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Precision surface characterization for finish cylindrical milling with dynamic tool displacements model

S. Wojciechowski[a], P. Twardowski[a], M. Pelic[a], R.W. Maruda[b], S. Barrans[c], G.M. Krolczyk[d,*]

[a] Faculty of Mechanical Engineering and Management, Poznan University of Technology, 3 Piotrowo St., 60-965 Poznan, Poland
[b] Faculty of Mechanical Engineering, University of Zielona Gora, 4 Prof. Z. Szafrana Street, 65-516 Zielona Gora, Poland,
[c] Turbocharger Research Institute, University of Huddersfield, Huddersfield HD1 3DH, UK,
[d] Faculty of Mechanical Engineering, Opole University of Technology, 76 Proszkowska St., 45-758 Opole, Poland

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ABSTRACT

In this work a new approach to surface roughness parameters estimation during finish cylindrical end milling is presented. The proposed model includes the influence of cutting parameters, the tool's static run out and dynamic phenomena related to instantaneous tool deflections. The modeling procedure consists of two parts. In the first stage, tool working part instantaneous displacements are estimated using an analytical model which considers tool dynamic deflections and static errors of the machine – tool-holder – tool system. The obtained height of the tool's displacement envelope is then applied in the second stage to the calculation of surface roughness parameters. These calculations assume that in the cylindrical milling process, two different mechanisms of surface profile formation exist. Which mechanism is present is dependent on the feed per tooth and the maximum height of the tool's displacement envelope. The developed model is validated during cylindrical milling of hardened hot-work tool steel 55NiCrMoV6 using a stylus profiler and scanning laser vibrometer over a range of cutting parameters. The surface roughness values predicted by the developed model are in good agreement with measured values. It is found that the employment of a model which includes only the effect of static displacements gives an inferior estimation of surface roughness compared to the model incorporating dynamic tool deflections.
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1. Introduction

Milling of difficult to cut materials in a hardened state is an efficient technology which is usually applied to the production of drop forging dies and casting molds (Urbanski et al., 2000; Wojciechowski, 2015). This machining technique is very often carried out to generate parts in the finished condition, which consequently imposes high dimensional accuracy and low surface roughness constraints on the process. The improvement of machined surface quality is a very important task, because it has direct influence on performance and tribological properties of product (Ruggiero et al., 2016; Ruggiero et al., 2015). Fulfilling the demanding surface quality requirements depends mainly on the machine – tool-holder – tool system's condition and appropriate selection of milling parameters. Selection of appropriate milling parameters and constraints on the machine tool accuracy requires the application of a reliable and versatile surface roughness model.

According to Twardowski et al. (2011), during cylindrical milling of hardened steel 55NiCrMoV6, the measured surface roughness parameters are significantly higher than theoretical values resulting from a kinematic–geometric model. These differences can be caused by the frictional effects in the tool-work material interface, which affect the tool wear (Kumar et al., 2016; Ulutan and Ozel, 2013) and process stability (Rusinek et al., 2015), plastic deformations of work material during decohesion, as well as tool displacements (Jozwik and Mika, 2015). Thus, the complexity of the surface formation mechanism during milling has resulted in many modeling approaches. The proposed models usually include kinematic–geometric parameters, insert setting errors, radial and axial run outs and static tool deflections. Baek et al. (2001) formulated a surface roughness model for the face milling process considering cutter insert run out errors and feed-rate. The verification results confirmed that the proposed model was valid for

* Corresponding author. Fax: +48774499927.
E-mail addresses: sjwojciechowski@o2.pl (S. Wojciechowski), pawel.twardowski@put.poznan.pl (P. Twardowski), marcin.pelic@put.poznan.pl (M. Pelic), r.maruda@ibem.uz.zgora.pl (R.W. Maruda), s.m.barrans@hud.ac.uk (S. Barrans), g.krolczyk@po.opole.pl (G.M. Krolczyk).

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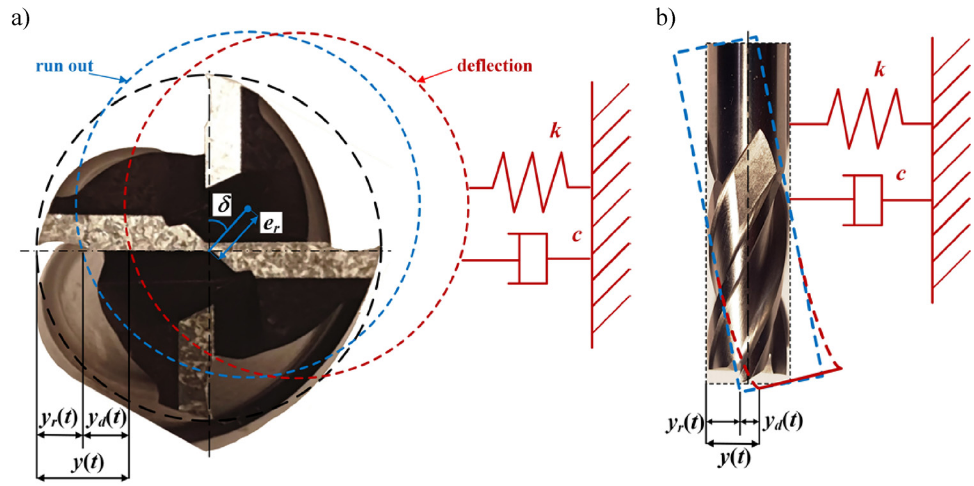

Fig. 1. Cylindrical end mill displacements during machining: (a) face of the cutter; (b) reference plane.

