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TECHNOLOGY FOR MODERNIZING WEAR-PRONE TRANSMISSION SYSTEMS IN LIGHT INDUSTRY MACHINERY USING COMPOSITE MATERIALS

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Abstract: The operational efficiency of light industry transmission mechanisms is strongly influenced by friction, wear, and material tribological properties. Conventional metal gears exhibit accelerated wear under high speed and load conditions. This study evaluates the modernization of wear-prone transmission elements using composite materials. Experimental investigations of PA66 polyamide and PT-610/ PT-650 textolite composites focused on friction coefficient, wear rate, and thermal behavior. Results show that the friction coefficient decreased from 0.15 to 0.06, mass wear rate from 4.8 to 1.0 mg/h, and contact temperature from 82 °C to 54 °C compared to metal gears. Numerical simulations in SolidWorks Simulation confirmed improved stress distribution and reduced deformation. The findings demonstrate that composite-based transmissions enhance durability, reduce energy losses, and improve overall energy efficiency.
Keywords: light industry machinery; tribology; friction; wear; composite materials; textolite; polyamide; transmission mechanisms; polymer gear; spur gear; wear rate; contact temperature; energy efficiency.

Introduction

Transmission mechanisms in light industry machinery operate under high rotational speeds and continuous loading, resulting in intensive friction, wear, and energy losses in metallic components [1,2]. Elevated contact temperatures, surface deformation, and unstable lubrication regimes significantly reduce the service life of transmission elements [3]. Therefore, improving tribological stability and operational efficiency remains a critical challenge in light industry machine building [4].
Recent studies indicate that composite materials outperform traditional metals due to their low friction coefficients, high wear resistance, and partial self-lubricating properties [5,6]. Materials such as textolite, polyamide, and fiber-reinforced polymer composites contribute to reduced vibration, lower frictional heat generation, and improved energy efficiency [7,8]. In addition, their corrosion resistance and adaptability to varying operating conditions make them particularly suitable for light industry applications [9].

Structural modernization of transmission mechanisms using composite materials enables improved stress distribution, reduced maintenance costs, and enhanced operational reliability

[10]. The integration of CAD/CAE tools further allows optimization of material selection and design parameters prior to implementation [11]. Accordingly, this study investigates the tribological performance of selected composite materials and assesses their applicability for modernizing wear-prone transmission elements under industrial operating conditions [12].

Methods

Research object and geometry

A cylindrical spur gear transmission commonly used in light industry machinery was selected. The gear parameters were: module m = 2.5 mm, number of teeth z = 24, face width b = 25 mm, pressure angle α = 20°, and center distance a = 60 mm. The density of metallic materials was 7800 kg/m³, while composite materials ranged from 1350 to 1450 kg/m³. Metallic gear hardness was 200–280 HB, whereas composite materials exhibited 60–90 HB.

Materials

Two metallic materials (AISI 1045 steel and heat-treated AISI 4140 steel) and three composite materials (PA66 polyamide, PT-610 textolite, and PT-650 textolite) were investigated. Metallic gears served as reference materials.

Manufacturing of composite gears

PA66 gears were produced by injection molding and conditioned at 23 ± 2 °C and 50% relative humidity for 24 h. PT-610 and PT-650 textolite gears were manufactured by laminated compression molding, followed by thermal treatment at 120 °C for 2 h to reduce residual stresses.

Tribological testing

Tribological tests were carried out on a gear test rig in accordance with ISO 6336 and ASTM G99 principles. Tests were performed under loads of 200–800 N, rotational speeds of 500–1500 rpm, and durations of 1–5 h, under dry and lubricated (Industrial-20 oil) conditions. Load and speed were continuously monitored using calibrated sensors.

Wear and temperature measurement

Gear wear was evaluated by mass loss measurements using an analytical balance with 0.1 mg resolution, and wear rate was expressed in mg/h. The maximum contact temperature in the meshing zone was recorded using a non-contact infrared thermal camera.

