HUNGARIAN UNIVERSITY OF AGRICULTURE AND LIFE SCIENCES

EVALUATION OF TRIBOLOGICAL BEHAVIOUR OF POLYMER GEARS USING CONVENTIONAL AND XCT TECHNOLOGY

DOI: 10.54598/003820

Theses of Doctoral (PhD) dissertation

By

Miklós Odrobina

Gödöllő
2023

Name of Doctoral School:	Doctoral School of Engineering
Discipline:	Mechanical Engineering
Head of School:	Prof. Dr. Gábor Kalácska, DSc Institute of Technology Hungarian University of Agriculture and Life Sciences, Gödöllő - Hungary
Supervisor:	Prof. Dr. Gábor Kalácska, DSc Institute of Technology Hungarian University of Agriculture and Life Sciences, Gödöllő - Hungary
Co-Supervisor:	Dr. Róbert Zsolt Keresztes, PhD Institute of Technology Hungarian University of Agriculture and Life Sciences, Gödöllő - Hungary

....	....
Approval of Head of Doctoral School	Approval of Supervisor(s)

TABLE OF CONTENTS

NOMENCLATURE

A	coefficient of the function describing the temperature of gear tooth root	[-]
B	coefficient of the function describing the temperature of gear tooth root	[-]
C	coefficient of the function describing the temperature of gear tooth root	[-]
DSC	Differential Scanning Calorimetry	[-]
$k_{wtömeg}$	weight-loss wear coefficient	$[10^{-6}$ mm /Nm$]^3$
k_{wWm}	wear coefficient calculated by microscopy	$[10^{-6}$ mm^3 /Nm$]$
m_w	mass difference between the unworn and the worn gear	[mg]
N_L	number of load cycles	[-]
PA12	polyamide 12	[-]
PA6	polyamide 6	[-]
PEEK	polyether-ether-ketone	[-]
pv	pv value	[MPa m/s]
SLS	selective laser sintering	[-]
v	average sliding velocity	[m/s]
VDI	Verein Deutscher Ingenieure	[-]
W_m	averaged linear wear	[mm]
X-ray	X-ray Computed Tomography	[-]

1. INTRODUCTION, OBJECTIVES

1.1. Introduction

Gears have been known and used since ancient times as a means of transmitting force and motion. However, the development of materials science has brought new aspects to an old technical solution, such as gear. The use of plastic gears began some 70 years ago, but initially, they were completely overshadowed by metal gears because their material properties meant that they could only be used in low-load conditions. The rise of engineering plastics over the last 30 years has brought a change of attitude, as is shown by the number of articles about plastic gears.

The production and use of plastic gears now rival that of metal gears, thanks to their beneficial properties, and they are now found in many areas of industry, such as automotive, office and household equipment, food and textile machinery, aerospace, and medicine. Compared to metal gears, which are subject to chemical corrosion, lubrication-related failures, and expensive manufacturing, operation, and maintenance costs, plastic gears weigh significantly less and therefore have lower inertia forces during rotation; they have a low coefficient of friction against motion; they can also have self-lubricating properties; they run at lower noise levels; they can withstand dynamic stresses thanks to their damping capacity; and they can be produced in small or large quantities at a much lower cost.

The use of plastic gears is complicated by their non-linear material properties. Sliding during gear contact causes thermal expansion, which leads to the deterioration of mechanical properties and high elongation due to the viscoelastic behaviour of polymers, and this has a significant impact on the performance of plastics. Given these complex processes, determining the material properties of polymers is a challenging task, without which accurate calculations of the drive elements are impossible. Properties such as fatigue limit, mechanical-thermal behaviour, and tribological characteristics, which are the friction and wear mechanisms of gears, must be considered.

There is no design standard for plastic gears in research or industry. At present, VDI 2736 guideline, which origins from metal gear standard, that contains material properties for fatigue limit (Wöhler curve), temperature, and tribological properties for accurate gear calculations for only a few material combinations.

In contrast, high-performance engineering plastics are now available, and additive manufacturing technology has become part of everyday life. However, the material properties needed to design plastic gears are not available. The challenge for researchers soon will be to determine the mechanical, thermal, fatigue, and tribological properties of these new plastics to design gears accurately and optimize their performance.

1.2. Objectives

The main objective of my doctoral research is to determine the thermal and tribological characteristics of polymer gears made by selective laser sintering (SLS) and semi-finished polymer gears made by conventional gear cutting. I also aim to develop regression models that can be used to estimate the equilibrium temperature, friction, and wear coefficients of gears as a function of input parameter variation. In addition, I aim to evaluate gear wear by weight measurement, microscopy, and X-ray tomography and to compare the wear evaluation methods used. My research objectives also include the investigation of the toughness of magnesium-catalysed cast polyamide 6 semi-finished products, which are widely used as gear materials.

2. MATERIAL AND METHOD

2.1. Material testing methods

The production technology of magnesium-catalysed cast polyamide 6 is a well-controlled process; however, one of the drawbacks of the exothermic chemical process during casting is the temperature difference between the inside and outside of the cast rods, which affects the mechanical properties of the resulting material.

The effect of diameter on the toughness of magnesium-catalysed cast polyamide 6 was evaluated by carrying out several test procedures in the diameter range of 40mm to 300mm. The test specimens for the tests were formed from the rods by a machining process. A schematic representation of the location of test specimens is shown in Fig. 1. In the first instance, a Charpy impact test was carried out. Subsequently, the cause of the deviation of the impact strength was searched for using differential scanning calorimetry (DSC).

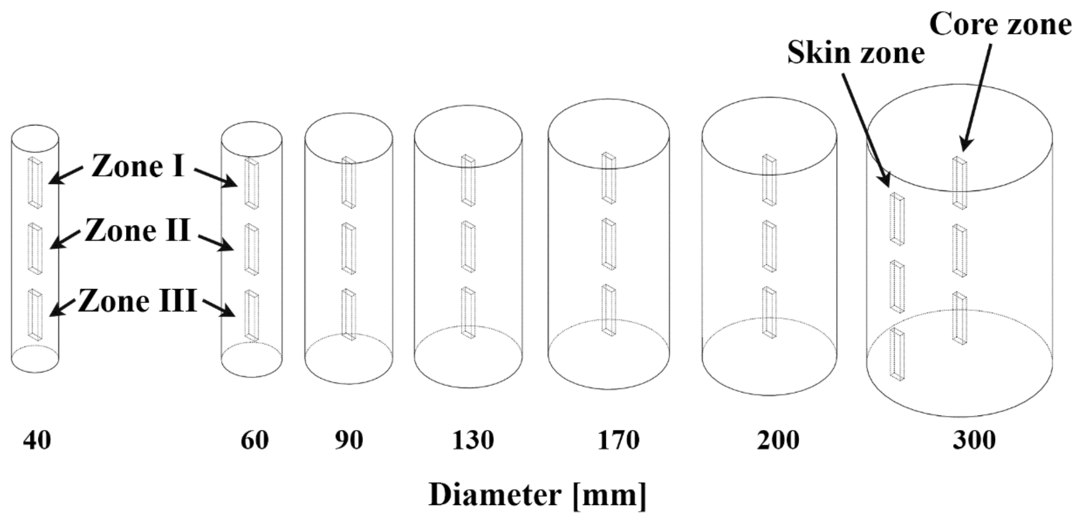

Fig. 1. Schematic diagram of the location of the test specimens

The Charpy impact tests were carried out with an INSTRON CEAST 9050 impact hammer in the laboratory of QuattroPlast Ltd. according to MSZ EN ISO 179 at room temperature (23 °C). The anvil used for the measurements has a support distance of 62 mm. The hammer energy is 1 joule, and the impact velocity is 3 m/s.

