Durability of involute gear pairs manufactured by rapid prototyping methods

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Abstract: The durability of cylindrical spur gears made of ABS and PU manufactured using the FDM (Fused deposition modeling) additive method and vacuum casting was investigated. The tests were carried out for pairs of gears with an involute profile for three values of the profile angle: 20, 25 and 30° to determine the effect of the profile angle on the gear operation time. The effect of running-in on gear durability was also assessed.

Keywords: gears, involute profile, additive manufacturing technologies, ABS, PU.

Trwałość ewolwentowych par kół zębatych wykonanych metodami szybkiego prototypowania

Streszczenie: Zbadano trwałość walcowych kół zębatych o zębach prostych z ABS i PU wykonanych metodą przyrostową FDM (Fused deposition modeling) i odlewania próżniowego. Badania przeprowadzono dla par kół zębatych o zarysie ewolwentowym dla trzech wartości kąta zarysu: 20°, 25° i 30° w celu określenia wpływ kąta zarysu na czas pracy przekładni. Oceniono również wpływ docierania na trwałość przekładni.

Słowa kluczowe: koła zębate, zarys ewolwentowy, technologie przyrostowe, ABS, PU.

Rapid prototyping (RP) is employed in numerous industries due to its capability to fabricate parts with complex and non-standard geometries without dedicated tooling [1-6]. Consequently, many components that were conventionally manufactured can be replaced by a reduced number of parts or even a single part. This not only shortens the time required for product launch but also reduces mass and, most importantly, costs associated with traditional manufacturing methods [7–10].

Although the application of RP systems theoretically enables the fabrication of any functional part with intricate shapes, it is crucial to acknowledge that each method possesses certain limitations in its application. For instance, the fused layer extrusion method exhibits varying mechanical properties depending on the material deposition direction [11-13]. The designer must consider the material properties, which are of paramount importance for selecting the appropriate process and meeting design requirements (geometry, surface quality, physical properties).

These attributes render rapid prototyping methods suitable for the fabrication of gears [14–20], which find application where, for example, lightweight and custom transmissions, tailored to specific operational demands or with optimized tooth geometry for mass and noise reduction–difficult or impossible to achieve with conventional machining methods–are required. Due to their lower durability compared to metal gears, they are used, for instance, in the verification of design concepts prior to production implementation and can serve as functional prototypes for preliminary testing.

Fused deposition modeling (FDM) is one of the most popular additive manufacturing techniques, which involves the deposition of successive layers of molten polymer extruded through a nozzle [21, 22]. Filaments are fed to the nozzle using a roller mechanism. The machine control system regulates the heating temperature of the polymer, which is selected so that the extruded material, after cooling after leaving the nozzle head, connects with the previously deposited layer.

Vacuum casting (VC) is a method offering the possibility of obtaining complex geometries. It is particularly useful in prototyping and the production of elements with high aesthetic and functional requirements. Manufacturing parts under reduced pressure minimizes the formation of air bubbles and ensures high surface quality and dimensional accuracy [23–26].

To enhance the durability of gear transmission, the gears can undergo a running-in process. This process

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involves operating the gear set under a light load for a specific duration, during which microscopic removal of surface irregularities and improved conformity of the flank surfaces of the mating teeth occur. The effect of running-in is a more uniform distribution of loads acting on the teeth, a reduction in friction, noise, and vibration, which consequently improves the efficiency of the gear transmission [27].

The running-in of polymer gears differs from that of metal gears due to the inherent properties of polymeric materials. In contrast to metals, polymers exhibit greater elasticity and lower wear resistance. Consequently, the running-in process for polymer gears is particularly significant in applications demanding quiet operation and minimal friction, such as in precision mechanisms.

The aim of the work was to investigate the durability of spur gears made of ABS and PU, manufactured using the FDM (Fused deposition modeling) method and the vacuum casting method, respectively. The influence of changes in the involute pressure angle and the running-in process on the service life of the gear transmission was also determined. The gears made of ABS were fabricated using a uPrint (Stratasys, Eden Praire, MI, USA) with the following parameters: layer thickness – 0.254 mm and a high-density infill. PU resin mixture was injected into the mold and placed in a vacuum chamber. Initial curing of the prototype occurs after a period of several dozen seconds to several (about ten) minutes. Parts made from PU achieved their strength parameters after thermal treatment involving baking the prototypes in the molds for an appropriate time at a constant temperature. After curing, the element was removed and optionally subjected to final finishing.

