Hungarian University of Agriculture and Life Sciences

Tribology of polymer composites machining

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Thesis of the doctoral (PhD) dissertation

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CONTENTS

LIST OF SYMBOLS

μ	coefficient of friction	[-]
A	factor of the friction force function	[-]
B	factor of the friction force function	[-]
C	factor of the friction force function	[-]
$F_{dynamic}$	dynamic alternating force due to vibration	[N]
F_{static}	static force due to static mass and self-weight	[N]
pv	multiplication of surface pressure and cutting speed	[MPa·m/s]
R^2	coefficient of determination	[-]
s	sliding distance	[m]
v_c	cutting speed	[m/min]

1. INTRODUCTION AND OBJECTIVES

In this chapter of my thesis, I present the timeliness and importance of the topic, as well as my objectives.

1.1. Introduction

Technical progress in the field of engineering plastics is particularly rapid. A prominent place is occupied by various types of doped polymer composites. The two main components of these structural materials are a tough matrix and a high-strength reinforcing material.

Composite machine components are increasingly used in mechanical engineering practice because of their numerous advantages. These machine parts are most often produced by injection moulding or a machining process.

One of the most used cutting process is turning, where usually machining is done with a single-edged, stationary tool. It is important to know the magnitude of the main cutting force during machining. Knowing this will allow a more uniform load to be applied to the cutting tool and, if the correct cutting parameters are set, minimise internal stress in the material being machined.

The parameters you set also affect the heat generated during machining. With the correct process settings, the characteristics of the chip removal system -

forces, friction, heat generation - should not cause significant changes or damage to the composite material, as this may lead to changes in the properties of the composite material.

Machining, as a tribological process between tool and workpiece, is influenced by the heat dissipated from the resulting friction and shear work, which can have a significant effect on the quality of the machined surface. The roughness, microcracks, the size of the bearing surface, the effective surface bearing capacity, the achievable dimensional accuracy, which is a major advantage of machining processes, are directly affected. The type of removed chip is also influenced by the friction generated on the tool face, which is further complicated by the vibration effect that characterises the technological process in the machine tool-workpiece contact.

This complex effect is less well understood for polymers. Consequently, the optimisation of machining and the potential engineering utility, sizing, design and manufacturability of friction machine components will be a task for the near future.

1.2. Objectives

My research objective is to determine the tribological aspects of single-edge machining (turning) for some basic and composite engineering polymers commonly used in engineering practice.

To achieve this, I set the following objectives:

- perform machining tests on extruded polyamide 6 (PA 6 E) base polymer and two types of composites with different parameters. Measure the main cutting forces and feed forces acting on the tool. The measured values will show the forces during turning different engineering polymer composites by varying the cutting parameters. I will also investigate how the main cutting force varies from material to material by changing the technological parameters,
- additional turning tests are carried out to determine the tribological contact zone between the chip and the face surface of the tool. I determine how the area of the zone depends on which parameters,
- I perform simple tribological tests on small specimens, setting the input parameters of the tests based on the output parameters of my machining tests,
- I will analyse the results of the tribological tests, and then, using a mathematical statistical method, I will describe the relationship between the parameters and friction force.

2. MATERIAL AND METHOD

In this chapter, I describe the experimental methods and tools used to achieve my research goals.

2.1. Turning tests

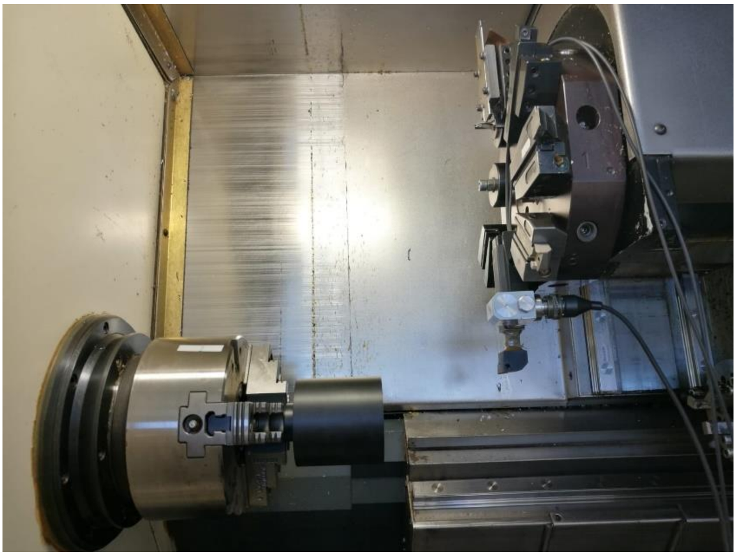
I used three types of workpiece materials (PA 6 E, PA 66 GF30 and PA 6G-H ELS) to carry out my turning tests. I prepared 3 cylindrical workpieces of each of the three material types for my turning tests, with a measuring length of 4 20 mm sections. The measuring diameters were continuously varied between 12 values, which I determined so that the main spindle of the NCT EUROturn 12-B CNC lathe could take 4 different speeds (780, 1080, 1380 and 1680 rpm) and the cutting speed values were between 100 and 400 m/min according to the general catalogue data and divisible by 50.

In the machine tool, I placed a custom tool holder made from a standard B7-20x16x30 tool holder, which holds a SCLCR 20.20 K09 type tool shank. For turning insert I chose a CCGW09T304FST type with a KD1425 grade polycrystalline diamond coated insert, considering the workpiece materials.

