Final report

on the completed research work and its results in the project titled

"Effect of environmental-load-reducing manufacturing procedures on the lifetime of machine industry components"

Contents

1. Background

The topic of the research was the investigation of machining processes that increase the service life of machine industrial component surfaces and reduce environmental impact.

Its aim was the overview of lifetime increasing manufacturing procedures, examination of characteristics of manufacturing procedures, and revealing the theoretic background of changes take place in the surface layer, as well as analysing the effects of technological parameters for producing parts having increased surface quality and accuracy.

We intended to increase the examination of surface and subsurface layer creating procedures with (e.g., hard turning) and without chip removal (e.g., diamond burnishing) for different materials (steel and non-ferrous material alloys) when creating surfaces by analysing of factors affecting of the environmental load reduction.

The research methodology includes - considering the principle of cutting theory and low plasticity manufacturing - the determination of the surface pressures formed in surface layer of the machining tool and workpiece, the level of residual stresses, and the surface roughness measurements.

As the result of research, we discovered the function relation among the manufacturing process parameters and residual stresses, we evaluated the emerging phenomena of the tool life increasing effect of the examined procedures, furthermore those phenomena which occur in environment load reducing metal cutting and we determined its effecting conditions.

Calculations and simulations were also performed using the finite element method.

2. Hard turning

2.1. Modelling of roughness

During our research, we introduced a new method for determining the theoretical roughness values of hard turning processes. The tests were focused on the hard turning process, which is suitable for processing the surface of hardened parts. The performed simulations and real cutting tests showed that the method is suitable for estimating the roughness of surfaces cut with previously used inserts, on which significant wear was observed on the cutting edge. The tests were performed on 34CRMO4 - equivalent CMO3 - workpieces. During the proposed simulation method, we examined the profile of the cutting tool with an optical microscope and recorded the contour of the cutting edge. We imported this image into a parametric CAD system, and then described the contour with a spline. This method can be used for more accurate modelling of the cutting tool during theoretical roughness calculations, since the roughness profile changes significantly in case of tool wear (which is unavoidable during cutting). Our research has shown that significant distortions can be observed in the roughness profile even with relatively small tool wear, so the accuracy of the theoretical roughness values calculated with the methods used for new, sharp inserts decreases. Based on the comparison of the simulated and measured data, it could be concluded that with the help of the proposed new method, the topography of the surface formed during the real cutting process can be well approximated. We conclude that the accuracy of the approximation improves as the feed rate increases. The presented method offers a new approach to the examination and determination of surface roughness occurring during turning. The practical applicability of the method can be an accurate prediction of the relatively permissible tool wear value, which limits the permissible change of the Ra parameter of the machined surface. (Figure 1, 2)

2.2. Examination of alternative machining

In the automotive industry, the machining of hardened surfaces has become a hot topic in recent decades, both from a production and economic point of view. This is due to the difficulty of machining hardened parts and the need for machining that results in greater accuracy and surface quality. In addition to grinding as the traditional smoothing process, alternative processes such as hard turning have appeared. It can be used to achieve the same surface quality and accuracy values as grinding. In our study, we analysed different machining processes (traditional hole grinding, hard turning and combined process) on hardened internal cylindrical surfaces. We compared them in terms of the time parameters of machining and the practical material removal rate as a material removal efficiency parameter. While the practical parameter of the material removal rate enables an efficiency-based comparison of the same or different processes (machining with grinding or by single point cutting tools), the time parameters of the machining (mainly the operation time) were aimed at a direct comparison of the costs of the processes. We also analysed the cost relationships of the procedures.

At this stage of our research, we analysed five precision machining processes for machining internal cylindrical surfaces based on the efficiency of material removal. The analyses were performed on gears with different bore geometry values, which are manufactured in a large-scale factory. Among the selected procedures, we also analysed those that can create a random topography. This expanded the range of possible procedures. Instead of the theoretical parameter, the Material Removal Rate (MRR) of the five procedures is defined by the so-called practical MRR parameter. This made it possible to consider the time spent and introduce efficiency calculated based on the entire production process. We determined the ranking of the analysed processes, which is as follows: 1. hard turning with a wiper insert for roughing and a standard insert for smoothing; 2. combined procedure with wiper insert during roughing; 3. hard turning with a standard insert for both roughing and smoothing; 4. combined process with a standard insert during roughing; 5. hole grinding. Of the two geometric parameters (bore length and diameter), the effect of the bore length is decisive: a change in bore length can cause rank reversal.

At this stage of our research, we dealt with the production process of a heavy-duty gear as well. The tested gears are installed in the transmission systems of trucks and buses and require high-precision machining. The machining of precision parts required relatively complicated processes and we quantified the process for a specific component. Based on the analysis, we have shown that the one-piece flow can significantly reduce the throughput time, but the time spent handling the material increases, which burdens the operator or the material handling equipment. Therefore, multivariate optimization is required. The available results can be used to improve the production processes of other groups of parts produced with similar technology.

Furthermore, we compared the effectiveness of hard machining in terms of accuracy and surface quality. The basic principle of the comparison was to achieve the same accuracy and surface quality by the procedures; that is, the procedures should be interchangeable, alternative versions. We have shown that the widely used parameters characterizing the material removal efficiency (operating time, material removal rate) are lower than those of hard turning in conventional grinding. When using the "joint" procedure, which results in the same (random) topography, the values from grinding are also worse than those of the "joint" procedure. In addition, we also demonstrated through a specific example that the level of environmental impact can be reduced by 80% with the "joint" process. Hence the joint procedure is recommended when machining parts that can be machined by this procedure.

In the experiments our goal was to determine the minimum acceptable grinding allowance on hardened workpieces machined with the combined process. The amount of acceptable or unacceptable margin was determined using the "painting" method. After bore grinding tests for 2D roughness, roundness and 3D topography measurement were carried out. It was found that a 0.03 mm allowance in the bores of gearbox wheels of cars is satisfactory and necessary to obtain the required level of topography when combined machining was applied and when no white layer was formed in the turning procedure. This is a significant finding, because the usual allowances of 0.05 mm or higher (in many cases significantly higher) can be decreased to 0.03 mm (and even a 0.02 mm allowance value may be obtainable) and the machining time of bore grinding can be reduced in proportion to this extent.

2.3. Tool life tests

As is known, in continuous chip removal the tool life changes according to a particular curve having two extreme values, and this depends on cutting speed. From these extreme values the tool-life curve can be divided into three stages. In Stage I, with increasing cutting speed the tool life first decreases to a minimal value, from where – in Stage II – the tool life increases to a maximum, and then in Stage III it decreases again. To describe the changes in tool life several solutions exist besides the well-known Taylor formula, which is restricted mainly to the description of Stage III. In an earlier work by the authors a general tool-life equation was suggested which can be extended to all three stages. With the value pairs of v_c, T referring to the extreme values and with additional v_c, T data, the constants of this function can be defined.

In this part chapter of our research the machinability of hardened steel was investigated in a wide range of cutting speed. The aim was to determine the physical causes leading to tool degradation in the whole interpretation domain of the general $T(v_c)$ function. For this, a nonlinear differential equation of the wear rate was applied, which describes tool degradation because of abrasion and adhesion in Stages I and II. In Stage III the tool degradation results from a thermally activated process that increases with higher speed. This can be characterised by the activation energy determined by the results of tool-life examinations, by which the physical nature of the current degradation of a particular tool can be interpreted. The method was verified in the boring of hardened steel carried out with a PCBN tool. The measurement results proved that the tool degradation can be characterised by abrasion and adhesion in Stages I and II, while in Stage III activation energy was gained, making it probable that recrystallization occurs in the surface layer of the tool, modifying it from a cubic structure into hexagonal one.

