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Design and Development of Novel Lubricant Free Transmission System for Manual Bone Drilling Machine

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Bone Drilling Machine, Design and Development, Lubricant Free, Transmission system, Polymer PEEK Gear

ABSTRACT
This paper describes design and development of novel lubricant free transmission system for manual bone drilling machine. In order to design the transmission system, applied forces and torques on the gears has to be achieved. In this regard, bone drilling forces and torques were detected, preforming experimental tests of the drilling operation by CNC milling machine. At this point, various drill diameters and machining parameters were considered. After achieving the bone drilling forces, they were utilized for gears design process. The design process including gear geometry, material and detailed design analysis were done according to German norm VDI 2736- Part 3. In this context, the mating worm gears materials were selected out of stainless steel 316 and Polyether Ether Ketone (PEEK), which can reduce weight, noise, moment of inertia, and necessity of lubrication, etc. In order to evaluate the gears performance, numerically and experimentally were performed. The static stress and deflection of the PEEK gear tooth were investigated numerically by finite element analysis. According to the numerical results, each tooth force carrying capacity (until yield stress) were estimated until 302 *N*. Surface temperature and wear rate for two types of PEEK gears were examined, experimentally, while applying two resistance torque values, 0.75 and 0.5 *Nm*, to the manufactured transmission system. The selected torques were three and five times bigger than drilling torque values, enabling us to simulate the bone drilling operation considering unexpected loaded in the extreme case, misuse, emergence situation, and degradation. The maximum temperatures of the tooth contour of the transmission system raised to 127 *°C*. According to the results, the maximum achieved PEEK gear life was 200 minutes for the Natural PEEK polymer at the 0.5 *Nm* torque.

INTRODUCTION
Bone fracture treatment is usually done by conventional and direct approaches. In the conventional approach setting and alignment of the fractured parts is performed from outside, however, direct approach implies internal fixation by insertion of screws, steel wires, and fixators [1] and [2]. In the later approach bones are drilled by manual or electric drilling machines. The application of the manual machine is in the least developed countries (where there is an electricity shortage problem) or in military. Moreover, many surgeons prefer to use the manual one due to the usage convenience and avoiding excessive heat generation during drilling operation [3]. The drilling machine needs to be cleaned and sterilized after usage to prevent postoperative infection occurrence [4]. However, the current manual drilling machines have serious design and development defects related to their transmission system.

One of the major problems with the mentioned design process is the necessity of lubrication of the drill transmission system. In this way, the transmission system can be a potential unhygienic environment for the orthopedic surgery. Figure 1 shows the current drills transmission system, in which the fixation wire passes through drills greasy transmission system, which can deliver lubricant to operating bone. Therefore, a solution to the mentioned problem can be design of a lubricant free transmission system.

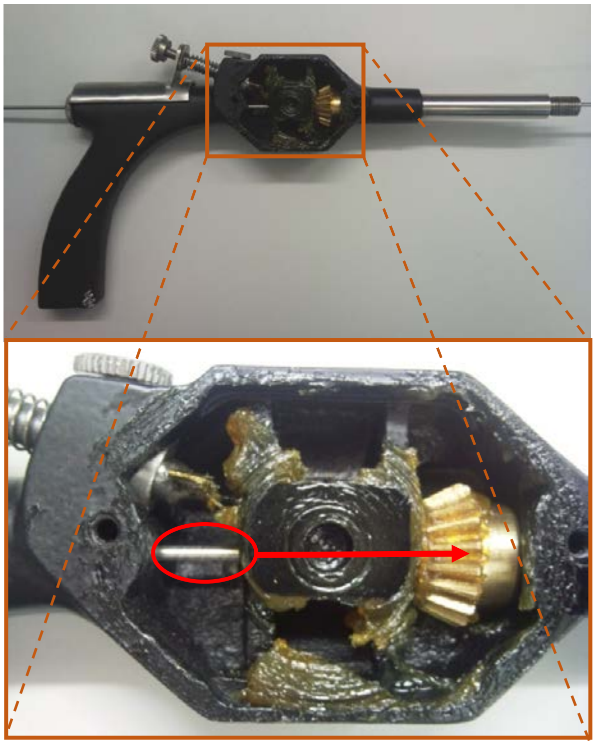

Figure 1 – Manual hand drilling machine and K-Wire, passing through the unhygienic transmission system

Up to date, there have been several research works, in which plastic gears have been proposed as a non-lubricated gears running condition [5], [6], and [7]. From this angle, plastic gears have been utilized by success in various industrial applications such as automotive, office machines, and food industries due to their economical and technical advantages [8]. They offer unique properties such as low cost, low weight, easy manufacturability, and functioning without lubrication, etc. [9]. In order to select proper plastic material for the transmission system application, they have to be withstanding against the sterilizing temperature, 121-138*°C*. Furthermore, they have to be able to work in non-lubricated contacts, while having appropriate tribological performance. Dearn et al. [10] have reported polymer materials tribological performance, while, applying rolling-sliding contact tests. They have also tested and simulated rolling–sliding wear behavior of two poly-ether-ether-ketone (PEEK) discs running against each other. Moreover, Mao et al. [11] have investigated wear behavior of dissimilar polymer gears engagement, numerically and experimentally. They have investigated the wear behavior of a range of dissimilar polymer gears such as acetal against nylon gears, PEEK and PEEK, PEEK against steel, and steel against PEEK. Although, some initial proper findings (as an example, improvement of gear tip wear) have been reported on the PEEK gears, the research work for PEEK is still in early stage and further and extensive work has to be carried out to understand the performance of the PEEK gears and their design [11].