When measuring the main cutting forces, I always used the same depth of cut (0.5 mm) and four different feed rates for the four measuring stages (0.1; 0.15; 0.2 and 0.25 mm/rotation).

The tool shank was connected via cable to a Spider 8 type measuring amplifier, which was also connected via cable to a computer, where I monitored the measurement in real time using Catman software and saved the results for later processing.

I measured the vibration values of the tool shank with an SLD-144S type vibrometer. To do this, the tool extension was adjusted to 50 mm relative to the tool holder (2.1. Figure). The vibration meter was connected to a Leonova Diamond DIA-300 data acquisition unit via cables, which saved the data for later processing. Processing was done on a computer using Condmaster Ruby software.



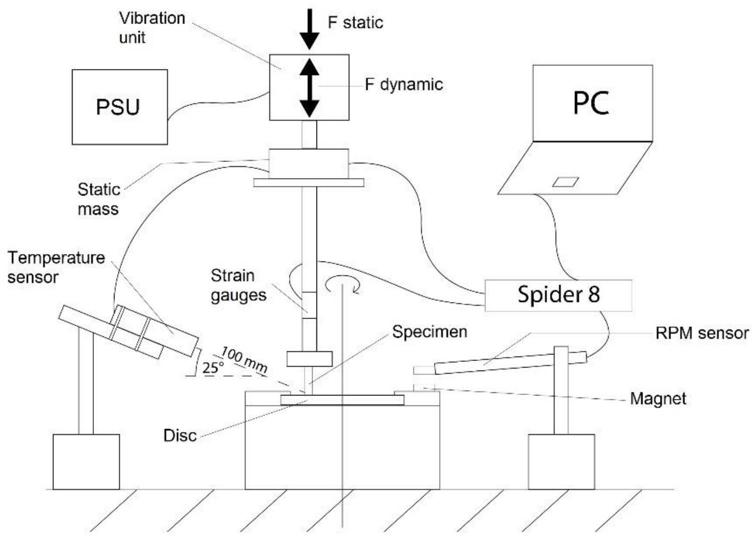
2.1. Figure Environment of workpiece before measurements

The contact area is the effective friction surface area between the face of the tool and the chip removed from the workpiece. This is an important data from a tribological point of view, so further investigations were carried out to determine this. Four feed rates (0.1; 0.2; 0.4 and 0.6 mm/rev) at a constant depth of cut (0.5 mm) and a constant 530 rpm main spindle speed were applied on an E 400 type lathe machine. The tool shank and turning insert type were the same as those used for force measurement. The insert was carefully cleaned and painted before each measurement. After turning, the insert was placed on the table of a BMS 74290 microscope and photographed with a BMS 764595 digital camera. The images were saved using ScopePhoto 3.1.615 software and the contact zone was calculated using Adobe Photoshop CC 2018 software.

2.2. Tribological tests

As a tribological test, I performed Pin-on-Disc type tribological small sample model tests. I used the output parameters of the turning tests as input parameters for the tests. The specimen materials were the same as the workpiece materials for the turning tests, and the disc material was a Hard Carbon coated carbide disc. To provide the added vibrations, I prepared a vibration unit providing vibrations at frequencies of 13, 18, 23 and 28 Hz. The vibrations resulted in alternating forces (0.23; 0.53; 0.8 and 1.2 N) in normal directions on the disc surface, which I called dynamic forces. I added this to the static force, which resulted from the mass of the devices and sometimes other added masses, also in the direction perpendicular to the disc. After summation, I obtained the resultant compressive force.

The friction force was determined by calculation from the friction force components measured in both directions. The schematic diagram of the test apparatus is shown in 2.2. Figure.



2.2. Figure Theoretical structure of my tribological tests

2.3. Method of function fitting and regression tests

To establish the relationship between turning and tribological tests, I used pv, which is the multiplication of surface pressure and sliding velocity in a sliding system.

In accordance with the DIN 50322 standard, I performed tribological small sample model tests based on 250th part of the pv values calculated for turning tests.

The results of my tribological tests were subjected to function analysis using the function search function of MATlab R2019b. After selecting the family of functions, I used the software to calculate the values of the factors contained in the function.

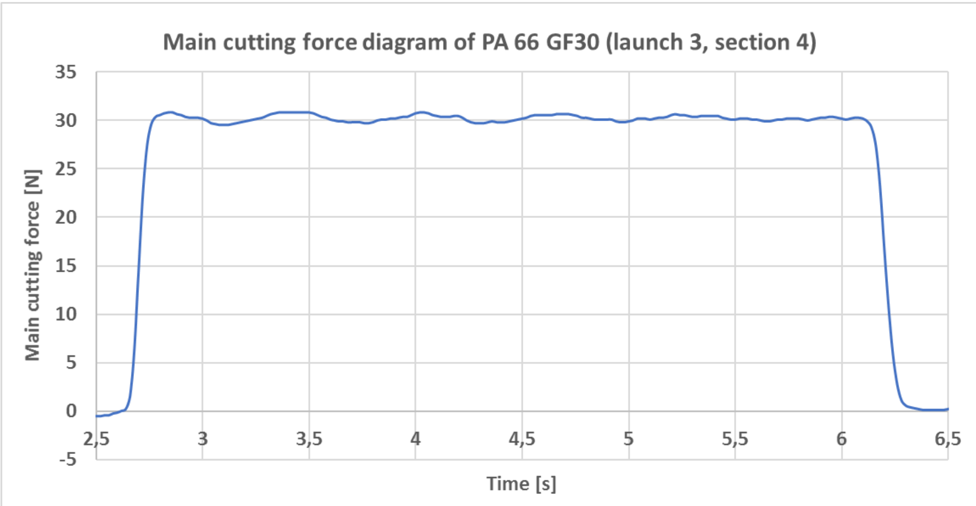
Regression analyses of factors were performed using IBM SPSS 27 software.