The crystallization and melting behaviour of polyamide 6 were investigated using a METTLER TOLEDO DSC 1 Star eSystem measuring system at Robert Bosch Ltd., Budapest, Hungary. The samples used for the DSC tests were cut directly from Charpy specimens. According to the test program, the samples were first heated from -10 °C to 290 °C and then cooled down to -10 °C under continuous nitrogen flow. The cooling and heating rates were 10°C/min.

This research is of great importance because PA6 semi-finished products are used in the production of many functional parts and machine components, including gears, which are subject to mechanical stress, but their lifetime and durability depend heavily on the properties of the material. On the other hand, it is well-known that the degree of crystallinity varies widely within the range of sizes used in production, and it is therefore important to clarify the range of sizes from which gears are produced. Because they will have completely different properties in terms of toughness and load capacity depending on whether they are made from 60- or 300-mm-diameter rods. Therefore, the first chapter of my research objective is to clarify this uncertainty by performing preliminary experiments on cast polyamides.

2.2. Durability testing for gears

The raw materials used for research are available in different ways. The PA12 used for 3D printing can be purchased in the form of powder, which can only be used on 3D printers with SLS technology. Cast PA6 and extruded PEEK are commercially available as semi-finished products, which are understood as slabs or rods. According to the gears to be tested, Ø70x1000 mm rods of both materials were purchased, and the gears were fabricated in several steps using a machining process.

For the plastic gear experiments, a testing device was developed that is suitable for long-term durability tests, load capacity tests, wear tests, and other tests under operating conditions (Fig. 2). The gear testing device is located in the tribology laboratory of the Technical Institute of the Hungarian University of Agricultural and Life Sciences in Gödöllő.

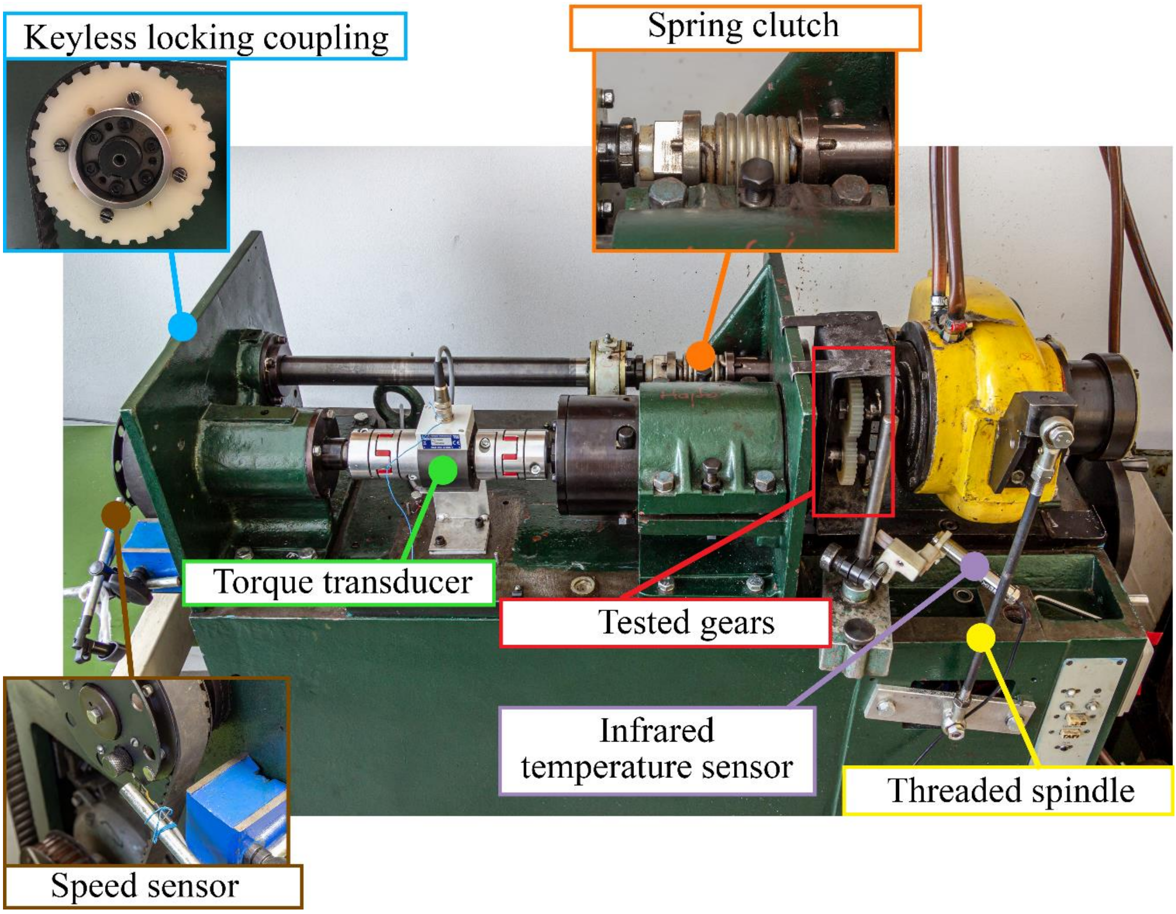

Fig. 2. Plastic gear testing equipment

The torque in the closed drive train, including the torque from the load spring and system losses, is detected by the built-in HBM T22 torque sensor with a nominal measuring range of ± 50 Nm and an accuracy class of 0.5. The temperature of the gears is measured by a Calex PyroCouple PC CF MT - 0 type close focus non-contact infrared temperature sensor with a measuring range of 0°C to 250°C, an accuracy of ±1% or ±1°C whichever is greater, and a field of view of Ø5mm at 100 mm. The output signals of the sensors are recorded by an HBM Spider 8 Data Acquisition System.

In my research, the temperature was measured directly under the tooth root, as the temperature in this area is more stable than at the contact surface and the appropriate calculation method has been developed.

The measurement settings and conditions for the gear tests are summarised in Table 1. The experiments were carried out with identical gear geometry, i.e., 1:1 ratio, under dry, unlubricated operating conditions, and in all cases, gears of the same material were run together.

Table 1. Measurement settings and conditions

		Load levels		
	Material from	1.	2.	3.
Applied loads [Nm]	PA12	1,	251,	82,5
	PA6	3,	55,	37
	PEEK		57,	510
Speed of rotation [min^{-1}]		1000		
Circumferential speed at pitch circle [m/s]		3,14		
Cycle [$x10^6$]		1,5		
Environment		Air		
Temperature		23±2°C (air-conditioned room)		
Humidity		50 ± 10 %		

For plastic machine components that slide on each other, such as plain bearings, the design is based on the surface load multiplied by the sliding velocity, known as *pv value.* Therefore, in addition to the wear characteristics, the temperature and friction coefficient were investigated as a function of *pv*.

2.3. Wear testing for gears

Two different measurement methods have been developed to assess gear wear. One is based on weight measurement, and the other on monitoring the shape of the tooth profile. These methods are used to determine the wear coefficient, for which separate methodologies are known. To complement the traditional wear assessment methods, an X-ray tomographic examination method has been developed in order to obtain further details on the wear mechanism of gears.

The traditional and simplest method of assessing gear wear is to measure the weight using an analytical balance. The wear coefficient due to loss of weight is the $k_{wweight}$, which can be determined according to the VDI 2736 guideline. For this methodology, the difference between the weight of an unworn and a worn gear, m_w, is measured.