In order to design the polymer gears, there are a number of standards and design methods e.g. British standard, Polypenco, and ESDU. However, almost no known attempt has been reported to compare the design standards with the experimental results. This point has been mentioned in the research works [11], [12], and [13]. Authors in these papers have tried to investigate the wear, fatigue and surface temperature behavior of a range of engineering polymers by continuous monitoring approach. Moreover, the design standards such as German norm 2736 covers calculations of gear tooth load carrying capacity, lacking gear wear and surface temperature prediction. Therefore, the gear performance in terms of wear and temperature growth on the tooth contour has to be an analyzed experimentally.

Here in this research work, the gears design and development are described according to the standard 2736- part 3, which is a guideline for design of thermoplastic gears. Additionally, gears performances evaluation is reported numerical and experimental. The above-mentioned assessments take into the account the bone drilling application limitations. In the following chapters, firstly, the bone drilling operation by CNC machine and measurement of the forces by piezoelectric dynamometer are going to be described. Later on, the gears material and geometry selection in addition to the detailed design are explained. Finally, gears performance are analyzed and discussed in terms of gears static stress, deflection analysis, surface temperature, and wear behavior.

BONE DRILLING EXPERIMENTS

In order to specify the maximum possible forces and torque which can be applied to the transmission system during bone drilling operation, the drilling forces have to be achieved, experimentally. In this context, various studies investigated the effect of drilling operation parameters such as rotational speed on the trust force and torque during bone drilling [14], [15], [16], and [17]. The influence of feed rate was also explored, where; higher feed rate causes higher trust force and torque [17] [18]. Therefore, it is necessary to explore the drilling force and torque considering feed rate and rotational speed as well as the effect of drill diameter.

The bone drilling experiments were done in order to determine the drilling forces and torques, while changing the machining parameters (such as spindle speed, feed rate and drill bit diameter). In this context, the drills were tungsten carbide with the point angle of 120 degree, in two diameters 4.5 and 6 *mm*. The selected specimen was bovine bone, since it replicates the properties of human bone [19]. Table 1 shows the comparison of mechanical properties human and bovine cortical bone [20].

Table 1 –Comparison of human and bovine bone mechanical properties

Properties	Human bone	Bovine bone
Density (kg/m^3)	1800-200	2060
Young's Modulus (Gpa)	10-17	10-22
Tensile Yield Strength (Mpa)	45-150	45-150
Shear Modulus (Mpa)	3	3
Compressive Strength (Mpa)	130-200	140-250

Drilling operation were performed by Hermle C40, 5-axis milling machine, and the force measurement were done by Kistler Piezoelectric dynamometer in radial direction, *X* axis, and axial direction, *Z* axis (see Figure 2)**.**

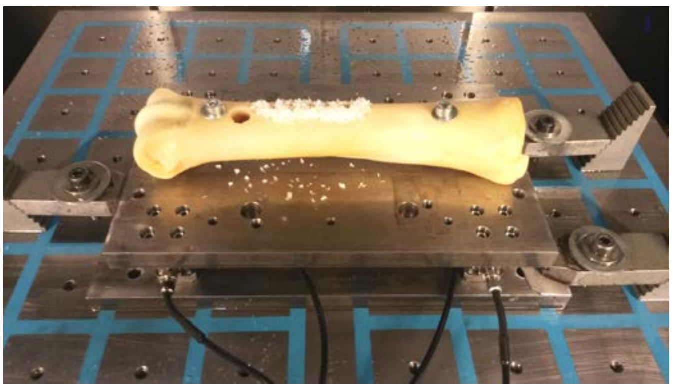

Figure 2 – Drilled bone by Hermle CNC milling machine

For this purpose, design of experiments of the drilling operations was performed in four test levels (see Table 2). The total number of the drilling operations were twelve, in which, two different drills (diameters 4.5 and 6 *mm*), three various rotation speed (200, 300, and 400 *rpm*), and two feed rate values (0.1, and 0.2 *mm/rev*) have been applied to the process.