3. RESULTS

In this chapter I present the new scientific results of my research. Due to the large number of results, I will only show one example of the resulting diagrams in each case.

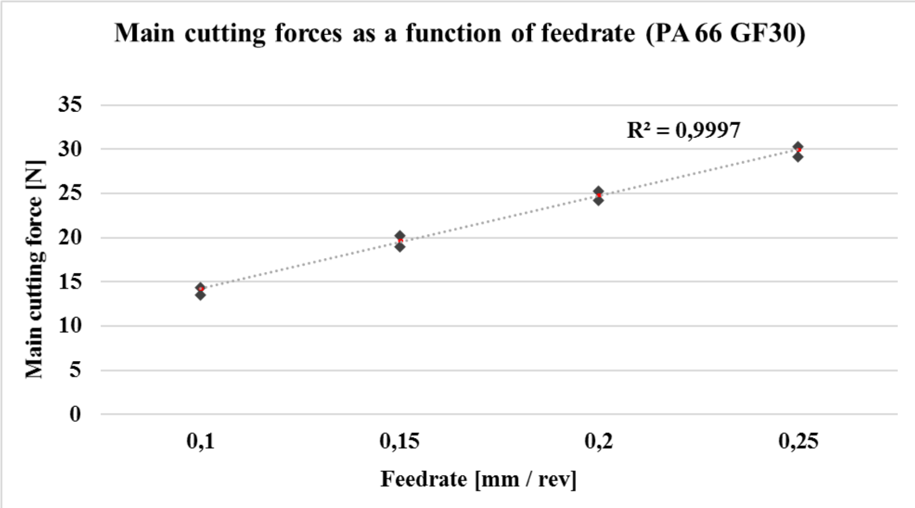
3.1. Results of measuring the main cutting force

From the saved files, I created diagrams using Microsoft Excel, showing the main cutting force as a function of time. One such diagram is shown in 3.1. Figure. In the titles of the diagrams, "launch" refers to the number of the CNC program. Each launch represents a different initial diameter. "section" is one of the 4 20 mm long measuring stages mentioned above.



3.1. Figure An example for main cutting force diagram (PA 66 GF30)

At the measurement section, I used Excel's 'AVERAGEIFS()' function to determine the average main cutting force. I tabulated the results and then created further charts by material, plotting the main cutting force as a function of feed rate. An example is shown in 3.2. Figure. A linear trend line can be fitted to the mean values as a good approximation.



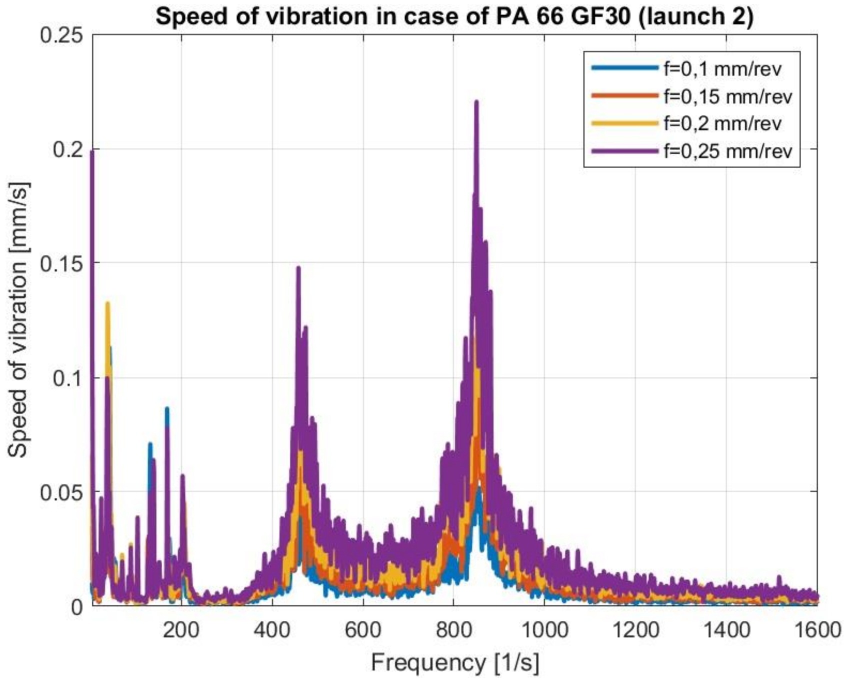
3.2. Figure Main cutting force as a function of feed rate (PA 66 GF30)

