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Cad-based simulation and surface topomorphy prediction in ball-end milling

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***Abstract*—Optimization of ball end milling processes has been an area of great interest, on the grounds that such processes are extensively used for precision and high-efficiency machining of freeform and complex surfaces. The selection of optimal cutting conditions, involved in such processes, can be accomplished by utilizing models that simulate the kinematics of the milling process, therefore allow the analytical prediction of the produced surface topomorphy and quality. The present study introduces a model developed for the simulation of milling processes, integrated in a commercial CAD software. Furthermore, several ball-end milling of Al7075-T6 experiments were carried out under various cutting conditions, so as to verify the completeness and accuracy of the above mentioned model, through the comparison of the predicted and the machined surface. According to the validation outcomes, the developed model demonstrates high computational efficiency.**

***Keywords*—ball-end milling, cad-based simulation, surface topomorphy**

I. Introduction

A. *Previous milling and finishing modeling approaches*

An important issue concerning optimization of all machining processes is the detection of a functional relationship between cutting parameters and the resulted machined surface including several critical technological data.

There have been numerous investigations on the simulation and modeling of milling processes performed by different researchers in order to achieve theoretical or cad-based estimation of not only the machined surface topomorphy, but also of other characteristics.

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Mizugaki et al. [1] presented a theoretical estimation method of machined surface profile and concluded that the boundary form of the machined surface texture changes widely according to the tool direction.

Antoniadis et al. [2], introduced the MSN-Milling Software Needle simulation model, which enables the estimation of the produced surface and the resulted surface roughness, for ball end milling. The model simulates precisely the tool kinematics and considers the effect of the cutting geometry on the surface roughness. What is more, the simulation model was experimentally verified.

In order to predict the workpiece roughness in multi-axis finishing milling with ball end tools, Bouzakis et al. [3] developed and experimentally validated a computer supported milling simulation algorithm which allows the determination of the expected final surface topomorphy along with other characteristics, considering the individual movements of the cutting tool and the workpiece due to milling kinematics.

Liu et al. [4], [5] developed stochastic and deterministic surface generation models of micro end milling. The deterministic model characterizes the three-dimensional surface topomorphy over the entire floor surface. The models simulate micro-machined surfaces under various conditions to gain a deeper understanding of the effects of tool geometry, process conditions, tool tip run-out and process kinematics.

An analytic roughness model, the ridge method, was proposed by Jung et al. [6], [7] for the evaluation of the maximum geometrical roughness and texture of the machined surface in ball-end milling.

Zhang et al. [8] presented a model for the prediction of surface topography in milling operations considering tool wear during the cutting process.

B. *Positive aspects of Cad-Based Simulation*

The increasing demand for precision and high-efficiency machining of products with free-form and complex surfaces, has brought about the need for optimization of ball-end milling processes.

The task of machining optimization can be accomplished through the simulation of the cutting process, resulting in the prediction of several crucial cutting characteristics that can be used as measures of the efficiency of the process, hence the quality and accuracy of the produced part. Topomorphy of the machined surface, especially in finishing processes is of great importance, since it is a key measure of the produced surface quality.

Current state of research and trends in machining simulation indicate that cad-based simulation can be used as an efficient tool so as to estimate and predict surface topomorphy, together with other significant characteristics, in most manufacturing processes. In addition, the extensive use of modern CAD systems provides an excellent platform for the development of such CAD-based tools. One of the most beneficial aspects of this simulation approach is the use of solid modeling, through a sufficient parametric 3D-CAD system, in order to accurately represent both cutting tool and workpiece geometry. Three dimensional solid models are employed to simulate the penetration of the tool inside the workpiece and to produce 3D models of the machined workpiece, consequently the resulted surface topomorphy. What is more, cad-based simulation approaches enable the parametrization of optimization process, thus enhance its efficiency and universality.

Within the context of the present study, a model developed for the simulation of milling processes, embedded in a commercial parametric CAD software, is introduced. Furthermore, several ball-end milling of Al7075-T6 experiments were carried out under various cutting conditions, so as to validate the above mentioned model, through the comparison of calculated and machined surface.

