Plastic gears: State-of-the-art design and technology (review)

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Abstract. *A review of the retrospective and modern state in the field of theory and practice of plastic gears is presented. Various aspects of such gears design, technology and applications are discussed. It is noted that corresponding problems are under consideration permanently on the last common engineering meetings and specialized ones. The analysis of the papers allows to conclude that main trends in plastic gears are the following once: comparison the experimental results with VDI 2736 and JIS 1759 normative paper data; development of the methods of accelerated tests; investigation on fatigue bending strength, pitting and wear resistance; improvement of the noise, vibration and harshness behaviors; analysis and optimization of reinforced composite materials structure; application of additive technologies; fabrication of high precise plastic gears and development of computer-aided design methodology.*

1 Introduction

Design, technology and application of the plastic and polymer composite gears are remaining a subject of intensive investigation. Modern state and the last results in this field permanently discussed on the common engineering and especially topical conferences on gearing are discussed.

From the rest ones it should be mentioned the followings:

- International Conference on Gears (Garching near Munich, Germany) (ICG) 2005, 2010, 2015, 2017, 2018, 2019.
- The 10th and 11th International ASME Power Transmission Conference (Las Vegas, Nevada, USA) (PTC) 2007, 2011.
- International Conference "Theory and Practice of Gearing" (Izhevsk, Russia) (TPG) 2014, 2017.
- International Gear Conference (IGC) (Lyon, Villeurbane, France) 2014, 2018.
- International Conference on High Performance Plastic Gears (Garching near Munich, Germany) (HPPG) 2015, 2017, 2019.
- International Conference "Machine and Industrial Design in Mechanical Engineering" (2010, Palic, Serbia; 2012, Balatonfüred, Hungary; 2018, Novi Sad, Serbia) (KOD).
- International Conference "Problems of Quality and Lifetime of Gears and Power Transmissions" (GPT) (the last ones: 2013, Sevastopol; 2014, Odessa, Ukraine).
- International BAPT Conference (BAPT) – 2019.
- Belarussian National Congress on Theoretical and Applied Mechanics (Minsk, Belarus) (CTAM), 2013, 2016, 2019.

It should be noted in general the crossover from the separate lectures (ICG, TRG, KOD, GPT, CTAM) to the special conference sessions (PTC, IGC) and even to the special purpose conferences (HPPG). More detailed distribution IGC, PTG and HPPG plastic gear topic papers is showed below.

IGC-2014: Session 1: Worm gears – 1; Session 4: Plastic gears – 3; Session 29: Monitoring detection of failures – 1; Poster session – 2.

IGC-2018: Sessions 26 and 30: Plastic gears – 7.

PTG-2007: Session: PTG-08: Design and analysis (DET C 2007 – 34155; 34170; 34057; 34470; 34093) – 5.

PTG-2011: Session: Plastic gears (DET C 2011 – 47426; 47501; 47554; 48372) – 4.

HPPG-2015: Sessions:

- Possibility and potentials of plastics in gear application – 4.
- Plastic materials and tribology – 4.
- Typical and future materials – 3.
- Limits and chancer of shape and form – 4.
- Plastic gears – prediction and calculation of endurance and lifetime – 3.
- Plastic gears – experimental and analytical determination of load carrying capacity – 4.

HPPG-2017: Sessions:

- Possibilities and potentials of plastic gear application – 4.
- Tribology of plastic gears – 4.
- NVH of plastic gears – 6.
- Comparison of typical and future materials – 4.
- Load carrying capacity of plastic gears – 4

HPPG-2019: Proceeding divisions (pp. 1267-1495):

- Strength evaluation – 10.
- Tooth flank load capacity – 4.
- NVH/condition monitoring – 3.
- Application – 4.

General share of polymeric gear topic papers in the total amount of conference papers is shown in Table 1. In connection with frequent mentions of aforesaid conferences in references we shall use its abbreviations.

Table 1. *Share of conference polymeric gear topic papers in the total amount ones.*

Conference denomination, year	Total conference paper number / Polymeric gear topic paper
ICG-2015 -2010 -2015 -2017 -2019	112/3 26/3 71/- 134/- 104/-
PTG-2007 -2011	116/5 70/4
TPG-2014 -2015 -2017	80/4 – 39/1
IGC-2014 -2018	125/7 144/7
HPPG-2015 -2017 -2019	22/22 22/22 21/21
KOD-2010 -2012 -2018	70/- 107/- 167/1
GPT-2012 -2013 -2014	60/2 62/1 57/1
BAPT-2019	83/2
CTAM*-2013 -2016 -2019	39/- 28/1 12/1

*The paper numbers of the conference session "Reliability, dynamics, strength of machines and constructions" are indicated.