Wear of gear can be evaluated graphically using a microscope. After the gear inspection, the averaged linear wear, W_m, i.e., the thinning of the tooth along the pitch circle, can be reliably measured from the image of the worn gear profile. The value W_m can be used to calculate the wear factor k_{wWm} according to VDI 2736. In my research, averaged linear wear was determined by comparing the theoretical involute profile with the worn tooth profile. The process of microscopic wear evaluation is summarized in Fig. 3.

X-ray tomography can create 3-dimensional volumetric files and offers the possibility to measure and characterize parts with complex external and internal geometric features that are difficult or impossible to perform with conventional metrology instruments.

X-ray Computed Tomography (XCT) is also suitable for imaging the surface of plastic gears, but it is not widely used due to its high cost and lack of availability. In the evaluation of wear in gears, 3-D tomography has an advantage over other wear evaluation techniques because it provides information on the tooth profile not only at the extremities but also along the entire tooth surface.

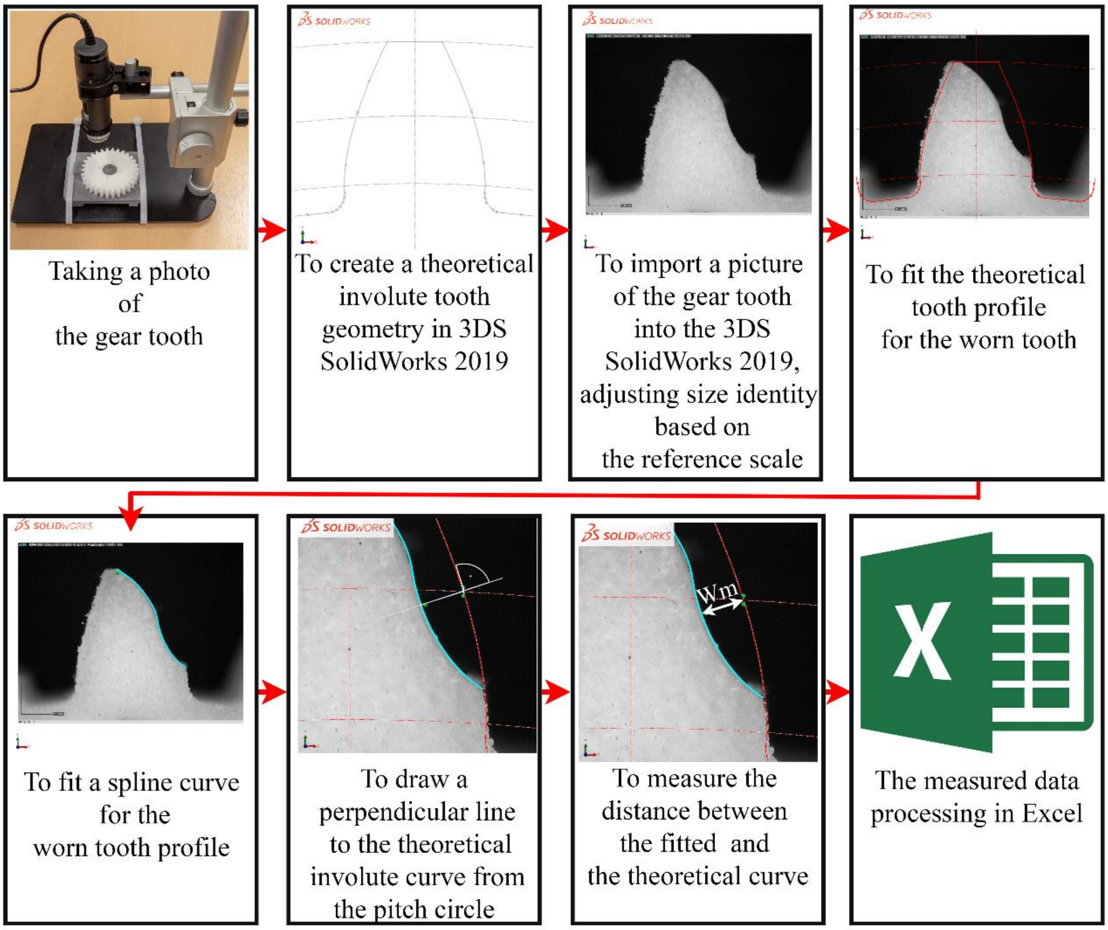

Fig. 3. Flow diagram of microscopic wear evaluation

The XCT images were obtained with a GE Phoenix Micromex equipped with a digital flat panel detector and a 180 kV, 20 W transmission X-ray tube. The images were taken with the same setup for all gear samples, which are summarized in Table 2. Image reconstruction was performed using Phoenix Datosx 2 software. A specific methods was developed to evaluate the CT images with VGStudio MAX 3.4. The wear evaluation process using X-ray tomography is shown in Fig. 4.

Table 2. GE Phoenix Micromex 180kV measurement settings

Parameter	**Value**	**Parameter**	**Value**
Filter material	Copper	Exposure time	333 ms
Filter thickness	1,8 mm	Voxel size	46,18μm
Tube voltage	50 kV	Number of compounds	360
Tube current	300 μA	Detector size	1000 x 1000 pixels

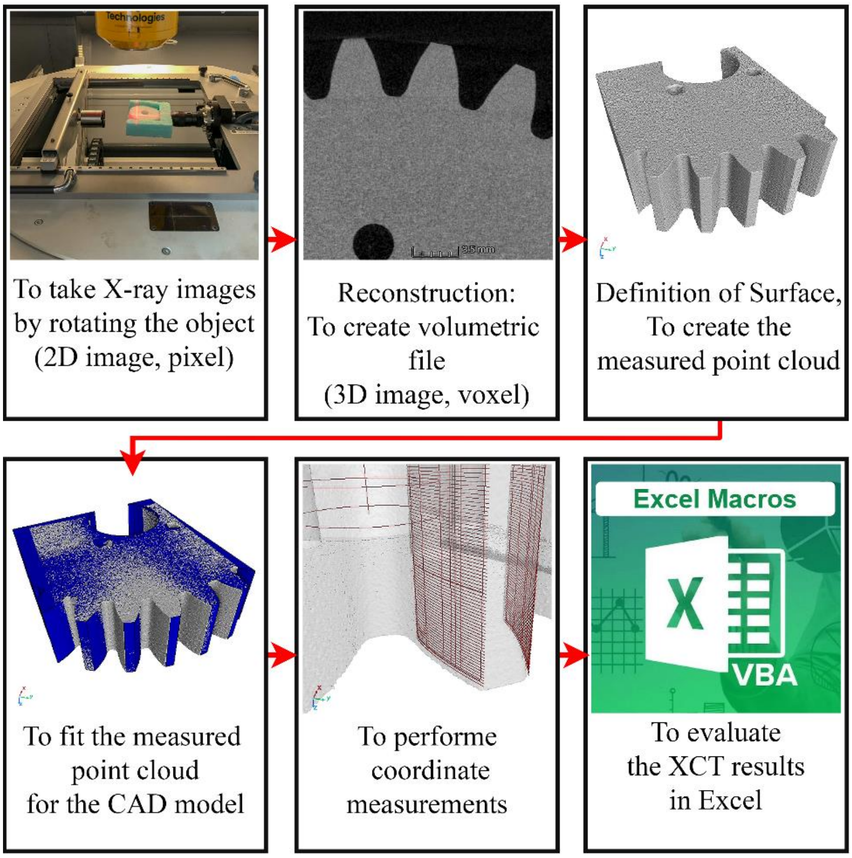

Fig. 4. Flow diagram of X-ray tomography wear evaluation

2.4. Function fitting, outlier filtering and multivariate linear regression

Several mathematical procedures were used to process the measurement data series, which were performed in Origin 2023b software.