Table 2 – Applied machining parameters in bone drilling

Test Level	Drill Dia. (mm)	Rotation speed (rpm)	Feedrate (mm/rev)
1	4.5	200, 300, 400	0.1
2	4.5	200, 300, 400	0.2
3	6	200, 300, 400	0.1
4	6	200, 300, 400	0.2

Results and Discussion

The results of the drilling force measurement are presented for the maximum values in *X* and *Z* axes for the drill diameters 4.5 and 6 *mm*. Figure 3 shows the forces measurement in *X*, and *Z* axes for the drill diameter 4.5 *mm* and the cutting parameters corresponding to rotation speed, 400 *rev/min* and feed rate 0.2 *mm/rev*. According to the figure, the maximum force in *Z* axis (axial force) is 120 *N* and the maximum force component in *X* axis (radial force) is 18.5 *N*.

Figure 4 shows results of the forces measurement in *X*, and *Z* axes for the drill diameter 6*mm* and the cutting parameters corresponding to rotation speed, 400 *rev/min* and feed rate 0.2 *mm/rev*. According to the figure, the maximum force in *Z* axis (axial force) is 195 *N* and the maximum force component in *X* axis (radial force) is 25 *N*. Furthermore, the axial forces (trust force) shape is described in three steps. Firstly, the drill comes in to the contact with the bone, so that there is a sharp increase of the trust force. Secondly, the force reaches to the maximum values until the end of the drilling operation. Finally, the drill exits the hole and the forces values are suddenly decreased to the zero value.

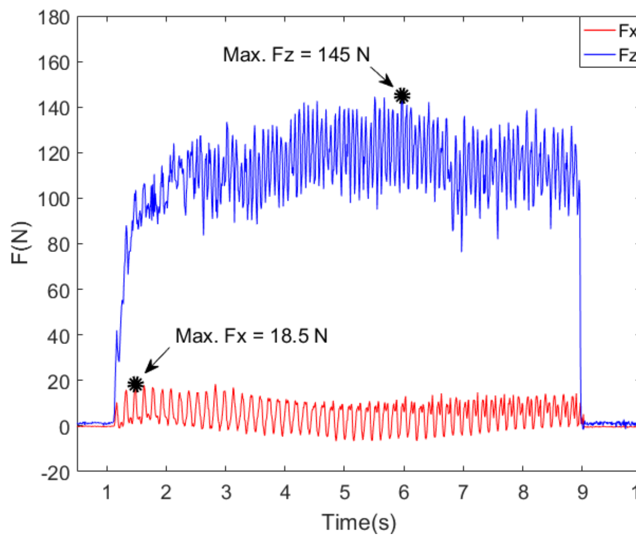

Figure 3 - Drilling forces applying test level 2 parameters (rotation speed 400 rpm)

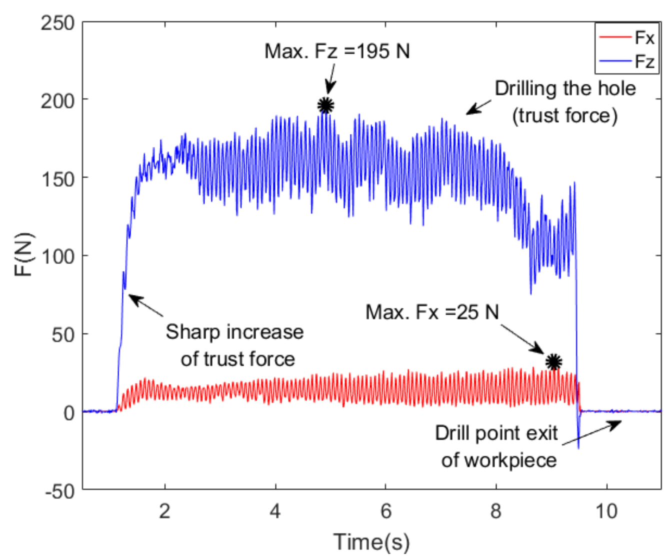

Figure 4 - Drilling forces applying test level 4 parameters (rotation speed 400 rpm)

More information about drilling forces and torques exist in the paper, [21], in which bone drilling operation have been modeled and drill-bit geometry and drilling thrust and torque have been analytically described.

Table 3 shows results of the axial and radial forces for the four test levels of drilling, measured experimentally. According to the values rotational speed does not have influence on the axial and radial drilling forces, nevertheless the forces are increased by increasing the feed rate and drill diameter.

Table 3 – Measured axial and radial forces

Test Level	F_x (N)	F_z (N)
1	18.5	95
2	18.5	145
3	22	120
4	25	195

The drilling torque, T_d, is calculated as following [22]:

$$T_d = \frac{d}{2} \times z \times F_x \qquad (1)$$

Where *d* is the drill diameter, *z* is number if teeth, which is equal to 2, and F_x is the radial force. Accordingly, the maximum calculated torque value is equal to 0.15 *Nm*, belonging to the drill diameter 6 *mm*, feedrate 0.2 *mm/rev*, and rotation speed 400 *rpm*. The calculated maximum torque and radial forces are going to be used for the numerical gear design purpose (tooth stress analysis) as well as the experimental gear wear and temperature analysis.