The goal of paper is to extant and to present in a structural fashion information presented in above conference papers.

2 Comparison of experimental results with standardized document VDI 2736 and Japanese Standard JIS B 1759

One of the main topic discussed at above mentioned conferences is analysis of standardized documents VDI2736 [1–4] and JISB1759 [5] regulating approach to design and calculation of plastic gear load-carrying capacity. Document VDI 2736 represents renewed version VDI 2545 [6], complemented by new information, presumptive modern state in the theory and practice of gears made of thermoplastic polymers. In given division the review of this topic is represents [7-15, 17-22]. It is stated in [7] that measured data according to the VDI 2736-4 [4] should be converted correctly to become usable for strength calculation according to the VDI 2736-2 [1]. Software tool was developed and the extrapolate method for plastic gear lifetime determination is briefly discussed too. Overview on the state of art in plastic gear material data for plastic gear calculation is considered and influence of the wear coefficient as a function of contact temperature, pairing, surface roughness and lubrication is discussed [8].

Calculation method [9] includes, by extending an approach based on VDI 2736 [2] the effects of load-induced deflection as well as dynamic tooth forces and further more allows maintaining the known bending fatigue strength according to [2].

It is overviewed [10] in the whole the new VDI 27636 [1-4] standard. In [11] the overall performance comparison of different material mechanical, thermal and wear properties is given, in [12] – according to the VDI 2736 [1] temperature calculation and comparison with measurement are presented. Comparison of the first version of analogous standard VDI 2545 [6] with the new one for PA/POM gears is discussed in [13]. General test results and the problems of material selection for customer different applications are the contents of point [14]. In [15] the wear of the POM/Steel and PBT/Steel gear pairs (wear coefficient $K_w = 1.8 \div 2.5 \cdot 10^{-6}$ mm^3/Nm) is compared with magnitude of wear according to VDI 2637 [12] ($3.4 \cdot 10^{-6}$ mm^3/Nm) and KISSoft prediction ($2.8 \cdot 10^{-6}$ mm^3/Nm) [16]. It is shown that in spite of certain difference between wear magnitudes, LTCA analysis from KISSoft could be used to determine K_w with the use of worn profile and iterative calculations.

Problems of wear resistance, equal as influence of other failure types (pitting damage, creep resistance, melting, tooth root fracture, deformation etc.) at gear carrying capacity are discussed in [17-19], in particular on plastic gears, manufactured from the PA 66, PEEK [17], Delrin 100, 100P, 311DP, 511P [18], PEEK, POM [19].

In [19] the permissible tooth bending stress of POM gears was calculated in accordance with JISB 1759, using operating tests results.

Authors [20-22] present results of analysis of differences between normative document VDI 2736 and Japanese Standard JISB 1759. It is established, that VDI 2736 based on DIN 3990 (C method), JIS 1759 – on ISO 6336 (B method).

In [20] the different parameters of both documents are compared: methods of the bonding stress and permissible bending stress calculation; test rig setup and standard test condition; test gears and reach to conclusion that both equal in effectiveness. In [21] the deficiency of data for material properties is established. In [22] the example of calculating tooth bending strength from results of operating tests with POM gear pair according to the JISB 1759.

3 Accelerated tests

In [7, 8, 12] the necessity of renovation of thermoplastics nomenclature is discussed. In this context beside of standard long-term fatigue tests accelerated ones are carried out at variation of mating pairs of different materials which does not include in VDI 2736-1 [1].

Along with accelerated fatigue gear tests (usually until $10^5 \div 10^7$ cycles) the extrapolation is fulfilled used either Corten/Dolan plus Haibach approach [7, 12] nor tensile strength results [8].

It is remarked in [7, 12] that to make load spectrum calculation possible, measured data should be extrapolated according to some principles and they are proposing a combination of Corten/Delan approach extrapolation (from 10^7 cycles to 10^{10} cycles) and Haibach approach one (from 10^{10} to 10^{15} ones).

To minimize the influence of wear and speed up on test results of the curve S-N generation, a hybrid method is proposed [8], consisting in that, when a few gear tests are performed below or equal 10^5 cycles to define the temperature dependency of the material and avoid gear and remaining parts of the curves then extrapolated or competed with tensile fatigue tests.

Techniques for accelerated tribological, quasistatic and fatigue mechanical tests of engineering polymer composites for gears are presented in [23-25]. It is proposed complex of interrelated databases for the system of automated design, pre-operating and production assimilation of drive system components (among them databases of gears, gearings, other components polymer composite properties construction, technologies, techniques and design tools, test results, etc. [25]).

