Professional final report

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

"Theoretical and experimental investigation of high-feed face milling carried out by a special tool"

1. Background and preliminary experiments

1.1. Literature survey (previous research)

The processing of literature in the field of development of face milling was focused on the exploration of the results of recent years. The literature sources in the following areas of theories and practices of face milling were targeted: tool wear and tool-life, thermal conditions, cutting forces, vibration occurring during the milling process, detrimental effect of the milling burr, monitoring of the milling process, investigation of noise generation during face milling, conditions of the application of coolants and lubricants, surface integrity of machined workpiece, and investigation of the topography matching for the working (and tribological) requirements.

In addition to the main research targets and applied procedures, the literature survey showed that the effect of the cutting parameters are widely studied, but neglecting or only partly looking at the effect of the chip ratio (ap/fz) alteration, especially in high feed milling. Therefore it was necessary to study the main influencing factors of the material removal process and the quality of the machined surface.

1.2 Comparison of the mechanism of chip removal

We have conducted face milling experiments with the traditional ap/fz>1 undeformed chip ratio as well as with the so-called "inverse" cutting characterised by ap/fz<1 chip ratio. The experiments were first performed with constant feed and changing depth of cut, and after that with constant depth of cut and changing feed, and finally with the removal of a constant chip cross section with changing ap/fz ratio values. In this final case, the ap/fz ratio was varied between values of 8-0.5. We measured the cutting forces as well as the 2D and 3D roughness characteristics of machined surfaces. The investigations were conducted by a milling head with either one cutting insert or with five cutting inserts, and we analysed the effect of the setting error of the insert on the cutting process.

1.3. Material forming characteristics

The material forming conditions were analysed and furthermore examined by measuring the cutting forces which are specific to different ap/fz ratios. It could be stated that the effect of the ap and fz differs strongly at different ap/fz ratios with constant cross-sectional area: the removed layer thickness typically varies in traditional milling, while in our case this thickness is essentially constant with a high ap/fz chip ratio. This difference has an enormous effect on the material shaping and thermal processes.

2. Study of the chip removal process in high feed face milling, results

2.1. Analysis of the thermal processes

2.1.1. Characterization of discontinuous chip removal

Special attention was paid to the thermal phenomenon of the chip removal during the first phase of our study. We focused on two subfields. Firstly, a specific physical environment is established by the transient, cyclical repeating thermal changes specific to this procedure, and this affects the degradation of the tool in a particular way.

Secondly, we assumed that the thermal and mechanical processes are accompanied by an electrical phenomena (the Seebeck effect) during chip removal.

2.1.2. Thermal processes in the surroundings of the tool and the workpiece

The surroundings of the tool-workpiece contact zone were analysed in a new approach in the first phase of our research by considering the electric Seebeck effect in the thermal processes. The mathematical model was solved by a numerical method, where the inverse of the differential equation of wear was used. The wear curves determined by calculation fitted well with the measurement results.

Based on the model, anomalies might occur in some cases in the thermoelectric system. Further research is necessary to decide if this is only a special characteristic of the model or the model is accurately interpreting the actual processes.

The calculations and the measurements made to validate the calculations have shown that the ap/fz chip ratio significantly influences these physical processes of the chip removal due to the resistance of the contacting surfaces.

2.1.3 Mathematic model for discontinuous cutting

The thermal processes of the milling and the discontinuous chip removal in general were analysed in our study. This led to the development of a mathematical model which realistically describes the complex thermo-dynamical process in milling with a phenomenological method. The validation was carried out by results published in the literature and our experimental results.

The model and the measurements show that the cyclic alteration of the cutting temperature tends to increase in the start; however, a more stable process sets in very rapidly. This model enables the analysis of different technological variants according to the ap/fz chip ratio. The chip ratio not only determinates the thickness of the removed layer, but also defines its change over time, if the cross-sectional area of the chip is fixed to constant.

This phenomenon depends on the specifics of the technology which is detected by Salomon where the maximal temperature only increases to a limit in discontinuous chip removal with the increase in cutting speed and after that it decreases. However, the fluctuation extent of the temperature increases only to a limit with the increase in cutting speed, and after that it decreases. This is also true for the maximum temperature as a function of the cutting speed in high cooling.