To detect and exclude outliers, the "Residual Plot" function was used. In this procedure, linear regression was performed on the data series and used the standard residuals to determine which data points were outliers.

Prior to function fitting, a well-established method was used for processing the temperature data series, the Savitzky-Golay algorithm with a first-order polynomial, i.e., a linear function and a 500-point width, to smooth the noisy measurement data, which reduced the curve irregularities.

To determine the equilibrium temperature for the gear tests, diagrams was made plotting the temperature as a function of the cycle. The temperature curve was divided into two phases according to tribological principles and examined the equilibrium temperature in the running-in phase. An exponential-type saturation function was fitted to these sections of the temperature curve using the Downhill Simplex (Nelder-Mead) method.

Multivariate linear regression was applied to mathematically and statistically evaluate the large amount of measurement data obtained in my research to determine the effect of crystallinity on the Charpy impact of the material used in the basic research, as well as the effect of the material properties and test characteristics used for the gear tests on temperature and wear and their sensitivity.

Multivariate linear regression analyses were performed using IBM SPSS version 27 mathematical statistical software.

3. RESULTS

3.1. The selection process for cast PA 6

Based on the results of the Charpy impact tests (Fig. 5), it can be concluded that the impact energy values are not constant over the range of rod diameters tested. They are grouped into three categories. In the first category, rods are classified between diameters 40 and 90 mm with impact energy ranging from 16.2 to 18.5 kJ/m^2, which is higher than the average. The second category includes rods with diameters of 130, 170 and 200 mm, whose impact energy ranged from 14.7 to 16 kJ/m^2. The third category is the 300 mm diameter rod, as its impact energy was below average, ranging between 12.5 and 15 kJ/m^2. The results show that the production size of semi-finished rods produced by magnesium catalysed casting technology can affect the toughness of the parts and their behaviour under impact loading, which is a relevant factor for engineering applicability.

The degree of crystallinity of the semi-finished rods produced by the magnesium-catalysed casting technology was studied ranged from 15 to 27%, as illustrated in Fig. 5. Based on the results of the DSC study, it can be concluded that the variation in the degree of crystallinity affects the Charpy impact strength. Accordingly, a higher degree of crystallinity is able to cause a decrease in toughness. It was found that, among the factors affecting the properties of polyamide, the degree of crystallinity causes 62.3% of the change in Charpy impact strength, which was supported by linear regression.

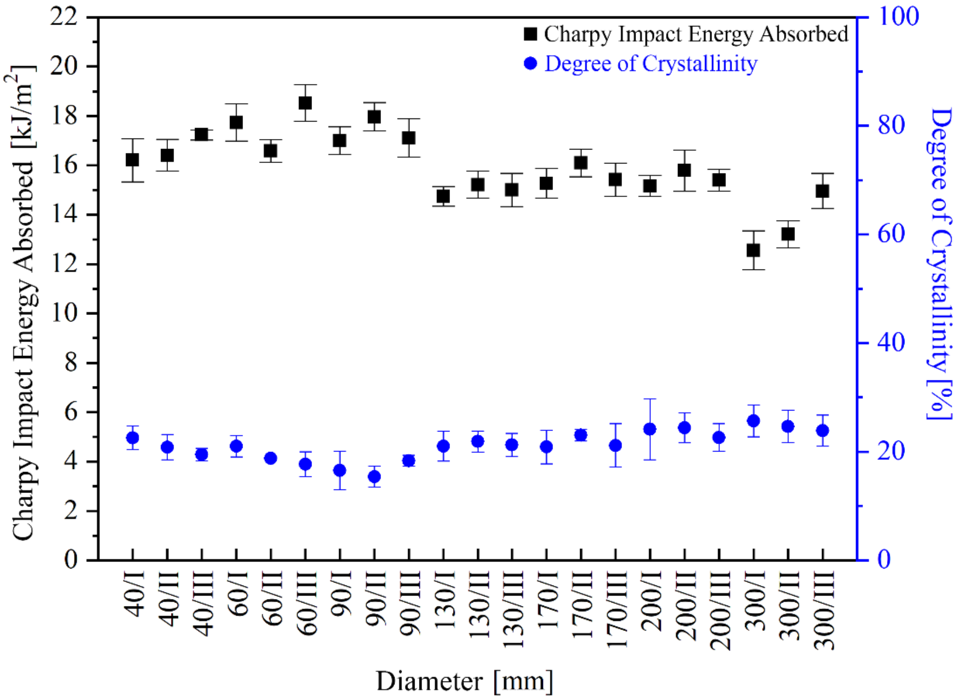

Fig. 5. Charpy impact energy absorbed and crystallinity values for magnesium catalysed cast PA6 rods

My research work and the reproducibility of the measurement results depend on the ability to define the toughness and crystallinity of the materials was tested.

Based on my research, it was found that the toughness of the ø70 mm magnesium catalysed cast polyamide 6 rod machined gears were used for the measurements, also known as Charpy's impact energy, is between 16.2 and 18.5 kJ/m^2. This is to define that the research results and conclusions for polyamide are for this material and not for polyamide 6 in the traditional sense.

3.2. Results of the gear tests

Fig. 6 is taken as an example from the measurement data series, which illustrates the online curves of the gear tests. The name of the plastic tested, the load level, and the number of repetitions can be shown. The graph plots torque and temperature as a function of cycle. The diagram shows that at a near constant torque, the temperature increases steadily in the running-in phase until it reaches the equilibrium temperature, then begins to decrease slightly in the steady-state phase, and this decreasing pattern is maintained permanently throughout the test.

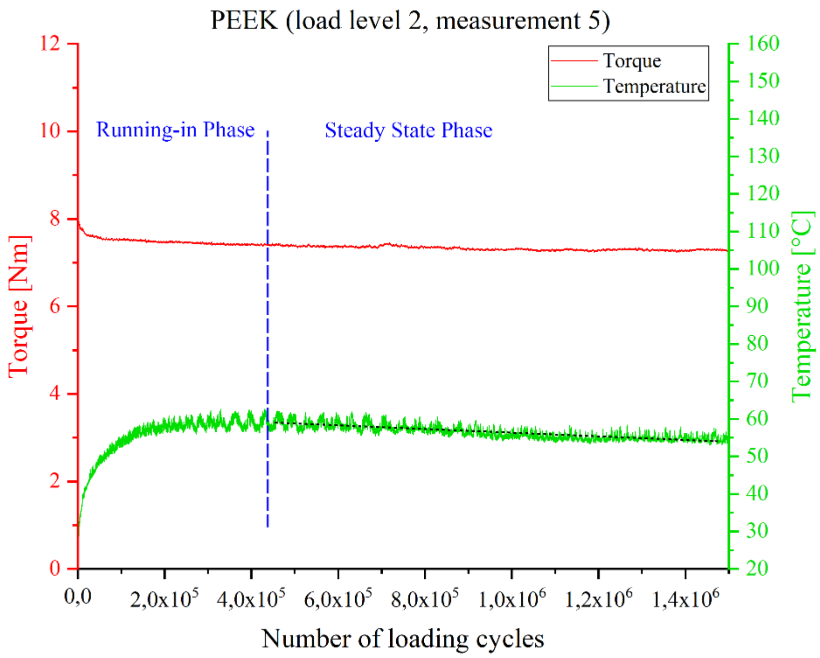

Fig. 6. Torque and temperature as a function of cycle for PEEK

Based on Newton's law of cooling, it was determined that a negative exponential saturation function is a good approximation of the temperature rise of the gear bulk as a function of the cycle. It has been found that the bulk temperature in the running-in phase can be well approximated by the following function as a function of the cycle:

$$T(N_L) = A - B \cdot e^{-C \cdot N_L}, \qquad (1)$$

where "A", "B" and "C" are the coefficients of the function, and their sign is always positive.