GEAR DESIGN

Gear design process for transmission system of the bone drilling machine are performed according to the German norm VDI 2736 part 3 as well as the finite element analysis. The standard includes the guidelines for design of the thermoplastic gear wheels, with crossed helical gears, and mating cylindrical helical gears configuration. It encompasses calculations for root and flank load carrying capacity of the thermoplastic gears [23].

Gear Geometry Selection

Selection of gear geometry was performed considering the application characteristics and constrains. Some of the limitations included less space occupation in the drilling machine housing, meshing effectiveness, smooth and silent operability, possibility of operation in lubrication free condition, easy manufacturability, ability to transfer power between non-parallel shafts, producibility from polymer materials, and resistance against impact and dynamic loads.

Taken into account the above-mentioned requirement for gear geometry selection, various geometries (such as bevel, spur, helical, spiral and worm gears) advantages and disadvantages were investigated. Among the mentioned drives, the most appropriate gear geometry for the manual bone drilling transmission system was “worm gear drive”.

Gears Material Selection

The Material properties of the plastic gear had to fulfill the requirements of the bone drilling application. These could be wear resistance when running dry, lubrication free applicability, low water and moisture absorption, resistant against chemicals, higher melting and service temperature than sterilizing temperature (121-138*°C*), biocompatibility, low thermal expansion, high creep resistance, and good manufacturability, etc.

In this regard, feasibility studies of various polymers which are usually used for gear applications, such as Polyacetal-C, Ultra-high Molecular Weight Polyethylene, Cast Polyamid 6, Calaumid, Polyether Ether Ketone “PEEK”, were performed. At this point, the Polyether Ether Ketone (PEEK) fulfilled the above-mentioned criterions. Table 4 and 5 present the properties of the materials according to the standards, ISO 527-2, ISO 718, ISO 604, DIN 53765, ISO 11359, and ISO 62.

Table 4 – Properties of TEKAPEEK MT Natural

Mechanical properties	Value
Density (g/cm^3)	1.31
Tensile strength (Mpa)	116
Tensile strength at yield (Mpa)	116
Flexural modulus (Mpa)	4200
Service temperature, long term (°C)	260
Service temperature, short term (°C)	300
Heat deflection temperature at 264 psi (°C)	165
Thermal expansion (23-100°C, 10-5 K-1)	5
Coefficient of friction-µ	0.05-0.075
Water absorption (weight %, 96h in 23°C)	0.03

Table 5 – Properties of TECAPEEK MT CF30 Black

Mechanical properties	Value
Density (g/cm^3)	1.42
Tensile strength (Mpa)	115
Tensile strength at yield (Mpa)	115
Flexural modulus (Mpa)	6000
Service temperature, long term (°C)	260
Service temperature, short term (°C)	300
Heat deflection temperature at 264 psi (°C)	165
Thermal expansion (23-100°C, 10-5 K-1)	5
Coefficient of friction-µ	0.05-0.075
Water absorption (weight %, 96h in 23°C)	0.03

The gear pair were selected dissimilar materials, stainless steel 316 for worm screw and PEEK polymer for worm wheel. The reason for selection of such a configuration is as following. The gear material pair can dissipate the generated heat easier, since thermal conductivity of the stainless steel (13-17 *W/m.k*) is higher in comparison to the selected PEEK polymers (0.25-0.59 *W/m.k* according to ISO22007-4:2008). Moreover, the surface quality of metallic gear can be enhanced, leading to lower surface friction between the mated pair. To further above, when the polymer gear wears for some time without failure, the point contact becomes line contact, which is more similar to a single enveloping worm gear. This increases the load carrying capacity.

Gear Design Numerical Analysis

In this research work, an accurate 3D model of the gear pair was created by PTC-CREO 3 software. The gear pair detailed design parameters are presented in Table 6.

Table 6 – Gear pair design parameters according to German norm VDI 2736-part 3

Parameter	Worm screw	Worm wheel
Material	SS 316	PEEK
Normal module (mm)	1.5	
Center distance (mm)	20	
Pressure angle (degree)	14.5	
Helix angle (degree)	40	
Number of teeth	8	16
Addendum height (mm)	1.15	1
Dedendum height (mm)	1.35	1.45
Root radius (mm)	0.75	0.4
Tensile strength (Mpa)	580	116
Yield strength (Mpa)	290	116
Max. drilling torque (Nm)	0.15	0.225

Since the material strength of polymer worm wheel is less than metallic worm screw, the tooth thickness of the polymer gear was greatly increased and the pressure angle was reduced to the typical value of 14.5 degree.

