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Modelling of surface roughness in inclined milling operations with circle-segment end mills

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ABSTRACT

There is currently a lack of knowledge in the manufacturing of high complexity aerospace components. Impellers or blade-integrated disks (blisks) are expensive, and manufacturers tend to prefer reliability over productivity. Thus, manufacturing times are higher than they should be. These challenging parts need to be machined using new advanced tools for several reasons, such as requirement of 1) special and complex tool paths, 2) smoother cutting forces, and 3) good accessibility. Circle-segment or oval-form cutters have recently demonstrated their usefulness and adaptability in the machining of profile and free-form surface operations, and are becoming a solution for a wide range of applications and materials. However, machinists who use them know very little about such tools. In fact, there has been a lack of real-world modelling applications. This paper proposes for the first time a geometrical model that allows the prediction of the surface topography in flank-milling operations using circle-segment end mills. This time-domain model includes the most important mechanical and kinematical parameters during cutting: the tool geometry, feed rate, radial immersion, and tool runout. Tool orientation angles commonly used in 5-axis operations are also included. The developed model was positively verified against experimentally measured values in a milled wall made of aluminium Al7075T. This knowledge-based tool is useful for manufacturing companies and suppliers interested in optimizing and controlling their production parameters.

1. Introduction

During the incoming years, the aerospace industry expects a high increase in manufactured parts for aircraft propulsion. However, impellers or blade-integrated disks (blisks) are challenging and expensive because their materials must be machined using five-axis machines and owing to their high tolerances required. For these reasons, manufacturers prefer security and reliability over productivity. There is a shared feeling that the production times can be further enhanced. The scientific literature has dealt with only partial aspects of this multi-disciplinary problem, mainly, 1) modelling of static cutting forces, using traditional mechanistic models [1,2], 2) machinability and tool wear when machining heat-resistant alloys, namely, wear behaviour, tool geometry and chip breakers, coating [3], and optimal cutting conditions, 3) CAM issues [4], 4) systems control using mechatronics and motion planning to achieve smoother and more accurate tool paths [5,6], and 5) dynamic problems, namely, chatter in the five axes [7–9]. Depending on the production stage, the problems and their

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Nomenclature

a_e [mm]	Radial depth of cut
a_p [mm]	Axial depth of cut
d_2 [mm]	Reference diameter
i_0 [°]	Tool helix angle
κ [°]	Side cutting edge angle
R_a [µm]	Average roughness
R_z [µm]	Ten-point mean roughness
r_2 [mm]	Radius of the circle-segment
$\mathbf{r(z)}$ [mm]	Tool radius
ψ [°]	Phase shift angle
ϕ [°]	Position angle
R_0 [µm]	Tool runout
$\boldsymbol{\varphi_{tl}}$	Tilt-lead transformation matrix
SLE [mm]	Surface location error
S [rpm]	Spindle speed
T [-]	Number of periods
Z [-]	Number of flutes
z [mm]	Axial distance

solutions move from one branch to another. For instance, while roughing operations are concerned with high productivity more than anything else, the finishing operations require a tight tolerance and low roughness.

In particular, mechanical models used for surface prediction have been a well-studied topic in the area of milling because they involve a majority of the issues above. Studies regarding surface formation mechanisms in machining are basically divided into two groups: static and/or dynamic. The first group is concerned with process kinematics, geometrical parameters, static tool deflections, or runout. The second group also considers chatter vibrations owing to dynamic/tool relative displacements.

Altintas and Budak [10] were pioneers on the study of surface roughness on the machining processes. Franco et al. [11] proposed a surface profile model for face milling considering both back cutting surface marks and runout effects. Buj-Corral et al. [12] developed a surface topography model for peripheral milling incorporating the feed per tooth, radius of each cutting tooth, tool eccentricity, and helix angle. They investigated the effects of the helix angle, and noticed that the roughness profiles vary along with the height of the workpiece owing to eccentricity. Tomov et al. [13] developed mathematical algorithms for predicting the surface roughness during turning operations. Their analytical models used the feed rate, tool radius, and most important tool angles as input parameters, and these were applied to 42CrMo. Liu et al. [14] developed a hybrid approach combining the calculation of specific cutting energy consumption and an empirical characterization of its relationship with the surface roughness in the slot milling of Al-7075.

The second group focuses on the dynamic effects considered. Lee and Cheung [15] proposed a surface topography model for the prediction of the surface quality in ultra-precision machining. Their approach includes the effect of the machining parameters, process geometry, relative tool-work motion, and crystallographic orientation of the materials being cut. An innovative technique was developed by Ratchev et al. [16] using the concept of re-meshing. With this calculation methodology, some of the intersected vertices are removed using a tool, and new nodes are created as additional vertices when calculating the machined surface. Peigné et al. [17] developed a dynamic deflection model for roughness prediction during peripheral milling. They assumed a coupled rigid tool-flexible workpiece. Liu and Cheng [18] proposed a 4 DOF model for surface roughness estimation in peripheral milling operations. A simulation model of the machining dynamics was implemented using Simulink, and then compared against the dynamic cutting forces, and the surface roughness and waviness. Schmitz et al. [19] estimated the surface finish, surface location error, and stability in peripheral milling with cylindrical end mills. In their work, they considered the evolution of the tool/workpiece relative displacement along the tool axis. Jiang et al. [20] reconstructed the surface accuracy for peripheral milling using measured signals, and then compared it against the machined surface. Surmann developed a model to predict and minimize the roughness and location error of the flank surface [21]. In that model, they considered the regenerative tool vibrations by introducing tool deflections into the chip thickness expression. Costes and Moreau [22] designed an experimental device using non-contact displacement sensors with the aim of predicting the surface topography. The tool deformation was modelled to calculate the surface topography, and the model was then positively verified. Zhang et al. [23] proposed a novel algorithm to simulate the surface profile in the milling of stainless steel. With this model, they also included the effects of the tool wear. Zhenyu et al. [24] studied the relationship between the machined surface roughness and runout errors induced through static deformation and forced vibration. Recently, Wojciechowski et al. studied the surface accuracy when milling hardened tool steel [25]. They introduced a dynamic displacement model that increases the accuracy of the roughness predictions by introducing the concept of a dynamic runout.