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Modeling and analysis of a novel approach in machining and structuring of flat surfaces using face milling process

Mohammadjafar Hadad [a],*, Mohammadjavad Ramezani [b]

[a] School of Mechanical Engineering, College of Engineering, University of Tehran, P.O. Box 11155/4563, Tehran, Iran
[b] Manufacturing Engineering Group, Department of Mechanical Engineering, Semnan University, Semnan, Iran

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ABSTRACT

In this paper, a new and innovative method for regular structuring and special patterning of workpiece surface applying face milling process is presented. The patterns have been generated on surface by particular positioning of workpiece and tool, milling passes in different directions, and as well as special angular position of spindle in typical vertical milling machine. The model for the geometry of the cutting tool was first developed and subsequently, a new simulation model for surface pattern by face milling process was established. Mathematical models are presented to describe the cutting tool geometry and position (including orientation and location) in space. To verify this method, calculation and simulation programs (MATLAB and CAD programming software) are developed. This study provides a fundamental understanding for the pattern milling process, based on this, the influence of different milling process parameters on pattern geometry (including insert angles and radius) is discussed. The simulation results could be used to optimize the pattern milling and conventional milling processes, and also to improve the workpiece surface quality or predict the surface pattern by given face milling parameters.

1. Introduction

1.1. Surface texturing (patterning)

Surface finish, also known a surface texture or surface topography, is the nature of a surface as defined by the two characteristics of surface roughness, and waviness. It comprises the small local deviations of a surface from the perfectly flat ideal (a true plane). Surface texture is one of the important factors that control friction and transfer layer formation during sliding. Considerable efforts have been made to study the influence of surface texture on friction and wear during sliding conditions [1]. Surface textures can be isotropic or anisotropic. Sometimes, stick-slip friction phenomena can be observed during sliding depending on surface texture. Each manufacturing process (such as the many kinds of machining) produces a surface texture. The process is usually optimized to ensure that the resulting texture is usable. If necessary, an additional process will be added to modify the initial texture. The latter process may be grinding (abrasive cutting), polishing, lapping, abrasive blasting, honing, electrical discharge machining (EDM), milling, lithography, industrial etching/chemical milling, laser texturing, or other processes. In other words, surface texturing has been used for many applications, such as sliding contact elements, magnetic storage disk surfaces, machine tools guide-ways, hydrodynamic bearings, cam followers, rolls of forming processes, and mechanical face seals to improve the tribological properties [2]. Many studies have shown that surface texturing offered good performance from boundary lubrication to hydrodynamic lubrication. The shapes of the surface patterns were usually dimples or grooves. These dimples and grooves can act as coolant-lubricant reservoirs and entrap wear particles. For hydrodynamic lubrication in particular, surface texturing supports the formation of the lubricating oil film. The textured surface in many cases may reduce the environmental pollutions and increase the performance of the machine [1–3]. For instance, quantitative estimation of friction losses in the initial design stages of an internal combustion engine is a crucial factor that determines the fuel economy and performance of the automobile. The analysis shows that the relative importance of various components to the total friction losses in an engine and the influence of design and other variables on these losses. The piston/cylinder system, in particular, accounts for a great part of the total friction losses in an engine. Several investigators have dealt with the friction issue and concluded that approximately 50% of the friction losses of an internal combustion engine are due to the piston/cylinder system, of which 70–80 percent comes from the piston rings. More effective or enhanced lubrication is needed to meet the increasingly more stringent operational conditions of future engine systems and

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* Corresponding author.
E-mail address: mjhadad@ut.ac.ir (M. Hadad).

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Nomenclature

D_{oc}	depth of cut (mm)
f_z	feed per tooth (mm/s)
t_2	time of second path with β angle (s)
t_i	time of entry and exit points of i^{th} cutting edge(s)
v_f	federate (mm/s)
x_c	X coordinate for pick of roughness (mm)
x_{int}	X coordinate for intersection of back and front path (mm)
x_k	X coordinate of k^{th} path (mm)
x_l	X coordinate of diagonal line (mm)
x_n	X coordinate of i^{th} cutting edge (mm)
y_k	Y coordinate of k^{th} path (mm)
y_{ws}	Y coordinate of workpiece surface (mm)
y_{wst}	Y coordinate of workpiece surface by tilting workpiece (mm)
z_c	Z coordinate for pick of roughness (mm)
z_k	Z coordinate of k^{th} path (mm)
z_l	Z coordinate of diagonal line (mm)
z_n	Z coordinate of i^{th} cutting edge (mm)
z_{ws}	Z coordinate of workpiece surface (mm)
z_{wst}	Z coordinate of workpiece surface by tilting workpiece (mm)
$\varnothing$	lead angle (degree)
i	cutting edge number
L	length of sweep (mm)
n_s	spindle speed (rev/min)
B	bandwidth of lozenges (mm)
D	diameter of face milling cutter (mm)
H	height of start point in diagonal line (mm)
K	cutting edge number
R	radius of face milling cutter (mm)
b	intercept of diagonal line (mm)
$dist$	minimum distance between back and front path (mm)
r	radius of cutting edge (mm)
t	time (s)
Ψ	workpiece tilt angle (degree)
β	angle of cutting edge into x coordinate
θ	deviation of spindle angle (degree)
ω	spindle speed (rad/s)