Taylor's exponent is a function of the technological parameters, and in the environment of the extremes in the v_c-T curve, it even changes its sign, so the optimization is strongly distorted. The tool life algorithm proposed by Kundrák can describe the entire range of the tool life curve, specifying the local minimum, maximum location, and value. These are influenced by technological parameters, and their effect can be described in detail and the validity range for the Taylor function can also be specified. For the analysis of the relationships, we also carried out cutting experiments.

The machining experiments were performed on hardened steel 100Cr6 with a K10 CBN tool insert at a speed range of v_c = 11-120 m/min, f = 0.05 mm/rev, a = 0.15 mm. Based on the analysis of the tool life measurements performed in the Ø45-Ø100 mm hole during hard turning, the following results were summarized.

- It is confirmed that the third-order rational fraction function proposed by Kundrák for describing the v_c-T relationship can be applied over the entire interval (range) of v_c cutting speeds under the assumptions examined.
- We defined the boundary coordinates of the three sections of the v_c-T formula with the constants of the new function. These are influenced by technological parameters in a specific way.
- We found that there is a close relationship between the constants of the new v_c-T formula and the k exponent of the Taylor formula valid in Section III.
- The experiments showed that the Kundrák's formula fits the measurement results well over the full range of the test speed, while the Taylor formula can only be used in section III of the v_c-T curve.

The theoretical results of the research can be directly applied in practice. The optimum technology parameters for operating costs or cutting performance can be determined over the entire v_c range.

2.4. Examination of machining time

The accuracy analysis was performed on surfaces machined with a novel cutting tool, which allows setting high feed rates. We analysed the effect of the cutting data on the cylindricity error and roundness error of the machined surface. The basis of our comparative study was the achievable quality of parts machined with standard cutting tools and technological parameters in a typical industrial environment. Due to the chosen high feed value, we also examined the change in the cutting force to analyse the stiffness of the mechanical system on the machine tool, which was carried out using the finite element method. The suitability of the selected parameter pairs to replace the traditional technology was evaluated.

Kundrák, J., Varga, G., Deszpoth, I.: Analysis of Extent of Environment … (2018)

Kundrak, J., Molnar, V., Deszpoth, I.: Analysis of machining time and … (2018)

Kundrak, J., Molnar, V., Deszpoth, I.: Analysis of machining time and material … (2018)

Kundrak, J., Molnar, V., Deszpoth, I.: MRR-based productivity decisions … (2018)

Molnár, V., Szabó, G., Kundrák, J.: Waste reduction possibilities in … (2018)

Kundrák, J., Mamalis, A. G., Molnár, V.: The efficiency of hard machining … (2019)

Kundrák, J., Deszpoth, I., Molnár, V.: Increasing Productivity of Combined … (2019)

Kundrák, J., Molnár, V., Markopoulos A. P.: Joint Machining: Hard Turning … (2019)

Kundrák J., Pálmai Z.: The change of tool Life in a … (2019)

Kundrák, J., Sztankovics, I., Gévai, M.: Comparative analysis of CBN cutting … (2019)

Molnár, V., Deszpoth, I., Kundrák, J.: Lead time reduction in manufacturing … (2019)

Kundrák, J., Pálmai, Z., Varga, G.: Analysis of Tool Life Functions in … (2020)

Felho, C., Varga, G.: Theoretical Roughness Modeling of … (2022)

3. Sliding friction diamond burnishing

3.1. Sliding friction diamond burnishing of cylindrical surfaces

The burnishing process has many favourable properties: it reduces the roughness of the machined surface, improves shape accuracy and stress conditions, as it generates compressive residual stress in the layer close to the surface, thereby increasing the material's hardness, residual stress, and at the same time its resistance to fatigue. Our examinations were extended to examine whether these advantages also occur in the case of different (stainless and non-stainless) steel workpieces, as well as in the case of workpieces with low alloyed aluminium material quality.

3.1.1. Burnishing of steel

In ensuring the proper quality working surfaces of the machine parts a significant role is played by the finishing cold-plastic processing processes, such as burnishing, rolling, or sand blasting. In our research we dealt, in detail, with the burnishing experiments of austenitic chrome-nickel steel workpieces. The interesting fact about the research is that the hardness of the examined austenitic chrome nickel steel workpieces was relatively low (HB30). The experimental variables were burnishing feed, burnishing speed, burnishing force, and number of burnishing passes. Due to the low hardness of the workpiece, the burnishing force used for structural steels was chosen to be 1/3 to 1/5. To increase the precision of the microhardness measurements, two microhardness values were measured, specifically the HV 0.2 and HV 1 values before and after burnishing on the examined test piece at the three positions of the cylinder former. We also examined the surface roughness, axial and tangential residual stresses before and after burnishing.

3.1.1.1. Examination of surface roughness in the case of different material qualities

A part of our research work was aimed at examining the theoretical and real roughness of surfaces machined with sliding friction burnishing. When determining the theoretical roughness, we also considered the surface topography created by cutting (turning) before burnishing. Two different modelling methods were used to obtain the theoretical surface roughness data: CAD modelling and finite element simulation. A method using CAD-based modelling of the machined surface was used to determine the theoretical roughness for both the turning and burnishing processes. However, this previously developed model is not directly applicable to plastic deformation processes such as diamond burnishing, so the principle of the Hertz theory for normal contact of elastic solids was used to calculate the penetration depth of the tool into the workpiece. The 2D FEM simulations were performed in the “DEFORM” software. To validate the applied modelling methods, real cutting experiments were performed, where the surface roughness values were measured during diamond burnishing experiments with different feed per revolution values. Based on the comparison of both used modelling methods with real roughness data, it can be concluded that the theoretical roughness values closely approximate the real data.

The conducted investigations are essentially concluded that the CAD modelling method combined with the Hertz theory calculation seems to be a good approximation of the burnishing process, or at least it is not significantly worse, than the applied FEM method. The main results of the performed modelling and experimental studies:

- It was found that the modelled and actual values correlated relatively well. In the case of the roughness parameter Ra, the results obtained with increasing the feed rate became more and more close to the real roughness values. With CAD modelling-based calculation, a better correlation was found with real roughness data in almost all cases than with FEM.

- For the Rz parameter, the measured roughness values were higher than the simulation results in all cases. The reason for this was thought to be discovered in the nature of the surface and this roughness parameter: The depicted roughness diagrams show that the real surfaces have significant protrusions which have a much more significant effect on roughness peak-dependent parameters such as Rz than on the arithmetic mean values of Ra.
- The wavelengths of the roughness profiles obtained after sliding burnishing were found to be independent of the value of the burnishing feed. The reason for this was that the wavelength of the roughness profile is primarily determined by the pre-burnishing operation (in this case turning), the burnishing process only smoothest the roughness peaks, which can be clearly seen in the roughness profiles presented in the paper.
- It may be noted that both the FEM simulation and the CAD modelling takes some simplifications into account, which may mean that the results achieved are encouraging, but should not be seen as universal. The area of diamond burnishing is an area with an enormous amount of untapped potential, where many more interesting results can be expected.

In next part of our research, we examined the effect of diamond burnishing, which in addition to improving the surface quality, also favourably changes the mechanical properties, on the roughness of different quality surfaces when burnishing a sample of S355J2G4 structural steel. Burnishing was carried out with a kind of parameter combination, after burnishing measurements were made, where the Arithmetic mean roughness value (Ra), Maximum peak to valley height of the profile (Rz), Root mean square average of profile height deviations (Rq). We found that the examined surface roughness parameters were significantly reduced. However, the result is not uniform, so the result of burnishing is also influenced by the surface quality before burnishing.