4 Study of gear lifetime

Gears of different plastics and polymer composite materials are studied on the object of gear life time [26-30, 32, 33]: fatigue bending strength; pitting; wear, creep and temperature resistance, other failure modes.

Separate fragments of the topics are below. Authors [26] compare the composite flow molding gears (FMG) and milled gears made of composite plate materials (GP) (composite material is 45% PEEK reinforced with 55% endless carbon fibers). It is noted that higher GP gear quality (8f) in comparison of FMG one (10e) according to DIN 58405 is very convenient in conditions of very high torque moments, high temperatures and rather slow motion. The tests were provided according to VDI 2736-2 [2] and test results were evaluated according to VDI 2736-4 [4].

The fatigue strength of plastic gears with taking into account material, design, operation conditions and environment is determined in [27]. For 4 values of temperature (60, 80, 100, 120^{o}C), 4 values of humidity (10, 65, 90%) and 2 modes of loading (pulsating and alternating) the formula for (let us cite [27]) "realistic service life fatigue strength calculation on the basis of a load, temperature and humidity spectrum" is presented.

Among the diverse combination of gear pair (m = 1.0 mm, $z_1 = z_2$ = 20, $\alpha_w = 20^o$) polymer materials (PA 66, POM reinforced with glass fibers, glass spheres, aramid fibers, PTFE) [29], the combination of POM (grade KAOOM) and PA 66 (Zytel 103 HSL NC010) demonstrates best performance.

The main topic of [4] is comparison and clarification of gear wear coefficient k_w equal to $3.4 \cdot 10^{-6}$ mm^3/N·m in accordance with VDI-2736-2 [2] with values obtained by authors [30] in pin-on-disc tests $(15 \div 21) \cdot 10^{-6}$ mm^3/N·m and gear ones (m = 0.8 mm, z_1 = 17, z_2 = 22, $\alpha_w{}^o = 20^o$, b_1 = 8 mm, b_2 = 16 mm, POM-Delrin 500P) tests (1.8÷2.8) mm^3/N·m. It is noted that combination of loaded tooth contact analysis (LTC A), iterative wear calculation method of KISSoft [30] and gear worn profile value it is possible to determine wear coefficient of a polymer gears.

Overview of the different wear resisting compounds and fillers Alcom® WP [31] is based on different thermoplastic matrix (PA, POM, PBT, PC, PPS). The example of improving the linear wear rate and coefficient of sliding friction for the unmodified and modified PA 66 is presented in [32].

The result of oil-lubricated PEEK spur gears (m = 3 mm, z_1 = 24, z_2 = 36, $\alpha = 20^o$, b_1 = 22 mm, b_2 = 20 mm) tests aimed to definition an adequate failure criterion for discrimination progressive and non-progressive pitting growth are presented in [32].

According to experimental data for Delrin 311DP gears, the methodology of lifetime prognosis of plastic gear systems is developed in [33], including some factors that can affect to fatigue life of plastic gears, i.e. creep, surface **finish**, humidity, aging, self-heating and frequency.

5 Polymer materials and composites

Different versions of polymer gears and gear engagement (steel-polymer, polymer-polymer) it is presented in above conference papers. It is discussed not only using traditional plastics gears [34-39], but also gears made of disperse filled polymer composites [40-46] reinforced with particles and short fibers of glass, carbon, Fe_2O_3 and so on. The most often used matrix materials are the polyoximethelene POM (Delrin 100, Delrin 100P [34, 38], Tecaform AH [37]), polyamide PA66 (Tecamid 66 [37]) and polyetheretherketone (PEEK) such as Victrex 450 [35].

The wear and fatigue behavior of polymer gears (SS steel driving pinion – POM driven gear wheal pair, m = 1.0 mm, b = 6 mm, z_1/z_2 = 17/20, $\alpha = 20^o$, $x_{1\ 2} = 0$) under controlled temperature conditions is discussed [38].

The results confirm the important effect of the temperature on the fatigue life of POM gears – at low of temperature 30°C the fatigue life of POM gears is greatly improved while life time was down to four times at 70°C and down to two times at 50°C, as compared to 30°C.

Step loading tests at the speed 1000 rpm significant differences in failure modes and performance have been observed for the five polymer gear materials [40] – high density polyethylene (HDPE), polycarbonate (PC), acetal (Delrin 500), Nylon (PA 46) and polyetheretherketone (m = 2 mm, z = 30, $\alpha = 20^o$, b = 17 mm, ε_α = 1.67).

For example, fracture failure for PC gears, thermal wear for Delrin 500 gears, progressive wear for the Nylon 46 and PEEK 650 gears were noticed. The best performance was achieved with acetal as a driver and PEEK as a driven gear. Significant performance improvement is reached for 28% glass fiber reinforced acetal gears. The lubricated PEEK gears against of nonlubricated PEEK gears load capacity has been increased over 40%.