EXPERIMENTAL PART

Materials

Acrylonitrile-butadiene-styrene (ABS) trade name Digital ABS Plus (Stratasys, Rheinmünster, Germany) and polyurethane (PU) trade name RenPIM® 5286 (Huntsman Advanced Materials, The Woodlands, TX, USA) were used.

Fabrication of gears models

CAD models of the gears for the test rig were created in the Autodesk environment. The tooth profiles were generated using a machining simulation method, and the remaining wheel components were created using solid modeling. This resulted in CAD models of a spur gear pair with a gear ratio of 17 : 67 (Fig. 1). Subsequently, the data were exported to STL format [28], and physical models intended for test rig experiments were fabricated using rapid prototyping methods – wheels made of ABS copolymer were produced using the FDM method, while polyurethane resin PU 5286 was employed in the VC method.

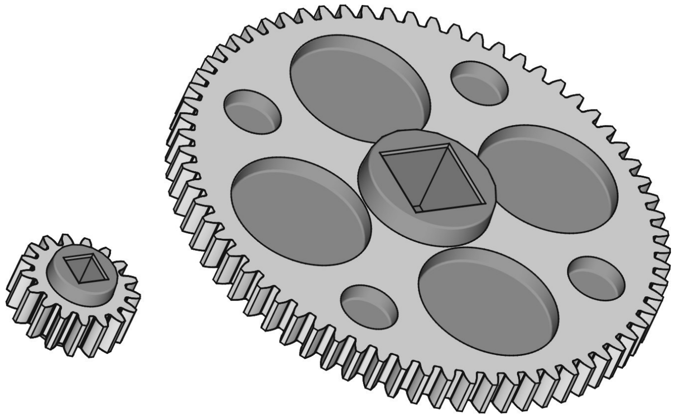

Fig. 1. CAD models of the tested gear pairs

The gear pairs for the test rig were manufactured with involute teeth (without correction) with a module of m = 1.5 mm and three pressure angle values: 20°, 25°, and 30°, which were designated as E20, E25, and E30, respectively. Each pair had a constant face width and the same hub dimensions.

Durability test

The stand for testing the durability of polymer gears shown in Fig. 2 is universal in nature, and its modular design allows for testing individual sets and pairs of gears of individual gear stages, as well as for connecting various sensors and measuring devices depending on the need to record selected parameters. Gearbox test stand (Fig. 2) consists of: a three-phase induction motor (1) controlled by a frequency inverter via clutch (5), which drives the tested gearbox (2). The gearbox is loaded by a brake (3), which introduces a tensioning torque into the system, measured by a torque meter (4). The angular position of the gearbox shafts is determined digitally by position transducers. The temperature of the gearbox is

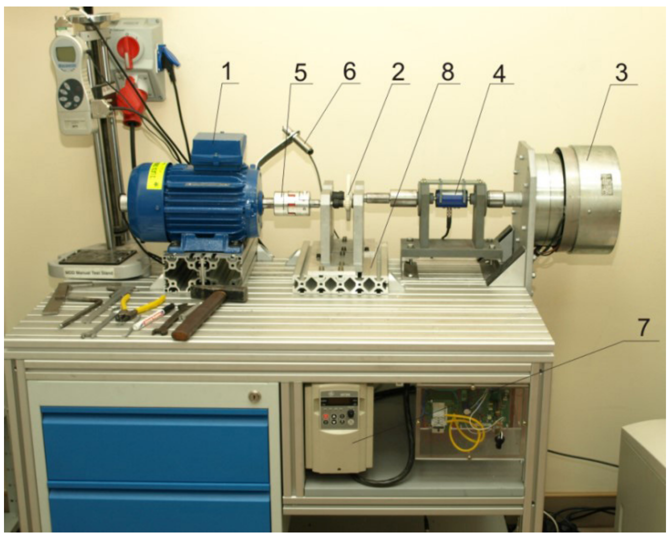

Fig. 2. Gearbox test stand: 1 – motor, 2 – gearbox, 3 – brake, 4 – torque meter, 5 – clutch, 6 – pyrometer, 7 – measuring system, 8 – movable supports