Numerical modeling

Finite element analysis was conducted in SolidWorks Simulation to evaluate stress distribution, deformation, and contact loading. Experimentally measured friction coefficients were used as input parameters, and numerical results were validated against experimental data.

Statistical analysis

All results are presented as Mean ± SD. Statistical reliability was assessed at a 95% confidence level.

RESULTS

During the experimental investigations, the coefficient of friction, mass wear rate, maximum contact temperature, and elastic deformation of spur gears manufactured from each tested material were determined. All experimental results are presented as average values obtained from at least three repeated tests, ensuring the reliability and repeatability of the measurements.

Evaluation of the coefficient of friction

The experimental results revealed a significant difference in the coefficient of friction between metallic and composite materials, as summarized in Table 1.

Table 1. Average coefficient of friction (μ) for the investigated materials

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Material	Coefficient of friction (μ)
AISI 1045 steel	0.15
AISI 4140 steel	0.13
PA66 polyamide	0.08
PT-610 textolite	0.07
PT-650 textolite	0.06

The results indicate that metallic spur gears exhibit higher coefficients of friction than composite materials. Among the tested materials, PT-650 textolite demonstrated the lowest coefficient of friction, confirming its superior tribological performance under the applied operating conditions.

Table 2. Mass wear rate of the investigated materials

Material	Wear rate (mg/h)
AISI 1045 steel	4.8
AISI 4140 steel	3.6
PA66 polyamide	1.7
PT-610 textolite	1.3
PT-650 textolite	1.0

The results indicate that spur gears manufactured from composite materials exhibit 3–5 times lower wear rates compared to metallic gears. Among the investigated materials, PT-650 textolite demonstrated the lowest wear rate, indicating superior operational stability.

Contact temperature

The measured maximum contact temperatures for spur gears manufactured from the investigated materials are presented in Table 3.

Table 3. Maximum contact temperature of the investigated materials

Material	Temperature (°C)
AISI 1045 steel	82
AISI 4140 steel	76
PA66 polyamide	65
PT-610 textolite	58
PT-650 textolite	54

The results indicate that spur gears manufactured from composite materials operate at contact temperatures that are approximately 25–35% lower than those of metallic counterparts. Among the investigated materials, PT-650 textolite exhibited the lowest maximum contact temperature, indicating enhanced thermal stability of the transmission system.

Elastic deformation of the gear tooth surface

The maximum elastic deformation at the gear tooth tip was determined based on numerical simulations performed using the SolidWorks Simulation environment. The obtained results are summarized in Table 4.

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Table 4. Maximum elastic deformation of gear teeth

Material	Deformation (μm)
AISI 1045 steel	5.1
AISI 4140 steel	4.6
PA66 polyamide	9.4
PT-610 textolite	7.8
PT-650 textolite	7.2

The results show that metallic materials exhibit the lowest elastic deformation due to their higher hardness and stiffness. In contrast, composite materials demonstrate relatively higher elastic deformation, which facilitates a more uniform distribution of contact loads along the tooth surface and enhances impact load damping. Among the investigated composites, PT-650 textolite exhibited an optimal balance between elastic deformation and mechanical strength, indicating favorable performance for gear transmission applications.