It is important to note that the coefficients have a physical content. The coefficient A represents the equilibrium temperature of the gear bulk to which the bulk is set during operation at the end of the running-in phase. Parameter B is the difference between the initial temperature and the equilibrium temperature. The coefficient C is the rate at which the equilibrium temperature is reached, expressed in cycles (N_L), i.e., the number of cycles after which the equilibrium temperature is reached asymptotically.

Regression analyses were performed in two ways. First, the analyses were run per material, where only (i) cycle, (ii) pv were defined as independent variables. In the second round, all materials were considered, and the following parameters were defined as independent variables: (i) cycle, (ii) pv value, and (iii) material properties (density, yield strength, elongation at break, elastic modulus, Poisson's ratio, glass transition temperature, melting point, thermal conductivity, thermal diffusivity, flexural strength, Charpy impact strength, Shore-D hardness, ball indentation hardness, H/E ratio). The aim of the latter analysis is to investigate which material properties play a role in the equilibrium temperature of the gear tooth.

The values of coefficient A per material as a function of pv are shown in Fig. 7.

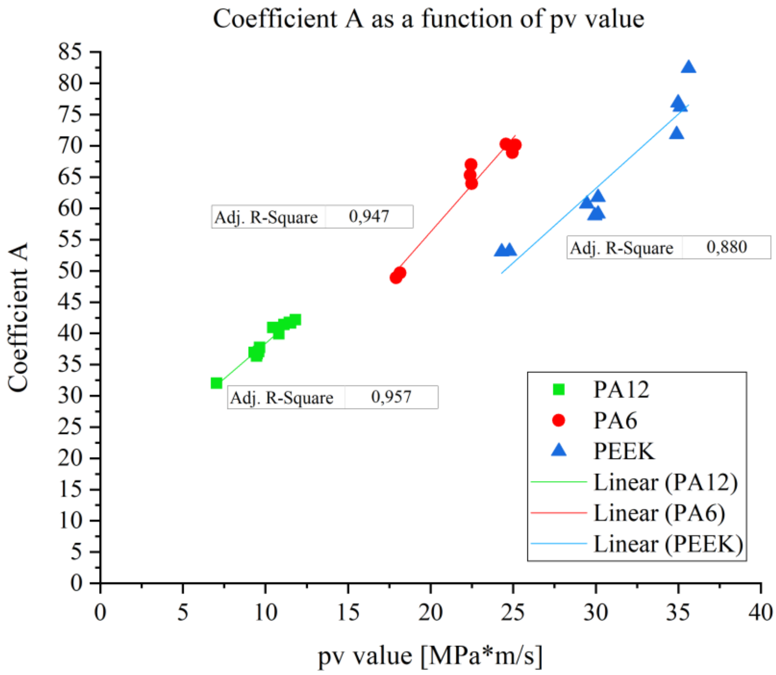

Fig. 7. Coefficient A values as a function of pv value

Based on the linear regression analyses performed per material, the coefficients of the exponential type of saturation function generally show that the pv value was the most significant independent variable, with an increase in the value of the coefficients A, B, and C.

The correlation between the coefficient A and the pv value is the same as for the material-by-material comparison, i.e., it increases with increasing pv value. In contrast, for coefficient B, there is a negative relationship with the Poisson's ratio, i.e., an increase in the Poisson's ratio causes a decrease in coefficient B. For the coefficient C, the independent variables in the regression model beta, coefficient β, indicate that the effect of the glass transition temperature is more significant than that of the pv value. Furthermore, the correlation also shows that an increase in the glass transition temperature has a negative effect on the value of the coefficient C, in contrast to the pv coefficient.

During the gear tests, the average friction coefficients were determined for each pair of materials (Fig. 8). The regression tests were performed separately for each material and in a matched manner. In the former, it was sought to find out whether the coefficient of friction per material pair is affected by the temperature of the tooth body or by the pv value. The latter to see how material properties affect the coefficient of friction. By analysing the results of the measurement and regression tests, it can be concluded that:

- For gears made of PA12 material using SLS 3D printing technology, the coefficient of friction developed after the running-in phase at steady state at pv values between 9.3 and 10.9 MPa·m/s is between 0.37 and 0.44.
- In PA12 gears, the temperature of the bulk was the determining factor for the coefficient of friction, and the beta coefficient shows that the coefficient of friction increases with increasing temperature.
- The coefficient of friction for gears machined from magnesium catalysed cast PA6 rod ranges from 0.29 to 0.33 depending on the applied load, in the range of 21.4 to 25.1 MPa·m/s pv.
- The coefficient of friction for gears produced by machining extruded PEEK rods is between 0.17 and 0.26 for pv values between 23.9 and 34.7 MPa·m/s, based on calculated data.

- For the PA6 and PEEK material pairings, the pv value has a dominant effect on the coefficient of friction, and there is a negative linear relationship between them, i.e., an increase in pv causes a decrease in the coefficient of friction.
- For all materials, material properties are taken into account in addition to pv value and bulk temperature, it can be concluded that torque, Shore D hardness, and bulk temperature play a decisive role in the coefficient of friction. In general, for the three materials, based on the beta coefficient, torque is the most determinant of the coefficient of friction, Shore D hardness is the second-most determinant and the bulk temperature is the least determinant. Furthermore, it is also found that increasing torque and Shore D hardness, as opposed to bulk temperature, decreases the coefficient of friction.

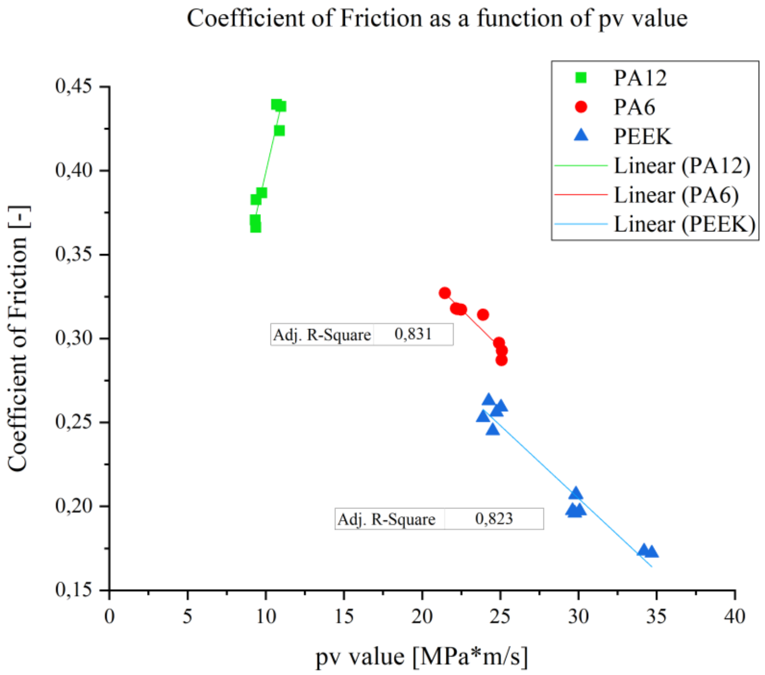

Fig. 8. Coefficient of friction as a function of pv value, separated by material pair

3.3. Results of the gear wear tests

The wear coefficient is used to predict the wear of plastic gears, which is very important for their lifetime, so materials that have been little researched or not researched at all have been investigated.

The weight of the gears was measured using a high-precision analytical balance before and after the gears were run, and the difference between the two gives the weight loss in milligrams. An overview of the measurement results shows that there is a difference in the values of weight loss and wear coefficient for different material pairings.