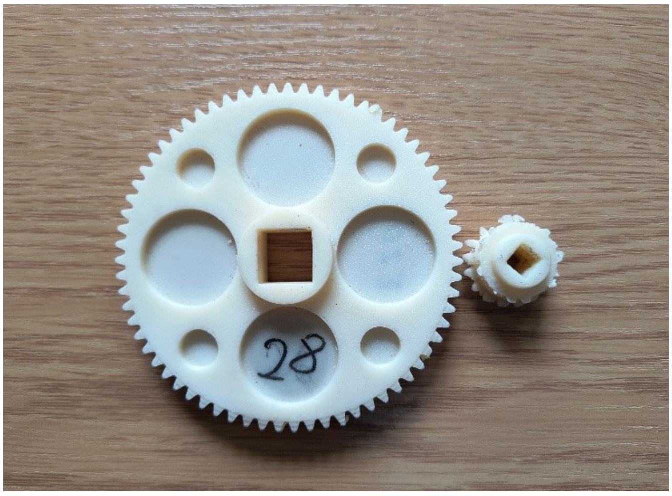

Fig. 3. View of an example pair of gears (made of ABS) after the test

measured contactless using thermal radiation via pyrometers (6). All data from the test are recorded by a measuring system (7) and transmitted to a computer.

RESULTS AND DISCUSSION

Gear pairs manufactured by rapid prototyping methods from ABS and PU polymers were conducted at a constant rotational speed of 1500 rpm and a loading torque of 4 Nm. After conducting the basic tests, the program was modified by introducing a running-in phase (under the system's own weight load) for the meshing gears. The measure of durability for the tested gears was the operating time until failure, defined by tooth breakage (Fig. 3). During the tests, the torque loading the transmission and the angular position of the shafts were recorded.

The aim of the research was to determine the operating time of the gears until failure and to compare the durability of selected polymeric materials used in rapid prototyping. A methodology for testing gears made of polymeric materials was developed, which can be applied in the evaluation of transmissions for serial production. The results of the test cycles are presented in Fig. 4 as average values from three repetitions for each material (ABS, PU) and involute profile geometry with pressure angles of 20, 25, and 30°.

Based on the data shown in Fig. 4, it can be stated that transmissions made of ABS have longer operating times than transmissions made of PU. It was also observed that the operating time of the transmission increases with an increase in the tooth pressure angle. The increase in operating time results from the increasing contact ratio while maintaining a constant center distance. The next stage of the research program implementation was the introduction of a preload originating from the unloaded operating system. Fig. 5 shows a representative change in the torque over the running-in time for an involute gear pair with a 20° pressure angle made of ABS. Based on the output torque curve as a function of running-in time, it can be observed that the highest load occurs in the initial phase of running-in, and after approximately 30 min, the decrease in torque is minimal. This is also confirmed by the sound intensity measurements: 83.4 dB at the start of the test, 81.8 dB after 30 min, and 81.6 dB after 60 min of running-in. This suggests that, in the general case for the adopted parameters, a running-in time of 30 min is sufficient. To better illustrate the differences, Figs. 6 and 7 show the influence of running-in and material type on the operating time of the tested gear pairs.

The operating time of the transmissions made of PU resin increases by approximately 41% for the transmission with a pressure angle of 25° compared to the transmission with a tooth pressure angle of 20°. For the transmission with a pressure angle of 30°, the operating time increases by about 47% compared to the transmission with a pressure angle of 20°. After the running-in process, the operating time increases for the transmissions with pressure angles of 20 and 25°, and 30% by approximately 25, 20, and 21%, respectively.

The operational lifespan of polyurethane resin gears can be further extended through the enhancement of their mechanical properties via the incorporation of fillers into the base material [29, 30].

For the ABS made transmissions gears, the operating time also increased with an increase in the tooth pressure angle. The increase in operating time relative to gears