3.2. Results of the vibration measurement

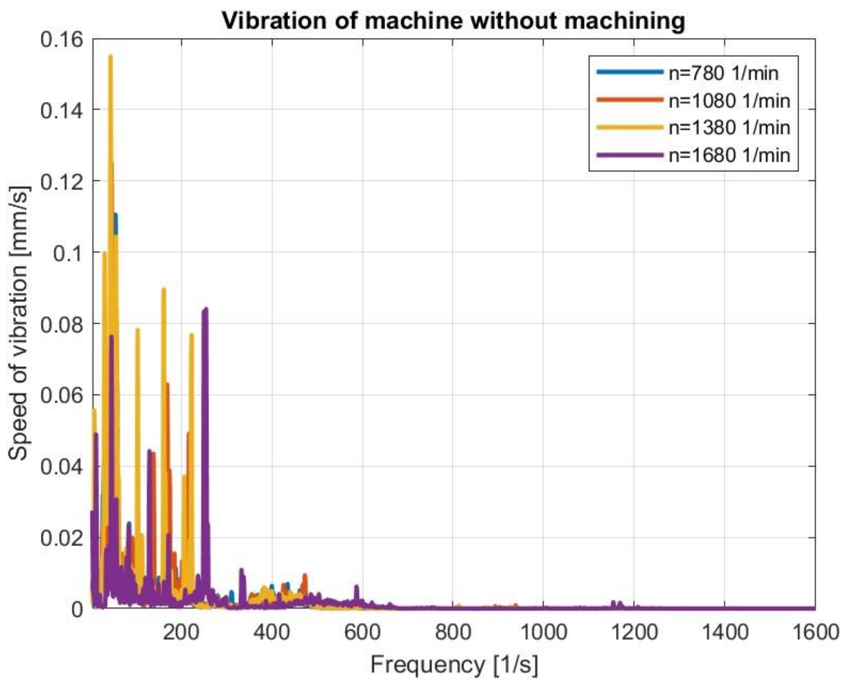
The results of the vibration measurements were also plotted in the form of diagrams, which were created using MATlab R2019b software. The diagrams show the value of the vibration velocity as a function of frequency. An example is shown in 3.3. Figure, where the different colours represent the four different feed rates. The diagram shows two characteristic peaks that were observed in all cases.

I also measured the vibration of the machine without machining. The conditions were the same as previously shown, but no machining was performed, and the feed rate was stopped after the program was started. A diagram of this is shown in 3.4. Figure.

The two typical peaks shown in the previous figure (3.3. Figure) do not appear at all in this case. Based on previous research, I concluded that where the peaks did occur, they were well separated from the modal frequencies, so I have ignored them here because if the harmonic component frequencies are well separated from the modal frequencies of the system, we can simply ignore the near-zero attenuation poles in the harmonics of the spindle rotation frequency because they represent the harmonic components of the response.

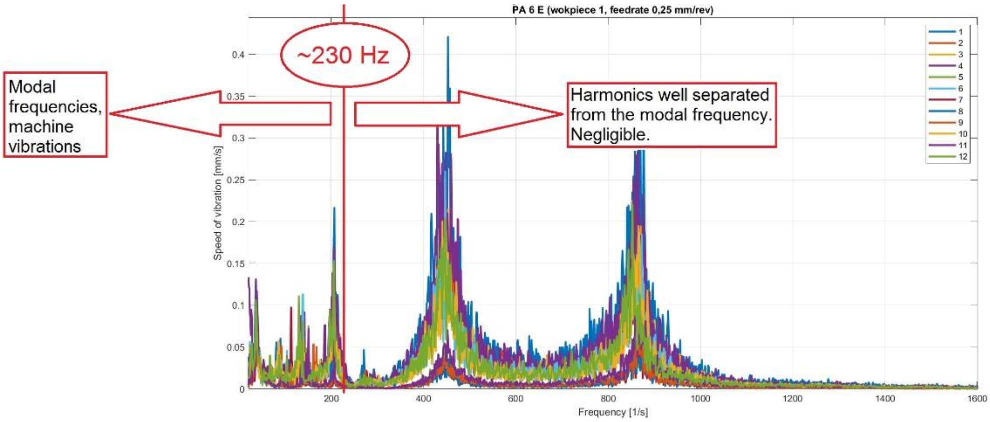


3.3. Figure Speed of vibration as a function of frequency (PA 66 GF30)



3.4. Figure Vibration values measured on the machine without machining and without feed

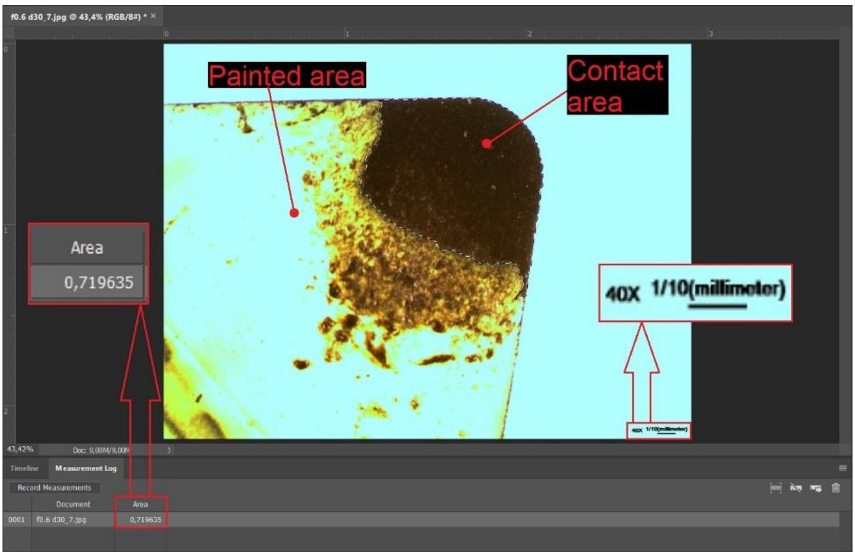
3.5. Figure shows the vibration ranges that are not negligible for my research.