Authors [41] used for experimental samples (co-rotating discs and gears (m = 1.0 mm, $z_{1,2}$ = 30, b = 6 mm, h^* = 2.25) polymer composite on the base Polyamide 4.6 matrix (PA 4.6) of two grades DSM Stangl® – TW241F10 (50% Glass fiber GF) and TW271F6910 (30% GF + PTFE). It was attempt, using FEM analysis, to link wear rates experimentally obtained from a co-rotating discs' experiment to the wear of gear. In [42] two grades of composite are used for experiments – PEEK-1 (reinforced by carbon fibers) and PEEK-2 (carbon fibers + graphite + titanium dioxide + zink sulfide). Samples (10x4x4 mm) were tested by means of sliding friction in dry sliding conditions. Anisotropic thermal conductivities of above materials are calculated using analytical and numerical homogenization. The results are compared to experimentally determined values.

The methods and results of disperse filled composite gear design are described in [43-46]. The optimization procedure based on iterative calculating stress-strain state and prediction of wear resistance of disperse-filled composite joints, including gears, by the effective two-level method [44]. The method allows to determine the parameters of stress-strain state, elastic compliance, strength and wear resistance of gears, as well as to find an optimum composition of the material in terms of technical requirements.

The effectiveness of the proposed two-level method for gears consists of a rational combination of analytical micromechanical approach of the elasticity theory and numerical macromechanical techniques (first of all, finite element approximation) of machine part strength analysis. Due to the first level it is suitable to describe the deforming process of essentially heterogeneous composite materials and due to the second one – to determine the parameters of the stress-strain state of intricate in shape parts, i.e., the gear.

Some experimental results are presented in [44, 45] (carbon-filled antifriction composite material "Fluvis", MPRI NASB), detailed description of methodology and results of composite gear design – in [46].

An experimental study of the wear resistance of two dispersion-filled composite materials based on polyamide used in metal-polymer gear drives with a 30% volume content of short glass or carbon fibers was performed and described in [47, 48]. As a result of tribotests in the "pin-disk" scheme, the mass wear of these composites was determined under dry friction conditions for steel 45 at room temperature in the range of contact pressures of 10-40 MPa, as well as the kinetics of the coefficient of sliding friction and the contact temperature of the tribosystem elements.

It was established that polyamide strengthened by carbon fibers has almost four times higher wear resistance in comparison with a polyamide filled with glass fibers. The wear resistance characteristics are calculated, using the durability of the straight spur metal-polymer gear drive on the basis of the original calculation method [47, 48]. It was established that gear drive durability with a pinion or a wheel reinforced with carbon fibers is more than eight times the durability of gear drive with gear wheels from polyamide filled with glass fibers. The gear drive durability with the steel pinion and the composite gear wheel increases in proportion to the gear ratio as compared to the gear drive with the composite pinion and the steel wheel.

6 Multi-criteria computer-aided design optimization and quality improvement of plastic gears

As is known, there is many universal CAD/CAM/CAE systems (for example Pro/Engineer, Solid Works, Compas 3D, AutoCAD and others), which have special modules for computing various types of gear trains. Ones of them intend for plastic gears PC-aided design, for example, KISS Soft [49], StarGear [50], "Plastic Gearing" [51] and so on.

Computer program Opti Tooth 10.0 for spur and helical polymer gears, described in [52], enables to select and to optimize, step by step, the optimum geometry of gear pairs takes into account the criteria of root and flank stress, gear temperature, wear, tooth deformation, and allowed load level for the selected material.

Another PC-aided software offered by authors [53] allows to calculate nominal dimensions and geometrical parameters of gear wheels; accuracy grade and backlash norms; quality of engagement, animated visual control over the gear wheel meshing process; full calculation protocol; data for drawings; contact and bending strength. Calculation of gear forming mould dies is performed which results are used as the data for their manufacturing by CNC machines. Nominal dimensions of cylindrical gear drive and gear wheels are calculated as per GOST 16532-83. The tolerances are selected automatically in accordance with the accepted grades of accuracy as per norms of kinematic accuracy, smoothness of operation, teeth contact, type of gear mating and backlash tolerance based on GOST 1643-81 at $m > 1$ and GOST 9178-81 at $m < 1$.

The procedure of strength calculations (including the design and verification calculations) meets GOST 21354-85 requirements. Strength design uses the basic calculation dependencies to determine contact strength of the active tooth flanks and teeth bending strength as specified in standard (some specialities see in [54, 55]).