Before performing the finite element stress analysis on the worm wheel, it is necessary to calculate the force component on the wheel. In this scenario, worm screw tangential force F_{tw}, was calculated from the drilling torque, T_d, at the worm screw pressure circle diameter, d_p, as following:

$$F_{tw} = \frac{2 \times T_d}{d_p} \tag{2}$$

Considering the maximum calculated drilling torque, 0.15 *Nm*, the tangential force on the screw was calculated 18.75 *N*. According to the Figure 5, the tangential force on the worm screw, F_{tw}, is equal to the axial force on the gear wheel, F_{ag}. Moreover, the tangential force on the worm wheel, F_{tg}, corresponds to the axial force on the worm screw, F_{aw}, which is listed in the axial force values of Table 3, F_z. The normal force, F_n, on the gear tooth contact area was calculated as following:

$$F_{tg} = F_{aw} = F_n(\cos\alpha_n \cos\gamma + \mu \sin\gamma)$$
$$\Rightarrow F_n = \frac{F_{aw}}{(\cos\alpha_n \cos\gamma + \mu \sin\gamma)} \tag{3}$$

Where, α_n, is the pressure angle 14.5 degree, γ, is the helix angle 40 degree, and μ, is the transmission efficiency, 1.2. Considering the maximum axial drilling force 195 *N*, the normal force value is calculated 127.1 *N*. This value was applied (as a static load) in the worm wheel tooth stress analysis.

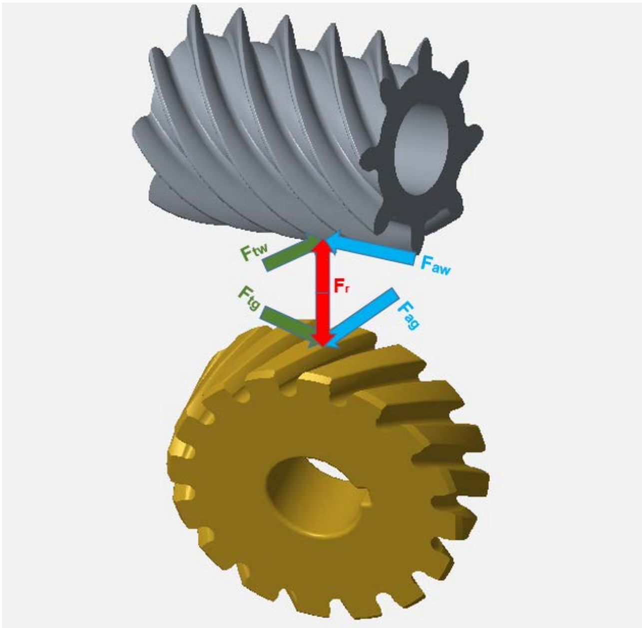

Figure 5 – Force components on the worm gear and screw wheel

Tooth Stress Analysis by Finite Element Analysis (FEM): Finite element analysis of the helical worm was done under various static load and constant temperature to analyze the tooth stress value by PTC-CREO 3 software. In order to consider the impact of unexpected loaded, which is usually occur during manual drilling of the bone, the amount of applied load was taken into account multiple time greater than bone drilling forces. After applying the mesh refinement, constrains and material properties assignment, the normal force component were applied to the single worm wheel gear tooth. To eliminate the numerical errors of applied load to the edge elements, pressure value, which represent the force normalized by the contact area, was examined. Linear elastic analysis was done to determine whether the applied static pressure would induce stresses to go beyond the yield stress of the PEEK gear material. In this regard, four simulation were performed which are presented in Table 7. In the table, the values pertaining applied normal force and applied normal pressure, in addition to the results of calculated tooth stress (according to von Mises yield criterion), and displacements are presented. In this context, the simulation was continued until the maximum stress was equal to the yield stress of the material.

Table 7 – Worm wheel tooth stress analysis

Parameters	Sim.1	Sim.2	Sim.3	Sim.4
Force (N)	127	160	250	302
Pressure (Mpa)	10.079	12.69	19.84	23.96
Von Mises stress (Mpa)	37.7	60.1	93.96	113.5
Max. Disp. (mm)	0.0455	0.057	0.09	0.109
Yield stress (Mpa)	116	116	116	116

Figure 6 shows the maximum value of tooth stress, 113.5 *Mpa*, which is approximately equal to the material yield stress. The corresponding normal force applied to the worm wheel tooth was calculated 302 *N*. The gear safety factor was calculated as follows:

$$\text{Factor of Safety} = \frac{\text{Material Yield Stress}}{\text{Bone Drilling Induced Stress}} = \frac{116}{37.7} = 3.07 \quad (4)$$

The value of the safety factor shows that the designed gear can withstand against unexpected load, emergency situations, misuse, and degradation, approximately, up to three times the calculated bone drilling induced stresses.