For the PA12 material pairing, the wear coefficient, $k_{wweight} = 23.6 - 303.4*10^{-6}$ -mm^3 /Nm, is in the range of pv tested (Fig. 9). The results of the regression studies show that the pv value is the dominant factor for both the weight loss and the weight-loss wear coefficient for the PA12 gear pairing. With an increase in pv value, an increase in the values of weight loss and $k_{wweight}$ wear coefficient is expected.

For PEEK gears, there is a negative linear relationship between the weight-loss wear coefficient and the pv value, so that the wear coefficient decreases significantly with increasing pv value. In contrast, regression analyses show that it is not the pv value but the coefficient of friction that is the determinant of the wear coefficient, the increase of which also increases the wear coefficient. In the case of PEEK, there is a negative linear relationship between the pv value and the coefficient of friction, i.e., an increase in the pv value decreases the coefficient of friction, so the relationship between the pv value and the coefficient of wear is clear. For the PEEK gear, the weight-loss wear coefficient ranged from 0.99 to 2.2*10^{-6} -mm /Nm.^{3}

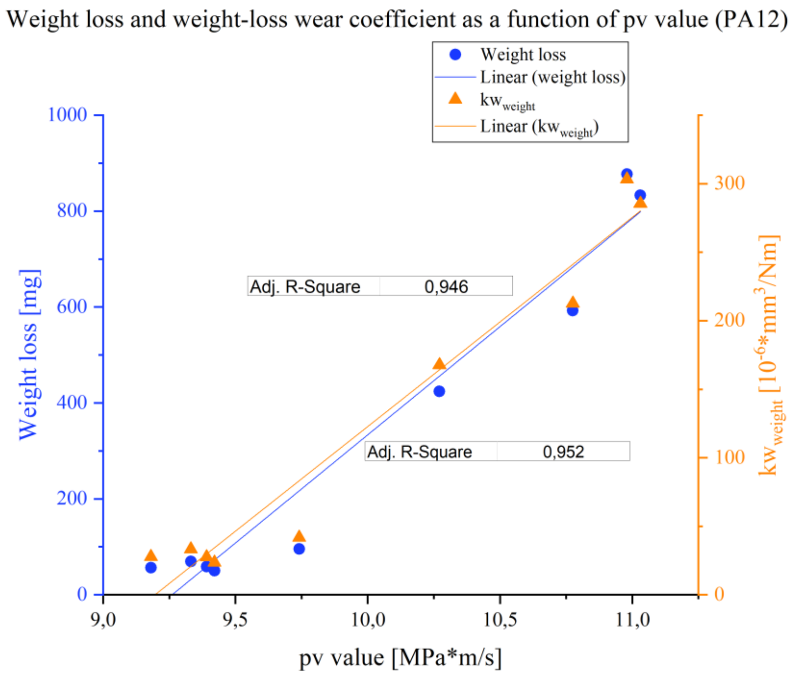

Fig. 9. Weight loss and weight-loss wear coefficient as a function of pv for PA12 gears

If all materials are considered in the regression analyses, it can be generally stated that the friction coefficient is the dominant factor among the independent variables for the weight loss and the weight-loss wear coefficient.

The results of the microscopic wear assessment, i.e., the averaged linear wear, W_m , and the resulting wear coefficient, k_{wWm} , as a function of pv, are illustrated in Fig. 10 and 11. In the regression analyses, the averaged linear wear and the wear coefficient based on this distance were considered dependent variables for the model separated by material, while the pv value, the coefficient of friction, and the tooth body temperature were considered independent variables. In the model summarising the materials, the independent variables are complemented by the material properties.

The results of the microscopic wear evaluation of PA12 gears are shown in Fig. 10. For the PA12 gears, it can be observed that the wear coefficient is in the range of 56 - 512 x 10^{-6} -mm^3 /Nm between 9.2 - 11.03 MPa-m/s pv.

Based on the regression models, it can be concluded that there is a linear relationship between the averaged linear wear and the pv value, as well as between the k_{wWm} wear coefficient and the pv value, and that an increase in the pv value contributes to an increase in both the averaged linear wear and the wear coefficient.

For PA6 gears, it can be stated that over the load range pv 17.8 - 24.6 MPa-m/s, the wear coefficient ranges from 6.6 - 9.8 x 10^{-6} -mm /Nm^3.

The microscopic wear evaluation of PEEK gears shows a different phenomenon compared to the materials studied so far, as illustrated in Fig. 11. For PEEK wheels, the loss of material on the active tooth side, i.e., wear, increases with increasing load, like the previous two materials, but the wear coefficient responds with a decreasing trend as the load increases. For PEEK gears, it can be observed that the wear coefficient in the range 23.7 - 35.2 MPa-m/s pv is in the range 7 - 9.5 x 10^{-6} -mm /Nm.^{3}

The averaged linear wear and the wear coefficient for PA6 and PEEK gears are an order of magnitude lower than for PA12 gears.

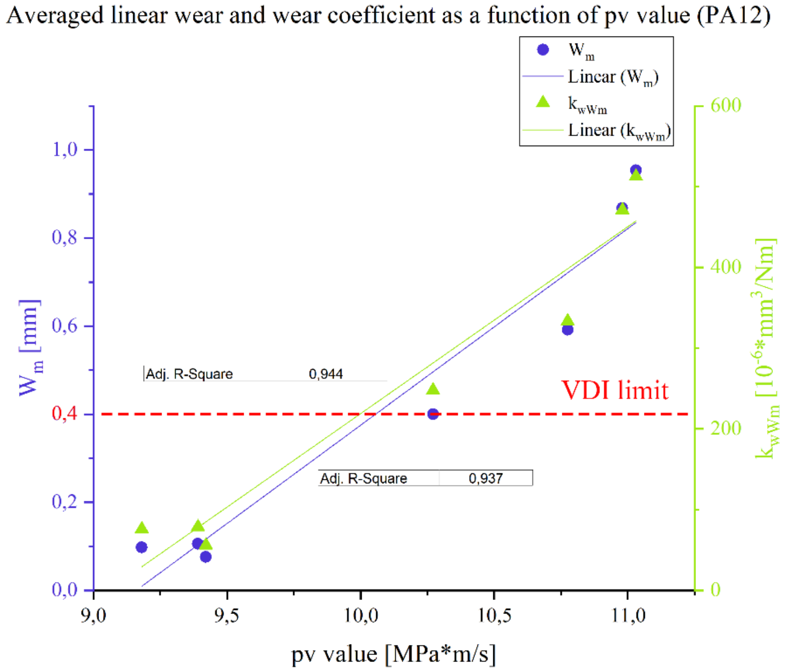

Fig. 10. Averaged linear wear and coefficient of wear as a function of pv for PA12 gears

For PEEK wheels, the results of the regression tests show that:

- The averaged linear wear can be described by a linear relationship between the averaged linear wear and the pv value, so as the pv value increases, the averaged linear wear increases.
- The relationship between the wear coefficient and the pv value can also be described by a first-degree polynomial, but there is a negative linear relationship, so an increase in the pv value promotes a decrease in the wear coefficient.

Based on the regression analyses, where material properties were taken into account, it can be generally stated that the ball indentation hardness is the dominant factor among the independent variables for the averaged linear wear and the wear coefficient, k_{wWm}.

The typical results of X-ray tomography wear assessment for PEEK, i.e., nominal wear, are illustrated in Fig. 12.

For PA12 gears, it can be concluded that nominal wear of 0.058 - 0.98 mm can be expected in the range of 9.3 - 11.03 MPa-m/s pv. Based on regression analysis, there is a strong positive linear correlation between XCT nominal wear and pv value for PA12 gears.