3.5. Figure Vibration ranges of my research

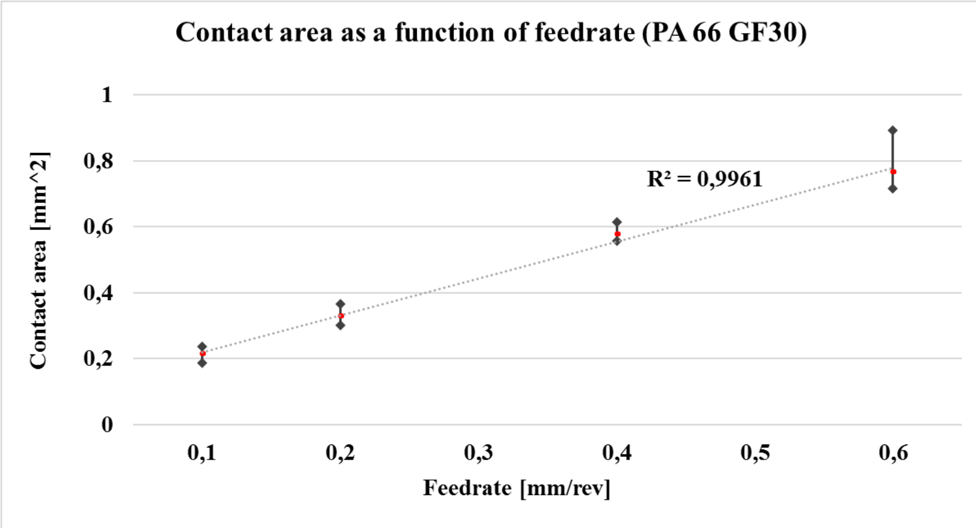
3.3. Measurement results of the contact area surface

I loaded the microscope images into Adobe Photoshop CC 2018 software and selected the area of paint bleed on the face surface of the insert (3.6. Figure). In the software, I preset the number of frames corresponding to how many mm of length, considering the magnification. Based on this, the software calculated the size of the selected area in mm^2.



3.6. Figure Highlight the contact area in the software

I tabulated the results and plotted them in diagrams showing the area of the contact zone as a function of feed rate (3.7. Figure).



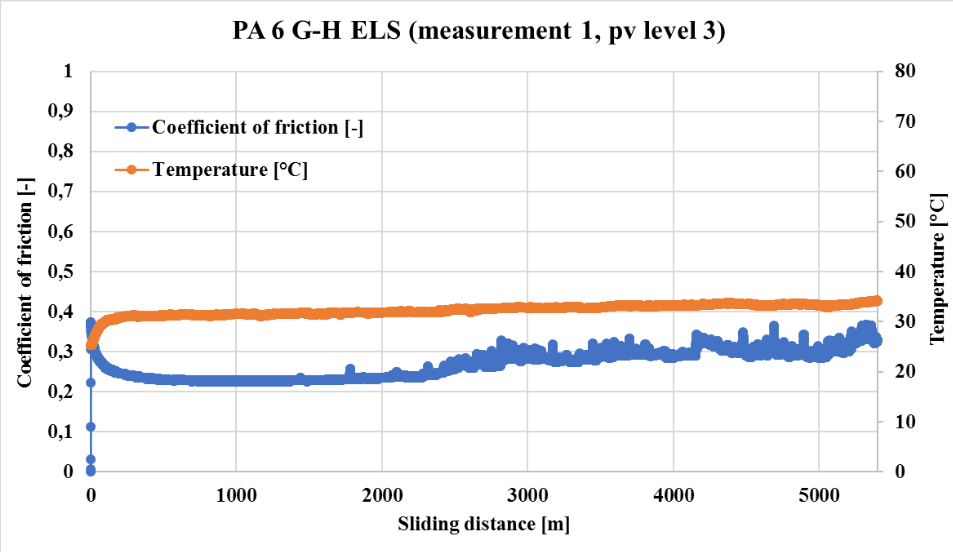
3.7. Figure Surface of contact area as a function of feed rate (PA 66 GF30)

The measurements were repeated 8 times per feed rate and per material. I have marked the range of the corresponding feed values and the average of the values. I fitted a linear trend line to the averages as a good approximation.

3.4. Results of tribological tests

The results of the tribological tests are also presented in the form of diagrams. The diagrams have been prepared in Excel. The diagrams initially plotted the values of friction coefficient and temperature as functions of sliding distance. Later, the temperature was ignored, and the friction forces were plotted instead of the friction coefficient. This change did not change the characteristics of the curves, since the difference between the two terms is a constant divisor. An example is shown in 3.8. Figure. The friction coefficient diagram becomes unstable after a certain distance. There are several possible reasons for this, which I described in my dissertation. However, the unstable phase is preceded by a stable curve phase of negative exponential character. I observed this character in all measurements.

The title of the diagram shows which of three replicates is shown, and I have marked the pv levels determined in the machining tests, which are given in my dissertation.



