A computer supported simulation of multiaxis milling to determine optimum cutting kinematics concerning the occurring surface roughness

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ABSTRACT

CAD/CAM systems offer various possibilities for milling of free form surfaces, but most of them do not take into account the expected surface topomorphy. The surface topomorphy depends on the milling strategy (up-, down-, pull up-milling etc.) and on the cutting conditions (cutting speed, feedrate, cutting depth etc.). In the present paper, a computer supported procedure is introduced, which among others enables the calculation of the surface topomorphy and roughness in multiaxis milling with ball end tools. With the aid of a further developed interactive method, optimum cutting parameters can be suggested, in order to achieve low roughness values.

INTRODUCTION

in order to determine the expected roughness and surface topomorphy considering the cutting kinematics, the computer program "BALMIL" developed, based on a multi-axis milling process description and on the determination of the tool penetration into the workpiece. In this simulation the initial part geometry, the NC code and the tool geometry are taken into account.

Figure 1. Potential kinematics in milling with ball end tools.
he initial part geometry (i.e. before end milling) is stored in neutral files as for example IGES, created by the used CAD system. The NC code yields from the AM system and among others includes the tool paths. By means of the developed milling simulation, the parameters like the undeformed chip geometry, the cutting force components etc. are also determined [9].

IMULATION OF THE MULTIAXIS MILLING.

Multiaxis milling the chain, tool-workpiece-machine tool, is analysed by means of five individual coordinate systems (see figure 2). The various tool and workpiece motions are described through distinguished displacements or rotations, in the corresponding coordinate systems and these motions are overlaid by means of coordinate transformations.

The kinematic and the geometry of the tool and of the workpiece, are defined in the coordinate system 1, where the calculations of the tool penetration into the workpiece and the topomorphy of the workpiece surface take place.

To describe the cutting tool shape, the cutting edge is considered to be divided into elementary edges. On the other hand the workpiece geometry is calculated in parallel reference section levels (see lower part of figure 2), considering the stored workpiece data into a standard CAD system output file as for example into IGES file.

With the aid of the developed algorithms the resulting surface topomorphy and its roughness values for various cutting kinematics can be calculated. Moreover other parameters, like the undeformed chip geometry, the effective cutting angles and the cutting force components can also be determined [9].

ANALYTICAL RESULTS OF WORKPIECE SURFACE TOPOMORPHY AND ROUGHNESS.

Based on the developed computer supported simulation of the milling process, the penetration of the cutting tool edge into the workpiece can be determined (see figure 3). Every elementary cutting edge follows a three dimensional path according to the process kinematics, included in the relevant NC-code.

Each elementary cutting edge path intersects the workpiece reference levels L. From the trace of the cutting edge path on these reference planes, in relation to the instantaneous workpiece shape, the tool penetrations into the workpiece, the instantaneous workpiece geometry and the resulting surface topomorphy and roughness occur.

The influence of some manufacturing parameter as for example of the feed rate, of the radial cutting depth and of the tool axis inclination angle on the surface topomorphy is investigated by means of the developed mathematical procedure. In figure 4 for the case of down milling (tool axis perpendicular to the end workpiece surface), the relation between the feedrate and the calculated surface roughness as well as the occurring topomorphy are shown.

An increase of the feedrate results in a not constant progressive magnification of the roughness, according to the occurring surface topomorphies, illustrated in the figure.

Similar dependencies are also found out through the increasing of the radial cutting depth (see figure 5).
The inclination angle of the tool axis relative to the final workpiece surface significantly influences the occurring surface roughness [5, 6, 8, 9]. This effect is shown in figure 6, in the case of pull down milling. Increasing this angle from 0 up to 5°, the roughness values initially sinks. Subsequently the roughness increases progressively with the tool angle. These trends are occurring from the corresponding calculated surface topomorphies, inserted in the lower part of the figure.

To check the validity of the previous introduced computational results, appropriate investigations were carried out.

In figure 7 the influence of the tool axis inclination on the surface roughness for the milling cases, push up, pull down, oblique plunge up and oblique reverse down milling is shown. The calculated and the measured values indicate the same behavior, although a deviation of the experimental results from the corresponding calculated ones, depending on the material properties and on other parameters like the chip formation and the chip flow exists. Especially the chip formation and the chip flow differ in each of the investigated milling cases.

According to the obtained milling results with further workpiece materials, the measured roughness mean values lie higher, at a distance of dm concerning the corresponding computed values and within a scatter region of a width d (see figure 8). The parameters dm and d vary, depending on the workpiece material and on the cutting kinematics as it can be seen in the
lated diagrams for some materials in this figure. The estimation of the expected roughness, presented in the following paragraph of this paper, is based on these analytically-experimentally determined parameters.

II investigations were conducted in one way milling processes. Reciprocating milling kinematics, leading to shorter machining times, were not included in the described investigations in the present paper, due to the fact that the resulting surface roughness is generally higher than the occurring one in one way milling kinematics [1,11].

![Graph showing calculated and measured roughness in milling with various kinematics](image)

**OPTIMISATION OF THE MULTIAXIS MILLING KINEMATICS CONSIDERING THE SURFACE ROUGHNESS**

Based on the above mentioned analytical experimental results, a computer supported algorithm is developed. Hereby, by means of an interactive procedure for various machining parameters, the expected roughness values are predicted.

