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Mold manufacturing optimization: a global approach of milling and polishing processes

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Abstract

Within the context of molds and dies production, frequent changes in design and increased competitiveness require an overall optimized manufacturing process. The finishing process is typically composed of an accurate milling stage to manage shape deviations, followed by polishing operations to reach required surface roughness. Local improvements of milling and polishing set independently do not necessarily lead to an optimal manufacturing process planning. This study aims to propose a method to improve the whole sequence of milling and polishing considering constraints from polishing process and machine tool. The turning point between milling and polishing operations consists in linking them by the evaluation of the surface topography obtained after milling. From there, thanks to a predictive model of surface roughness, the design of polishing operations can be performed, and polishing time evaluated. On the other hand, for a given machine tool and a desired intermediate surface topography, milling parameters for finishing can also be modified and actual machining time predicted. Thus the whole process is evaluated balancing the milling and polishing times to reduce the total manufacturing time. Experiments are carried out on an aluminum mold for blowing process of plastic bottles.

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Keywords: Mold ; Finishing ; Manufacturing process ; Milling ; Polishing ; Predictive model ; Topography

1. Introduction

The design and the production of molds have a decisive role on the final products quality and cost [1]. With the increasing competitiveness and frequent changes in molds design, it is very useful to estimate precisely the production costs to improve the manufacturing process.

The process of mold manufacturing is generally composed of two successive stages: mold machining then surface polishing. Indeed, starting from a raw piece, the CAM process leads to a final shape close to the CAD model. Nevertheless, the surface topography produced after milling (especially roughness criteria) are not reached. It is thus impossible to directly use the mold for injection: for a mold used for blowing process of plastic bottles, a ”mirror” surface quality is needed in order to give the required bottle transparency. Hence, the abrasion process is used to polish the machined surfaces and reduce the scallop height to achieve a ”mirror” aspect.

In literature, one can find numerous studies to improve each one of these two processes independently.

Concerning milling, several models are developed to improve the actual surface quality. The aim is to get the best surface quality in terms of surface criteria with a given chordal deviation [2]. With a machining strategy point of view, different tool path have been developed, such as iso-scallop height, in order to obtained the desired surface roughness in a shorter tool path [3]. Studies are also carried out to reduce the machining time. Feedrate planning of tool path for freeform surfaces is often improved taking into account machine kinematics (maximum axis velocities, accelerations and jerks) [4]. Thanks to the optimization of the tool path geometry and its interpolation for real-time execution, the surface quality can be improved, avoiding deviations from CAD design and avoiding marks caused by feedrate slowdowns. As the actual feedrate differs from the programmed one, the prediction of the velocity profile along the tool path is a real issue to predict machining time and can be used to estimate the actual machining productivity and costs.

Regarding polishing, modeling the abrasion process for freeform surfaces remain a scientific and technical obstacle towards and optimized and automated process [5]. The quantification of abrasion is most frequently given by the material removal rate (MRR) which corresponds to the thickness of material removed per time unit. To model the MRR, two different approaches can be distinguished: analytical models and experimental models [6]. The analytical models are based on the modeling of the interaction between the tool and the workpiece

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at the level of the abrasive particle [7]. Within the context of mechanical parts such as blowing mold, the models used are rather the experimental ones derived from the analysis of many polishing trials. The model developed by Preston within the context of glass polishing is probably the one that is today the most used [8]. For other materials, Klocke et al. propose a more generic model involving three constants to be determined [9]. In these models, the MRR depends on the polishing tool velocity and on the polishing pressure. Most of these models don't take into account the geometric characteristics of the surface to be polished.

However, considering the whole manufacturing process of molds and its optimization, the milling and polishing stages cannot be improved independently. They are strongly linked by texture and deviations let on the surface by milling. Indeed, polishing range depends on the surface topography after milling. These two processes are then strongly interlinked.
Few papers try to characterize this link between milling and polishing. Souza et al. evaluate the roughness according to the tool path strategy and determine polishing time according to the roughness [10]. Boujelbene shows the impact of tolerances and interpolation on polishing time which follow milling [11]. Although these studies provide predictive models for polishing time and the interaction with the milling operation, various machining strategy parameters that generates the finish surface are not investigated. In particular, the feed per tooth and the radius of the tool are not considered for the surface topography. The polishing range should also depend on the finish operation in milling. It is therefore necessary to study more in detail the relationship between machining strategy and range of polishing to optimize the overall process.

