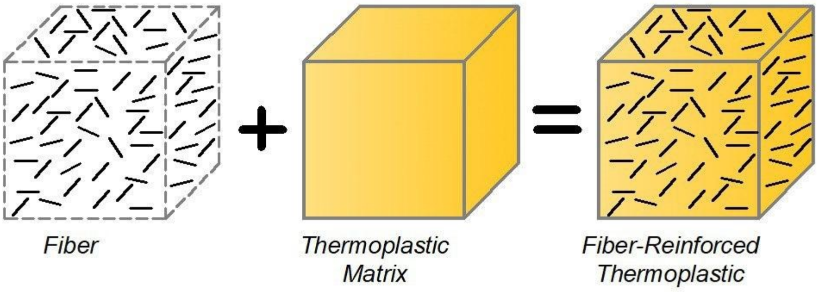

Fig. 1. Composite material reinforced with fibers

A composite filament based on an ABS thermoplastic matrix reinforced with short carbon fibers (CF, 0.2–1.0 mm) and Kevlar (aramid fibers, 0.4–1.0 mm) at a content of 5–15% by mass is characterized by increased impact toughness (up to 25–45 kJ/m² compared to 15–20 kJ/m² for pure ABS), tensile strength of 40–60 MPa, and retention of impact resistance under dynamic loads.

Kevlar fibers provide high impact energy absorption capacity due to their microfibrillar structure and high crystallinity, which prevents rapid crack propagation, while CF fibers increase stiffness and the elastic modulus to 4–6 GPa. The composites are compatible with ABS, ASA, and polyamide matrices, where aramid fibers improve interlayer adhesion in FDM printing (increasing shear strength by 20–30%) and reduce the coefficient of friction, making the material promising for parts subjected to friction and impact loads.

This filament requires matrix drying (4 hours at 80°C), extrusion at 220–250°C, and optimization of fiber orientation to minimize anisotropy in 3D-printed parts.

After describing the properties of the composite filament, we should move on to the method of its formation, since it is the extrusion process that determines the uniformity of the structure, the stability of the diameter, and the quality of the finished filament. For processing such materials, the most suitable method is screw extrusion, which provides simultaneous heating, mixing, melting, and extrusion of the polymer mixture through the die head.

The screw extruder was designed to efficiently heat and process large volumes of plastics. At its core is an Archimedes screw, which feeds the material along the barrel, facilitating its melting, intensive mixing, and delivery to the die. Pelletized or ground raw material enters cylinder 1, where the rotation of screw 2 causes friction between the particles, and during melting, the polymer transitions to a viscous state and begins to resist movement (Fig. 2) [5]. This further increases the material's temperature due to viscous or shear heating. Importantly, most of the heat is generated directly within the polymer, so its low thermal conductivity does not hinder the melting process.

For composite materials based on ABS thermoplastic reinforced with carbon and Kevlar fibers, this principle is particularly important, as it allows for sufficient matrix fluidity without excessive overheating of the reinforcing components. This is why screw extrusion is the basic process for producing composite filaments with predictable properties [3].

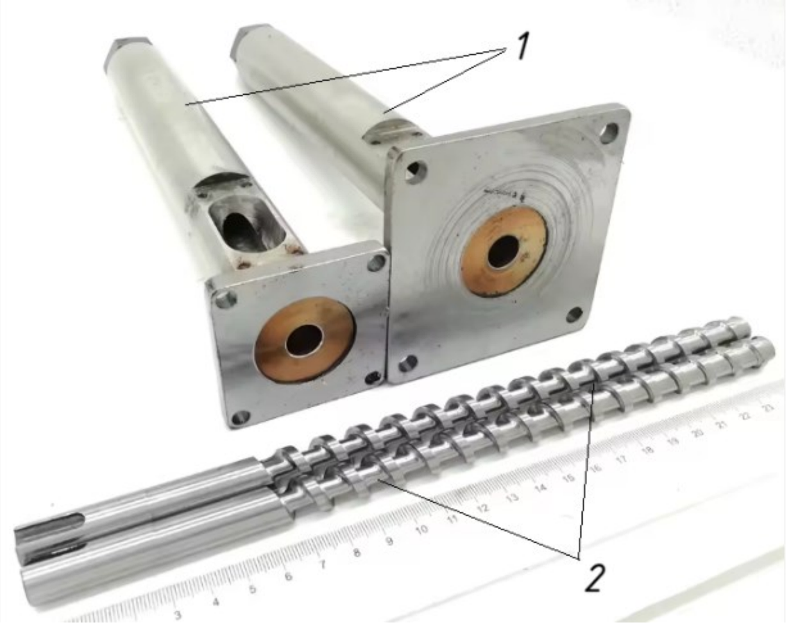

Fig. 2. Extruder barrel: 1-barrel; 2-screw [5]

The efficiency of screw extrusion of composite materials largely depends on the plasticizing screw design, which determines the quality of melting, homogenization, and process stability. Although there are many screw designs, a simple screw with a single compression zone is optimal for laboratory filament production, even though it is significantly more complex than a metal drill bit or a household screw.