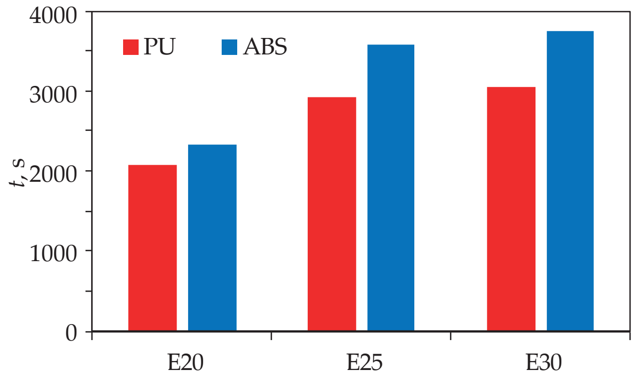

Fig. 4. Operating time of involute gears at tested pressure angles

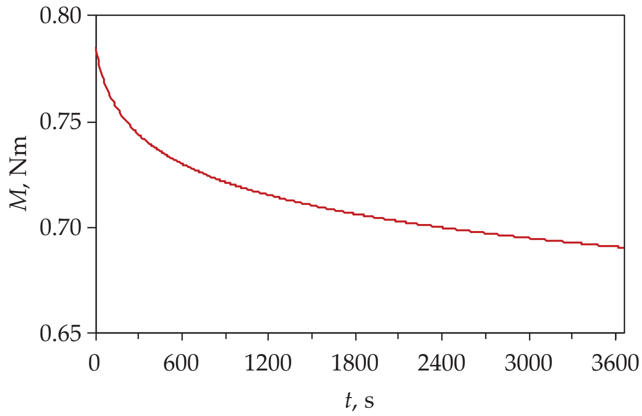

Fig. 5. Changes in the load on the gear pair (E20, ABS) during running-in

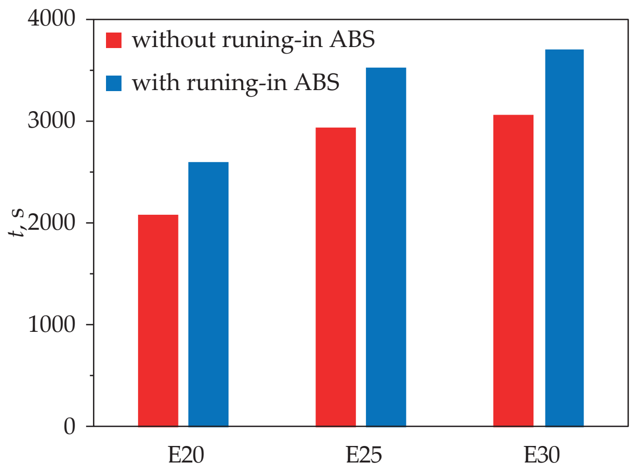

Fig. 6. Operating time of involute gear pairs for examined pressure angles

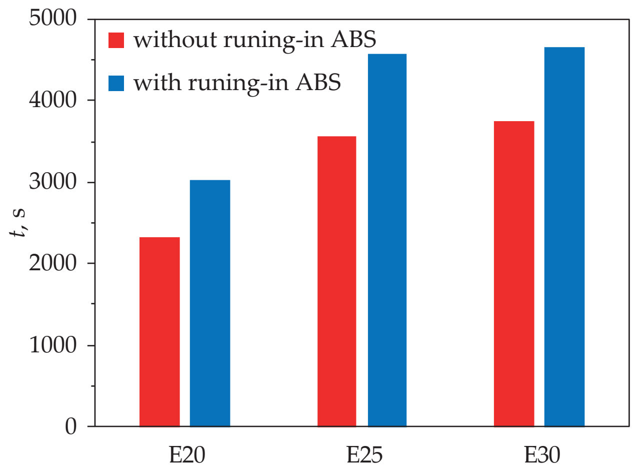

Fig. 7. Operating time of involute gear pairs for tested pressure

with a 20° pressure angle was 53% longer for gears with a 25° pressure angle and approximately 61% longer for gears with a 30° pressure angle. After the running-in process, the operating time of the transmissions for gears with pressure angles of 20°, 25°, and 30° increased by 30%, 28%, and 24%, respectively.

After the current investigation, future research aimed at extending the operational lifespan of additively manufactured gears may involve the implementation of thermal post-processing [31, 32] to enhance the mechanical performance of FDM fabricated components [33].

CONCLUSIONS

Comparative analysis of operating times showed that, among the tested polymers, ABS showed a higher durability by 12–30% than PU, depending on the pressure angle and running-in conditions. For both tested materials, the operating time of the gears increased with increasing pressure angle. The introduction of the running-in process (30 min) affected the operating characteristics of the gear, which was observed on the basis of changes in the load torque as a function of time and an extension of the operating time of each tested gear pair by 20–25% for PU and 17–30% for ABS. The decrease in the torque during running-in indicates the adaptation of the mating tooth surfaces. This suggests the need to run-in polymer gears with an involute profile before working under full load. The correlation with this phenomenon was confirmed by sound intensity measurements.

Authors contribution

B.K. – conceptualization, methodology, writing-original draft, supervision, writing-review and editing, validation; J.P. – conceptualization, methodology, writing-original draft, formal analysis, validation; M.D. – investigation, software, visualization; T.D. – investigation, software, visualization.

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Conflict of interest

The authors declare no conflict of interest.

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