3.8. Figure Friction coefficient and temperature as functions of sliding distance (PA 6G-H ELS)

3.5. Results of the function fitting

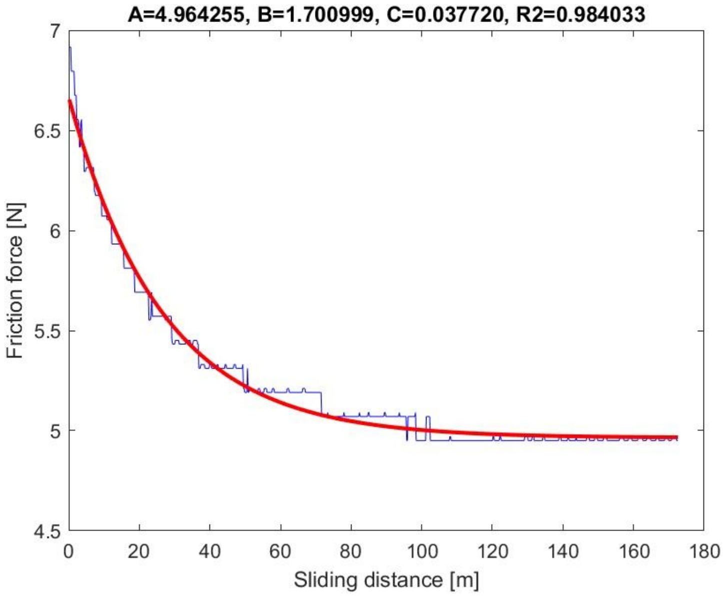
With a few exceptions, the stable phases were characterised by a negative exponential function. As a result, I performed a function fit in MATlab. After the function fit, I found that the frictional force on the stable sections can be well approximated by the following function as a function of the sliding distance:

$$F_S(s) = A + B \cdot e^{-C \cdot s}$$

where: "A", "B" and "C" are the factors of the function.

The factors have a physical meaning. The "A" represents the value of the friction force to which the frictional system is (or would be) set at steady state, based on the function. B represents the difference between the initial value and the steady-state value, and C represents the extent to which the steady state is reached, expressed in terms of friction length, i.e., the length of the path to steady state.

An example of a function search is shown in 3.9. Figure.



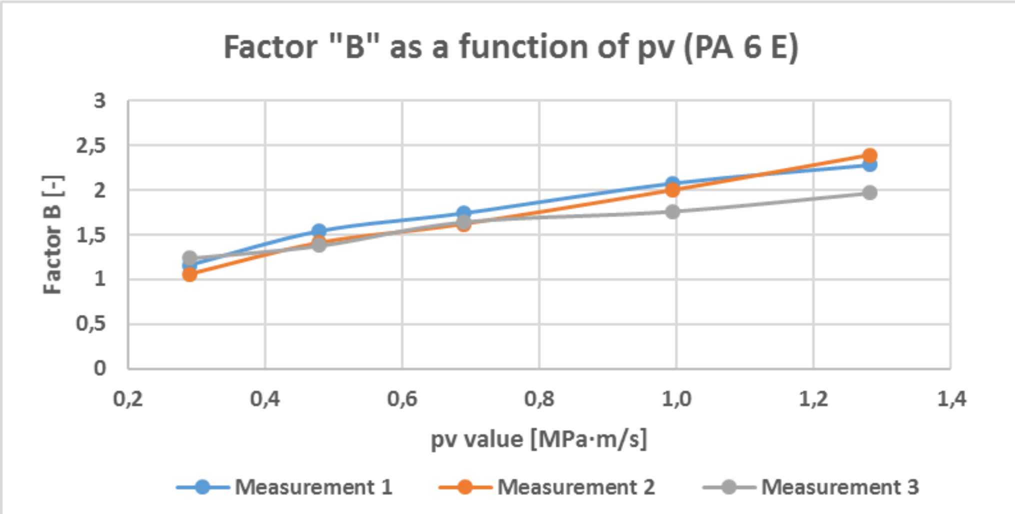
3.9. Figure Function search in MATlab (PA 66 GF 30, measurement 1, pv level 1)

I used the software to calculate the values of the factors, as well as the degree of fit with the coefficient of determination. I tabulated the results of the factors for further analysis.

3.6. Results of the regression analyses

I performed the regression tests after data cleaning, as regression tests are sensitive to outliers, presumably from erroneous measurements.

For the regression analyses, the factors are plotted separately for each of the three materials as a function of pv. An example is shown in 3.10. Figure. The example shows the value of factor B as a function of pv for PA 6 E. The different colours indicate the measurement repetitions. It can be assumed that in this case there is a linear relationship between the coefficient and the pv value. The regression analysis was performed in IBM SPSS 27 software.



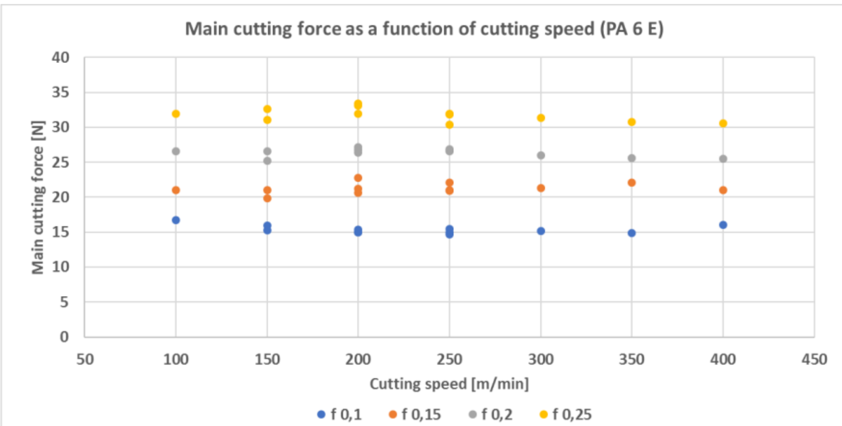
3.10. Figure Factor „B” as a function of pv (PA 6 E)