Software [53] has module which promote to rise of plastic gear accuracy by means of female die dimensions' correction after measuring the experimental gear batch with simplest measuring technique and to compute clarified mold shrinkage of tip circle diameter, base circle diameter and angle tooth thickness on the base circle.

Example of increasing plastic gear accuracy of electro mincing machine drive is presented in the Table 2.

Table 2. *Increasing plastic gear accuracy of electro-mincing machine drive by correction of mould die specified dimensions [56].*

Parameter		**Parameter numerical value**					
Module m, mm		**1.5**		**2.0**		**2.5**	
Tooth number, z		**12**	**36**	**15**	**32**	**15**	**33**
Nominal tip diameter d_a, mm		21.9	56.1	35.2	66.8	44.0	86.0
Probability $P(d_a)$	Before	0.370	0.297	0	0	0	0
	After	0.941	0.990	0.684	0.776	0.335	0.999
Measurement over pins, M_D, mm		22.189	57.641	35.532	70.254	47.648	90.046
Probability $P(M_D)$	Before	0	0	0.390	0.144	0.492	0
	After	0.937	0.998	0.973	0.949	0.905	0.999

7 Additive manufacturing technologies

Trends in the development of modern technical objects and their generation in many ways reflect the ideology of Industry 4.0 (i4.0), in which the kay role is prominent in the creation of sensor base, intellectualization of machines and materials, generation of Digital Twins (DT), Internet of Things etc [57, 58]. The fundamental concept of i4.0 is a "cyber-physical system" (CPS), which is characterized by physical object and its DT – i.e. computer realization of mathematical model (model complex), simulating behaviors of the physical object [57, 58].

Significant element of DT process for gears of polymer and composite materials is additive technologies substantially accelerating preproduction of that style of products. DT of physical object acts here as a CAD-model, which it is necessary as of yet to adapt for the concrete 3D-printer. Authors [46, 59-64] was developing above CPS by way of elaboration of hardware environment, computer software (CSW) and consumable materials for 3D-printers, as well as in implementation of additive technologies in gear train and transmission production.

Key elements of 3D-printing in that event are the gradient materials and issues manufacturing as well as CSW [59, 64]. Using 3D printing for polymer materials, which should provide simultaneously of high mechanical and antifrictional properties has significant benefits in comparison with traditional technologies. Controlled and relatively rapid process of gear manufacturing is realized desired form of article and optimal material property gradient. It is significant to note that material composition necessary to optimize by known methods of mechanics of composites (in simplest case that is rule of additivity), what permits to create CAD-models for 3D-printing polymer composite gears from gradient materials, optimized with volume distribution of its mechanical characteristics [59, 64].

Computer software for 3D-printing is elaborate by the companies USG, IBM, Autodesk, Solid Works, Siemens PLM Software and others and overlap the whole circuit on control with life time of goods and control of technological processes, as well to simulate the items as to make analysis of completed model taking into account features of manufacturing and used materials. 3D-printing design possibilities unobtainable with other technologies the planetary gear train is demonstrated (Figure) where any and all gears are herringbone ones. Prototype is printed on 3D-printer "Engineer V2-K", which design is described in [62]. Some peculiarities of CSW for 3D-printing are described in [60].

Fig. *Model of the planetary gear train with the herringbone gears, manufactured with additive technology. (The specimens and their photographs have been rendered by V. Dubrovskii).*

Authors [65] on the example of planetary train ("Backlash Drive") consider possibilities of the novel design to integrate the gears into either fully or mostly additively manufactured gear boxes. Realization of technology is carried out with step by step generation from the half tooth profile points through the full tooth – 2D – representation of gear to the 3D point cloud. There is reference [66] to algorithm for different profiles (involute, cycloid), variations of tooth systems (helical, herringbone and spiral), some types of gears (spur, bevel, internal, ones and cylindrical worms). It is noted [65] that additive manufacturing of gears offers potential in the fast drafting and design of arbitrary gear boxes, leading to accelerated testing of mechanisms and prototypes.

8 Gear train noise, vibration and harshness (NVH) improvement with plastic gears

Some paper topics of the last scientific conferences dedicate to NVH problem study [67-70]. It is noted [67] that the PEEK gear solution provides up to 45% reduction of the gear rattle emission and did exhibit an in overage 70% reduction of gear whine emission (gear whine noise) of the first three gear orders.

The influence of different motor speed on the change the meshing frequencies is studied [68] with the change the motor pinions with a lower tooth number (7 instead of 9) and higher tooth number (13 instead of 9). It is established, that a damping of the transfer parts shows the best results, followed by the macrogeometry of the teeth and the quality of the parts. A combination of all measure can lead to an even higher reduction.