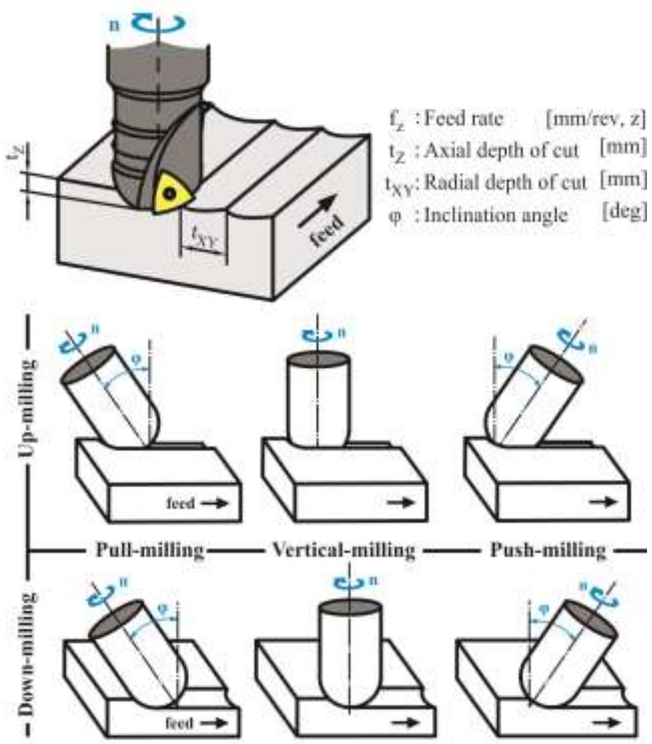

Figure 1. Ball-end milling strategies

II. Cad-Based Milling Simulation Process

The simulation model was developed with the use of Visual Basic for Applications integrated within a commercial parametric 3D CAD system. The use of VBA and Application Programming Interface (API) of the CAD software enables the generation of 3D solid models. The model was structured in such a way that it includes the influence of various cutting parameters and conditions, namely the radial and axial depth of cut, feed rate, cutting speed, and tool inclination angle, on the machined surface topomorphy. Moreover, simulation can be implemented for a wide range of different cutting tools and workpieces.

The model analytically predicts the topomorphy of the surface produced in milling, and in the context of this study it is applied in the case of ball end milling. Specifically, the model considers all four possible combinations of down and up milling at radial depths of cut t_{XY}=0.3mm and t_{XY}=0.6mm, all with the axial depth of cut set to t_Z=0.3mm.

Simulation process is initialized after the input of valid data, i.e. the geometrical features of the cutting tool and the workpiece together with the above mentioned cutting conditions. The use of all these parameters has as a result the extended applicability of the model.

Once all the required input data are defined by the user, milling simulation initiates by implementing the automatic calculation and generation of both workpiece and tool 3D solid geometries, followed by the estimation of the milling process kinematics. The outcome of milling simulation includes the creation of the produced 3D surface topomorphy, allowing the recognition of various patterns formed under the influence of the assigned cutting parameters. The complete flowchart of the milling simulation method is schematically presented in Fig. 2.