3.1.1.2. Examination of residual stress after burnishing for different material qualities

a)

The aim of our research work was the 2D Finite Element Analysis of the residual stress occurring during diamond burnishing. Based on the performed simulations and laboratory experiments, it can be concluded that the diamond burnishing process can be modelled with a relatively good approximation using two-dimensional modelling. We concluded that it is important to consider the initial surface topography during two-dimensional studies. The results indicate that the diamond burnishing process improved the residual stress properties of EN 1.4301 austenitic stainless steel by creating relatively high compressive stress, whose magnitude was between 629 and 1138 MPa depending on the applied force. However, the stress distribution is not uniform; it is mostly concentrated under the roughness peaks.

The finite element investigations were performed using the roughness profiles measured on the turned surfaces. Based on the results of the simulations, it was established that the residual stress is tensile in the immediate vicinity of the surface and changes to compressive stress at a depth of about 2 µm, reaching its maximum absolute value at about 10 µm (the actual value depends on the applied burnishing force). The values of the maximum compressive stress reached were between 442 and 1260 MPa. These results were compared with the residual stress data measured on diamond burnished surfaces during the experiments. Based on the investigations, it could be established that with two-dimensional modelling it is possible to model the diamond burnishing process with a relatively good approximation; the difference between the measured and FEM results for Stress-X was between 2 and 25%, while the average difference was 13%. It should be mentioned that the sliding friction between the tool and the workpiece was ignored during the simulations due to the characteristics of the procedure applied. However, it should be highlighted that there is lubrication at the real burnishing process as well: in the actual experiments, SAE 10W40 oil was used to reduce the friction between the tool and the workpiece. Another disadvantage of two-dimensional modelling is that it cannot evaluate tangential stresses. On the other hand, a clear advantage compared to three-dimensional modelling is that the calculation is much faster, and the structure and management of the FEM model are simpler. Based on the results of the tests carried out, it can be concluded that even in two-dimensional simulations it is extremely important to consider the initial surface topography: during the burnishing process, the profile obtained during the previous operation is plastically formed, so the actual forming is concentrated on the roughness peaks. Since the burnishing force is concentrated on a smaller surface area on the rough surface, the surface pressure will be higher. Since the experiments also proved that increasing the burnishing force has a clear positive effect on the residual stresses in this process, two factors should be considered to achieve the required stress state of the surfaces: the right value of the burnishing force and the appropriate choice of the preceding operation resulting in the desired roughness profile. If the previous operation creates a surface that is too rough, then the distribution of stresses remaining in the material after burnishing will be less uniform, which may be unfavourable in terms of service life.

b)

Next part of our research work, we also performed sliding friction diamond burnishing on 42CrMo4 hard-turned cylindrical steel workpieces. The effect of three technological parameters of the diamond burnishing process (burnishing speed, feed, and burnishing force) on surface roughness, surface residual stresses and micro-hardness was examined. The experimental results showed that a significant reduction of the surface roughness was achieved, in addition to the fact that high compressive residual stresses were generated in the axial and tangential directions to a significant depth of about 135 µm. The micro-hardness of the surfaces also improved, reaching 51% improvement in some samples. After simultaneously examining the effect of the three burnishing parameters, the results showed that it is not enough to examine the effect of changing only one parameter while keeping the others unchanged. The results showed that the influence of one parameter is greatly influenced by the range in which the other parameters were applied. Therefore, we determined the optimal burnishing parameter combination that gave the best result. With these parameters, we obtained a lower surface roughness than was achievable by grinding. Furthermore, in contrast to grinding, favourable compressive stresses were applied to the surface regions of the treated specimen. Based on these, it can be stated that, in the case of the examined steel type, the grinding after hard turning can be replaced by diamond burnishing.

3.1.1.3. FEM analysis of the burnishing process of X5CrNi18-10 stainless steel

We analysed the effect of burnishing speed, feed, and burnishing force on the residual stresses when burnishing using by the “Third Wave AdvantEdge” finite element software. The affected width and depth were analysed in one pass of the burnishing tool. We also examined the maximum pressure and the stress distribution of the surface layer. The values of the examined parameters were selected according to the “Design of experiments” method. The equations defining the investigated properties were also given. It is found that the increase of the burnishing force has the highest effect, followed by the feed.

Varga, G., Ferencsik, V.: Examination of residual stresses … (2017)

Varga, G., Ferencsik, V.: Analysis of shape correctness … (2017)

Csóti, B., Sztankovics, I.: Gyémántszerszámos vasalás hatása … (2020)

Felhő, C., Varga, G.: CAD and FEM Modelling of Theoretical … (2022)

Felhő, C., Varga Gyula: 2D FEM Investigation of Residual … (2022)

Varga, G., Smolnicki, S., Babic, M., Caesarendra, W.: Energy efficiency analysis … (2022)

Zaghal, J., Molnár, V., Benke, M.: Improving Surface Integrity of … (2022)

Nagy, A., Varga, G.: Analyzing the effect of the … (2022)

Smolnicki, S.: Ökohatékonysági elemzés különböző … (2022)

Smolnicki, S.: A gyémántvasalás energiahatékonyságának … (2022)

Smolnicki, S., Varga, G.: Eco efficiency analysis in case … (2022)

Sztankovics, I., Varga, G.: FEM Analysis of the burnishing process … (2022)

Varga, G., Ferencsik, V.: Investigation of the Effect of … (2022)

3.1.2. Burnishing of low-alloy aluminium

In next part of our research work the subject of our investigations was the sliding friction diamond burnishing of EN AW-2011 low-alloy aluminium cylindrical workpieces. This material is increasingly used in the machine and vehicle manufacturing industry, thanks to their favourable mechanical properties and low density. During the experimental work, the axial and tangential residual stresses were measured using the X-ray diffraction method when burnishing outer cylindrical workpieces. We used the factorial experimental design method, when examination of residual stresses as well.

The aim of the experiment was to analyse how the parameters (burnishing force, feed rate, speed, and number of passes) affect the surface micro-hardness and stress condition and how they correlate with each other. Based on the analysed results of the experiments performed, the following conclusions were drawn:

- The change in number of passes had no significance for the residual compressive stress.
- From the point of view of hardness, it was advantageous if the tool passes through on the workpiece surface more times (e.g., 3 times) at the larger feed rate (f=0.005 mm/rev).
- According to the numerical results, lower burnishing speed (v=15 m/min) causes more favourable changes.

It was found that in the case of setting the number of the passes for 3 when applying a higher value of feed (f = 0.005 mm/rev) provides the best result, while in case of setting the number of the pass for 1 only, the lower feed rate (f = 0.001 mm/rev) was more advantegeous.

The shape correctness of shaft-like parts is crucial not only from the point of view of the given part, but also from the point of view of the complete machine element, that is why the analysis of the effect of burnishing on this characteristic was also part of our research work. The measurements were carried out using a Talyrond 365 circular shape and positional error measuring device. For According to the dimensionless ratios illustrating the change caused by the process, the improvement was small, but it can be stated that burnishing can also be advantageously used as a finishing machining method from this point of view.

In our experimental investigations of burnishing of low-alloyed aluminium shafts, in which the examined parameters were the burnishing force, feed rate, speed and number of passes. The purpose of the studies was to examine the influence of these burnishing parameters on different surface-roughness parameters, such as Ra, Rq, Rz and Rt. The full factorial experimental design method was applied to examine the changes caused by burnishing and to make it even more vivid, dimensionless ratios were used when creating empirical formulas and 3D diagrams were created for each roughness parameter.