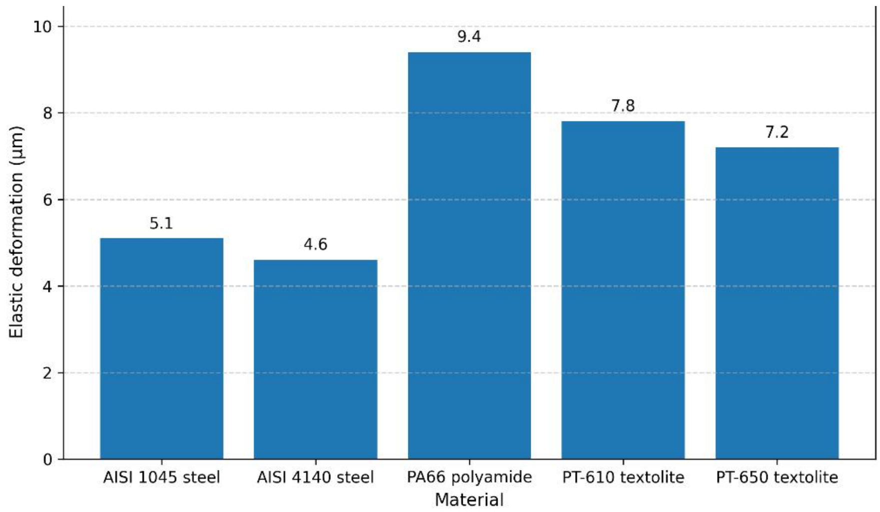

Figure 1. Maximum elastic deformation of the gear tooth surface.

Figure 1 presents the maximum elastic deformation at the gear tooth tip obtained from SolidWorks Simulation. The figure highlights the differences in deformation behavior between metallic and composite materials under identical loading conditions.

Distribution of contact stresses

The distribution of contact loads and Von Mises equivalent stresses was analyzed based on numerical simulations performed in the SolidWorks Simulation environment.
For metallic spur gears, localized stress concentrations were observed at the tooth tip and root regions. In contrast, gears manufactured from composite materials exhibited a more uniform stress distribution along the contact interface. Notably, the spur gear made of PT-650 textolite showed a significant reduction in peak stress values, indicating improved load-sharing behavior and enhanced resistance to stress concentration under identical loading conditions.

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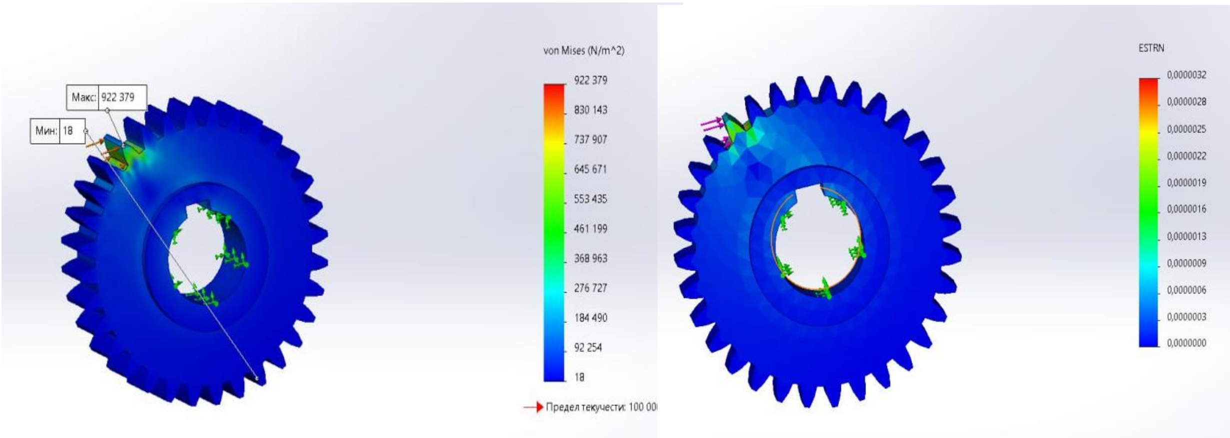