4. NEW SCIENTIFIC RESULTS

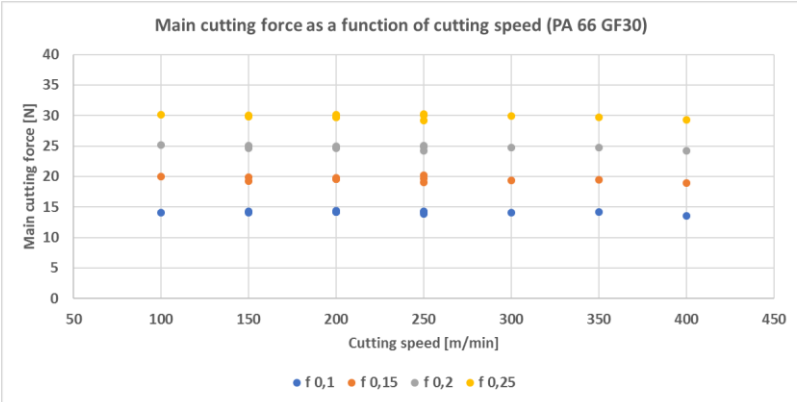
Based on my machining tests (NCT EUROturn 12-B CNC lathe and E 400 universal lathe, flat face type CCGW09T304FST, KD1425 class polycrystalline diamond coated turning insert, strain gauges mounted on the tool shank, Leonova Diamond DIA-300 vibration diagnostic tool, SLD-144S vibration measuring unit, BMS 764595 digital camera), I discovered the following new results in the tool-workpiece relationship.

1. Thesis

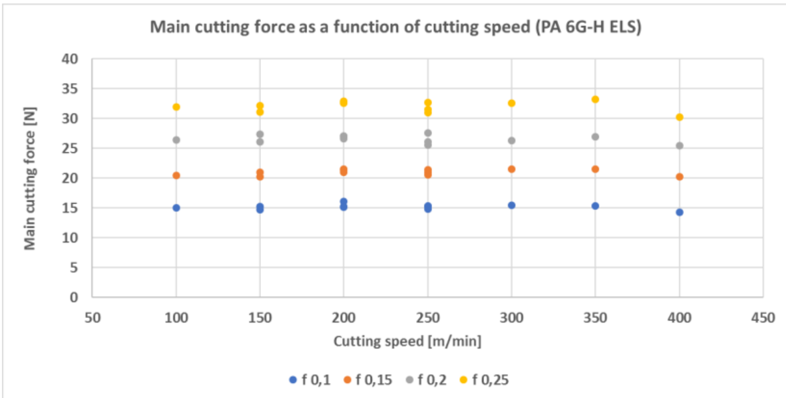
My measurements have verified that for turning the engineering polymers under investigation, at a given depth of cut (0.5 mm), at different feed rates (0.1; 0.15; 0.2; and 0.25 mm/rev), for varying main spindle speeds (in range 780 - 1680 rpm) and for different cutting speeds (150-400 m/min) depending on the actual machining diameter, and in the average vibration speed range 0-0.4 mm/s, **the main cutting force does not depend on the cutting speed** (4.1. Figure, 4.2. Figure and 4.3. Figure)



4.1. Figure Main cutting force as a function of cutting speed (PA 6 E)



4.2. Figure Main cutting force as a function of cutting speed (PA 66 GF30)



4.3. Figure Main cutting force as a function of cutting speed (PA 6G-H ELS)

The dependency does not exist because, with these set cutting parameters, there is no local heat generation at the tool tip to affect the main cutting force. Note: the points in the figures represent the arithmetic means of the repeated measurements.

2. Thesis

My measurements have verified that for turning the tested engineering polymers (PA 6 E, PA 66 GF 30 and PA 6 G-H ELS), at a given depth of cut (0.5 mm), at different feed rates (0.1-0.6 mm/rev in range), at a given main spindle speed (530 1/min), **the size of the contact area depends linearly on the feed rate . (Figures 4.19, 4.20, 4.21)**

As a simplified tribological model of the machining process in a Pin-on-Disc system (DIN 50322, Class VI.), I made the following findings based on my measurements (PA6 E, PA 6G-H ELS and PA 66 GF30 as materials of the pin, HC (Hard Carbon) coated disc, dry contact, in the range of 0.3-2.01 pv, modified normal load with a vibration amplitude of 0.23-1.2 N and a frequency of 13-28 Hz).

3. Thesis

In the dry friction of polymer material samples and HC (Hard Carbon) coated surfaces, I found that stable friction - steady-state - is followed by a frictional instability phase, which is associated with a sound effect and an increase in unstable friction. The length of the steady-state friction path depends on the material combination and pv level used. For native PA 6 E, increasing pv level resulted in a longer and lower friction steady-state phase, whereas a different trend can be observed for composites. A good approximation of the steady-state friction phase can be described by

$$F_s(s) = A + B \cdot e^{-C \cdot s}$$

where Fs is the frictional force [N], s is the sliding distance [m], factor A is the near steady-state value of the frictional force, factor B is the difference between the initial value and the steady-state value, and factor C is the rate of decrease of the frictional force.

4. Thesis

Based on my tests, I have found that the friction function can be described by

$$F_s(s, pv) = A(pv) + B(pv) \cdot e^{-C(pv) \cdot s}$$

where among the coefficients A, B and C, B is linearly dependent on pv and A and C are second degree polynomials of pv.

Members of the function:

F_s: friction force [N],

s: sliding distance [m],

pv: multiplication of surface pressure and cutting speed [MPa·m/s],

A: near steady-state value of the frictional force,

B: difference between the initial value and the steady-state value,

C: rate of decrease of the frictional force.