According to the measured and calculated results, the following statements could be drawn:

- In the experiment, when the number of the passes were i_1=1 and i_2=3, and the burnishing force is increasing from F_1 = 10 N to F_2 = 20 N had a negative effect on the numerical value of the surface-roughness-improvement ratio for all four examined surface-roughness parameters.
- Increasing the feed from f_1 = 0.001 mm/rev to f_2 = 0.005 mm/rev for the higher number of passes (i_2 = 3) had a clear positive effect on the value of the surface-roughness improvement ratio both when applying the lower and higher burnishing force (F_1 = 10 N and F_2 = 20 N). In contrast to this.
- When increasing the burnishing force from F_1 = 10 N to F_2 = 20 N at v_1 = 15 m/min burnishing speed showed a positive trend in the values of all the four surface-roughness-improvement ratios at the application lower feed (f_1 = 0.001 mm/rev).
- At the higher speed and burnishing force (v_2 = 30 m/min, F_2 = 20 N), increasing the feed from f_1 = 0.001 mm/rev to f_2 = 0.005 mm/rev had a negative effect on the tested surface-roughness-improvement ratios. Therefore, the application of a higher burnishing speed (v_2 = 30 m/min) and a lower burnishing force (F_1 = 10 N) is more beneficial in terms of surface-roughness improvement.

Varga, G., Ferencsik, V.: Investigation of the influence of … (2018)

Ferencsik, V., Varga, G.: Gyémántszerszámos vasalás okozta … (2019)

Ferencsik, V.: A felületvasalás alakhelyességre és … (2019)

Ferencsik, V., Gál, V.: FE Investigation of Surface … (2019)

Varga, G., Ferencsik, V.: Analysis of Surface Microhardness on … (2019)

Varga, G., Ferencsik, V.: Examination of 3D Surface Topography … (2019)

Ferencsik, V., Varga, G.: Examination of the change in … (2019)

Ferencsik, V., Varga, G.: Examination of surface state-change … (2020)

Ferencsik, V., Varga, G.: Examination of the effect of … (2020)

Ferencsik, V.: Az élettartam-növelő környezetbarát … (2020)

Ferencsik, V., Gal, V.: FE investigation of surface burnishing … (2020)

Ferencsik, V., Varga, G.: Investigation the influence of … (2022)

Ferencsik, V., Varga, G.: The effect of burnishing process … (2022)

Ferencsik, V., Varga, G.: The Influence of Diamond Burnishing … (2022)

3.1.3. Burnishing porous materials

A common feature of additive manufacturing technologies is that they cannot achieve the dimensional accuracy and surface quality usual with classical manufacturing technologies in one production step. Therefore, additive manufacturing must be incorporated into a multistep manufacturing process. The operations following additive manufacturing are collectively known as postprocessing. Diamond burnishing is a well-known technology that can be used cost-effectively due to its simplicity, and according to its working principle, it can simultaneously reduce surface roughness and improve surface hardness. Therefore, it is a promising candidate for the post-processing of cylindrical surfaces produced by additive manufacturing.

During our research, we examined test specimens made of Ti6Al4V using additive manufacturing. This material is widely used in industry, medical instruments, and tools, which is made suitable by its chemical resistance, biocompatibility, and excellent weight-bearing capacity ratio. During the research of the literature, we noticed that no scientific publications have been published yet on the machining of components made of Ti6Al4V using additive manufacturing with diamond burnishing. These circumstances together motivated us to start our research in this direction.

3.1.3.1. Examination of surface roughness

During our research, we examined how the surface roughness of the parts melted with a selective laser can be modified by sliding friction burnishing. The 2D and 3D characteristics of the surface roughness were measured with a confocal chromatic roughness measuring device. We investigated the effect of three burnishing parameters and two selective laser melting (SLM) production parameters. The indices showing the improvement in surface roughness can be used for the complex characterization of the surface roughness formed by diamond burnishing of Ti6Al4V parts treated with SLM power density (energy input) itself is not applicable for predicting machinability, and it stands in relation directly with power density and scanning speed and provide an opportunity to compare and rank the machining results, as they contain the most important surface roughness parameters. The specimens were manufactured with five (signed A, B, C, D and E) different SLM manufacturing parameters and 8 specimens were prepared and tested in each case. On the base of the manufacturing parameters of the specimens the two manufacturing parameters (infill laser power (P) and infill laser speed (u)) were varied: A) P=233.33 W; u=1200 mm/s; B) P=280.00 W; u=1000 mm/s; C) P=336.33 W; u=1440 mm/s; D) P=233.33 W; u=1000 mm/s; E) P=280.00 W; u=1200 mm/s. During our research, we found that modification of the surface of the Ti6Al4V test pieces produced by SLM with sliding friction diamond burnishing resulted in a significant improvement in the surface roughness of the titanium parts fused with a selective laser, especially about the 2D roughness parameters Ra, Rz and Rq, as well as the Sa, Sz and Sq for 3D roughness parameters. It was found that among the investigated burnishing parameter setting, the most favourable roughness improvement results for both 2D and 3D improvement ratios when v = 8.321 m/min; f = 0.0125 mm/rev; F = 120 N. SLM power density (energy input) itself is not applicable for predicting machinability, and it stands in relation directly with power density and scanning speed. Our study has attested that SLM processing parameters significantly influence machinability that is surface quality improvement by diamond burnishing. Parameter combination P = 280 W, u = 1200 mm/s (workpiece code: E) was found to be optimal on a studied parameter domain. This parameter set differs from default settings of the SLM machine.

3.1.3.2. Examination of shape error

Metal parts made by additive manufacturing, usually require post-processing to achieve the desired shape accuracy. We produced cylindrical specimens from Ti6Al4V powder with different processing parameters by selective laser melting. The purpose of the post-processing was to modify the shape accuracy. As a post-processing method, we used diamond burnishing with sliding friction. A five-factor, two-level, full factorial experimental design was implemented with the following factors: loading laser power (P), loading laser scanning speed (u), burnishing speed, feed, and force. The improvement rates of two roundness parameters were determined, which were calculated from experimental data and examined with main effect and interaction analysis. Burnishing feed has been shown to have the greatest effect on improving overall roundness and cylindricity. In addition, the parameters for both selective laser melting and diamond burnishing are presented in three largest interaction terms. The empirical functions were fitted to the measurement data. The results show that the improvement of roundness parameters is a highly non-linear function of all factors.

The aim of our research work related to this part project, was to investigate the effect of sliding friction diamond burnishing (SFDB) on the roundness parameters of cylindrical parts made of Ti6Al4V alloy by selective laser melting (SLM), where SFDB was applied as a postprocessing method. We also used the factorial experimental design method during our shape error investigations, and by using it we examined how the SLM processing parameters (laser power, laser scan speed) and postprocessing parameters (burnishing speed, feed, and force) influence improvement in shape accuracy (namely circularity error and deviation of cylindricity) in the case of cylindrical test specimens made of Ti6Al4V ELI alloy.

- In general, sliding friction diamond burnishing improves unambiguously and effectively both circularity and cylindricity. For the cylindricity deviation the lowest improvement ratio observed was ICYLt=12.97%, and for the circularity error the highest improvement ratio was IRONt=70.38%. Roundness parameters always got better results in our experiments.
- Each experimental factor has positive main effects on circularity improvement.
- Burnishing feed (f) has the largest positive main effect on both circularity and cylindricity improvement.

