THESIS OF THE PH.D DISSERTATION

Optimization of setup period and production time for thermoplastics machining

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Introduction

Nowadays there is a tendency to notice that demand for plastics, thus plastic products, is growing year by year. In thermoplastics manufacturing, the most commonly used manufacturing technologies are based on thermoforming, where the material is in its molten state during the forming process. Additive technologies, for example rapid prototyping, are not widely used for series production, and subtractive technologies are also rarely employed, and in most cases only in follow-up processes. Machining can be an appropriate manufacturing technique for prototyping and low-quantity production, as injection moulding becomes expensive due to the high cost of producing the mould. In addition, certain materials such as polytetrafluorethylene cannot be manufactured using the more commonly used methods. Due to the nature of the machining process, the time requirement for high material removal rates must be balanced with the need for continuous production.

One disadvantage of cutting is the relatively high cycle time, and the big amount of waste (chip), what is often contaminated by the cooling fluid. During the turning, the geometry, and the surface micro geometry is done with removing material parts. The tool with defined cutting edge enters into the material, and removed particles with shear. The process can be characterized with the following cutting parameters; „v_c” cutting speed, with „a”, the depth of cut and with, „f”, the feed rate per revolution. The most of the literature in cutting deals with metal cutting, but not only this kind of materials can be machined.

Objectives of the research

Based on the own experience and on the archived data available, one part of the failures comes from process management and process control, this topics are not mentioned in this dissertation. Another part of the failures are very hard and cost-sensitive to decrease or eliminate. However, the remaining failure reasons can be significantly decreased with higher knowledge in thermoplastics cutting progress. The following objectives were defined:

Investigation of the surface roughness: In this chapter, the effect on surface roughness of various cutting parameters and cutting tools were investigated for the turning of thermoplastics.

Investigation of the cutting force: In this chapter, the effect on cutting force of various cutting parameters and cutting tools were investigated for the turning of thermoplastics. Important to know the cutting force to determine the part deformation.

Effect of tool wear: The purpose of this research is to identify the changes in parameters, features, etc. that become evident as a tool wears. This is important for monitoring and can help to prevent unexpected downtime and improve production rates.

Investigation of heat treatment: Most of the material problems connected to the inadequate heat treatment. The parameters of this process are the following; heat/cool down speed, holding time. All of them were investigated to define the temperature difference between the part inside and outside (surface) temperature. The goal is to know this difference, also with various part diameter.

Materials and methods

The turning machine was an SL-150 from the Mori Seiki turning center. Experiments were carried out with a range of cutting parameters. A cooling emulsion comprising 95% water + 5% Sarol EP40 oil was used during all the experiments. The selected values are based on practical experiment and on the studies. All experiments comprised outer diameter turning over a length of 30 mm.

For the experimental work in this study, many types of unfilled thermoplastics were used. To obtain data for the initial basic calculations, PP (polypropylene), PC (polycarbonate), PET (polyethylene terephthalate), POM (polyacetal) and PVC (polyvinyl chloride) were employed. For the more detailed analysis, data for PPSU (polyphenylsulfone), PEI (polyetherimide), PEEK (polyetheretherketone), PA6 (polyamide 6) and PE (polyethylene) were also used.

Real-time cutting force signals were collected using an ME-system K-120-3D/1kN-AL load cell, connected to a computer through an A/D converter and amplifier unit as shown in Fig.1.

Both tactile and non-tactile techniques can be used to grade the surface roughness of a machined part. With tactile techniques, surface roughness parameters are measured using a stylus; and with non-tactile methods, roughness parameters are obtained from digitalized images and a computer is used to analyze surface textures. In this study, a tactile technique was employed and a Mahr Perthometer S2 was used in conjunction with a sensor with a 2 µm diameter tip.

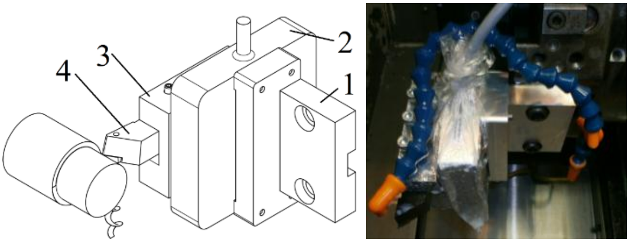


Fig.1. Measuring of cutting force

During the experiments correlated to the heat treatment, the effect of wall thickness and heat/cool down speed were investigated. Specimen with various diameter was applied, with 20, 30, 40, 50, 60 mm diameter and 60 mm length, made of POM. In the center of this specimen a diameter of 3mm hole was drilled, to fit the T-type temperature sensor inside. The data was logged with an USB data logger (serial number: 24371), with 10 seconds of sampling time. The heating and cooling down process was done with a calibrated Memmert UP 700 drying chamber.