The aim of this paper is to propose a method to predict the time necessary of the whole process (milling, polishing), taking actual milling and polishing conditions. Hence, by tuning different parameters, it is possible to find an optimized operating point between milling and polishing. Unlike the above mentioned papers, tool path strategy and tolerances don't vary. A parallel planes tool path strategy and confined error are used ; only tangential and transverse scallop heights are studied for their interactions with polishing.

The paper is organized as follows: Section 2 deals with the relations between surface topography achieve by the finishing operation and the actual milling time. Then, this surface topography is linked in section 3 to the polishing time according to the first abrasive disk used. In section 4, a method to choose the values of influent parameters in order to minimize the whole process time is detailed. Last section is dedicated to the experimental validation of the proposed method on an aluminum blowing mold used to product plastic bottles.

2. Relation between surface topography and milling time

2.1. Surface topography modeling

Surface topography models depend on machining strategy parameters. Two standpoints can be adopted: the experimental standpoint and the theoretical one. Based on surface topography measurements, most experimental methods attempt to establish the link between feedrates, machining direction, tool orientation and 3D topographies [12]. Unfortunately, these results are only qualitative and the relationship between the machining strategy parameters and the surface topography is not formalized. With the theoretical standpoint, it is possible to describe the texture obtained in ball-end milling [13] from numerical simulations. Recent works have shown that the surface topography can be simulated by taking into account cutting conditions (transversal step and the feedrate) [14] but also the evolution of the tool axis orientation in 5-axis milling [15]. Fig. 1 represents a typical surface topography achieve after ball-end milling where one can easily recognize the effects of the machining parameters.

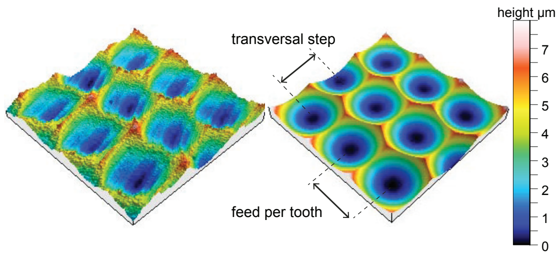

Fig. 1. Surface topography measurement and simulation

Quinsat et al. proposed a simple way to determine surface topography in ball-end milling [16]. Each tooth revolution can be locally modeled by a sphere, which radius corresponds to the tool radius. The pattern generated by the teeth revolutions and the tool displacement is thus the juxtaposition of several spherical cups (Fig. 2). This pattern depends only on the feed per tooth (f_z), the transverse step (p) and the radius of the tool (Ro). In order to characterize polishing after milling, the evaluation of the remaining volume to be removed is modeled. Such a macro-geometric model seems sufficient; studying the geometry at lower scale (including cutting edge wear for instance) is not necessary.

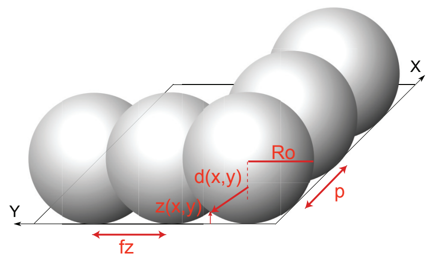

Fig. 2. Surface topography model

The volume V left after milling can thus be evaluated considering the height between the local plane and the spheres. Supposing that the juxtaposition of the spheres is symmetric, the remaining volume can be expressed on a pattern of size (f_z, p) by Eq. (1):

$$V = \int_{-\frac{f_z}{2}}^{\frac{f_z}{2}} \int_{-\frac{p}{2}}^{\frac{p}{2}} z(x, y)\, dxdy \qquad (1)$$