3.1.3.3. Examination of changes in hardness

The surface hardness of parts made by additive manufacturing was examined before and after surface modification performed by diamond burnishing. The cylindrical shape specimens were made by selective laser melting from Ti6Al4V. The parameters of diamond burnishing were determined by a three-factor, two-level full factorial experimental design. During diamond burnishing the burnishing speed, feed, and burnishing force were varied. This means that for each combination of different SLM manufacturing parameters, a diamond burnishing operation with 8 different parameters was performed. The surface Vickers hardness of HV10 was measured before and after burnishing on a hardness measuring equipment type HPO-250. Based on the HV10 surface hardness values, the surface hardness improvement ratios were calculated for each case.

It can be stated that from additive technological point of view the largest energy input (66.667 W/mm^3) was the most advantageous (Specimen code "B" where parameters: P=280.00 W; u=1000 mm/s). From burnishing technological point of view the largest burnishing force (F = 120 N), the largest burnishing speed v = 11.775 m/min and the smaller feed f = 0.0125 mm/rev served the best result.

Based on the research activity, we deduced the following statements:

- Maximum surface hardness improvement could be reached by applying F = 120 N burnishing force in each production cases (A–E) investigated in our research.

- Other burnishing parameters influence surface hardness change in different ways:

- In case of sample set, A, smaller v (burnishing speed) and f (feed) is necessary for achieving maximum surface hardness improvement.

- In case of sample set B, larger v and smaller f is necessary for maximum surface hardness improvement.

- In case of sample sets C and D, it is advisable for low v high f, and for high v low f.

- In case of sample set E, increase of both v and f is necessary to achieve maximum surface hardness improvement.

Dezső, G., Kósa, P., Szigeti, F.: Effect of manufacturing orientation … (2021)

Dezső, G., Szigeti, F., Varga, G.: Measurement of the surface hardness … (2022)

Dezső, G., Szigeti, F.: A fém alkatrészek additív gyártásának … (2022)

Dezső, G., Kósa, P., Szigeti, F.: Effect of manufacturing orientation to … (2022)

Dezső, G., Szigeti, F., Kósa, P.: Additív gyártással készített … (2022)

Dezső, G.: Material test, microstructure and … (2022)

Dezső, G., Szigeti, F., Varga, G.: Surface hardness modification of … (2022)

Varga, G., Dezső, G., Szigeti, F.: Surface Roughness Improvement by … (2022)

Szigeti, F., Dezső, G., Kósa, P.: 3D nyomtatással készített próbatestek … (2022)

3.2. Sliding friction diamond burnishing of flat surfaces

In our research, we present a possible method for sliding friction diamond burnishing of flat surfaces, where the burnishing head was fixed to the milling machine with a clamping device designed and manufactured by us. In the developed method, the tool is in a stationary position, while the table of the milling machine moves in an elliptical path, thus providing the speed required for the process. The advantage of this method is that conventional burnishing tools (used on a lathe) can also be used for burnishing flat surfaces. Burnishing experiments were performed by changing the following technological parameters: force, feed, and the number of passes. Based on these, we found that the most favourable roughness was given by the burnishing force of F=120 N, the feed of f=0.15 mm/rev and the number of passes of i=1. Our conclusion was that the roughness of the burnished surfaces is mostly influenced by the burnishing force, while the effect of the other two examined parameters is not clear yet. Further investigations are needed to clarify this, where special attention must also be paid to the proper quality of the surfaces prepared by milling.

Tesfom, F., Pásztor, I., Felhő, C.: Flat diamond sliding burnishing … (2022)

4. Environmentally friendly machining

4.1. Machining when the use of cryogenic cooling

Nowadays, industrial plastics are used in large quantities in various areas of industry for their various beneficial properties. Their dynamic development and the appearance of new materials are a constant challenge for the industry, as the optimal cutting parameters show significant differences depending on the quality of the plastic material. Determining the optimal parameters for cutting industrial plastics is a constant challenge for production technologists.

During processing, the dimensional accuracy and surface quality required by the designers must be implemented cost-effectively. During the processing of industrial plastics, it is known that the determining element of the cutting parameters is the heating, which arises due to the friction of the tool-chip, workpiece-tool and the energy used to separate the chip. In the case of a significant number of industrial plastics, the machinability of the material deteriorates because of heating, the plastics melt during processing and stick to the tool and the workpiece. One way to increase the cutting parameters is to use cooling lubricants, however, polymers have a negative effect on lubricants, so the literature recommends dry machining and compressed air cooling.

Industrial plastics cannot be machined above a certain temperature. In order to increase the cutting performance, the heating of the workpiece must be limited. To keep the workpiece and the tool under a certain temperature, we can use the cooling of different parts of the production system, thus reducing the heating of the workpiece, chips, and the tool.

The beneficial consequences of using a coolant in cryogenic cooling: during the cutting process, it can increase the tool life of the tool and the accuracy of its dimensions; can reduce cutting temperature, surface roughness and energy used in the metal cutting process, thereby improving productivity. In the literature, most cryogenic cooling applications have been investigated in turning operations, although they also occur in other machining operations such as grinding, drilling, and milling.

Based on the review of the literature related to processing in a cryogenic environment, the research can be divided into three groups: a) cooling of the tool, b) cooling of the workpiece, c) simultaneous cooling of both of them. During our tests, we dealt with the cooling of the workpiece.

During the hole machining experiments of cryogenically cooled polyethylene raw material (PE-HD 1000 type polyethylene), the tests covered the shape of the separated chip, the accuracy and surface roughness of the machined hole. Based on the results of the tests, we determined that because of drilling at (-35°C), the machinability of the polyethylene specimen improved, the surface roughness of the hole decreased, and its dimensional accuracy increased. The most important test results can be summarized as:

- Chips separated in a cold environment (-35°C) and they did not become fibrous, the heat generated during chipping did not melt them. When cutting at a temperature of room temperature (+20°C), on the other hand, the chips compacted, stuck in the flute of the twist drill and it was difficult to remove it from the flute.
- The chip does not screw onto the twist drill at the higher feed rate (f_2=0.62 mm/rev) in the cooled state, however, at the lower feed rate (f_1=0.32 mm/rev), even in the cooled state, the chip is screwed onto the twist drill.
- Rolling up the chip onto the twist drill is a significant disadvantage when machining on CNC machine tools because the machine tool must be stopped for removing the chip, thus increasing the time of machining.
- The change in the diameter of a hole machined in a cryogenic environment is significantly smaller than that of a hole machined at room temperature. In the cold environment, the cylindricity error of the holes (measured deviations from the theoretical cylinder diameter) is significantly smaller and the dimensional accuracy of the holes also improves.

- The experimental results show that the roughness of the machined surface improves during cryogenic cooling, the surface unevenness of the machined holes is significantly smaller, and we measured lower average roughness values for most combinations of cutting parameters.

Varga, G., Ravai-Nagy, S., Szigeti, F.: Examination of surface roughness … (2018)

Ravai Nagy, S., Szigeti, F., Varga, G.: Felületi érdesség vizsgálata ipari … (2018)

Ravai Nagy, S., Szigeti, F., Varga, G.: Krio környezetben történő furatmegmunkálás … (2019)

4.2. Analysis of environmental load

The auxiliary materials for machining facilitate the quality and accuracy of component manufacturing as well as efficient material removal and increasing productivity. However, the auxiliary materials used (coolants and lubricants) burden our environment. In machining of the machine industry, volume of such materials needed to produce one part may not be large, but there are millions of parts, meaning that a detailed analysis is needed to minimize the quantity of the series. In this part of our research, we performed a comparative analysis of coolants and lubricants used in hard machining processes, where the cutting data was adjusted so that the part had the same accuracy and quality.