Results and discussion

In the first experiment the effects of cutting parameters on cutting force and surface roughness were investigated. The first test parameter is the feed rate. Based on the theory and literature available, increasing the feed rate will cause the increase of surface roughness and cutting force too. During the experiments, the cutting speed and the depth of cut are constant (v_c=250m/min., a=2mm), the values of the tested feed rate are the following:

0,05 0,07 0,1 0,12 0,15 0,2 0,25 [mm/revolution]

Based on the measured data, the theoretic statement was verified, the cutting force and the surface roughness increases with the increase of the feed rate. With the roughness, the second-degree correlation is visible on Fig.2.

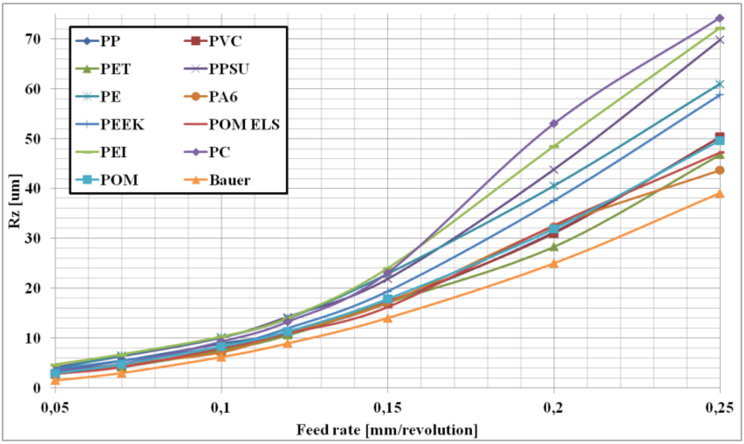


Fig.2. Effect of feed rate on surface roughness.

The following cutting parameter is the cutting speed. Studying the available literature with many materials and methods, no clear statement added to define the effect of cutting speed on surface roughness and cutting force. During the studying of the measurement data, a little decrease in surface roughness can be remarked, but this is only 10%. The cutting force also decrease a little or stay constant value, what depend on plastic type.

The last cutting parameter is the depth of cut. Based on the theory and literature available, increasing the depth of cut will cause the increase of cutting force, but there is no information about the effect of depth of cut on surface roughness. Only a little increase in surface roughness can be monitored, but this is not at all significant until an upper limit, where the complete cutting system starts to vibrate, what cause a very rough surface. The effect on cutting force is clear, increasing the depth of cut multiplies the cutting force value.

After the cutting parameters, the tooling properties were investigated. Because the surface is the combination of the feed rate and the tool tip, the surface roughness must bound to the tool nose radius. The values of this radius was increased from 0,2 mm to 0,8 mm, and the surface roughness became 300% finer. The increase in cutting force is not significant, this is only near 16%

The second tooling measurement is the effect of insert manufacturer. The aim is to compare the cutting with very similar insert, but with different manufacturer. The insert are similar with opening angle, rake angle, nose radius, there is only a 1° difference in clearance angle. The effect on cutting force is not significant, only a little difference visible with 0,15 mm/revolution feed rate.

The surface roughness is not equal, particularly by lower feed rates, under 0,05 mm/revolution. This can be interesting when a very smooth surface must be machined. In this case many insert should be tried.

The next measurement connected to tooling is the effect of entering angle, and nose angle. With increase of feed rate, the differences became more significant. The best solution from roughness side is the 50°entring angle, and the 35° nose angle, it is maximum 20%. To minimize the cutting force inserts with 55° nose angle suggested, because with this inserts the force is lower in all cases. The differences between 30°and 95° was not significant, 95° can be a better choice, from technical side, the 95° value is better, because of several geometry point of view.

Over and above the cutting and tooling parameters, the process can be influenced by other, environmental properties also, for example the cooling method. During thermoplastics turning the two most commonly used methods are the compressed air and the emulsion cooling. From surface roughness side, the effect of the cooling method is low, near 4%. In case of cutting force the effect is a little bit bigger, 8,5%, but this cannot be called significant also. To summarize the experiments it can be declared, that the difference between the two cooling method is low by the investigated thermoplastics, but the cooling emulsion can be better choice, because of the favorable ability to remove chip from cutting zone.

The main effect of tool wear is that it increases the cutting force required, and cutting force was found to be linearly related to wear. Monitoring of the cutting force is therefore a practicable route for wear detection and can be carried out without interrupting the machining process.

Tool wear also has a significant effect on the surface roughness of the finished part. In general, increased wear of the tool leads to a rougher surface finish, but surface roughness is not always a good indicator of tool wear. During turning of PTFE cones, edge wear on the turning insert resulted in a wavy surface texture with undesirable wear marks such as groove lines. Edge wear shown in Fig.3. was the dominant wear mode in most of the cases investigated. Examination of inserts which had seen industrial use revealed edge wear occurs on both grooving and turning inserts. Another frequently observed wear mechanism is chipping.