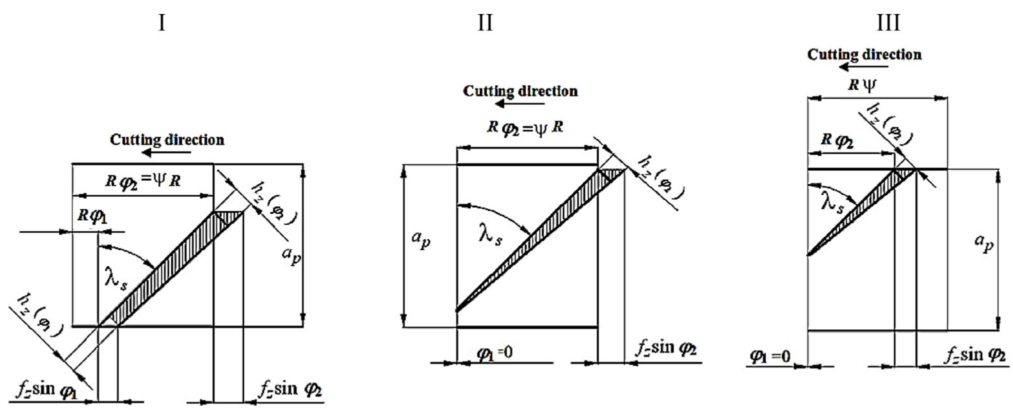

Fig. 2. Developed view of the contact area between the tool and work piece during milling.

controlling the surface roughness and maximizing the material removal rate. Li et al. (2002) established a surface generation model for the end milling process accounting for movement error of the principle rotation axis and the tool's static stiffness. It was concluded that tooth point curve radius significantly affects the height of surface roughness. Franco et al. (2008) proposed a theoretical surface profile model for face milling including back cutting surface marks and run out phenomenon. Research revealed that surface roughness parameters *Ra* and *Rt* can be minimized by reducing back cutting height deviation. Buj-Corral et al. (2011) developed a surface topography model for peripheral milling incorporating feed per tooth, the radius of each cutting tooth, tool eccentricity and helix angle. It was noticed that the roughness profiles varied along the work piece's height when eccentricity was present and tools with non- zero helix angles were used.

The application of the above-mentioned models improves the accuracy of the surface roughness estimation. However, during the machining process, surface texture can be affected also by the tool's dynamic displacements, which are caused by an instantaneous cutting forces and geometrical errors of the milling system. Thus, Baek et al. (1997) formulated a dynamic surface roughness model for face milling, which considers cutting conditions, edge profiles and relative displacements between the work- piece and the cutting tool. A similar dynamic modeling approach, proposed by Zhenyu et al. (2015) focused on surface roughness estimation during high-speed face milling with straight-edged square inserts. Peigne et al. (2004) developed a dynamic deflection model for surface roughness estimation during peripheral milling. The proposed system was of the rigid cutter—flexible work-piece type. Liu and Cheng (2005) also formulated a dynamic surface roughness model for peripheral milling. However, their approach was based on a 4 degrees of freedom dynamic model with a flexible tool and work-piece. Schmitz et al. (2007) applied the "Regenerative Force, Dynamic Deflection Model" for the estimation of surface finish, surface location error and stability during the end milling process. Furthermore, previous research by Wojciechowski (2011) related to cylindrical milling of hardened steel revealed that the application of a dynamic displacement model significantly increases the accuracy of roughness parameter estimation, in comparison to a traditional kinematic–geometric model.

Models which describe a tool's instantaneous displacements and the influence on surface roughness require reliable validation. However, this is inhibited by the difficulty of directly measuring the tool's dynamic displacement during milling. Therefore, the displacements are usually measured indirectly with the application of accelerometers fixed to the spindle head or work-piece. However, the acquired signal requires further processing (integration and filtration) and may not accurately represent the true tool displacement. Thus, novel, non-contact measurement methods of instantaneous tool displacements are being developed. These approaches are based on the application of laser vibrometry (Tatar and Gren, 2008), capacitive gap sensors (Miyaguchi et al., 2001), or laser displacement sensors (Wojciechowski et al., 2015).

The state of the art shows that surface formation during milling is affected both by static phenomena (kinematic–geometric parameters, insert setting errors, run out, static tool deflections) and dynamic tool displacements. However, the majority of works related to surface roughness modeling do not include these factors

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