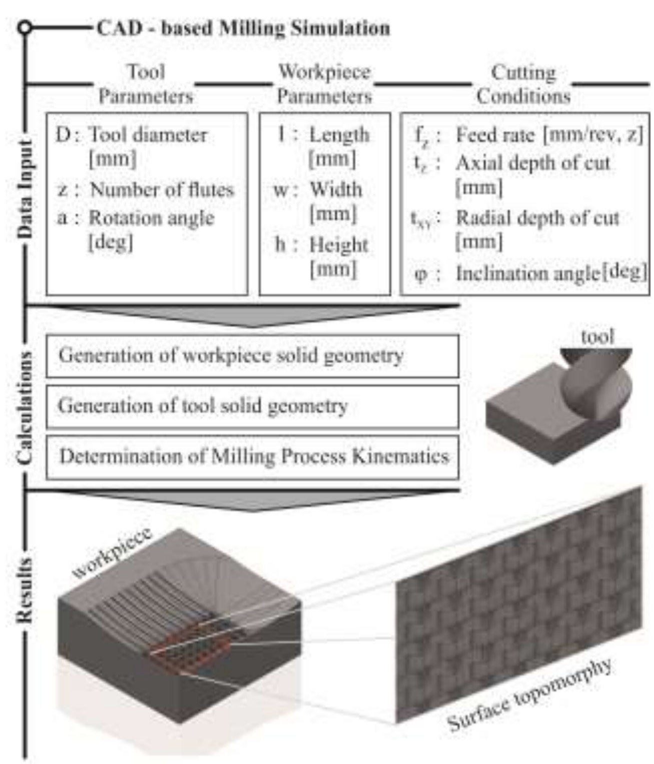

Figure 2. Milling simulation workflow

The resulted surface topomorphy is created as the subtraction of the cutting tool from the workpiece, in each respective position during the simulated cutting process, therefore the correct relative placement of the two models is crucial for the validity of the resulted surface.

The composite motion of the cutting tool against the machined surface consists of the concurrent rotation on its axis and a transverse displacement along the workpiece. This simulation process is implemented iteratively and the number of iteration steps is predefined by the user, so as to accomplish machining of the whole workpiece surface.

When this process is completed, simulation has ended and the final profile of the machined surface is produced, as illustrated in Fig. 3. At the end of each simulation, all the formed cutting tool paths in every iteration of the process, constitute the final resulted surface topomorphy.

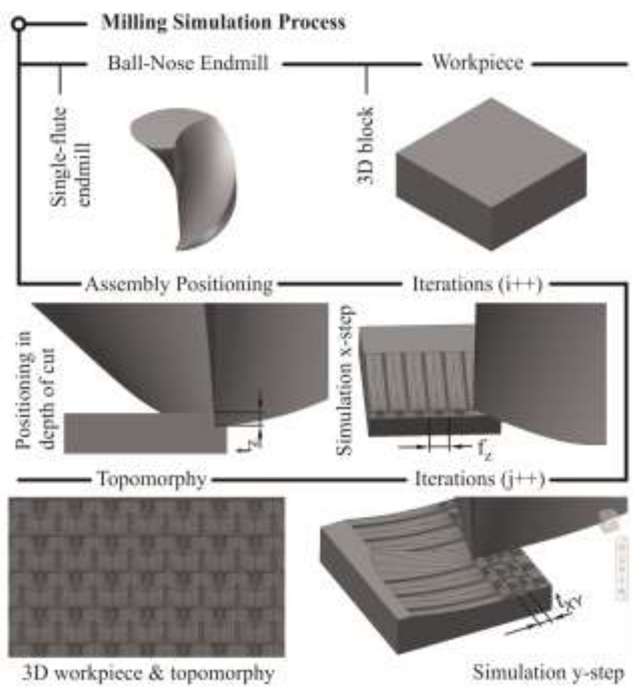

Figure 3. Milling simulation process

III. Results

A. *Model Validation: Simulation and Experimental Results Comparison*

As mentioned above, several ball-end milling experiments were conducted aiming at verifying the calculated topomorphy of the simulation. The experiments were conducted with the use of a 5-axis milling center and a D20 ball nose endmill was selected as cutting tool. The milled workpieces were Al7075-T6 cylinders. Al7075-T6 was selected as workpiece material due to its extensive use in a wide variety of structures and parts. The resulted topomorphy of the machined surface was captured with the use of a Leica M125 stereoscope.

The results of both processes, experimental and simulation, were thoroughly evaluated and revealed that surface topomorphies calculated by the simulation model adequately match the experimental ones.