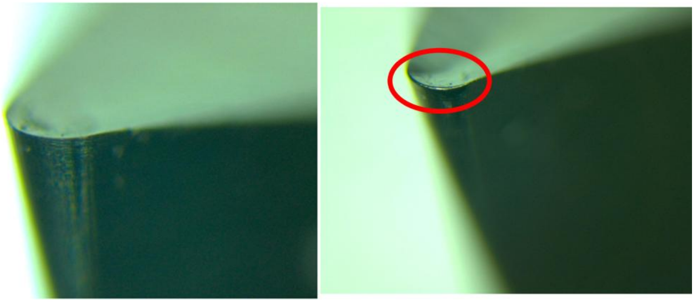


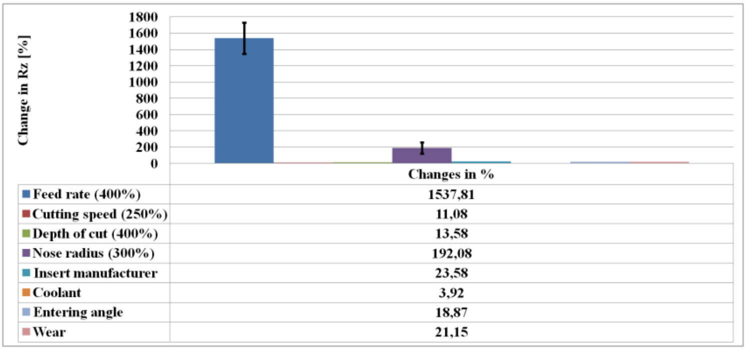
Fig.3.New and worn inserts for thermoplastics turning

During the measurement in heat treatment topic, as it was shown earlier, a method, what is similar to the real process was applied. The difference between the outside and the inside temperature was calculated from measuring data. The goal is to minimize this difference.

To summarize the experiences, this difference is mostly depends from the heating speed, because the maximum value was always at the end of heat-up section. To speed up the heat-treatment process, the cool down speed can be increased. After the experiments with various part thickness, with increase of the thickness, this difference will also rise. To give a real suggestion, in case of POM material, what was investigated, the following program can be used to minimize the difference; heat up to 155°C with two steps. In 8 or 10 hour to 125°C, then lower the speed, and heat up to 155°C in 3 hour additional, with 10°C/hour speed. The cool down speed can be the 8 hour to room temperature.

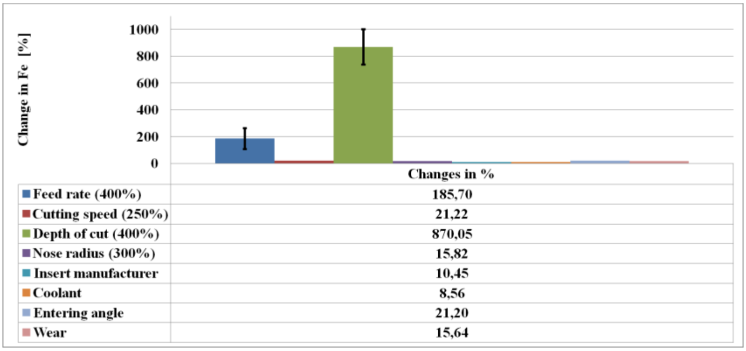
Summary

A wide range of cutting parameters and variety tooling applied during the investigations. The parameters affected the cutting force and the surface roughness with different value. Important to notice there are significant differences between values for the thermoplastics tested. To compare the importance of the parameters on the investigated values, average was calculated, the result were shown in Fig. 4. and Fig. 5.



	Changes in %
■ Feed rate (400%)	1537,81
■ Cutting speed (250%)	11,08
■ Depth of cut (400%)	13,58
■ Nose radius (300%)	192,08
■ Insert manufacturer	23,58
■ Coolant	3,92
■ Entering angle	18,87
■ Wear	21,15

Fig. 4. Effective parameters on surface roughness



	Changes in %
■ Feed rate (400%)	185,70
■ Cutting speed (250%)	21,22
■ Depth of cut (400%)	870,05
■ Nose radius (300%)	15,82
■ Insert manufacturer	10,45
■ Coolant	8,56
■ Entering angle	21,20
■ Wear	15,64

Fig.5. Effective parameters on cutting force

Based on the discussion above, the feed rate and the nose radius have the most significant effect on surface roughness. Therefore, in further calculations, only these two parameters will be included. It is clear that the predicted values by the original form of the Bauer formula are lower than the actual values, and that there are significant differences between values for the thermoplastics tested. To refine the Bauer formula such that it is applicable for a variety of plastics, it is necessary to add additional parameters.

