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A method of improving chatter-free conditions with combined-mode milling

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ABSTRACT

An analytical foundation for proposing a new method of highly productive finish slotting with 3-axis end-milling is presented. This is done by considering process stability of combined-mode end-milling with a combination of both up-milling (conventional) and down-milling (climb) modes. Physically the combined mode occurs when a pre-existing slot exists in what could have been a full-immersion process. A novel geometric consideration is presented for complete definition of size and location of the pre-existing slot in terms of the component radial immersions of the combined mode. The sum of component radial immersions constitutes the effective radial immersion. It is seen that some combinations of size and location of the pre-existing slot could engender heightened stability which reflects as elevated stability lobes with hyper-productive lobbing effects. Procedure for arriving at the stabilizing combinations of size and location of the pre-existing slot is summarized in five steps in the conclusion. This procedure was followed in arriving at combinations that yielded very high MRR per active pass and very low finish-slotting time for a numerically studied system. Incorporation of the productive combinations in Computer Numerical Control (CNC) code for mass finish slotting in future industrial workshops implementing the proposed technology of multi-spindle system with an arrangement of pre-slotting tools stabilizing the finish-slotting tool is expected to considerably reduce of manufacturing time.

1. Introduction

Regenerative chatter is the unstable self-excited vibration of tool relative to workpiece in machining operations like turning [1–7], milling [8–13], drilling [14–18], grinding [19–22] and boring [23–25]. Regenerative chatter leaves parts with vibration marks thus compromising surface quality and dimensional integrity. Normally at given spindle speed, regenerative chatter develops, for example, milling beyond some threshold value of axial depth of cut. This is evident in various stability analyses of milling process for which stability boundary curves separate the process parameter space of spindle speed and axial depth of cut into stable and unstable domains [10,26–34]. For this reason, simultaneous achievement of high material removal rate (MRR) and very smooth part surface is a tricky optimization problem. Stated differently minimization of machining time or maximization of MRR through some kind of optimization technique is another problem that arises after the problem of dynamical stability of a process is solved. A number of investigators have considered optimizing pocketing time of milling process by trying to prescribe a toolpath with the best compromise of geometrical and kinematic considerations [35–39]. This approach is normally confined within technological prescription on depth of cut thus disallowing making the most tool dynamics and attaining the highest possible optimal. The recent strategy of optimizing machining time involves making the most of tool dynamics through process stability analysis while prescribing a toolpath with the best compromise of geometric and kinematic considerations [40–43]. Tekeli and Budak [40,41] minimised pocketing time using limiting pairs of axial depth of cut and radial depth of cut. They found that investigating machining time at limiting depth pairs could save up to 40% of the machining time of conventional method of arbitrarily chosen radial immersion between 0.5 and 0.8 radial immersions. Heo et al. [42] considered as constraints of pocketing time stability limit and load capacity of the spindle. They used the genetic algorithm in arriving at minimum time of high-speed pocketing. Ozoegwu and Ezugwu [43] generalized and studied the time of rectangular pocketing with limiting depth pairs identifying the existence of a coordinate for maximum limiting MRR which gives minimum pocketing time for large pockets.

The tool is considered in this work to combine both up-milling and down-milling modes along the toolpath to form a

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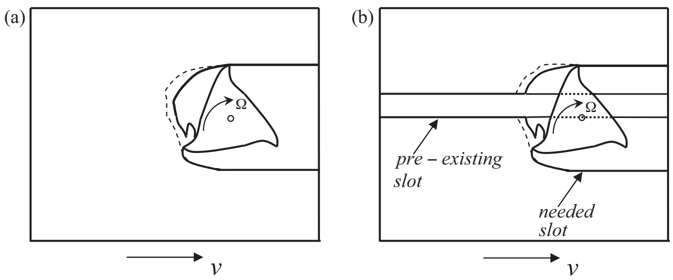

Fig. 1. Slotting processes. (a) Full-immersion milling. (b) Combined-mode operation for finish slotting.