Some examples of gears with symmetric and asymmetric teeth are discussed [69] and it is showed, that due to a well applied profile modification the operating characteristics (lifetime and noise) could be significantly improved. For sinter/POM pairing (symmetric teeth and tip relief value 30 μm) reduction of differences between effective contact ratio and theoretical one indicates on improvement of the NVH behavior; for asymmetric teeth tip relief modification value of 30 μm for both gears shows the smallest transmission error (reduction by 35%) and low wear (reduction by 25%). Compared to the symmetric design results of asymmetric one show much lower wear and transmission error. It is concluded – NVH properties in order to improve profile modification should be applying.

Comparative results of testing PEEK-Victrex 450 G^{TM} gears and steel ones on NVH behaviors are presented in [70].

Therefore, the benefits of polymer gear solution compared of metal ones are consisted of up to 3dB (50%) improvement in NVH, up to 68% weight reduction, which is resulting in 70% reduction of the moment of inertia and therefore requiring 9% less torque to operate to a cast iron gear set.

9 Conclusions

The main trends of the last investigation topics in the field of polymer material and composite gears are discussed. It is established that the dominant subjects of the papers are the outstanding normative papers VDI 2736 and JISB 1759, regulating the main aspects of thermoplastic gears – polymer material properties and selection, production methods, tolerances and accuracy, design, load-carrying capacity calculation of cylindrical gears and helical ones [7-22].

A part of publications [7, 8, 12] dedicates to the different techniques of the accelerated tests, consisted of as directly gear durability tests as well fatigue tensile strength tests. The accelerated tests for determining the polymer material and composite fatigue properties (strength and friction ones) in the context of gears are carried out too [23-25].

The other paper topics are the following: the gear lifetime study, namely the failure modes with fatigue bending strength; pitting; wear, creep and temperature resistance [26-30, 32, 33]; comparison of gear carrying capacity of different gear pairing (steel-polymer, polymer-polymer) and influence of different operating factors (temperature, humidity, lubricants etc.) [34-46]; computer-aided software and quality improvement of plastic gears [52-56]; additive technologies as an important element of the Industry 4.0 concept [57-66]; plastic gears for improvement of noise, vibration and hardness characteristics of gearboxes [67-70].

In the whole it is obeyed to acknowledge, that majority publications touch upon subject of gear bending and surface strength wear resistance, PC-aided gear design and their accuracy, study of polymer gear load-capacity.

Abbreviation

PA – polyamide (nylon)
POM – polyoxymethylene (acetal)
PBT – polybutadiene terephtalate
PEEK – polyetheretherketone
PC – polycarbonate