For PA6 wheels, it is found that the nominal wear in the pv range between 17.8 and 25 MPa-m/s is between 0.006 and 0.017 mm.

For PEEK gears, it can be observed that the nominal wear varies between 0.011 and 0.023 mm in the range 25 - 34.8 MPa-m/s pv. For PEEK wheels, the results of multivariate linear regression show that there is a negative linear relationship between the XCT nominal wear and pv value, i.e., an increase in pv value decreases the nominal wear.

Based on the results of the regression studies extended to material properties, it can be generally stated that the friction coefficient is the most important factor among the independent variables for the XCT nominal wear.

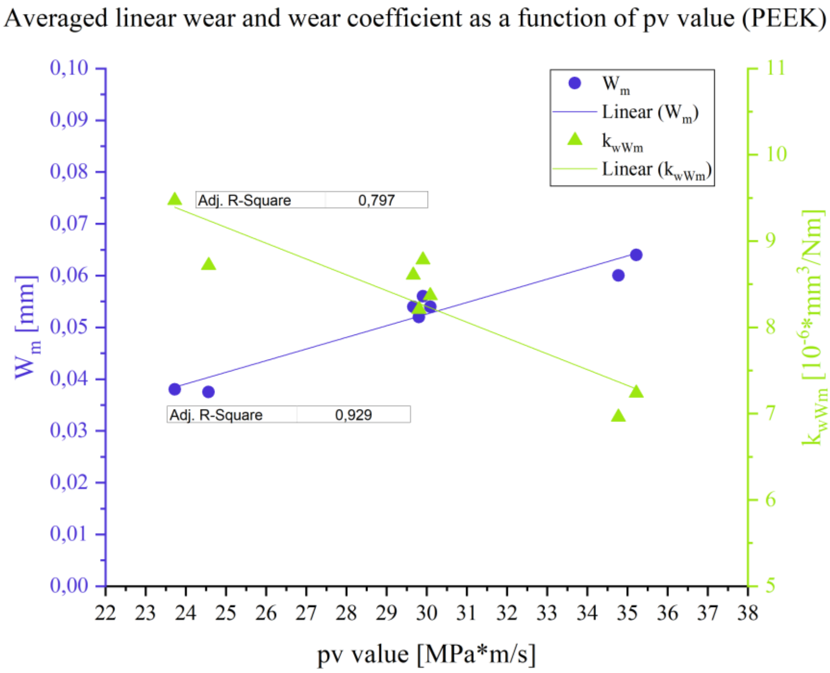

Fig. 11. Averaged linear wear and wear coefficient as a function of pv for PEEK gears

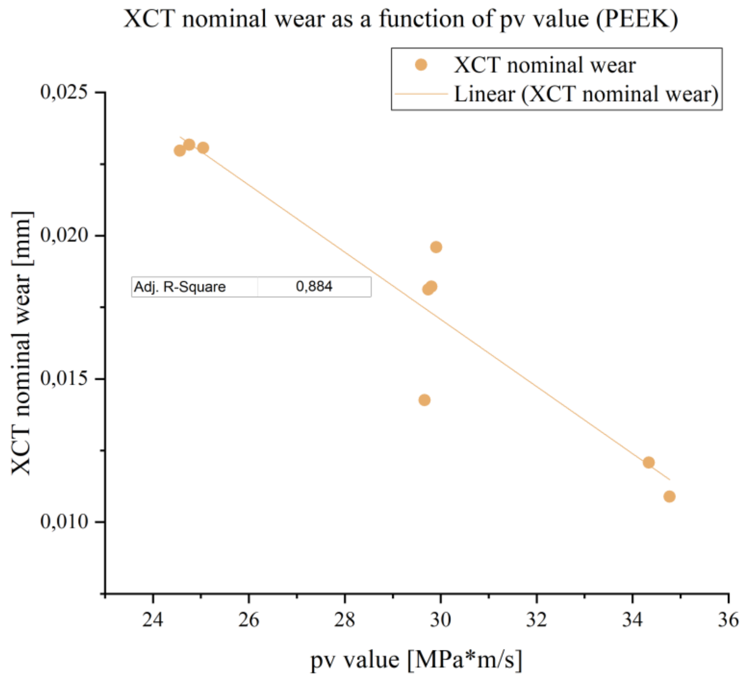

Fig. 12 XCT nominal wear as a function of pv for PEEK gears

4. NEW SCIENTIFIC RESULTS

Thesis 1

It has found that the impact values for cast polyamide 6 rod semi-finished products are not constant in the diameter range 40-300 mm, and that the production size of magnesium-catalysed cast rods affects the toughness of the material. Charpy impact tests have shown that the impact strength decreases with increasing diameter. DSC studies have shown that the crystallinity of magnesium-catalysed cast PA6 rods in the diameter range 40-300 mm is between 15 and 27%. Using multivariate linear regression analysis, it has shown that among the factors affecting the properties of polyamide, the degree of crystallinity alone influences the variation of Charpy impact strength by 62.3%. These results suggest that it is appropriate to design gears from magnesium-catalysed cast PA6 rods.

Thesis 2

For the cast PA6, PA12 (SLS), and PEEK materials used in the gear tests, and with the same material pairings, multivariate linear regression tests on gear temperature show that the temperature of the gear bulk is:

$$T(N_L, pv) = A(pv) - B(pv) \cdot e^{-C(pv) \cdot N_L}$$

where the coefficients A, B, and C depend linearly on the value of pv.
The members of the function: T: the gear bulk temperature [°C]; N_L: number of cycles; A: coefficient for the equilibrium temperature of bulk; B: coefficient of the difference between the initial and equilibrium temperature; C: coefficient is the rate at which the equilibrium temperature is reached.

Thesis 3

For polymer gears with the same material pairing, it has been found that PA12, PA6, and PEEK material pairs gave different friction responses to increasing pv in the test system: for PA12 gears made by SLS technology, friction increases with load, whereas for PA6 and PEEK gears made with conventional machining technology, the coefficient of friction decreases with increasing load.

Thesis 4.

Using the measurements and multivariate regression, it has been found that torque, Shore D hardness, and bulk temperature play a decisive role in the coefficient of friction. In the research system, the greatest influence on the coefficient of friction for the materials tested is exerted by the transmitted torque, followed by the Shore D hardness, and the least by the bulk temperature. It was found that increasing torque and Shore D hardness, as opposed to tooth body temperature, decreases the coefficient of friction.

Thesis 5

Based on wear evaluation, it was found that wear as a function of pv exhibited a bidirectional behaviour for PA12 and PEEK material pairs: for PA12 gears manufactured by SLS technology, a 17% increase in pv caused a 914% increase in wear, while for PEEK gears manufactured with conventional machining technology, a 46% increase in pv resulted in a 24% decrease in wear. Multivariate linear regression was used to demonstrate that wear is affected by friction and hardness in opposite ways, with an increase in friction increasing wear and an increase in hardness decreasing wear.

Thesis 6

A new wear evaluation method has been developed for polymer gears based on X-ray computed tomography (XCT), which, in contrast to conventional wear measurement methods (weight loss, microscopy), is able to quantify the differences between theoretical and real tooth profile in three dimensions and is suitable, e.g., to consider shape and geometric inaccuracies due to manufacturing processes when determining the actual wear. The method provides the possibility to map the wear of the tooth surface, which contributes to a deeper understanding of the wear mechanisms.

5. CONCLUSIONS AND PROPOSALS

My research has produced new scientific results that are useful in several areas. It supports the technical practice in the selection process of cast polyamide 6 semi-finished products. For designers, it provides material properties and correlations for more efficient design of polymer gears.