2.2 Mechanical, thermal and dynamical conditions of chip removal

2.2.1. The distributed mechanical load of the cutting edge

In the kinematic condition system of milling we have examined the distributed mechanical stress of the tool edge plane as a function of time, which is the determinant of tool wear and system stability. On the basis of our previous research we have used the inverse of the tool wear differential equation for the theoretical description of the tool degradation, taking into account the effect of the rapidly changing thermal load on the tool in time as well as the impact of the Seebeck effect. It has been found that the geometric shape of the cross-section of the currently removed material strongly influences the time-varying mechanical and thermal stress conditions when applying different ap/fz ratios. Depending on the ap/fz chip ratio, the spatially distributed edge load changes rapidly at different angles of rotation ϕ of the milling body, and the mathematical model which was developed for these criteria was validated in these conditions by force measurements.

Investigations were performed to verify the reliability of the force measurements and the signalling properties of the measuring system. There is a complex electronical and mechanical chain between the cutting force sensing sensor and the displaying of the measurement result. Due to the high speeds of the processes, the measuring system only provides information with phase delay and with modification. Thus, there is a difference both in time flow and value between the actual and the registered cutting forces. This difference can be described by the transfer function which is known in process control.

The intermittent nature of chip removal has the consequence that the increasing cutting speed increases the thermal and mechanical loading of the chip root due to the transient processes just to a limit. Based on our previous theoretical work and experiments we have verified the assumption that in case of increasing cutting speed there is a real decrease in the measured thermal and mechanical properties. It has been shown before that the cutting temperature decreases with increasing cutting speed, and this is now established for the cutting forces as well. This also proves the transient nature of the initial force process. Further publications of relevant results will be submitted.

2.2.2. Effect of up and down milling

The dynamic processes of the material removal depend partly on the changing speed of the operation intensity, but the starting conditions are also of decisive importance according to our force measurements in milling, which is cutting with time-varying chip cross-section. We found that the removed cross-section grows very rapidly and with a high extent at the start in down milling. After reaching its maximum value it gradually decreases, which means that the negative change defines the thermal and mechanical processes. In contrast, in up milling this happens in reverse. However, symmetrical face milling is not the sum of these two, though it should be the combination of the increasing and decreasing processes. It was found that the second phase in symmetrical face milling, where the removed cross-section decreases, differs greatly from down milling.

We found a specific characteristic of the process during the analysis of the different milling situations (up milling, down milling, symmetrical milling): the cutting force can be different in the same ϕ angle position of the milling tool depending on how we approach it. The transient mechanical model of the milling was worked out by us in this context; using this, it can be detected that the cutting force is always different at any point of the cutting edge path as a function of the starting point of the cutting. The same can be stated for the cutting temperature.

This is one confirmation for our working hypothesis, that the cutting force depends on the time as well as the technological parameters like ap/fz ratio.

2.2.3. Effect of the cutting edge position

The 3D mechanical stress relations of the milling tool were analysed by cutting force measurement. We concluded that the line of action of the resultant force and the mill axis of rotation can be interpreted as a skew line pair. The position of the skew is determined by two angles: tilt angle (ψ) related to the mill axis and deflection angle (χ). The latter can be interpreted in the reference plane of the tool and it means the angle between the projection of the resultant force and the line from the chosen point of the cutting edge to the intersection point of the mill axis. We have shown that this skewness fluctuates cyclically. Because of this the resultant force oscillates based on the ap/fz chip ratio, determining the direction of the cut chip. This knowledge is valuable information for technology safety and the preservation of the machined surface.

2.2.4. Effect of the cutting data

The theory of cutting treats the deformational and stress relations of material removal as a 2D problem, which determines the load of the cutting forces on the machining system and the energy need. The 3D analysis of steels considered as homogeneous and isotropic led to the assumption that the removal of the same volumetric material needs more mechanical energy due to the inner interactions of the spatial stress distributions, as the process varies further from the 2D description. Cutting experiments and FEM simulations with ThirdWave AdvantEdge were carried out to verify this assumption over a wide technological range of parameters.

As a consistent result of these experiments, we concluded that the least favourable case from the point of view of process energetics is the typical case of 3D constrained cutting, where the chip ratio of the cutting depth (ap) and feed (fz), determining the chip shape, approaches value 1. The farther the ap/fz chip ratio is from value 1, the more favourable is the energy consumption.

Our measurements and FEM calculations in altering cross-sectional discontinuous chip removal (milling) showed that the ap/fz<1 chip ratio is more advantageous than ap/fz>1 from the aspect of energetic demands. This result can be utilized directly in the technology used in practice.