5. CONCLUSIONS AND SUGGESTIONS

In my research, I have found results from my machining tests that provide useful information for engineering practice. Under the boundary conditions I have set, the cutting speed has no influence on the main cutting force, although it is known that in certain ranges the cutting speed is a decisive parameter. This fact also shows that the field of machining and tribology of polymers and composites still has a lot of new developments.

To get one step closer to a complete understanding of the tribology of the machining process, I have established the relationship between the area of contact surface between the tool and the chip removed from the workpiece, i.e. the tribological contact zone.

An important feature of frictional systems is the beneficial or damaging effect of vibration on friction. Research on the effects of vibration on frictional systems is still limited, although where different elements move, or possibly come into contact, vibration is generated. This is no different in machining, where there are many sources of vibration, such as vibrations from the operation of the machine or vibrations from the workpiece acting on the tool. Taking all this into account, I complemented my machining tests with vibration measurements and used the results as input parameters for my tribological tests.

I designed a vibration unit and thus supplemented my tribological tests with added vibration from an external source and ensured a nearly identical material pairing. The main output results were the frictional forces and the coefficient of friction calculated from them; the temperature was measured near the contact zone.

I have found that the frictional forces vary as a function of the sliding distance, and using the method of function fitting, I have written a general relationship to describe this variation in the stable phase of friction. I have examined the factors that take their place in the relationship and found that, to a good approximation ($R^2>0.95$), the relationship of the factors with the pv value is linear or second order polynomials.

I suggest exploring correlations where the results of tribological tests provide direct information on the optimised input parameters for machining tests.

6. SUMMARY

Today, technical practice uses polymers or polymer composites in many areas. Their advantageous properties over metals include, for example, an excellent mass-to-strength ratio, which opens applications that were previously unfeasible. Engineering polymers and composites also have the advantage of being relatively inexpensive and easy to machine.

Little is known about the relationship between the tool and the workpiece, especially if the workpiece is made of a polymer. Knowing the correct relationship is essential to ensure that machining is economical in the long term and the result is satisfactory.

The interaction between the tool face and the removed chip is a tribological system not yet known. My research is focused on this specific area, complemented by tribological studies that include the phenomenon present in all rotary motion, vibration.

In order to understand the relationship between machining and tribological model tests, I carried out single-edge turning tests and tribological small sample model tests. During the turning tests, I supplemented the force measurements with vibration measurements and the results obtained provided the input parameters for my tribological tests.

During my machining studies, I discovered new results concerning the cutting speed and the tribological contact area between the tool and the workpiece. The size of the contact area, the main cutting force and the cutting speed together form the number pv, which is of great importance in tribology and is the product of the surface pressure and the friction velocity in a friction system.

In my tribological studies, I have established a relationship describing the frictional force as a function of the sliding distance in the stable friction range, which includes the initial stage and the steady state in the corresponding pv range. I fitted a function to these sections and examined the factors in the relationship using the least squares method.

I established the relationships per material and wrote down the bivariate (pv and sliding distance) functions for the frictional force on the stable friction sections.

The results of my research can be applied to the material pairings under investigation, the idea being that, in addition to the general frictional forces, we can also obtain information about the frictional forces generated during the entry phase of the stable friction state.

7. MOST IMPORTANT PUBLICATIONS RELATED TO THE THESIS

Referred articles in foreign languages

1. **Sarankó Á.**, Kalácska G., Keresztes R. (2019): Analysis of Vibration During Turning Process of Different Materials, International Journal of Engineering and Management Sciences / Műszaki és Menedzsment Tudományi Közlemények, Vol. 4 (1), pp. 200-205., 6 p. ISSN 2498-700X
2. **Sarankó Á.**, Kalácska G., Keresztes R. (2019): Effect of sliding velocity and loads on friction coeffcient and temperature in DLC and PA 6 contact in dry sliding conditions, Mechanical Engineering Letters: Research and Development, Vol. 18, pp. 34-42., 9 p. HU ISSN 2060-3789
3. **Sarankó Á.**, Kalácska G., Keresztes R. (2022): Analysis of formed chips in the case of turning different polymer materials, Hungarian Journal Of Industry And Chemistry, Vol. 49 No. 2, pp. 71-75., 5 p. ISSN 2450-5102
4. **Sarankó Á.,** Keresztes R., Kalácska G. (2018): New method for dynamic tribological test of engineering polymers, International Journal of Engineering and Management Sciences / Műszaki és Menedzsment Tudományi Közlemények, Vol. 3 (1), pp. 25-29., 5 p. ISSN 2498-700X
5. **Sarankó Á.**, Keresztes R., Kalácska G., Sukumaran J. (2017): Evaluation of cutting force of PA6 and POM C, Mechanical Engineering Letters: Research and Development, Vol. 15, pp. 27-34., HU ISSN 2060-3789
6. **Sarankó Á.**, Szakál Z., Kalácska G., Samyn P., Sukumaran J., Klébert Sz., Károly Z., (2018): Adhesion and sliding tribological properties of polyolefins treated by diffuse coplanar surface barrier discharges, Express Polymer Letters, Vol. 12 (11), pp. 972-985. , 14 p., ISSN 1788-618X, (IF: 2,875)
7. **Sarankó Á.**, Zsidai L., Keresztes R., Schrempf N. (2019): Force Measuring methods of milling and turning for experimental use – A brief review, Mechanical Engineering Letters: Research and Development, Vol. 19, pp. 208-218., 11 p. HU ISSN 2060-3789