drivetrain components. From an environmental point of view, lower fuel economy also means higher environmental pollution; thus there is an urgent need for new engine systems with higher fuel economy and lower emissions than before. A novel idea to further reduce friction in mechanical components was mentioned above. It consists of using micro and sub-micro surface structure in the form of micro dimples obtained by laser texturing. Each micro dimple acts as a micro hydrodynamic bearing to enhance hydrodynamic lubrication. Various techniques for texturing surfaces have been developed recently including mechanical means such as grinding, turning and milling using a machine tool or shot blasting, as well as photolithography and etching processes such as reactive ion etching. An energy beam technique such as laser beam processing has been applied for texturing, and the frictional properties of these laser-textured surfaces have been investigated. Using the energy beam technique, it is possible to fabricate micron-sized dimples over the surface. A flexible method for creating a patterned grinding wheel was designed by Oliveira et al. [1] by employing a controlled shaker for dressing. The aim of those investigations is the generation of tribological optimized surfaces for friction reduction by means of face or cylindrical grinding. Patterns or micro-dimples are transferred from the grinding wheel topography to the workpiece. Those patterns or dimples increase the fluid retention capacity of a sliding system and therefore reduce the overall friction [1,2].

1.2. Milling operation

In milling process, machined surface patterns have been extensively studied in multiple scales. At fine scales (micron level), surface textures were correlated to a number of process conditions. Tool conditions were found to have a significant impact on surface texture [2–4]. Schmitz et al. [4] correlated tool runout, stability, and surface location errors to surface finish. Baek et al. [5] introduced a model to predict surface roughness that includes cutting conditions, edge profile, insert runout, and dynamic characteristics. Kline et al. [6] showed the effects of radial run-out and chip load on surface finish. Surface errors were also predicted along with cutting force considering system deflections [7]. At coarse scales (from several millimeters to the form), Takeuchi et al. [8] studied the effects of spindle tilt and thermal expansion on the surface form error. Camelio et al. [9] investigated the effect of fixturing and clamping on surface form error. Liao et al. [10] used FEM to model fixture-workpiece to study the influence of clamping preload and machining force on the machined surface quality. Gu et al. [11] used a finite element method called equivalent flexibility influence coefficient to predict the deformation of cutter-spindle and workpiece fixture assembly. The relative position between cutter and workpiece can be predicted to estimate surface errors.

Regarding the influence of tool path on tool wear and surface roughness, the research made by [12], demonstrated that the relative positions of tool and workpiece have a strong influence on flank wear and, consequently, on tool life and surface finish of the workpiece. Also they showed that as the distance between the end of the cutter diameter and the beginning of the workpiece is increased, the flank wear value increases throughout the tool life. Their studies were conducted on AISI 1045 carbon steel during a conventional milling process. In 2000, Ng et al. [13] studied the influence of the direction of cut when milling Inconel 718. The coating performance of the tool during the process was also studied. They concluded that horizontal downwards cutter orientation generated the longest length of cut. In addition workpiece surface improved, primarily due to a low specific force and absence of vibration. Regarding coating of the tool, they concluded that TiAlN performed better than CrN coating.

Vivancos et al. in Ref. [14] presented a mathematical model of surface roughness prediction in HSM of hardened steels for injection moulds using factorial designs of experiments combined with techniques of regression. They concluded that climbing machining leads to better surface finish compared to conventional machining and in both cases, the radial depth of cut is the most affecting parameter. Also they showed that it is possible to obtain surface values corresponding to the ones obtained with grinding processes when using high-speed machining process. With regard to surface roughness prediction, several studies have been made especially using computational methods such as: Artificial Neural Networks (ANN), Genetic Algorithms (GA) and Respond Surface Methodology (RSM).