Based on the tests carried out during our research, the procedures can be clearly classified based on the environmental impact. Compared to the traditionally applied grinding, the level of environmental impact can be reduced with hard turning processes, so the efficiency indicators of chip removal improve significantly. If hard turning is applied, the environmental impact can be reduced while productivity is increased. In all cases where a periodic surface is acceptable, only hard turning is recommended, the efficiency of which can be further improved with the advent of new tools.

We examined the effect and consequences of omitting cooling-lubrication when turning unalloyed steel. In the case of different values of feed rate and cutting speed, we examined the 2D and 3D surface roughness parameters and the parameter characteristics of the cylindricity deviations. It was found that with dry machining, the average roughness is slightly higher as productivity increases, but at lower feed and cutting speeds, the wear resistance and lubricant retention of the surface is better, and the cylindricity deviation can be minimized. Our aim was also to determine the roughness and roundness that can be achieved in the case of dry, environmentally friendly machining, in addition to the investigated technological parameters.

Varga, G., Puskás, T., Debreceni, I.: Examination of Shape Error … (2018)

Varga, G., Puskás, T., Debreceni, I.: Analysis of cylindrical error … (2018)

Kundrák, J., Varga, G., Deszpoth, I.: Analysis of Extent of Environment … (2018)

Varga, G., Sovilj, B., Jakubowicz, M., Babič, M.: Experimental Examination of Surface … (2019)

4.3. Examination of eco-efficiency, energy-efficiency of processes

The in-depth analysis of the manufacturing processes is a particularly interesting topic from the point of view of production efficiency, since in large-scale production the effective utilization of production capacities and the revenue-increasing capacity of production are the key conditions for competitiveness. That is why it is important to analyse the time and material removal rate closely related to production when planning the manufacturing process. In our examination, we compared three procedures used in hard turning based on these parameters, and we presented a new parameter, the practical parameter of the material removal rate. It not only measures the cutting efficiency, but also the entire machining process, because it also includes the values measured by time analysis. During the tests, we analysed the material removal rate, first based on the geometrical data of the component. Afterwards, we compared different machining processes (hard machining) on some typical surfaces. The results can provide useful clues for the selection of the machining process.

During our research work, we performed a series of grinding and diamond burnishing experiments. During the series of experiments, we changed the technological parameters of the machining processes, the cooling and lubricating fluids that help to implement the machining, we used an emulsion made from 3 different types of oil for grinding, while we used two different types of oil for diamond burnishing. After completing the series of experiments, we measured the 2D surface roughness parameters of the specimens, as well as the deviations of the roundness and cylindricity error. The measured results were evaluated in Kraljik matrix form. In the case of each applied emulsion, in the case of grinding, and in the case of which lubricating oils, when burnishing, we determined the percentage of the experiments that had a good result in terms of both energy consumption and surface quality, as well as round shape and positional error parameters. Next, we gave a kind of definition of the eco-efficiency indicator number. After calculating these indicator numbers, homogeneous machining processes using different types of cooling and lubricating fluids could be ranked in terms of eco-efficiency. We also experienced the surprising result that the surface quality resulting from machining that requires higher power consumption will not necessarily be better. Our other observation is that the correct selection of the cooling-lubricating fluid is one of the decisive factors in machining. Its choice affects all aspects of the result of the machining, but its environmental damage can also be significant. Based on this line of thought, the most eco-efficient may be dry processing, but not all technological processes can be carried out dry.

Kundrák, J., Molnár, V. Deszpoth, I.: Comparative analysis of machining … (2018)

Varga, G., Smolnicki, S., Babic, M., Caesarendra, W.: Energy efficiency analysis … (2022)

Smolnicki, S.: Ökohatékonysági elemzés különböző … (2022)

Smolnicki, S.: A gyémántvasalás energiahatékonyságának … (2022)

Smolnicki, S., Varga, G.: Eco efficiency analysis in case … (2022)

5. Examination the vibration of machining

Our earlier results proved that laser measurements using Laser Doppler Vibrometer (LDV) are suitable for sufficiently accurate diagnosis of the machining process. At the beginning of our research, it became apparent that the signals of the stand holding the instrument were also included in the received measurement signal. To eliminate this, in the first step, we examined several methods, which yielded unsatisfactory results.

Therefore, in the second step, we performed measurements with an LDV (or target object) on a vibration-free table. It then became clear that the instrument itself has (own) vibrations that cannot be isolated during operation. To eliminate this, according to the theory found in the literature, additional sensors had to be placed on the instrument, whose signals can be used to isolate the noise of the environment.

For the latter measurement, on the one hand, we further developed the device, on the other hand, we coordinated the signal processing and programmed the corresponding mathematical background. With the help of the program, we get a more detailed picture of the change of the machining process over time, all while being able to eliminate the disturbing effect of environmental signals.

The physical background of the vibrations generated during drilling is determined by the (tool)-(machine tool)-(environment) together. Therefore, we examined the vibration characteristics of the (machine)-(machine tool) system itself in the case of a real working environment. Since the laser (LDV) measurement is not directly part of the chip removal system, its parameters can be determined objectively. The transverse natural vibrations of the twist drills clamped in the drill chuck and equipped with pulse excitation were investigated with a LDV.

During our research, we established that the transverse free vibrations of the drill bits clamped into the chuck and pulse-excited are usually dominated by the flutter resulting from the superposition of two components with frequencies close to each other (within a few %), which belong to the transverse vibration of the twist drills in the direction of the groove end and perpendicular to it. This is especially true in the case of vibration of the drill bit after excitation perpendicular to the laser beam, in which case the vibrations are harmonic. In the case of pulse-like excitation in the direction of the laser beam, the first oscillations are strongly disharmonic. We proved that the type of excitation also has a significant effect on the vibration spectrum. Excitation with a blunt device resulted in the fundamental frequencies, and more characteristic excitation resulted in several additional higher frequency vibrations.

We performed experiments to filter out background noise. We have noticed that the amount of noise is sometimes comparable to the magnitude of the measured responses. The vibrations were mathematically modelled as a cylindrical rod with a circular cross-section clamped in the drill chuck at one end. The tuning fork model used as a model of the clamped drill gives the natural vibration frequency of the Ø9 mm diameter twist drill with an accuracy of a few percent. On the other hand, with larger diameter drills (Ø10 mm and Ø12 mm), overestimation by 15-20% can be observed. This was due to the larger size of the flute of larger diameter drills. However, the sharp excitation resulted in several additional higher-frequency vibrations, which we could not interpret mathematically with the cylindrical rod model. For the further development of the model, we intend to introduce an equivalent diameter that also considers the chip drainage flutes.

During our examinations, when drilling on a lathe, we measured the torsional vibrations of the drill bit with a Laser Torsion Vibration Meter (LTV). At our literature survey, we found no trace of such kind of measurements. Due to the parameters of the LTV tool, conditions of use and other reasons, the linear vibrations of the drill bit have also changed. We have established that some torsional vibrations can be highlighted from the results of the measurement with the LTV device. Furthermore, a torsional vibration group with a lower frequency is also present in the spectrum. These coincide well with the harmonics of the drill's rotation speed, based on which the so-called pseudo-oscillations can be formed. At the same time, the results of the two measurement-series show significant differences.

During our investigations, we have summarized, based on recent literary sources, the laser measuring devices used in cutting and their methods of use and conditions.