This conclusion was drawn after the comparison of the surface topomorphies resulted from all the corresponding experiments and simulations that were carried out. Fig. 4 shows representative topomorphies for each milling strategy applied during the experiments and the respective calculated surfaces, obtained from the simulation process. The specific results presented in Fig. 4, regard ball end milling at t_Z=0.3mm, t_{XY}=0.3mm and feed rates f_Z=0.2, 0.6 [mm/rev,z] for negative, zero and positive values of inclination angle φ, which correspond to pull, vertical and push milling respectively.

As it can be easily observed, the results of the experiments are in a good agreement with those extracted from the simulation, considering that the modeled single flute ball endmill does not identically match the geometry of the real endmill that was used for the experiments. What is more, the effect of the machine tool vibrations has obviously not been taken into account during the modeling and simulation procedure.

B. *Surface Topomorphy Prediction*

Since the simulation model is experimentally verified, it can be sufficiently used for the prediction of the machined surface depending on the cutting parameters and conditions, thereby enable the optimization of ball end milling process.

When the feed rate is adjusted to f_Z=0.2 [mm/rev,z] and the inclination angle is set to φ=-10° (pull milling), the resulted surface consists of uniform patterns that greatly resemble parallelograms formed in the direction of feed rate both in up and down cut. This is not the case when f_Z equals 0.6 [mm/rev,z] at the same inclination angle φ= -10° where oblique parallelograms, formed with opposite gradients as to the feed direction, are observed in up and down milling process.

As regards vertical milling (φ=0°) with f_Z=0.2 but larger feed rate f_Z=0.6[mm/rev,z] as well, both simulated and experimental surfaces consist of non-uniform curved patterns, owing to the fact that when the tool axis is normal to the machined surface, tool drags on the surface with negative effects on the surface quality. The most obvious difference between these two produced surfaces is that in the case of f_Z=0.2, topomorphy shows greater variations at inclinations within a few degrees from the normal to the machined surface, compared to that produced with f_Z=0.6 [mm/rev,z], which is justified by the higher value of feed rate in the latter case.

Concerning push milling at φ=10° with f_Z=0.2 [mm/rev,z] the resulted profiles for both up and down milling are similar to the ones described above, i.e. the ones formed as a result of pull milling. In contrast to this, when machined with larger feed rate f_z=0.6 [mm/rev,z] the workpiece surface is composed of more irregular inclined forms generated at opposite inclinations compared to the respective ones with f_z=0.2 [mm/rev,z].