Features of extruder screw design (Fig. 3) [3, 6]:

1. High L/D ratio. Extruder screws are characterized by a large length (L) relative to their diameter (D). A high L/D ratio (20:1–30:1) allows for better mixing and thermal processing of the plastic. A longer length ensures better homogenization of ABS composites with fibers.
2. Compression. The screw has a conical shape, with the channel depth decreasing from the feed zone to the metering zone. Compression creates pressure to extrude the material through the nozzle and promotes melting. For ABS, the optimal ratio is 2.5:1.
3. High lubricity. The chrome-plated screw coating prevents melt adhesion, ensures forward movement, and extends service life, which is critical for fiber-reinforced composites.
4. Hardness. CF/Kevlar composites require a nitride coating (TiN, WC/Co) to protect against abrasive wear. Without it, the screw can wear out in 50–100 hours of operation.
5. Precise clearance between the screw and the barrel. There must be a minimal radial clearance between the screw and the barrel—approximately 0.001 times the screw diameter (for example, for a screw with D = 25 mm, this is 0.025 mm). If the clearance is too large, the melt flows backward instead of moving forward, which drastically reduces the extruder's productivity. Achieving high precision in this clearance along the entire length of the screw (300–900 mm) is a complex and expensive process, which is why industrial extruders are costly.

These parameters will allow for the production of a stable 1.75±0.05 mm filament with uniform fiber distribution and preservation of the composite's mechanical properties.

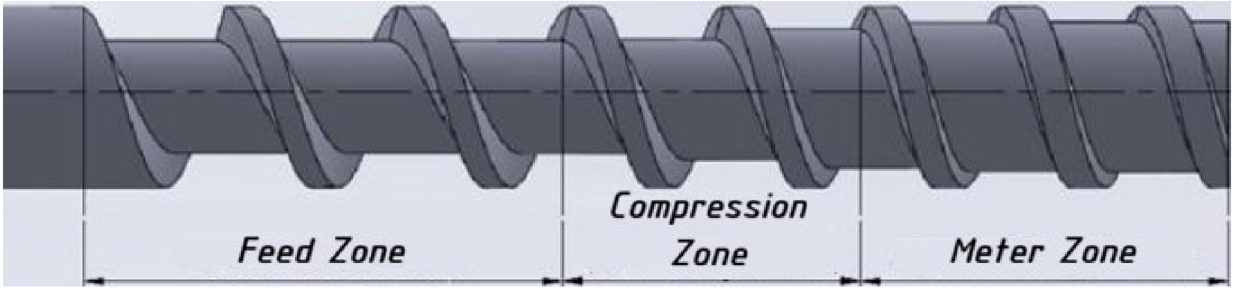

Fig. 3. Screw geometry of a single-screw extruder [6]

Plasticizing Screw Zones [3, 6].

The geometry of a conical screw consists of three clearly defined zones: feed, compression, and metering (Fig. 3). Each zone performs a specific function in the process of melting, mixing, and stabilizing the composite.

Let's examine the operational characteristics and potential issues of each section.

Feed Zone [3, 6]. ABS pellets and chopped fibers from the hopper fill the deep channels of the screw's initial turns by gravity. The rotation of the screw relative to the stationary barrel pushes the solid material forward. After passing through the feed gaps, the pellets are completely isolated by the cylinder walls, which leads to compaction and the displacement of air back into the hopper. In most of the feed zone (40–50% of the screw length), the material moves in a plug flow—all particles have the same velocity.

Feed performance depends on the flow properties of the composite. Low-density materials (less than 0.5 g/cm³) are prone to plugging and throat blockages. Highly compressible composites (Kevlar fibers, ground ABS) also cause feeding problems due to volume compaction. For ABS/CF/Kevlar, a vibratory feeder and a gravimetric feeder are recommended for stable operation of the feed zone. This zone is critical for continuous extruder operation, as feeding issues lead to output pulsations and filament irregularities.

Compression Zone [3, 6]. The friction that propels the pellets forward in the feed zone, together with the active barrel heaters, initiates the melting of the material. Although partial melting may begin as early as the feed zone, the main transformation of solid ABS pellets into melt occurs precisely in the compression zone. During melting, the volume of the material decreases, so the height of the screw flights gradually decreases along the entire length of this section (30–40% L). This creates the pressure necessary to extrude the melt through the die.

The transition from a solid to a viscous state changes the transport mechanism. Shear flow becomes dominant—the melt, trapped between the stationary barrel and the rotating screw, moves forward. The shear flow not onl ly transports the material but also generates friction between the melt, the screw, and the cylinder, which intensifies the heating and final melting of the thermoplastic composite.

Recommended compression ratios for thermoplastic matrix composites based on ABS are given in Table 1.

For pure ABS, a compression ratio of 2.5:1 is standard, which optimally accounts for the material's thermal sensitivity (decomposition temperature ~260°C) and its average compression [7]. This parameter ensures sufficient pressure for filament formation without excessive heating, which can lead to degradation of the polymer chains.

