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Optimisation of machining parameters during ball end milling of hardened steel with various surface inclinations

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ABSTRACT

This paper proposes a method for the reduction of forces and the improvement of efficiency during finish ball end milling of hardened 55NiCrMoV6 steel. The primary objective of this work concentrates on the optimal selection of milling parameters (cutting speed – v_c, surface inclination angle α), which enables the simultaneous minimisation of cutting force values and increased process efficiency. The research includes the measurement of cutting forces (F_x, F_y, F_z) during milling tests with variable input parameters and calculation of process efficiency accounting for cutting parameters and surface inclination. The paper then focuses on the multi-criteria optimisation of the ball end milling process in terms of cutting forces and efficiency. This procedure is carried out with the application of the response surface method, based on the minimisation of a total utility function. The work shows that surface inclination angle has a significant influence on the cutting force values. Minimal cutting forces and relative high efficiency can be achieved with cutting speed v_c = 375 m/min and surface inclination angle α = 15°.

1. Introduction

The ball end milling process is used mainly for the production of drop forging dies and casting mould made of hardened steel [1], or in the aerospace industry in manufacturing wing parts made from aluminium alloys and composites [2]. The fundamental challenges of curvilinear surface milling are related primarily to the machined surface quality [3], process efficiency, and tool life [4].

The key factor which influences the machining process' technological and economic effects is cutting force and its components. Excessive cutting force values are undesirable because they induce tool deflections, which in turn form dimensional errors or high levels of surface roughness [5]. High cutting force values can also result in chipping of the tool and thus significantly reduce tool life [6]. During milling, process kinematics determine variations of cross sectional area of cut, and thus cutting forces [7]. Therefore it is important to be able to reliably simulate the physical and technological effects of the milling process.

The literature shows that the problem of cutting force estimation during the machining processes has been investigated by the many researchers. Their work can be divided into two distinct approaches: the analytical and mechanistic. According to Fontaine et al. [8] the analytical models focus mainly on the physical mechanisms of chip formation, as slip stress and strain. In contrast, the mechanistic models estimate cutting forces based on the assumption that their values are proportional to the sectional area of cut and specific cutting force coefficients [9]. These models can be used to estimate the cutting forces for a selected combination of cutting parameters and tool geometry. However, from a practical point of view, the selection of cutting parameters which enable minimisation of cutting forces and simultaneous improvement of process efficiency is of great importance. In order to achieve this objective, machining process optimisation can be applied.

From the literature it can be seen that the most widely considered optimisation objectives include maximisation of tool life [10] and minimisation of tool wear [11], machining vibrations [12], surface roughness [13], and cutting forces [14]. López de Lacalle et al. [15] optimised the toolpath during ball end milling on the basis of the predicted cutting forces, in order to minimise dimensional errors. A similar approach was proposed by Lazoglu et al. [16], who selected tool paths optimised to minimise cutting force. The results showed that the optimum path can achieve almost a 60% reduction in mean

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Table 1
Chemical composition of the alloy steel 55NiCrMoV6.

C	Si	Mn	Cr	Mo	Ni	V
0.5–0.6%	0.1–0.4%	0.65–0.95%	0.6–0.8%	0.25–0.35%	1.5–1.8%	0.07–0.12%

force. Gok et al. [17] optimised the cutting force and tool deflection during ball end milling of X40 CrMoV5-1 tool steel considering variable cutting parameters and tool path strategies. The results obtained revealed that the most significant parameter was pick feed (step over) in the machining of inclined surfaces using three different coated cutting tools. Masmiati and Sarhan [18] applied Taguchi optimisation and signal-to-noise ratio (S/N) response analysis of the surface integrity after ball end milling of S50C steel. Through the analysis, it was found that surface inclination angle had a significant influence on microhardness and residual stress in the feed direction. Furthermore, as Vakondios et al. [19] found during ball end milling trials on Al7075-T6 alloy, the selection of surface inclination angle can affect also the surface roughness. Their results showed that the surface roughness parameter (Rz) was significantly affected by the surface inclination angle and milling kinematics. Kuram and Ozcelik [20] investigated the effects of spindle speed, feed per tooth and depth of cut on tool wear, force components and surface roughness during micro-milling of aluminium Al 7075, with the application of Taguchi experimental design method. It was found that the minimum tool wear, cutting forces and surface roughness were achieved by milling with the lowest investigated cutting speed, feed per tooth and depth of cut values.