PPS – polyphenylene sulfide
HDPE – high density polyethylene
GF – glass fillers

References

1. VDI 2736. Thermoplastische Zahnräder Werkstoffe, Werkstoffauswahl, Herstellverfahren, Herstellgenauigkeit. VDI-RICHTLINIEN. Entwurf. **1** (2016)
2. VDI 2736. Thermoplastische Zahnräder Stirnradgetriebe Tragfähigkeitsberechnung. VDI-RICHTLINIEN. Entwurf. **2** (2013)
3. VDI 2736. Thermoplastische Zahnräder Stirnradgetriebe Paarung Zylinderschnecke Schrägstirnrad Tragfähigkeitsberechnung. VDI-RICHTLINIEN. Entwurf. **3** (2012)
4. VDI 2736. Thermoplastische Zahnräder Ermittlung von Tragfähigkeitskennwerten an Zahnrädern. VDI-RICHTLINIEN. Entwurf. **4** (2016)
5. JIS B 1759 Estimation of tooth bending strength of cylindrical plastic gears (2013)
6. VDI 2545. Zahnräder aus Thermoplastischen Kunststoffen. Dusseldorf (1981)
7. A. Pogačnik, S. Beermann, *Inter. Conf. on HPPG*. 145-2294 (2017)
8. J. Cathelin, R. Janssen, *Intern. Conf. on HPPG*. 146-2294 (2017)
9. C. Hasl, P. Oster, T. Tobie, K. Stahl, *Intern. Conf. on HPPG.* 155-2294 (2017)
10. S. Oberle, *Intern. Conf. on HPPG* (www.vdi.de/plasticgears) (2015)
11. D. Merken, *Intern. Conf. on HPPG* (www.vdi.de/plasticgears) (2015)
12. A. Pogačnik, *Intern. Conf. on HPPG* (www.vdi.de/plasticgears) (2015)
13. S. Beermann, *Intern. Conf. on HPPG* (www.vdi.de/plasticgears) (2015)
14. W. Schmidt, *Intern. Conf. on HPPG* (www.vdi.de/plasticgears) (2015)
15. S. Matcovič, A. Pogačnik, M. Kalin, *Proc. of the Int. Conf. on HPPG*, 1311-1322 (2019)
16. U. Kissling, S. Hauri, IGCC (2015)
17. C.M. Iluberger, T. Tobie, S. Stahl, *Proc. of the Int. Conf. on HPPG,* 1379-1390 (2019)
18. R. Ratnagirb, M. Kato, H. Kuchelka, *Proc. of the Int. Conf. on HPPG,* 1357-1366 (2019)
19. H.-J. Dennig, A. Vadermager, *Proc. of the Int. Conf. on HPPG*, 1279-1290 (2019)
20. I. Bae, U. Kissling, *Proc. of the Int. Conf. on HPPG*, 1267-1278 (2019)
21. Ju. Gathelin, *Proc. of the Int. Conf. on HPPG,* 1335-1344 (2019)
22. I. Moriwaki, A. Ueda, M. Nakamura, K. Ioneda, D. Iba, *Proc. of the IGC* (Lyon, Villeurbane, France, 2014)1172-1178 (2014)
23. V.L. Basinyuk, V.E. Starzhinsky, E.I. Mardosevich, M.P. Lobkova, *Proc. of the Int. Symposium TRG* 521-528 (Sc. Ed. V.I. Goldfarb, Izhevsk: IzhSTU 2014) (in Russian)
24. V.L. Basinyuk, V.E. Starzhinsky, E.I. Mardosevich, M.P. Lobkova, *Proc. of the Int. Symposium TRG* 529-534 (Sc. Ed. V.I. Goldfarb, Izhevsk: IzhSTU 2014) (in Russian)
25. V.L. Basinyuk, V.E. Starzhinsky, A.A. Kalina, A.V. Kuleshova, Coll. of Sci. papers «Actual problems of Machine Science» (CTAM) (Minsk: JIME of NASB) **2** 334-338 (2013) (in Russian)
26. N.-J. Dennig, S. Monn, A. Wodermayer, *Proc. of the 3th Int. Conf. on HPPG,* 1279-1290 (2019)
27. K. Humm, M.-S. Wirth, A. Linnemann, T. Schalk, *Proc. of the 3th Int. Conf. on HPPG*, 12791-1298 (2019)
28. G. Hlebanja, M. Hriberšek, M. Erjavec, S. Kulovec, *Proc. of the 6th Int. Conf. BAPT* (2019)
29. S. Matkovič, A. Pogačnik, M. Kalin, *Proc. of Int. Conf. on HPPG*, 1311-1321 (2019)
30. K. Smrczkova, *Proc. of Int. Conf. on HPPG,* 1345-1356 (2019)
31. PIP Alcom® WP – Wear Protect, Company Publication, ALBIS Plastic, GmbH, Hamburg (2018)
32. C.M. Illenberger, T. Tobie, K. Stahl, *Proc. of Int. Conf. on HPPG,* 1379-1390 (2019)
33. R. Ratnagiri, M. Kato, H. Kuchelka, *Proc. of Int. Conf. on HPPG,* 1357-1366 (2019)
34. A. Pogačnik, S. Beermann, *Int. Conf. on HPPG*. 145-2294 (2017)
35. R. Weidig, *Proc. of the Int. Conf. on HPPG*. 142-2294 (2017)
36. M. Baar, P. Oster, T. Tobie, K. Stahl, *Int. Conf. on HPPG,* 151-2294 (2017)
37. B.Cerne, D. Zorko, J. Duhovnik, *Int. Conf. on HPPG* (2017)
38. M. Kalin, A. Kuper, *Int. Conf. on HPPG,* 154-2294 (2017)
39. C. Hasl, P. Oster, T. Tobie, K. Stahe, *Int. Conf. on HPPG,* 155-2294 (2017)
40. K. Mao, V. Goodship, N. Madhov, R. Ramakrishna, P. Langlois, *Int. Conf. on HPPG.* 153-2294 (2017)
41. M. Kanters, B. Wissen, R. Nickel, *Int. Conf. on HPPG* 142-2294 (2017)
42. N.S. Ecke, A.K. Schearb, H. Holler, J. Wiedermeyer, P. Klein, *Proc. of the 3th Int. Conf. on HPPG*, 1411-1420 (2019)
43. S.V. Shil'ko, V.E. Starzhinsky, E.M. Petrokovets, D.A. Chernous, J. of Friction and Wear. Part 2, **35, 1** 40-47 (2014)
44. S.V. Shil'ko, V.E. Starzhinsky // *Proc. of the 26th Working Meeting on Standardization of Terminology* (WMST – Bucharest: Politehnica Press) 57-64 (2016)
45. S.V. Shil'ko, V.E. Starzhinsky, E.M. Petrokovets, T.V. Ryabchenko, Coll. of Sci. Works «Actual Problems of Machine Science» (CTAM-2016). (Minsk: JIME NASB), 233-236 (2016) (in Russian)
46. S.V. Shil'ko, V.E. Starzhinsky, E.M. Petrokovets, Theory and Practice of Gearing and Transmissions (Eds.: V. Goldfarb, N. Barmina, Springer, 2016)
47. M.V.Chernets, S.V.Shil'ko, M.I. Pashechko, M. Barshch, J. of Friction and Wear. **39, 5** 361–364 (2018)
48. M. Chernets, S. Shil'ko, M. Pashechko, Tribologia, **3** 19–23 (2018)
49. KISSsoft. URL: (www.kisssoft.AG)
50. Star Gear. URL: (http://www.stargear.com)
51. Plastics Gearing Technology, Inc. URL: (www.abapgt.com)
52. J. Tavčar, J. Kos, D. Zorko, J. Duhovnik, *Proc. of Int. Conf. on HPPG,* 1473-1484 (2019)
53. V.E. Starzhinsky, RB Certificate **370** (2011)
54. V.E. Starzhinsky, S.V. Shil'ko, E.M. Petrokovets, V.V. Supin, E.V. Shalobaev, Ye.I. Gutman, *KOD 2018 IOP Publ. Conf. Series: Mat. Sci. and Eng.* 393 (2018)
55. V.E. Starzhinsky, S.V. Shil'ko, E.V. Shalobaev, M. Rackov, Col. of Sci. Works "Actual Problems of Machine Science", (CTAM-2019) (Minsk: JIME NASB) **8** 195-198 (2019)
56. V.E. Starzhinsky, Yu.L. Soliterman, A.M. Goman, *Monograph "Machine Design"* (Un. of Novi Sad, Fac. of Tech. Sci., Novi Sad) 237-242 (2008)
57. V.B. Algin, S.N. Paddubko, V.E. Starzhinsky, S.V. Shil'ko, Mechanics of Machines, Mechanisms and Materials, (CTAM-2019) **49, 4**, 5-19 (2019) (in Russian)
58. V.B. Algin, N.N. Ishin, V.E. Starzhinsky. S.V. Shil'ko, M. Rackov, M. Čavić, *Coll. of Sci. Papers "Actual Problems of Machine Science".* **8** 172-184 (2019)
59. S.V. Shil'ko, T.V. Ryabchenko, S.L. Gavrilenko, E.V. Shalobaev, *Proc. of the Int. Scientific and Pract. Symp. "Challenges of Additive Technologies Development in Republic Belarus"* (Minsk, Belarus) 194-207 (2017) (in Russian)
60. F.A. Perepelitsa, E.V. Shalobaev, S.V. Shil'ko, *Proc. of the Int. Scientific and Pract. Symp. "Challenges of Additive Technologies Development in Republic Belarus"* (Minsk, Belarus) 128-135 (2017) (in Russian)