2.2.5. Study of the chip ratio alteration

In examining the ap/fz ratio, the applicability of the ThirdWave AdvantEdge FEM program was validated for wide-scale milling with special tests carried out in Magdeburg. A good match between measurements and calculations proved that the program is suitable for studying the rapidly changing thermomechanical processes of milling. It was found that the ap/fz chip ratio provides good characterization of the effect of shape of the material cross-sectional area removed by milling and thus also the specific characteristics of the technology. When applying the chip ratio ap/fz<1 or ap/fz>1, the role of the main and the side cutting edge is changed and this significantly affects the mechanical load of the machining system.

We have shown that the Kienzle type empirical power function, which is commonly used to calculate the cutting force in practical calculations, cannot be used for milling. We have determined that from the energetic point of view, it is advisable to avoid the ap/fz=1 chip ratio with the applied technology. It is preferable to set its value as far from 1 as possible, preferably by applying ap/fz<1.

In the case of intermittent chip removal, the initial, transient characteristics of the material removal process prevail. Starting from the fact that material structure accumulation, characterizing the deformation, is time-consuming, we assumed that this transient phase is characterized by rapidly changing thermodynamic processes. That is why our initial hypothesis was that the cutting force reaches the stationary state in a finite time. A phenomenological method was used to describe the transient initial phase. It was assumed that the transient growth of the cutting force can be described in a manner where the Kienzle empirical force formula is supplemented by an exponential function. Validation of this force model was performed by force measurement during machining of normalized C45 steel. The measurements demonstrated the usability of the model (correlation Pearson index R2 > 0.9). From the new model it can be deduced that the change in the thickness of the removed layer and its direction (sign) have a significant effect on energy consumption and this is the consequence of the supposed, then proven, transient process.

2.2.6. Analysis of the transient processes

The energetic (dislocation theoretical) study of the structural changes during the deformation of metals led to the assumption that the thermal and mechanical processes change in a transient manner at the start of the deformation of metals. In discontinuously altering cross-sectional material removal (milling), this transient character determines the whole process. We worked out a new mathematical model to theoretically describe the transient thermal and mechanical process, which was verified consistently by our measurements in milling experiments and by the experimental results found in the literature. The models of the two transient processes were combined into a thermo-dynamical model, which is an autonomous differential equation with time offset. This is capable of detecting the micro-vibrations formed during alteration of the thickness of the layer removed in milling.

3. Topographic analysis using a CAD-based model developed for rotating tools

3.1. CAD-based investigations of surface roughness at rotating tools

An algorithm for the CAD-based investigation of surface roughness at rotating tools was developed in the project. At the first stage of the modelling, we prepared a three-dimensional model of the workpiece, which is a prismatic part, for the investigated face milling process. After that, the two-dimensional projection of the cutting part of the tool was drawn in the axial section of the milling tool (which is the tool reference plane Pr). Next, we formed the description of the trajectory of the cutting insert, which is a curtate cycloid curve. This curve was fed in parametric form into the CAD system. The two-dimensional cutting insert shape was guided along this trajectory, thus resulting in the volume which was scrubbed by the tool, and its intersection with the solid model of the workpiece gives the cut chip volume. In the case of multi-point tools, this procedure should be repeated for each insert. There is also a possibility to take into account the radial and axial differences between inserts (tool setting errors) by defining the shift values in the respective directions. A model of the machined workpiece can be obtained by subtracting the resulting chip volumes from the workpiece model.

In the next stepwe dealt with elaboration of an interface programwhich is able to communicate with the CAD system and is also capable of saving the points in a convenient file format. A measurement plane was defined in the model, the intersection of which, with the machined surface of the workpiece, creates the curves which are the theoretical profile curves. Points of these curves were queried with x and y steps, which can be set on the user interface of the developed program, and then the points were stored in a file with SURF file-format. This file can be directly imported into the AltiMap professional surface topography evaluator program, where the evaluation can be conducted according to standard roughness parameters. A great advantage of the worked-out method is that the theoretical and real roughness data can be evaluated on the same basis, thus they can be more easily compared.

Overall, we have developed a CAD model and interface program that can determine the theoretical roughness in the application of machining by rotary tools.