Our published paper “Application of laser measurements during cutting II., laser testing of drilling, milling and turning” presents a summary of examples from the literature for the application of cutting, which only covers laser measurement techniques. At the same time, it provides a certain insight into the possibilities of laser measurements for classical cutting processes. In our publication, we presented laser measurement techniques used only for cutting in a summary manner with examples from the literature. At the same time, this provides a certain insight into the possibilities of laser measurements for classical cutting processes (Figures 3, 4).

Béres, M., Paripás, B.: Measuring of drill bit vibration by … (2018)

Béres, M.: Lézeres mérések alkalmazása forgácsoláskor I. … (2020)

Béres, M.: Lézeres mérések alkalmazása forgácsoláskor II. … (2020)

Béres, M., Jenyó, T., Paripás, B.: Tokmányba fogott fúrószár szabad … (2021)

Béres, M.: Precíziós lézerinterferometrikus mozgásanalizálási … (2022)

6. Another researches related to the topic

6.1. Examination of rotational turning

During our research, we investigated how the cutting force changes because of increasing the feed rate in the case of rotational turning. Through experiments with tools with different edge geometries, we analysed the course of the cutting force components over time and determined the specific cutting forces. We found that the passive force acting on the cutting tool can be effectively reduced by using rotational turning.

During the experiments, we analysed the effect of the feed rate on the specific cutting forces for different turning procedures. The experiments were carried out at 6 feed rates with 2 rotational lathe tools with different inclination angles and 1 conventional lathe tool. The calculation of the specific cutting forces showed that the specific main cutting force is almost the same in rotational and conventional turning. However, the specific passive forces are significantly lower in the turning process (almost half of the traditional ones), while during rotational turning (2-4 times increase) we obtained higher values for the specific forces in the forward direction than in the traditional turning. Accordingly, with the same cutting power requirement, the force to remove the workpiece from the tool will be smaller, and the axial load on the spindle and tool holder will be higher in rotary turning than in the traditional process, which resulted in a reduction of errors related to workpiece deflection, because the dynamic system's elastic deformation was smaller. Differential axial force must be considered when designing or selecting tool holder construction.

6.2. Examination of honing

In our study, we examined the effect of feed and tool structure on the shape error of the surfaces of holes machined with honing. When honing, it is important to analyse the shape error of the machined surface and to explore the effect of individual technological data. In our experiments with different technological parameters, we measured the cylindricity, out-of-roundness, and conicity of the hole. In our analysis, in addition to the numerical values of the three parameters, we also compared the surface profiles recorded by the measuring equipment.

By changing the feed and the structure of the abrasive tool, we examined the cylindricity, conicity and roundness of the surface in the case of honing internal cylindrical holes. Examining 9 settings, we found that in terms of cylindricity, the smaller grain size and the more closed structure are more favourable, and the most unfavourable values were measured at a feed (f=50 mm/rev). Both investigated parameters have a significant effect on the roundness of the surface. By increasing the feed, speed between the tool and the workpiece and by refining the grain size, the degree of cylindricity error can be effectively reduced even while keeping the other technological data unchanged.

6.3. Examination of the residual stress of turning

During the X-ray diffraction examination of the elastic residual stress of 100CrMnSi6-4 steel bearing rings, we showed that the effect of soft turning parameters (feed, speed, and tool radius) cannot be examined independently. Based on these, it is not possible to formulate clear conclusions about the effect of certain turning parameters.

Zaghal, J., Molnár, V., Benke, M.: Improving Surface Integrity of … (2022)

Sztankovics, I.: Components of the cutting force and … (2020)

Nagypál, G., Sztankovics, I.: Furatok alakhibájának vizsgálata … (2020)

Zaghal, J., Mertinger, V., Filep, A., Varga, G., Benke, M.: Characterization of residual stresses … (2021)

Sztankovics, I., Pásztor, I.: Preliminary analysis of surface topography … (2022)

7. Comments

According to the points of the work plan, the progress of the research was reported in the annual reports, while the main research works belonging to each main objective and their results were reported in the final report.

Two PhD dissertations are being prepared on this topic at the University of Miskolc. One of the dissertations is currently under review. An MSc student prepared two scientific student theses [TDK] and a diploma project on this topic.

The results of the research work were continuously published in: journals (54), conferences (14), book chapters (5).

So far, 58 independent citations have been received for the publications uploaded to the report.

Some summarizing Figures can be found in Chapter 8.

8. Figures

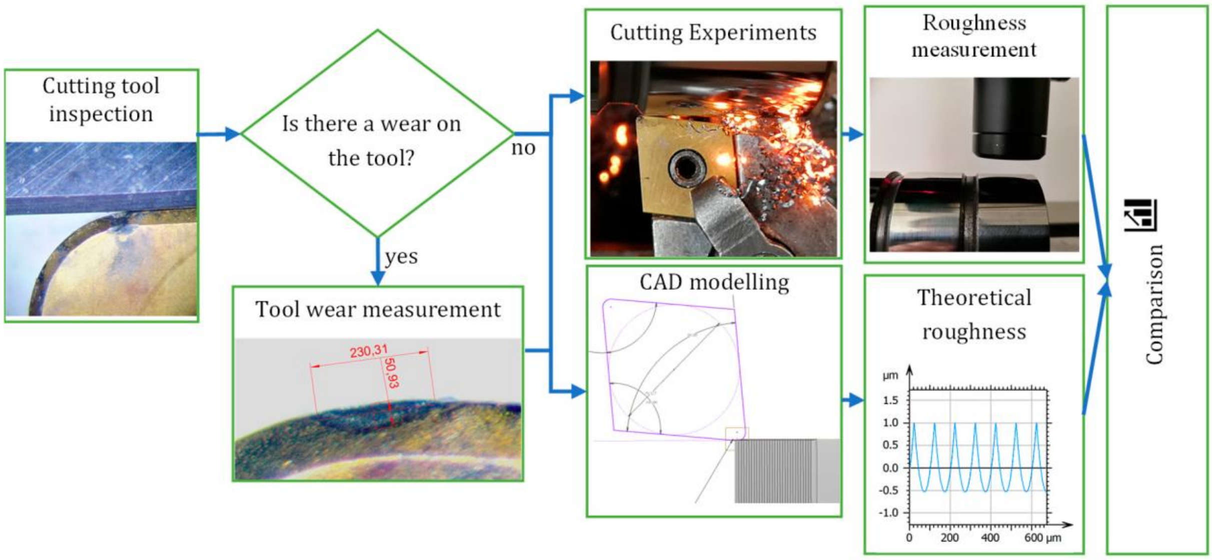

Figure 1. The applied investigation method.