When carbon fibers (CF) are introduced, the ratio is reduced to 2.0–2.5:1 due to the high abrasiveness of the filler and the lower bulk effect of the fibers compared to pellets. Reduced compression decreases friction, extends the screw's service life, and prevents local overheating, as CF impairs the composite's thermal conductivity.

Table 1

Recommended compression ratios for ABS composites

Material	Compression ratio	L/D
Pure ABS	2.5:1	24:1
ABS + carbon fiber (CF)	2.0–2.5:1	22–24:1
ABS + Kevlar fibers	2.5–2.8:1	24:1
ABS + CF + Kevlar (hybrid)	2.2–2.6:1	24:1

A ratio of 2.5–2.8:1 is recommended for Kevlar reinforcement, as aramid fibers are less abrasive than CF, have higher compressibility, and promote better homogenization due to their microfibrillar structure. This allows for a slight increase in compression without the risk of wear or degradation.

In ABS + CF + Kevlar hybrid composites, a compromise ratio of 2.2–2.6:1 is recommended, which accounts for the combined effect: the abrasiveness of CF is offset by the ductility of Kevlar, ensuring a balance between productivity, melt quality, and equipment longevity.

For fiber-reinforced composites, the compression ratio is reduced by 0.2–0.5 compared to a pure matrix to avoid excessive heating, channel clogging, and accelerated screw wear.

Metering section [3, 6]. The geometric section of the screw is the metering section, also known as the transport section. Here, the channel depth is constant along the entire length (30% L), ensuring a stable melt flow before exiting the die head. In this zone, all solid ABS particles are fully melted, allowing for effective mixing. Mixing is critically important for compounding when small doses of colorants or modifiers are added to the hopper—the spiral motion of the melt during screw rotation evenly distributes the components. Additionally, the metering zone equalizes the melt temperature throughout the entire volume.

Extruder heating zones [3]. The geometric zones of the screw correspond to the individual temperature zones of the barrel. Although the barrel is a solid tube, the low thermal conductivity of steel and heat loss through the material allow for the creation of different operating modes using independent heaters (150–300 W/zone) and thermocouples. In a 3D printer, the heaters provide 100% of the melting energy. In a screw extruder, heaters provide only 10–20% of the heat—the majority is generated by shear heating. Therefore, the temperature is set close to the melting point to minimize degradation of the ABS composite.

Functions of zone heating: initiating melting in the feed zone (210–220°C), partial softening of the pellets before shear heating; regulation in the compression zone (225–240°C), a higher temperature reduces viscosity near the cylinder wall, decreasing shear heating; a lower temperature intensifies it; stabilization in the metering zone (240–250°C), fine-tuning of melt viscosity for a stable 1.75 mm filament.

Zone temperature settings. Pellet manufacturers typically provide recommended settings for a three-zone extruder, which serve as a starting point for configuration but require adjustment depending on the process conditions. Optimal values for ABS composites are determined by the characteristics of each screw zone. The feed zone heaters should be set to 210–220°C, which is sufficient to soften the ABS pellets without fully melting them. Too high a temperature (above 225°C) leads to clogging of the feed zone, where the melt fills the channel and blocks the feed of raw material. Conversely, too low a temperature (below 205°C) increases pressure in the cylinder, as the melting rate cannot keep up with the volume reduction in the compression zone.

In the compression zone, 225–240°C is recommended—at or slightly above the melting point of ABS (~220°C). Temperature affects shear heating. A higher temperature reduces melt viscosity near the cylinder wall and decreases friction, which can lead to incomplete melting before reaching the metering zone. A lower temperature intensifies shear heating, ensuring complete conversion of solid polymer particles into a homogeneous melt.

The metering zone operates at 240–250°C, which is slightly higher than the temperature in the compression zone. This mode ensures stable melt viscosity, complete dissolution of residual particles, and optimal rheological properties for forming a 1.75 mm diameter filament. The temperature gradient across the zones (feed < compression < metering) creates a controlled melting process without overheating the heat-sensitive composite.

Process control is based on pressure stability, melt color, and filament diameter. Pulsations, color changes, or unstable geometry indicate the need to adjust the temperature profile.

In addition to the screw unit, the integrated design includes a gravimetric feed hopper (preferably with a vibrating feeder for stable dosing of the ABS/CF/Kevlar mixture), a forming head with an adjustable 1.8 mm nozzle, a cooling system for filament crystallization in 15–20 seconds, a laser diameter sensor (±0.01 mm) with a servo-driven take-up unit and a winding device with tension control.

Conclusions

A single-screw extruder is the optimal solution for manufacturing composite filaments based on ABS thermoplastic reinforced with carbon and Kevlar fibers. Key design features include the zonal division of the screw into feeding, compression, and metering sections with an optimal compression ratio that accounts for the thermal sensitivity of the matrix and the abrasiveness of the fillers. Precise cylinder clearance, gravimetric feeding, and zonal heating ensure a stable melt with uniform fiber distribution without material degradation. The proposed temperature profile and design solutions guarantee the formation of a 1.75 mm diameter filament with high mechanical properties for the additive manufacturing of parts in mechanical engineering, robotics, and other industries requiring impact-resistant structural elements.

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