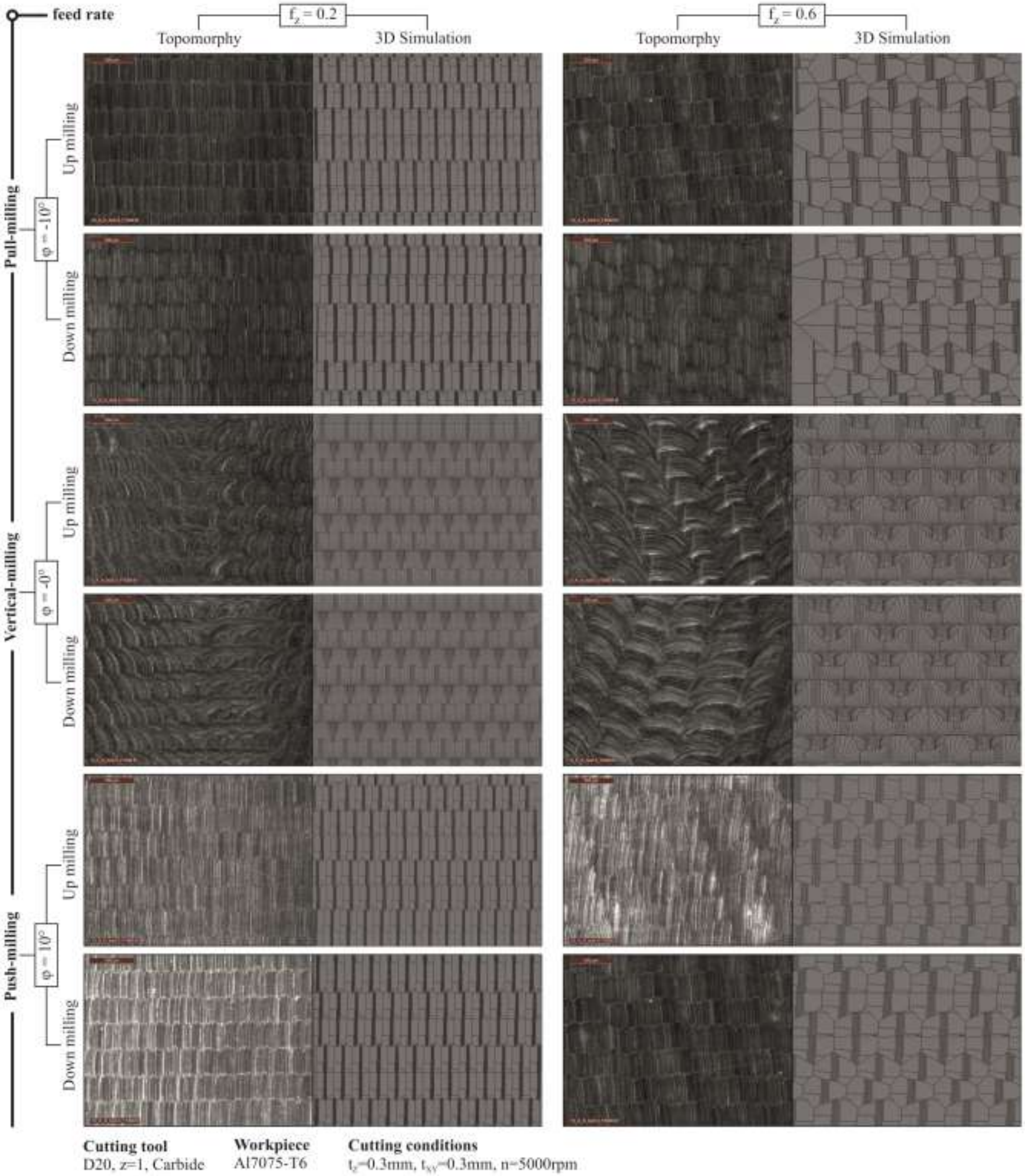

Figure 4. Comparison between experimental and calculated topomorphy

IV. Conclusions

A novel simulation model for the manufacturing process of milling was developed and the model was integrated into a parametric CAD system. In the context of this study, the model was implemented in the case of ball end milling, so as to accurately determine the expected surface topomorphy depending on various cutting parameters and conditions. What is more, the model was thoroughly verified through numerous ball end milling experiments.

In regard to the efficiency of the simulation model, the following conclusions can be drawn:

- The combination of simulation model and experimental results enables well funded estimations on surface topomorphy.
- The results of the simulation correspond to the experimental ones.
- The model can be efficiently employed to predict surface topomorphy and correlate values of different cutting conditions and surface profiles, enabling the selection of optimal cutting conditions in the case of ball-end milling of Al7075-T6. Moreover, the model is developed in such way that enables simulation of a wide range of milling processes.

The examination of the effect of various cutting conditions on the resulted topomorphy of the surface, led to the following deductions:

- Ball end milling of a surface perpendicular to the tool axis leads to the formation of non-uniform curved patterns which indicates the low quality of the machined surface, thereby the need for further finishing.
- When the inclination angle is set to φ= -10° or φ= 10° in pull and push milling respectively, the resulted surface consists of uniform patterns that approximate parallelograms formed either exactly in the direction of feed, in the case of low feed rate f_z=0. 2[mm/rev,z], or inclined at various angles with respect to this direction, in the case of higher feed rate f_z=0.6[mm/rev,z].

The development of the described simulation model sets the ground for predicting several other crucial technological data, such as surface roughness which can be estimated from the predicted workpiece surface together with cutting forces that may be calculated from the undeformed chip.

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