$$Rz_{calculated} = \frac{(30f - 0{,}8)^2 + 5}{5 \cdot r_{\varepsilon}} \qquad (1\ )$$

In case of cutting force experiments, it's clear, that the depth of cut, and the feed rate have the most significant effect on cutting force. The correlations of both parameters are linear with the measured force values, so the classic definition of cutting force (2) can be applied. The coefficient of cutting force was also defined to almost all thermoplastics contained in this dissertation.

$$Fe = \kappa_c \cdot a \cdot f \qquad (2)$$

Thesis

(1) From cutting parameters side, it was clarified, the ***feed rate has significant effect on the cutting force and surface roughness***, with increase of the feed, both property will rise. With various levels of ***cutting speed only a small change appreciable*** on both output parameter, none of them are dominant. With the ***increase of the depth of cut***, the ***surface roughness stays unchanged***, but the ***cutting force grows*** to multiple value. [85]

(2) From tooling parameters and geometry the nose radius must be mentioned. The effect on cutting force is limited, but ***increasing of the nose radius caused much finer surface roughness.*** The manufacturer factor of the cutting insert has effect only with slower feeds on roughness. The ***entering angle has an approx.. 20% impact on surface roughness and cutting force***, so it can't be consider as a dominant factor. From technical side, the 95° value is better, because of several geometry point of view. [86]

(3) During thermoplastics turning the cooling emulsion is a commonly used material. Comparing with compressed air cooling it can be declared as a ***low effect factor, both on force and roughness values.*** The cooling emulsion can be better choice, because of the favorable ability to remove chip from cutting zone. [86]

(4***) With the wear of cutting insert the cutting force and the surface roughness changes.*** Measuring the cutting force during machining can be a preferable method, because it has straight linear correlation with the wear rate, and it can be used without interrupt the process. The two wear mode were the ***edge wear and the pitting of cutting edge***. [84][86]

(5) Based on the experiments it became clear, that the ***feed rate and the tool nose radius have the most significant effect on surface roughness.*** The correlation with feed rate is a second-degree parabola, so the Bauer formula can be used with optimized coefficients. ***A value for each thermoplastic, and a well usable general form were defined.*** One exception is the PC, where the increasing of the nose radius deteriorates the fitting onto a parabola. The second exception is the PVC, with greater nose radius than 0,2 mm the turned part became a worse, feathered surface. [83]

(6) Based on the experiments it became clear, that ***the feed rate and the depth of cut have the most significant effect on cutting force.*** This can be expected from the theory of cutting, but now experiments confirm this. ***Both of the cutting parameters have a linear correlation with the force***, so a linear was suited to measurement result. In the form, the third member the coefficient of cutting force. With statistical inspection the ***feasibility of this value for thermoplastics was verified.*** The only exception is the PEEK material, where no correlation was found. [85]

(7) In industrial practice the two surface roughness parameter commonly calculated with a simply multiplication from each other. In case of thermoplastics, the ***Rz = 4,1 x Ra is applicable, but hits number can be bigger when the feed rate is low, and when an insert with greater nose radius selected.*** [83]

(8) During heat treatment the most ***critical value of temperature difference can be measured at the end of heat-up section. The increase in wall thickness also increases this difference***. When the heat-up speed decreased at his section, the difference can be lowered to acceptable limit.

List of publications

[1] János Farkas, Etele Csanády, Levente Csóka: Optimisation of the Bauer Equation Using the Least Squares Method for Thermoplastics Turning. International Journal of Manufacturing, Materials, and Mechanical Engineering 8 (2018). 21-36.

[2] János Farkas, Etele Csanády, Levente Csóka: Effects of Tool Wear on Surface Roughness and Cutting Force in Thermoplastics Turning. International Journal of Materials Forming and Machining Processes 5 (2018) 1-11.

[3] Farkas János, Csanády Etele, Csóka Levente: Parameters affecting the cutting force and the surface roughness during turning of thermoplastics I.: Effect of cutting parameters. Műanyagipari szemle 14 (2017) 78-88. ***(Available only in hungarian)***

[4] Farkas János, Csanády Etele, Csóka Levente: Parameters affecting the cutting force and the surface roughness during turning of thermoplastics II.: Effect of tooling and other parameters. Műanyagipari szemle 14 (2017) 92-104. ***(Available only in hungarian)***

[5] Viharos Zs. J., Kis K. B., Paniti I., Belső G., Németh P., Farkas J.: Artificial Neural Network Model Based Setup Period Estimation for Polymer Cutting: Industrial and Manufacturing Engineering journal. International Journal of mechanical aerospace industrial mechatronic and manufacturing engineering 11 (2017) 452-458.

[6] Viharos Zs J., Paniti I., Farkas J.: Predicting of setup time in plastics machining Gépgyártás 55 (2015) 99-103. ***(Available only in hungarian)***