61. E.V. Shalobaev, F.A. Perepelitsa, N.S. Krasnorutskaya, *Coll. of Scient. Papers «Instrument-making in XXI centery», Proc. of the XII Int. Conf.*, 319-323 (2019) (in Russian)
62. G.A. Demidov, A.H. Karandashev, E.V. Shalobaev, F.A. Perepelitsa, S.V. Shil'ko, V.E. Starzhinsky. V.V. Dubrovskii, Polym. Mater. and Techn., **5**, **3** 59-63 (2019) (in Russian)
63. V.E. Starzhinsky. S.V. Shil'ko, E.V. Shalobaev, Polym. Mater. and Techn., **4**, **2** 6-31 (2018) (in Russian)
64. S.V. Shil'ko, Yu.M. Pleskachevsky, S.V. Panin, B.A. Lyukshin, Mechanics of Machines Mechanisms and Materials, **3-4 (20-21)** 149-157 (2012) (in Russian)
65. S. Detsel, Y.S. Krieger, N.F. Tralger, T.C. Lueth, *Proc. of Int. Conf. on HPPG* 1401-1410 (2019)
66. Y. Sun, T.C. Lueth, *RAAD-2019 Advances in Service and Industrial Robotics*, 357-364 (2019)
67. R. Weidig, H.J. Welnar, *Proc. of Int. Conf. on HPPG*, 1421-1430 (2019)
68. J. Fechler, S. Oberle, M. Knöpfle, V. Merz, *Proc. of Int. Conf. on HPPG*, 1431-1442 (2019)
69. A. Pogačnik, U. Kissling, *Proc. of the Int. Conf. on HPPG*, 1461-1472 (2019)
70. R. Weidig, *Proc. of Int. Conf. on HPPG* 147-2294 (2017)