Considering as optimisation criteria the achievement of the following targets:

- the resulting surface roughness must be less than the prescribed one,
- the machining time have to be kept as low as possible,

the optimum cutting conditions, to obtain the prescribed roughness at the lowest milling time can be determined.

The investigated materials are widely used by the Greek company "Metallic Constructions" (METKA S.A). This company manufactures among others, hydrodynamic machine blades by means of CNC milling machine tools. Since in these investigations HSS ball end tools were used, the cutting speeds vary between 50-100 m/min. Within these limits it was found out that the cutting speed has a slight influence on the surface roughness.

![Diagram showing tool contact angle](image)

Furthermore the cutting tool is selected. According to the tool and the workpiece material the cutting speed is chosen, as well as the axial cutting depth. Since this programme concerns profile milling, the axial cutting depth is the profile stock allow.

To apply an optimum milling kinematic, the capabilities of the NC machine tool are considered. If a 3-axis milling machine is used, the possible cutting kinematics are up and down milling. In this case it is...
suggested up milling as default, due to the resulting better surface roughness. If a 4-axis milling machine is available, the user must choose with the aid of displayed illustrations, the possible cutting kinematics, taking into account the workpiece set-up, with respect to the milling machine's 4th axis (A, B or C), and to the capabilities of the CAD-CAM system.

For example, in case that a workpiece surface as shown in figure 9 is to be machined using a 4-axis milling machine, such as that one, demonstrated in figure 2, all the cutting kinematics described in figure 1 are possible, and the only limitation can occur due to CAD-CAM system's capabilities. Once the possible cutting kinematics are selected, the programme lists them in descending order with respect to the estimated roughness, so that the user can choose the most appropriate one. In order to complete the selection of the cutting kinematic, the tool inclination angle regarding the final workpiece surface must be chosen.

This angle is interactively selected with the aid of the corresponding analytical-experimental result referring to the selected kinematic and workpiece material.

To complete the determination of the cutting parameters, the feedrate and the radial cutting depth must be calculated, so that the resulting machining time is minimised.

In order to speed up the calculations, the machining time is determined using a "model surface". As "model surface" is defined a rectangular with dimensions approximating the real workpiece surface dimension. This rectangular can be for example a mean plane through the free form surface (see figure 9). The calculated machining time is expressed in normalised form dividing by the shortest time, due to the fact that a "model surface" is used instead of the real one.

Using values between a minimum and a maximum one for the feedrate and for the radial cutting depth (f_{min}, f_{max}, a_{min}, a_{max}), automatically pairs of feedrate and radial cutting depth values are created, using certain increment (Inc), as shown in figure 9. The feedrate - radial cutting depth pairs are numbered as matrix elements. For each pair the expected roughness is calculated and the combinations leading to a roughness smaller than a prescribed one are selected. For these combinations the cutting times are calculated, and then normalised by dividing them by the shortest one. The selected combinations are the listed with respect to cutting time in ascending order and a graph of roughness versus cutting time is created (see figure 10). With the aid of this information, the user can choose the appropriate combination of feedrate and radial cutting depth, considering the prescribed roughness.

**Figure 9. Model surface and combinations of feedrate and radial cutting depth.**

**Figure 10. Graph of combinations of feedrate and radial cutting depth with respect to cutting time and roughness.**

**APPLICATION EXAMPLE OF THE DEVELOPED PROCEDURE.**

In the following an application paradigm explaining the most essential steps of the developed computational procedure is presented.
In the first step, with the aid of the menu "Effect", the user has the possibility to see the influence of various cutting parameters (cutting depth, feedrate, tool inclination angle etc.) on the surface roughness, as for example the effect of the cutting kinematics in milling of various workpiece materials, shown in figure 11.

In a further step the tool is defined and its geometry as well as the workpiece material are described using the menu "Cutting tool" (see figure 12).

The machine tool motion facilities (3-axis or multiaxis) and the cutting kinematic are inserted with the aid of menu "Cutting kinematics" (figure 13). In the same display the prescribed roughness value is also inserted. The prescribed roughness is the maximum permitted workpiece surface roughness. For the selection of the appropriate cutting kinematic, with respect to its influence on the surface roughness, the user can use the menu "Effect" for help, as illustrated in figure 11.

Moreover, considering the tool and the workpiece material, the cutting speed and the axial cutting depth are selected with the help of the menu "Cutting conditions", as indicated in figure 14.

If a multiaxis milling machine is used, the tool inclination angle relative to the workpiece and the surface must be also selected in this step, using for help the menu "Effect".

In order to calculate combinations of radial cutting depth and feedrate, which satisfy the permitted workpiece surface roughness, the dimensions of the workpiece "model surface" have to be defined, as well as the minimum and the maximum values of the feedrate and radial cutting depth and the corresponding increments (see figure 14).

With the aid of the previous selected and registered parameters, pairs of values for radial cutting depth and feedrate are calculated, as shown in the display "Optimised fz, ax", illustrated in figure 15.

For each combination, the expected roughness value and the normalised cutting time are also calculated and graphically presented.
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