For magnesium-catalysed cast polyamide 6 rod semi-finished products, it was found that the production size has an effect of toughness. Based on the results of the impact tests, a recommended rod diameter range has been proposed for the selection of the gear material. Based on regression studies, it was showed that the degree of crystallinity of polyamide 6 influences the Charpy impact strength.

In addition to the traditional gearing process, gears made with the still-novel 3D printing technology (SLS)have also been studied to explore their potential.

It has been determined for given gear combinations how the equilibrium gear bulk temperature of the gear varies as a function of the revolutions travelled and using function fitting, a general relationship was determined to describe the variation in the running-in phase. After analysis of the coefficients in the context, it was determined that the relationship between the coefficients and the pv value can be described by a first-order polynomial in most cases with a good approximation ($R^2 > 0.9$).

One of the major drawbacks of the polymer gear design guideline, the coefficient of friction, which is an essential material property for design, has been determined for some material combinations not yet available, at the steady state stage. This was done by defining the variation of the coefficient of friction over a given load range. Furthermore, the relationship between load and friction was pointed out for the given materials and gave a linear relationship to define the coefficient of friction as a function of pv value with a good approximation ($R^2 > 0.9$).

A cardinal issue in the design of polymer gears is the estimation of service life, which is determined by the wear coefficient. Therefore, three different wear evaluation methods have been used to determine the wear of gears as accurately as possible. For the material pairs, PA12/PA12; PA6/PA6; and PEEK/PEEK were investigated, and the wear coefficient was determined under given operating conditions. Based on linear regression, a correlation was given for the relevant material pairs in order to determine the wear coefficient as a function of the pv value over the load range under investigation with a good approximation ($R^2 > 0.8$).

A new wear evaluation method has been developed for plastic gears based on X-ray computed tomography (XCT). With this method, tooth wear can now be evaluated not only in 2D but also in 3D, and the profile changes can be followed along the tooth flank, giving a deeper insight into the wear mechanisms.

Based on my research work, I would propose to extend the relationships of established results to apply to a wider range of loads.

In addition, I would encourage the investigation of further material combinations, even for different material pairings, but in any case, focusing on polymer-polymer pairings.

I also find it useful to examine parameters other than load, such as rotational speed, lubrication, module, and controlled ambient temperature. These are all missing in the literature and in the standards and guidelines.

6. SUMMARY

Gears are an essential part of power transmission systems, without which our everyday lives would be unimaginable. Alongside metal wheels, plastic gears have also gained ground and are used in many industrial sectors, even in prominent areas such as medicine and the automotive industry. Polymer gears have several advantages over metal ones, which make them unique in certain areas of application. Such characteristics include, for example, a weight-to-strength ratio, self-lubricating properties, corrosion resistance, good damping capacity, a low noise level, and economical production. However, the use of plastic gears is limited by their material properties, such as load-carrying capacity, low stiffness, and sensitivity to temperature changes, which lead to a deterioration of the mechanical properties.

Currently, only the German VDI 2736 guideline provides guidance for plastic gears, with the drawback that the material properties for design have been developed for only a few material combinations. Thus, despite the availability of high-performance materials and the fact that additive manufacturing technology is now commonplace, designers cannot use these materials for gear applications, as it is not possible to design gears without proper material properties.

My research in the field of gears is multifaceted. On the one hand, the selection of gear material was contributed for semi-finished products made of polyamide 6. On the other hand, the design of innovative and high-performance polymer gears was contributed for which the appropriate material properties for calculation have not been available so far but are suitable for such gear material.

The results of my material investigations have confirmed the hypothesis that the toughness of polyamide 6 rod semi-finished products produced by magnesium catalysis casting technology is dependent on the production size, mainly due to the degree of crystallinity.

Based on my gear tests, a relationship describing the gear bulk temperature as a function of the revolutions travelled has been established for a given material pair, which is a function of two variables (pv, cycle) and is valid over a given pv range.

On the other hand, the coefficient of friction was given for material pairs for the calculation of the gear bulk temperature, which is essential for the design and can be used in the investigated pv range. Furthermore, the relationship between friction and load per material pair was pointed out.

The results of my gear wear tests provide the possibility of making lifetime estimations, based on the wear coefficient. To determine the wear, three different measurement methods were applied: weight measurement, microscopy, and X-ray tomography (XCT). For the material pairs investigated, the wear coefficient was established, which can be used in a specific pv range.

For the evaluation of plastic gear wear, a new method has been developed based on X-ray tomography (XCT). The method allows the spatial assessment of tooth wear, i.e., the wear can be determined at any point along the tooth flank, which provides additional information on the wear mechanisms. In addition to wear, the method also offers other possibilities, such as checking the accuracy of manufacturing, mapping inclusions, or assessing the porosity of the material, which have an impact on the failure process of the gear.

7. KEY PUBLICATIONS RELATED TO THE THESIS

Referred articles in foreign language

1. Keresztes R. Zs., **Odrobina M.**, Kalácska G., Fledrich G. (2017): Development of polymer gear test rig for loadbearing examination. Mechanical Engineering Letters: R and D: Research And Development, Vol. 15, pp. 72-80., 8 p., ISSN 2060-3789
2. Keresztes, R. Zs., **Odrobina, M**., Nagarajan, R., Subramanian, K., Kalacska, G., Sukumaran, J. (2019): Tribological characteristics of cast polyamide 6 (PA6G) matrix and their composite (PA6G SL) under normal and overload conditions using dynamic pin-on-plate system, Composites Part B: Engineering, Vol. 160, pp. 119-130., 12 p., ISSN 1359-8368 (IF: 11,322)
3. **Odrobina M.**, Kalácska G., Keresztes R. Zs. (2018): The Effect of Sizes of the Cast Polyamide 6 Rods upon Tensile-Impact Strength, International Journal Of Engineering and Management Sciences / Műszaki és Menedzsment Tudományi Közlemények, Vol. 3 (1), pp. 21-24., 4 p. ISSN 2498-700X
4. **Odrobina M.**, Sarankó Á., Kalácska G., Keresztes R. (2018): Tribological behaviour of electrically conductive and self-lubricating cast polyamide 6 composites, Mechanical Engineering Letters: Research and Development, Vol. 17, pp. 67-73., 7 p., ISSN 2060-3789
5. **Odrobina M.**, Szakál Z., Kalácska G., Keresztes R. Zs., Eberst O., Pop S. (2017): The effect of sizes of the cast Polyamide 6 rods upon impact strength. Mechanical Engineering Letters: R And D: Research And Development, Vol. 15, pp. 56-61., 6 p., ISSN 2060-3789
6. **Odrobina, M.**, Deák, T., Székely, L., Mankovits, T., Keresztes, R. Zs., Kalácska, G. (2020): The Effect of Crystallinity on the Toughness of Cast Polyamide 6 Rods with Different Diameters, Polymer, Vol 12 (2) pp. 1-16., 16 p, Paper: 293, ISSN 2073-4360 (IF: 4,967)
7. **Odrobina, M.**, Kalácska, G., Keresztes, R. Zs. (2020): Overload and Lifetime Test of Machine Cut Polymer Gears, Acta Technica Jaurinensis, Vol. 13 (3), pp. 197-210., 14 p., ISSN 2064-5228
8. Szakál, Z., Zsidai, L., Al-Maliki, H., **Odrobina, M.**, Kári-Horváth, A. (2016): Shear Strength Behaviour of adhesive bonded Polymer and Steel Surfaces. Scientific Bulletin Series C: Fascicle Mechanics, Tribology, Machine Manufacturing Technology, Vol 30, pp. 110-115., 6 p., ISSN 1224-3264