Figure 2. Stress and deformation distribution in an AISI 1045 steel spur gear

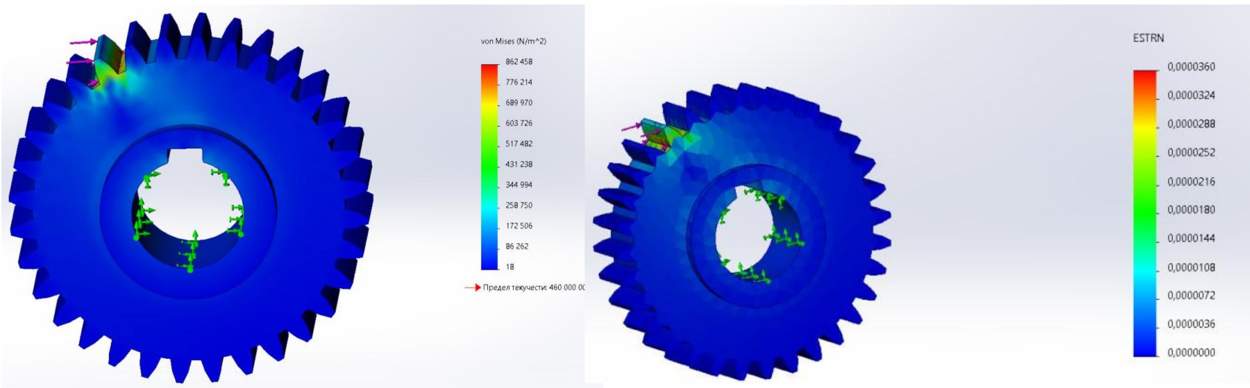

Figure 3. Stress and deformation distribution in a PT-650 textolite spur gear

Integrated performance assessment

The overall operational performance of the investigated materials was evaluated using an integrated approach based on the coefficient of friction, wear rate, contact temperature, and elastic deformation parameters. The results of the integrated assessment are summarized in Table 5.

Table 5. Integrated performance ranking of the investigated materials

Rank	Material	Overall assessment
1	PT-650 textolite	Most stable
2	PT-610 textolite	Good
3	PA66 polyamide	Moderate
4	AISI 4140 steel	Best among metallic materials
5	AISI 1045 steel	Reference material

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The integrated evaluation results indicate that PT-650 textolite exhibits the highest overall operational performance, considering the combined effects of friction reduction, wear resistance, thermal stability, and deformation behavior. This confirms its suitability as an efficient material for the modernization of wear-prone transmission components in light industry machinery.

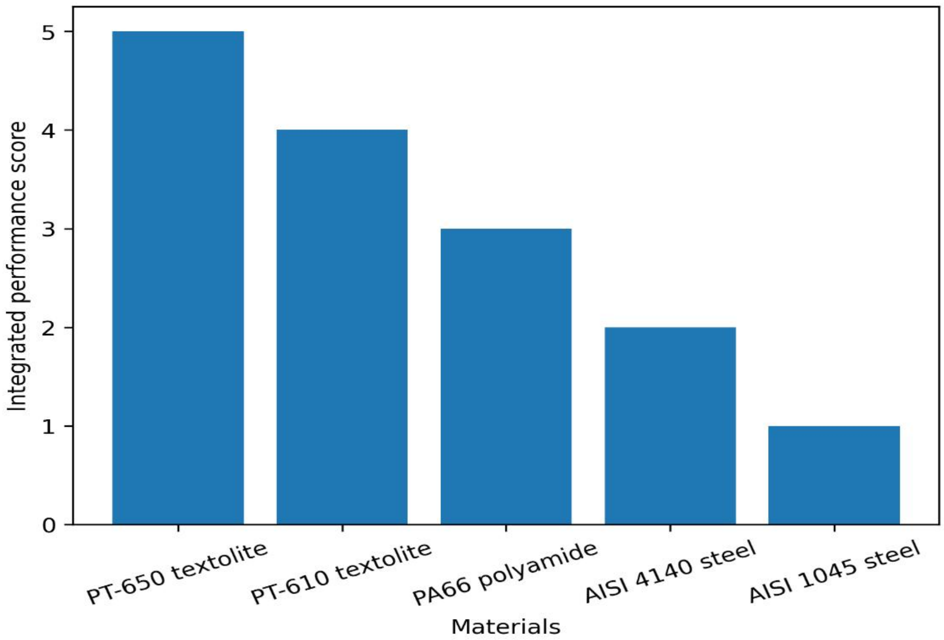

Figure 4. Integrated operational performance of the investigated materials.