3.2 Creating a 3D model simulating high-feed face milling

For the 3D model simulating the face milling process, a calculation method was elaborated on the basis of the algorithm which was developed in the previous phase of the research. This method is based on the CAD modelling of the machined surface. It can be used to determine the theoretical roughness characteristics of surfaces machined by face milling. This method was further developed and adopted to the high feed face milling processes. Within this framework, we have developed a new three-dimensional model, which:

- defines all geometrical and kinematical variables as user parameters;

- is suitable for examining all tool geometries and kinematics to be investigated within the framework of the project;
- is able to specify the axial and radial alignment errors for individual inserts.

We have refined the interface program that realizes the transfer between the CAD system and the surface roughness evaluation system. For this, we introduced a so-called magnification factor, which allows the model to be scalable, so that the accuracy of the calculation can be increased. With additional software refinements, the generating time of the theoretical surfaces was also reduced to about half the time compared to the previous version.

To investigate the applicability of the developed method, machining experiments were performed, theoretical surfaces were generated and the roughness characteristics were determined for the following cases:
- changing of the feed per tooth;
- investigations of surfaces generated by different tool edge geometries;
- removing of a constant chip cross section by different ap/fz values;
- examining the effects of axial and radial run-outs of individual inserts on machined surfaces.

As a result of this work, the CAD modelling method has been further developed for high-feed face milling with a special tool where the radial and axial setting errors of the individual inserts can be taken into account.

3.3 Further development of the analytical model of theoretical roughness determination for rotary tools and high feeds

For the linear feeding motion machining with a single point tool (e.g. turning) a method was developed to determine the theoretical roughness, which is based on analytical calculations. We have further developed this method for machining with rotary tools. This helps to verify the accuracy of both the CAD modelling and the theoretical roughness characteristics it determines. As the calculation of the surface topography curves generated by the rotating tool is difficult using purely analytical methods, we have primarily used numerical methods.

The refinement of the model – to make it easier to manage – has been carried out and several experiments have been done to validate it. For example, we have investigated the effect of the modified chip ratio (ap/fz ratio) on the roughness of the machined surface in the case of a constant chip cross-section at the depth of cut a_p = 0.2–0.8 mm and feed per tooth f_z = 0.1–0.4 mm domain, which correspond to ap/fz ratios of 8 to -0.5. During the research, we also investigated the extent to which the accuracy of the individual inserts (axial and radial alignment errors of the edges) affects the theoretical and real 2D and 3D roughness of the machined surfaces when using five rectangular inserts (κr = 45°). As a result of this work, we have developed a new analytical model based on numerical methods adapted to the CAD system which can be used to check the accuracy of the theoretical roughness characteristics determined by CAD modelling.

3.4 Evaluating and using the developed model to predict the expected roughness

We have investigated different combinations to find which cutting tool with the same technological parameters but different edge geometry provides a cut surface with the most favourable roughness values, and in which case the CAD-based modelling of the machined surface gives the best approximation to the real surface roughness. Three different insert geometries were examined: a diamond insert with a 90° major cutting edge angle, a circular insert, and a rectangular insert with a 45° major cutting edge angle. The technological parameters kept constant were the following: ap =

0.8 mm, fz = 0.4 mm, vc = 200 m/min. The roughness parameters examined are Ra, Rz, Rq, Sa, Sz, Sq. Using the previously developed CAD model of the machined surface, we determined the theoretical roughness values and measured the real roughness characteristics obtained during the machining experiments using the Altisurf 520 surface roughness measuring device. The Altimap software was used to evaluate the results for both real and theoretical values. From the results statistics were made and correlations between theoretical and real roughness data were determined by regression analysis. We found that the surface with the best roughness values was provided by the application of a circular insert. Furthermore, we found that it is not advisable to use the model developed for the calculation of theoretical roughness values in the case of a cutting insert having an edge section parallel to the machined surface, unless the value of the angular error (alignment error) of the parallel edge section to the machined surface is known. Result: We have provided relationships suitable for determining the expected roughness of face milled surfaces under given cutting conditions based on theoretical roughness.

4. Cutting tool for high feed milling

4.1. Assignment of load value ranges for tool design

The finite element simulations were carried out with the 3D version of the ThirdWave AdvantEdge software. We ran simulations on Al380 aluminium material (vc = 2473 m/min) in 0.06–3.0 mm/edge feed rate range with changing depth of cuts (0.5–1.5). We analysed the alteration of the temperature and the cutting force on the workpiece, tool and the combination of both with constant and varied chip cross-section. The experiments were carried out on C45 grade steel in varied cross-sections as well. The experiments were carried out with these process parameters: 45° and 90° major cutting edge angle, 0.3 and 3.0 mm depth of cut, 3.0 mm and 0.3 mm feed rate per edge, 0° and 12° axial rake angle, 0° and -40° radial rake angle. We carried out cutting experiments to validate the simulation results.