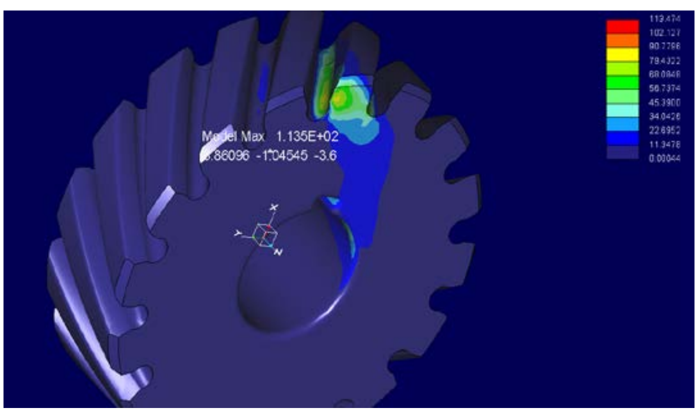

Figure 6 –Tooth Stress analysis by PTC-Creo software

GEAR SURFACE TEMPERATURE AND WEAR MEASUREMENT EXPERIMENTS

One of the major problems of polymer gears is the knowledge of their operation temperature. It is of utmost importance to predict or measure the tooth temperatures and compare it with the gears material Heat Deflection Temperature (HDT) and service temperature. Another important issue in the polymer gear design is their wear rate behavior, which determines the life of the gears. Therefore, the experimental test were performed to investigate the mentioned indications (temperature and abrasive wear) for the polymer gears performance measurement.

Experimental Setup

In order to evaluate the gear wear rate and the surface temperature behavior, the experimental tests were performed. The goal of the experiments were investigation of wear rate on the polymer PEEK gears in addition to the temperature evolution on the gears teeth contour and output shaft of the transmission system. In this context, a tests rig, which resembles the bone drilling machine transmission system were developed (see Figure 7). The test rig was driven by an electromotor from worm wheel side, while resistance torque was applied by braking motor to the output shaft.

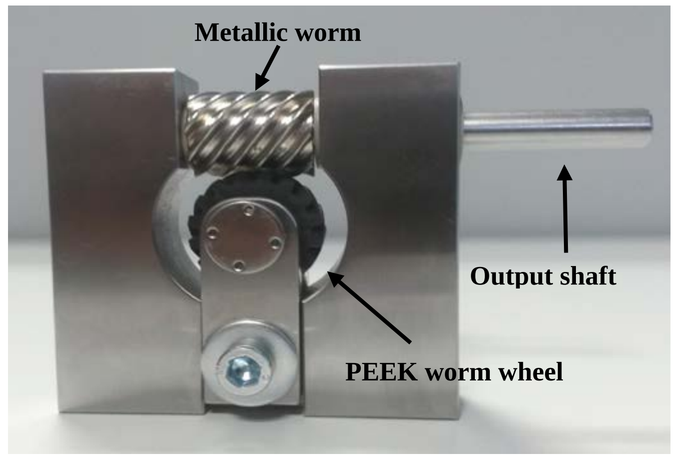

Figure 7 –Worm gear test rig

Figure 8 shows the test stand, which consists of the test rig of worm gear, an electromotor driving the gear, and a magnet braking motor (Fras 21- Mobac GmbH) to apply the desired torque to the transmission system.

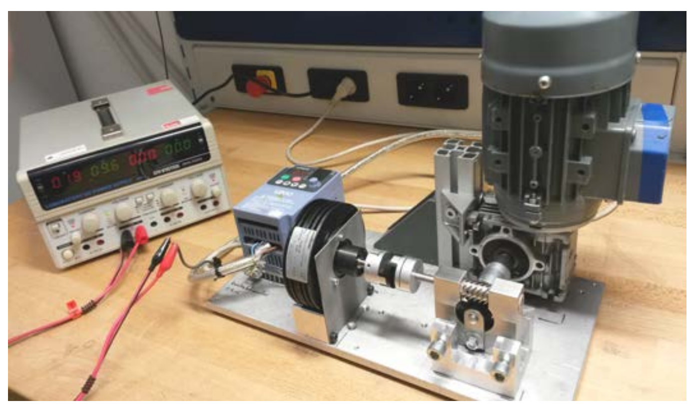

Figure 8 –Experimental test stand

In order to apply various torques to the brake motor, different current values from power supply were provided. Figure 9 depicts the linear relation between the input current and output torque from brake motor according to the producer's technical data. Two levels of resistance torques were applied to the transmission system, 0.5 and 0.75 *Nm*, corresponding to the current 0.1 and 0.15 *A*, respectively. The selected torques were three and five times bigger than drilling torque the maximum calculated values, measured from bone drilling operation. This enabled us to simulate the bone drilling operation considering unexpected loaded. Given the constant input rotational speed to the transmission system (by the electromotor) 135 *rpm*, the output shaft rotational speed increased to 270 *rpm* due to the 1:2 worm gear ratios.

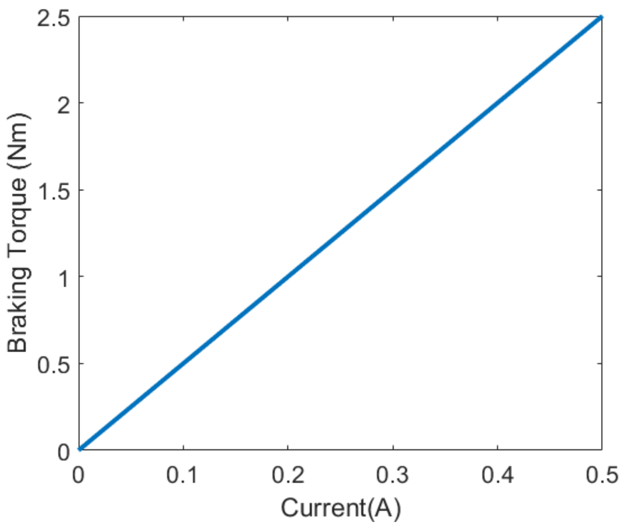

Figure 9 - Linear relation between the input current and output braking Torque

Experimental Results and discussion

The temperature evolution around the gear tooth contour was measured by thermal imager FLUCKE Ti 20 instrument for two types of the PEEK polymers applying the torques, 0.5 and 0.75 *Nm*.