Figure 4 presents the integrated performance assessment based on the coefficient of friction, wear rate, contact temperature, and elastic deformation parameters, allowing a comparative visualization of the overall operational behavior of the tested materials.

DISCUSSION

Experimental investigations combined with SolidWorks Simulation analyses revealed pronounced differences in the tribological performance of metallic and composite spur gears. Similar comparative trends between metallic and polymer-based gears have also been reported in earlier tribological studies [16–18]. The results clearly indicate that composite gear materials provide superior frictional, wear, thermal, and operational characteristics compared with conventional metallic designs [19].

Metallic gears exhibited relatively high friction coefficients ($\mu = 0.13–0.15$), which can be explained by rigid contact conditions, limited elastic compliance, and unstable lubrication regimes at the meshing interface [20,21]. In contrast, PT-650 and PT-610 textolite composites demonstrated substantially lower friction coefficients ($\mu = 0.06–0.07$), primarily due to their laminated structure and partial self-lubricating behavior, which is consistent with previously reported findings on phenolic- and fabric-reinforced composites [22,23].

Wear analysis showed that metallic gears were predominantly affected by abrasive and adhesive wear, manifested by surface grooves, micro-scratches, and localized material transfer. Similar wear mechanisms in steel spur gears operating under mixed friction conditions have been widely documented in the literature [24,25]. Composite gears, especially PT-650 textolite, exhibited enhanced surface stability, fewer severe wear features, and wear rates reduced by a factor of 3–5 compared with metallic counterparts. The fibrous structure of textolite contributed

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to energy dissipation and more compliant contact interaction, which aligns with reported observations for laminated composite tribo-pairs [26,27].

Thermal measurements indicated that metallic gears reached contact temperatures of 76–82 °C, which may accelerate surface degradation and lubricant breakdown during prolonged operation [28]. In contrast, composite gears operated at significantly lower temperatures (54–58 °C), improving thermal stability and reducing the risk of material degradation [29]. Similar reductions in frictional heating for polymer and composite gears have been reported by other researchers [30].

Numerical simulations further confirmed that the higher elastic deformation of composite gears (7–10 μm) promotes more uniform load distribution and effective damping of impact loads. Comparable effects of elastic compliance on stress redistribution and vibration attenuation in composite gear systems have been demonstrated in FEM-based studies [31,32]. Conversely, metallic gears tend to develop localized stress concentrations at tooth roots and contact edges, which may accelerate fatigue crack initiation and propagation [33].

Based on an integrated performance evaluation, PT-650 textolite was identified as the most balanced material for wear-prone transmission components [34]. PT-610 textolite is suitable for moderately loaded gear systems, while PA66 polyamide is particularly effective in applications requiring reduced noise and vibration [35]. Metallic gears remain preferable for operating conditions involving severe impact and heavy loading [36].

Conclusion: This study investigated the modernization of cylindrical spur gear transmissions in light industry machinery using composite materials through experimental testing and numerical modeling. The results demonstrate that composite gears exhibit friction coefficients 2.0–2.5 times lower and wear rates 3–5 times lower than metallic gears, leading to reduced energy losses and improved operational efficiency. A reduction in maximum contact temperature by 25–35% enhanced thermal stability and minimized surface degradation during prolonged operation. Increased elastic deformation in composite gears promoted more uniform load distribution and effective damping of impact loads. Among the investigated materials, PT-650 textolite showed the most balanced performance for wear-prone transmission elements, while PT-610 textolite and PA66 polyamide were suitable for moderate-load and low-noise applications, respectively. Overall, the findings confirm that composite-based transmission modernization provides an effective approach for extending service life and improving the energy efficiency of light industry machinery.

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