The review of the literature above has shown that ball end milling process optimisation procedures focus mainly on cutting forces, milling strategies, surface quality and tool life. However process efficiency is not usually considered. It should be emphasized that during ball end milling, cutting speed is dependent on the spindle speed and the tool's effective diameter, which in turn is a function of tool diameter, axial depth of cut and surface inclination angle. Consequently, these factors have a direct influence on material removal rate and machining time. According to Rybicki [21], an increase in surface inclination angle from 10° up to 60°, during ball end milling with constant cutting speed mode, resulted in an approximately 55% increase in cutting time. In addition, Chen et al. [22] have shown that surface inclination angle has a significant influence on the cutting forces, due to variations in edge force values along the length of the cutting edge. Therefore, reliable optimisation of the ball end milling with variable surface inclinations should focus both on cutting forces and process efficiency.

In this paper the analysis of forces and process efficiency during finishing ball end milling of hardened 55NiCrMoV6 steel is presented. The primary objective of this work concentrates on the optimal selection of cutting speed and surface inclination angle, which enables the simultaneous minimisation of cutting force values and growth of the process' efficiency. A multi-criteria optimisation process, based on minimisation of a total utility function is carried out. The application of the obtained results can be used to improve the technological and economic effects of the process by enhancing machined surface quality and reducing cutting time and tool wear.

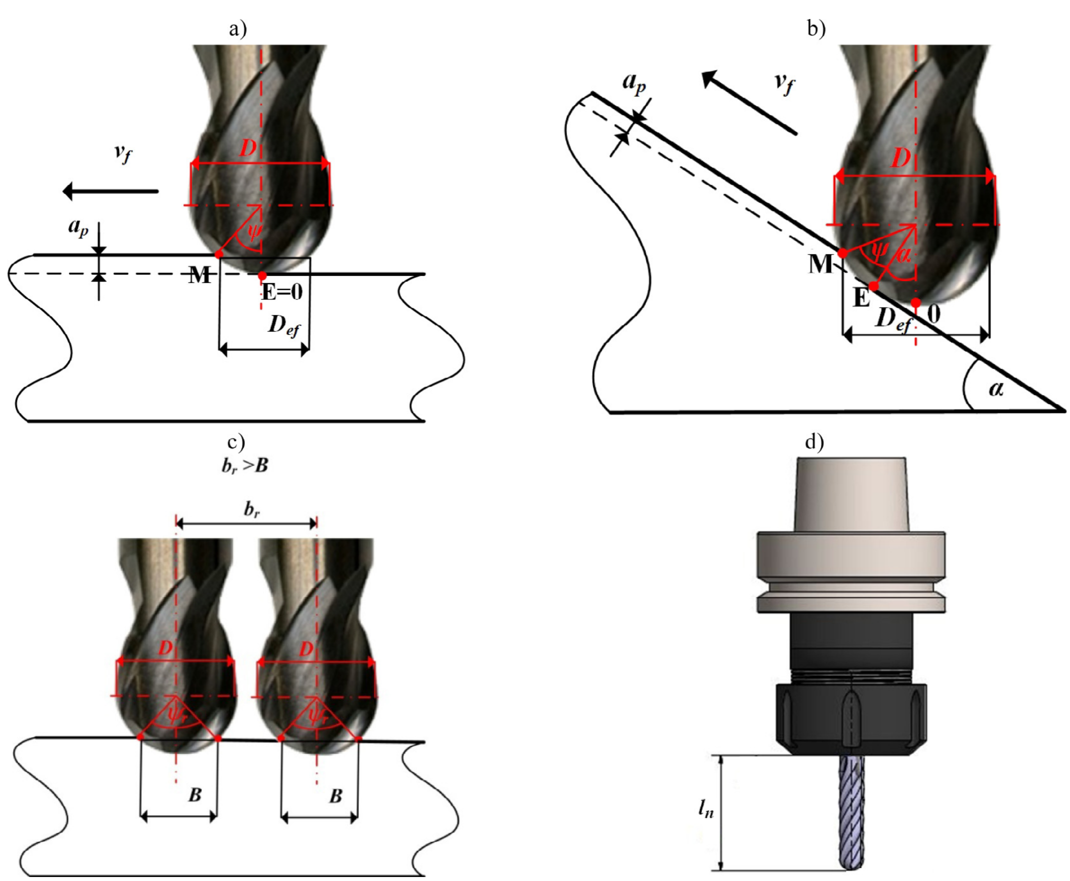

Fig. 1. Cutting modes of ball end milling: (a) slot milling with $\alpha = 0°$; (b) upward ramping with $\alpha > 0°$; (c) selection of pick feed b_r; d) the designation of tool overhang.