4.2. Baseline data determination for the design of a special tool

Numerous experiments were carried out for the determination of the possible position and placement of the cutting inserts and the optimal cutting edge geometry.

We analysed the alteration effect of the chip ratio and the technological parameters on the stresses, the plastic strain and the temperature by the ThirdWave AdvantEdge FEM program on C45 steel with 150 and 200 m/min cutting speeds and 4–0.25 ap/fz ratios in constant cross-sectional chip. Furthermore we analysed the effect of the cutting edge geometry on the insert-workpiece contact on C45 steel with 0°–12°axial rake angle and -40°–+10° radial rake angle to optimize the position, the placement and the geometry of the cutting edge. Cutting experiments were carried out to validate these results.

For the verification of the milling tool physical load, we analysed the effect of the ap/fz rate on the stresses, plastic strain and temperature in milling operations with high feeds and divided depth of cuts to determine the alteration effect of the chip ratio and the technological parameters. We studied the load of the cutting edges as a function of the ap/fz ratio.

We determined that the chip removal was done on the side edge at ap/fz > 1 ratio, near the nose in ap=fz and on the front edge in ap/fz>1. The power consumption decreases and the chip height also favorably changes with the decrease of the ap/fz ratio. This favourable change can be seen in the values and distribution of the chip removal characteristic temperature. The temperature will be higher and loads mostly the side edge in high ap/fz ratio, while in lower ap/fz ratios the cutting temperature will be lower and the load is mostly on the face edge.

4.3. Analysis of the edge geometry and insert arrangement

The analysis of the edge geometry and the insert layout was carried out for the advantageous placement of the cutting edges. We studied the effect of the cutting edge geometry on the insert-workpiece contact to optimize the placement of the cutting inserts and the geometry of the edge. We performed simulations with the ThirdWave AdvantEdge FEM program on C45 steel with 0°-12° axial rake angle and -50°-10° radial rake angle. The results were validated with cutting experiments, which proved the gathered data.

In the second set of experiments the axial rake angle was adjusted to -12°, 0° or 12° and the radial rake angle was adjusted to 30°, 35°or 40°. We analysed the changes in the heat processes, the stress relations, the occurring cutting force and its components during cutting over time for each setup.

4.4. Experiments with the new tool

4.4.1. Analysis of the edge geometry change

We determined the character of the insert-workpiece contact as a function of the rake angle and the inclination angle. We analysed nine case, from which 4 show point-like load, 4 linear load and 1 areal load on the insert in the impact to the workpiece. The cutter diameter was 120 mm, the width of the C45 steel workpiece was 60 mm. The cutting speed was 200 m/min, ap/fz ratio was 10 or 0.1, the depth of cut and feed were 0.15 and 1.5. We carried out computer simulations (ThirdWave AdvantEdge) for each case with -20°, 0° or 10° radial rake angle and with -12°, 0° or 12° axial rake angle. Cutting experiments were also carried out for the validation of the results. We compared the calculated results and the experimental results based on the change of the cutting force and its components, the temperature and the stress relation in time.

Finite Element analyses were also made to determine the minimal removable chip height. The force, torque, stress and temperature results were analysed for various cutting data and edge radiuses (rβ). Based on this we determined the values of the chip deformation coefficient (ξh) and the main deformation coefficient (εϕ) for different cutting edge radiuses, rake angles and flank angles. From these the theoretical values of the minimal chip thickness (hmin) could be calculated.

4.4.2. Cutting experiments with the tool machined by the German partner in Magdeburg

We investigated the effects of the individual tool geometry parameters, such as the main cutting edge angle κr, γp axial rake angle and the ap/fz chip ratio on surface roughness. The parameter values to be studied in the research were determined by a full factorial experimental design method, and the response function was approximated by a three-parameter first-degree linear polynomial. It was found that the most favourable roughness can be achieved by using the tool with a main cutting edge angle of κr = 90° and by using a high ap/fz ratio and γp = 0° rake angle. We also investigated how the roughness of the generated theoretical surfaces and the actual roughness vary in the rotational axis of the tool as well as in parallel planes at the entry and exit sides of the tool at different feed rates. Both theoretical and real roughness values decrease as we move away from the rotational axis of the tool. While the theoretical roughness is the same on the entry and exit sides, the actual roughness on the exit side is always higher, which is justified by the magnitude of the force components changing along the curtate cycloid track and with different chip deformation. We determined that the elaborated modelling procedure is suitable for estimating roughness values on real surfaces.