Figure 10 shows the temperature change versus time, using Black PEEK and Natural PEEK, while applying the torques 0.5 *Nm*. The measurement was performed continuously, in several time intervals until 20 minutes. According to the figure, the maximum temperature around the gear contour reaches to 92.8 *°C* and 69.1 *°C* for the Black and Natural PEEKS, respectively. The temperature growth gradient for Black PEEK was higher than Natural PEEK up to 5 minute, while afterward is not changed, significantly. However, Natural PEEK had a gradual temperature growth until the measurement ending point 20 minutes.

Figure 11 shows the temperature change versus time, using Black PEEK and Natural PEEK, while applying the torques 0.75 *Nm*. The measurement was performed continuously, in several time intervals until 10 minutes. According to the figure, the maximum temperature around the gear contour reaches to 127.3 *°C* and 106.4 *°C* for the Black and Natural PEEKS, respectively.

Therefore, the maximum running temperature around the tooth contour is less than HDT and service temperature, 165 and 260 *°C*, respectively.

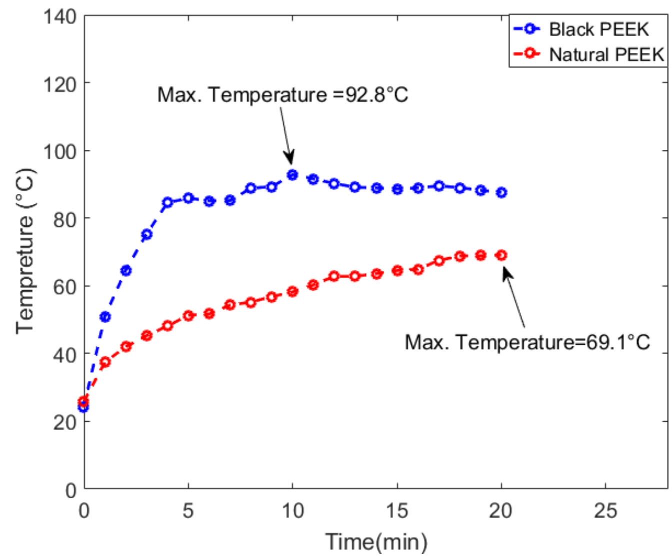

Figure 10 – Comparison of measured temperature growth on the gears contour, Black PEEK Vs. Natural PEEK, torque 0.5 NM

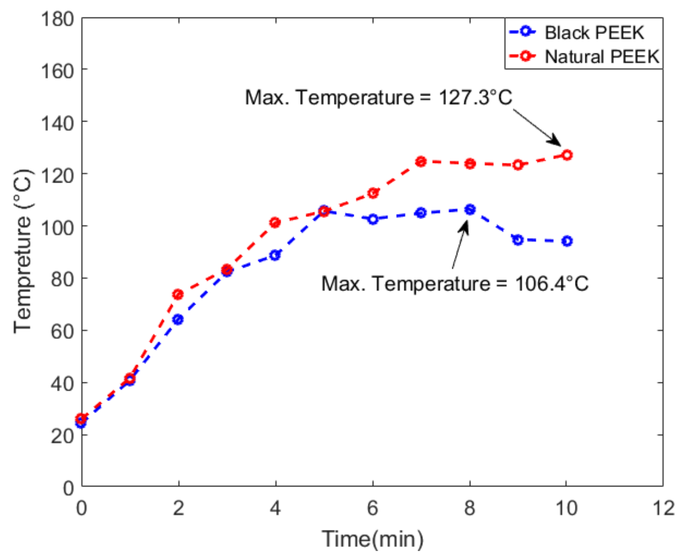

Figure 11– Comparison of measured temperature growth on the gears contour, Black PEEK Vs. Natural PEEK, torque 0.75 NM

The gear abrasive wear rate measurements were done by Keyence VHX 600 microscope. The wear rate of the PEEK polymers were measured in several time intervals until the rate equivalent to 0.7 *mm* on flank side of the gear is observed. Figure 12 shows the comparison between abrasive wear rate of the Black and Natural PEEK versus time until 700 μm value is exceeded (green line is the threshold). The applied torque in this case was 0.5 *Nm*. According to the figure, the maximum Natural PEEK life is 200 minute, while the Black PEEK life corresponds to 180 minute. In addition, it is seen that the initial wear rate (until 500 μm) of Black PEEK is taken place faster than Natural PEEK. However, the former's wear rate slows down from 500 to 700 *µm*.