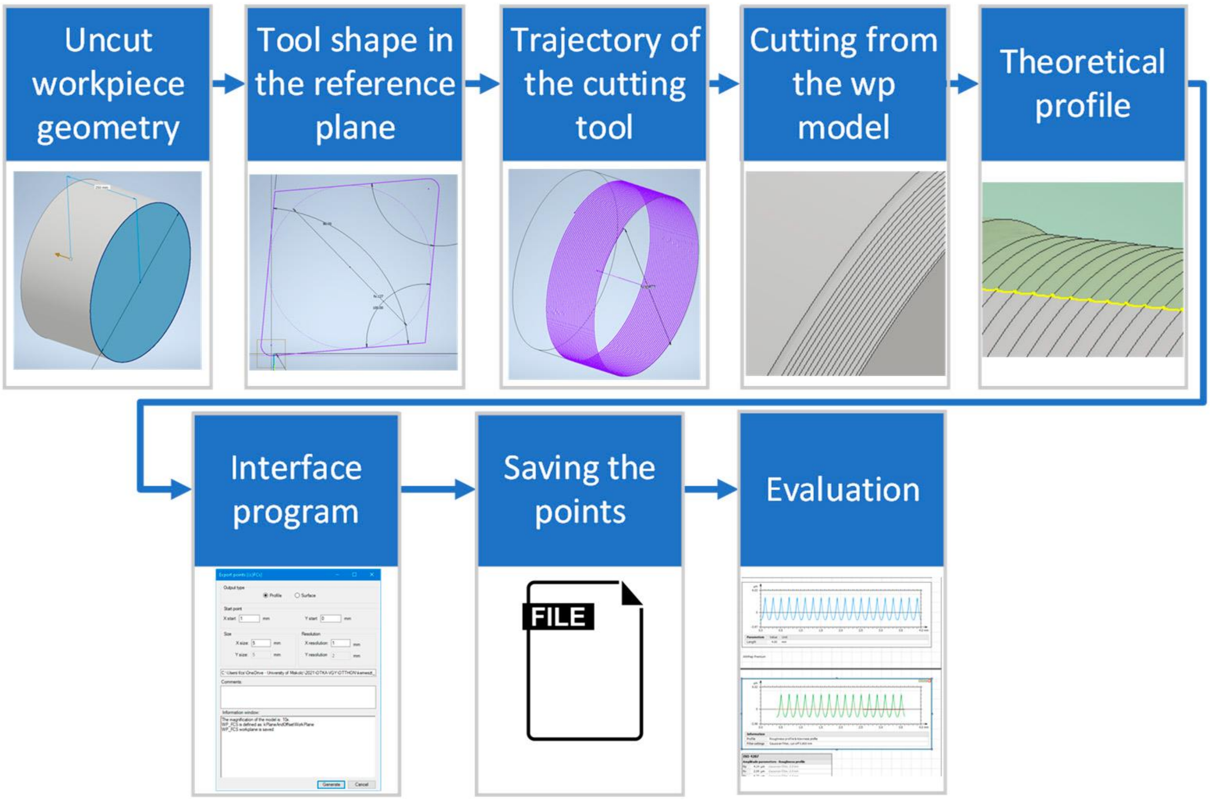

Figure 2. Overview of the applied surface roughness modelling method.

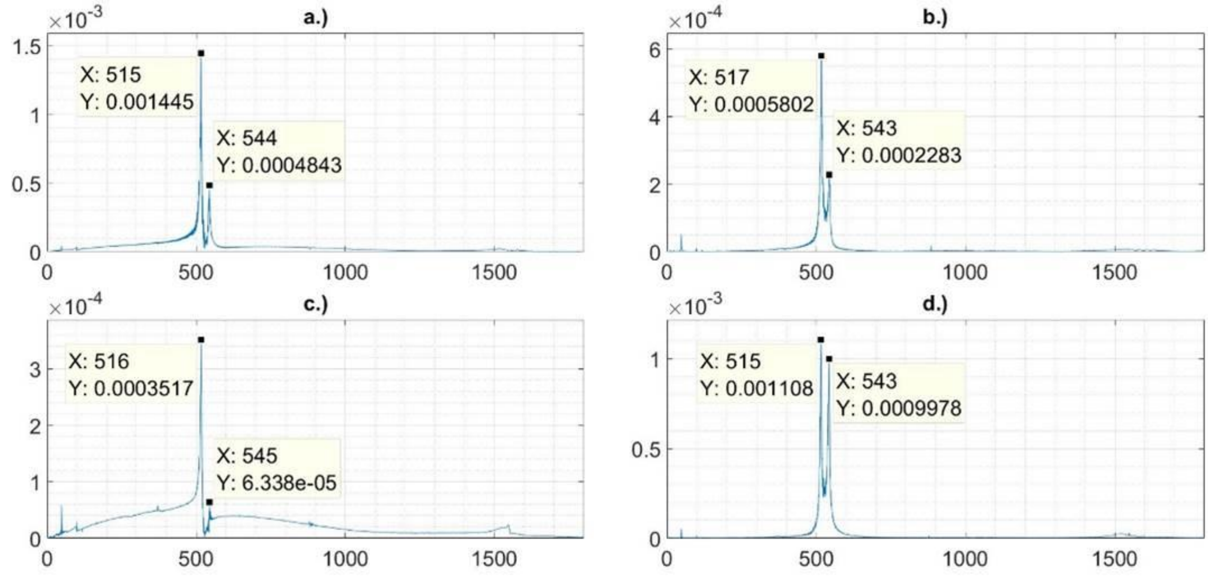

Figure 3. The natural vibration spectrum of a Ø10 mm twist drill clamped in a chuck measured with LDV in the case of a force shock in the direction of the laser beam (figures a and c) and a force shock in the direction perpendicular to the laser beam (figures b and d)

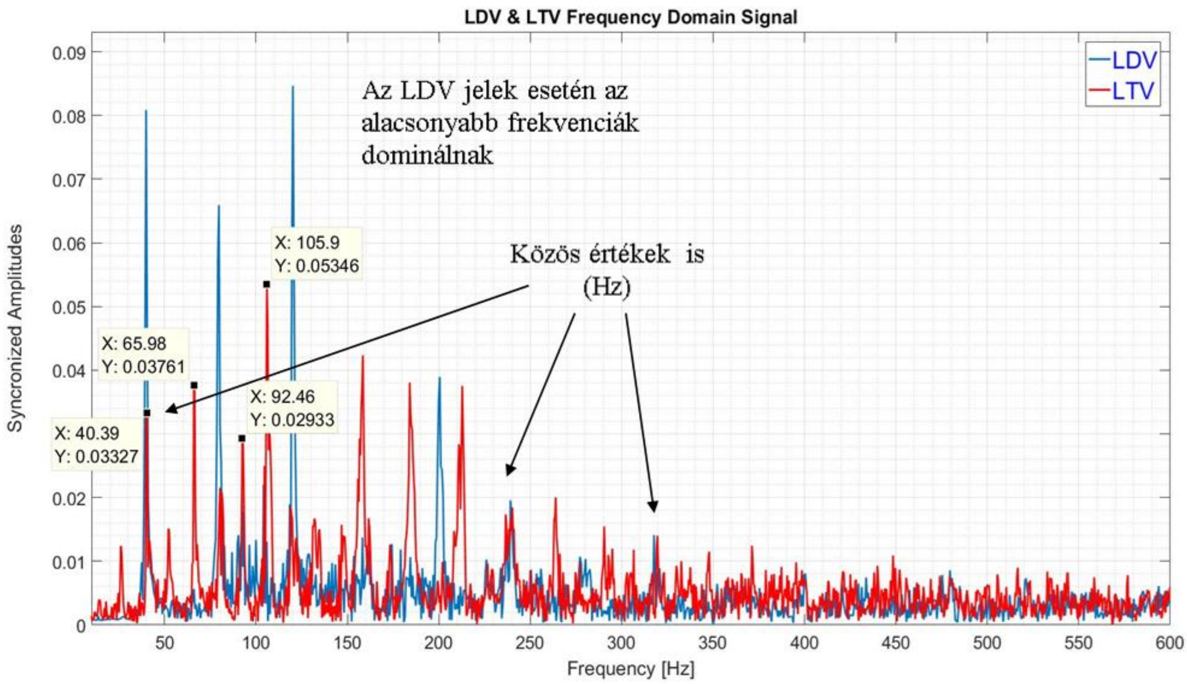

Figure 4, Vibration spectrum of twist drill during cutting: comparison of frequencies of LDV and LTV data