Experiments were carried out to assess the effect of the feed per tooth (fz = 0.5, 0.7, 0.9, 1.1, 1.3, 1.5) at a constant depth of cut. We investigated the changes in roughness characteristics, and we modelled the theoretical roughness of the surface as well. We determined the correlations between measured data and modelled values using regression analysis. We found that with a CAD model that takes into account tool set-up errors, it is possible to generate profiles and surfaces that show good correlation with the real roughness.

4.4.3. Effect of the cross sectional area of the chip – optimal cutting parameters

Complex analyses were carried out to study the chip ratio to be applied in high feed milling. We chose the insert geometry so that the three cases of the impact with the workpiece (point-like, linear-, surface-like contact) could be analysed in addition to the in-cut movement of the tool. The relative position of the workpiece and the tool was adjusted so that the insert, rotating on a 60 mm radius path, comes into contact in the symmetry plane of the tool with the workpiece layer to be removed. The axial rake angle was adjusted between -12° and +12°, while the range of the radial rake angle was between -20° and 10°. The depth of cut and the feed were analysed in 0.15 mm and 1.5 mm values; the chip ratio was 0.1 in high feed (inverse) milling and 10 in traditional milling. The setups were studied with simulation by the ThirdWave AdvantEdge FEM program and with cutting experiments as well. The optimal cutting parameters were determined by the cutting force components defined in the coordinate systems of the tool and the workpiece, by the temperature and by the stress conditions in the workpiece and the tool.

4.5. Topography analysis of the machined surface by the new tool

Based on our previous investigations, it has been found that the roughness of the machined surface is greatly influenced by the actual positioning angle of the edge section parallel to the machined surface relative to the surface. Using the CAD-based theoretical roughness calculation method that we developed, we have shown that even a 1° deviation when applying $f_z = 0.3$ mm feed per tooth generates theoretical roughness peaks of approximately 4 µm. The investigations were performed in the range of -5° to 5° minor cutting edge angle values using a wiper insert with a 90° major cutting edge, using the following feed per tooth values: $f_z = 0.3, 1.64, 2.98, 4.32, 5.66, 7$ mm. Other simulation parameters: $r_\varepsilon = 0.8$ mm; $D_s = 100$ mm; $a_p = 0.1$ mm; $a_e = 70$ mm. In the next step, we examined whether changing the major cutting edge angle to 45° has any effect on theoretical roughness values. Here, we were able to determine that the major cutting edge angle does not affect the roughness values. In the third investigation phase, we simulated a cutting insert with an extremely large nose radius of $r_\varepsilon = 2250$ mm. In fact, this can be considered almost as a parallel edge section, but the great advantage is that since it is a circular arc, it can compensate for the misalignment of the minor cutting edge. Here, the surface roughness values were examined with increments of 1 mm in the feed per tooth values of 1–8 mm range. The roughness parameters examined were Ra, Rz, Rq, Sa, Sz, Sq. We found that the use of this insert gives very favourable roughness values, with Ra = 0.0171 µm at $f_z = 1$ mm and Ra = 1.04 µm at $f_z = 8$ mm.

In addition to the above, to estimate the roughness of the machined surface and to support the theoretical studies, cutting experiments were carried out both with the cutting tools made by the German partner and with commercially available tools. The cutting experiments were carried out in the workshop of our partner university in Magdeburg. We then measured the surface roughness characteristics of the machined surfaces using the Altisurf 520 three-dimensional surface roughness measuring instrument at the University of Miskolc. During the tests it was proved that the determined method can qualify the machined surfaces by the new, special tool.

Remarks:

The progress of the research was presented (summarized) in the annual reports according to the points of the work plan, while in the final report the research work and its results were presented for each of the main objectives.

Two students (one in Miskolc and the other in Magdeburg) are preparing their PhD dissertations on this topic.

The results of the research work have been continuously presented in conferences and journals. So far there have been 143 independent citations of the publications uploaded to this report.

The tool that was designed based on theoretical and experimental results was manufactured and its laboratory testing was performed.