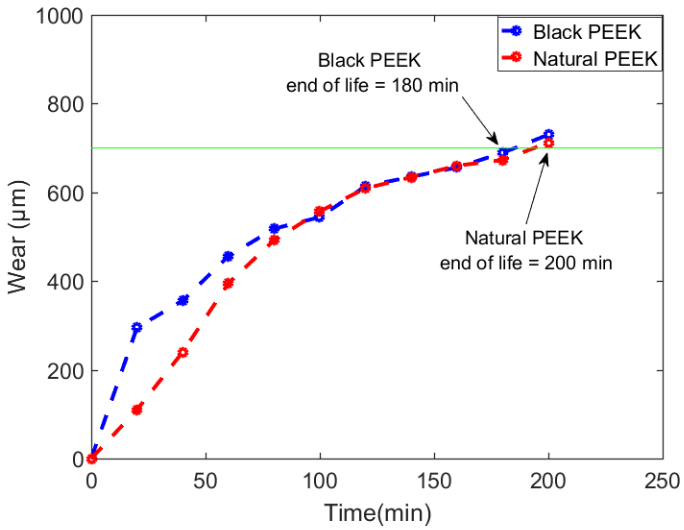

Figure 12 – Gear wear comparison between Black PEEK and Natural PEEK, when applying the torque, 0.50 NM

Figure 13 shows the abrasive wear evolution rate comparison between Black and Natural PEEK versus time until 700 µm value is exceeded (green line is the threshold). The applied torque in this case was 0.75 *Nm*. According to the figure, the maximum Natural PEEK life is 90 minute, while the Black PEEK life corresponds to 100 minute. Furthermore, it is observed that the initial wear rate (until 400 *µm*) of Black PEEK is taken place faster than Natural PEEK. However, the former's wear rate slows down from 400 to 700 *µm*.

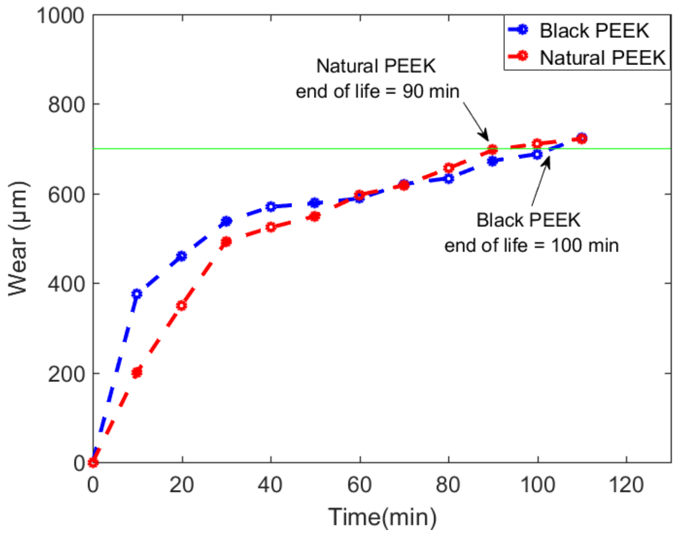

Figure 13 – Gear wear comparison between Black PEEK and Natural PEEK, when applying the torque, 0.75 NM

Therefore, the life of the Natural PEEK was higher in the lower torque amount, 0.5 *Nm*, while Black PEEK showed better performance in the higher torque value, 0.75 *Nm*. However, during the wear process, worn out particles of the Black PEEK are separated and can be transferred through the transmission system of the bone drilling machine to the operating bone area (see figure 14). This can be prevented by design of proper sealing on the machine housing.

Figure 14 – Separated particles during wear experiments

CONCLUSION

Design and development of the novel lubricant free transmission system for manual bone drilling machine was demonstrated. In this regard, bone drilling forces were achieved experimentally and used for the gear design process. The design process was done, while applying the real bone drilling forces and torques. Moreover, gear design process including gear geometry, material and detailed design analysis were done, using dissimilar mating worm gears materials, stainless steel 316 and Polyether Ether Ketone (PEEK). The design process considered the limitation and constraints of the bone drilling application. FEM analysis of the PEEK gear tooth was investigated and the results of the tooth von Mises stress and deflection were reported. The FEM results showed that the designed gear static strength were approximately three times bigger than the bone drilling induced stress. Thus, it may withstand against the unexpected loaded, misuse, and emergency uses. Testing facilities for gear surface temperature and wear rate measurement of PEEK gears were developed. According to the temperature experiments results, the maximum temperatures of the tooth contour is less than gears service life temperature. The tests results of the wear analysis showed longer life for Natural PEEK gear at the lower torque, while longer life for the Black PEEK at the higher torque. It is expected that the gears life in real application of bone drilling would be higher than the values, reported in this paper, since, the gear life experiments were performed with three and five times higher toques and in continuous running condition. This work hopes to contribute useful information and solutions to overcome the design and development defects of the industrial biomedical devices such as hand bone drilling machines.

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