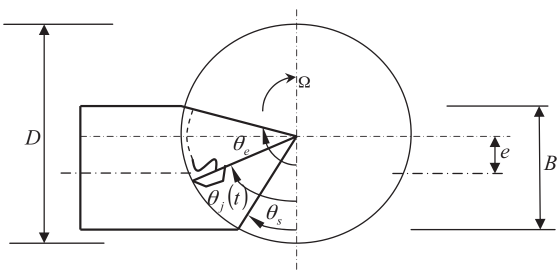

Fig. 2. General milling tool–workpiece disposition.

combined-milling mode. Even though the combined-milling mode as proposed here for 3-axis end-milling is new, it is known to occur in 5-axis operations [44] where varying cutter–workpiece engagement (CWE) is seen to cause multi-radial immersion. This work analytically seeks for configuration of combined-milling mode that stabilizes machining process. In other words, the effect of geometrical parameters of the combined-milling mode on end-milling process stability will be investigated in order to arrive at new knowledge-based method for further maximizing MRR and minimizing machining time.

Radial immersion in milling process means the ratio of radial depth of cut to tool diameter. It is a means to quantify the amount or duration of contact a cutting edge makes with the workpiece in a spindle revolution. The tool encounters only one radial depth of cut in which each of the cutting edges encounters one continuous contact with the workpiece in a part of spindle revolution in either up-milling mode or down-milling mode but encounters two radial depths of cut under combined-milling mode operation. Combined-mode operation will be encountered in the workshop when there is a discontinuity like pre-existing slot in the path of a slotting tool creating a situation that looks like finish slotting as indicated in Fig. 1b. Also knowledge gained in studying the combined mode

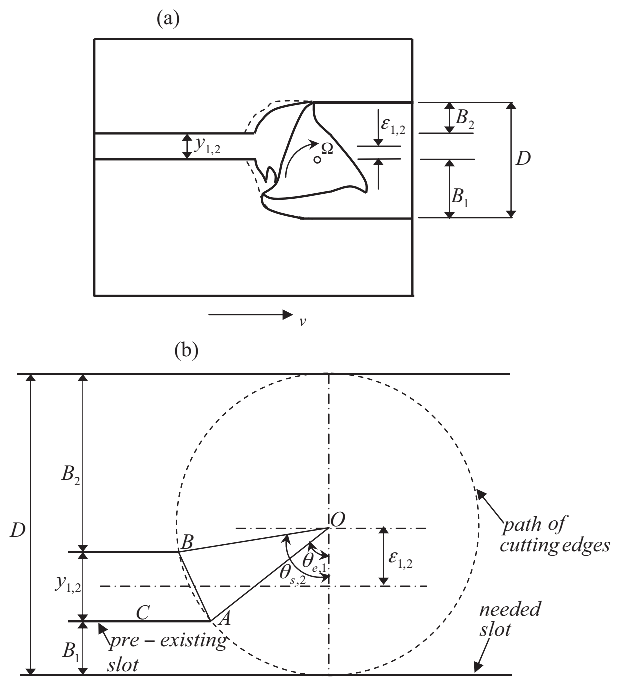

Fig. 4. (a) The geometry of combined-mode slotting. (b) Bi-radially immersed finish slotting (combined mode).

will be helpful in relative positioning of tools and discontinuities like holes, keyways, deep scratches and engravements on the surface of a workpiece in a way that reduces propensity to chatter. Should there be any dynamic disadvantages caused by short discontinuities like holes, they will have a short-leaved effect but long discontinuities like pre-existing slots would cause a dynamic problem to grow. This is why attention in this work is on the effects on process stability and productivity of size of pre-existing slots and relative positioning of centres of the pre-existing slots to the tool centres.

2. Mathematical model for combined-mode milling

The applicable delay differential equation model governing one degree of freedom (1DOF) regenerative chatter in the feed direction is identical with those in the works [30–32,43,45] given in scalar form as:

$$\ddot{z}(t) + 2\xi\omega_n\dot{z}(t) + \left(\omega_n^2 + \frac{wh(t)}{m}\right)z(t) = \frac{wh(t)}{m}z(t-\tau) \quad (1a)$$

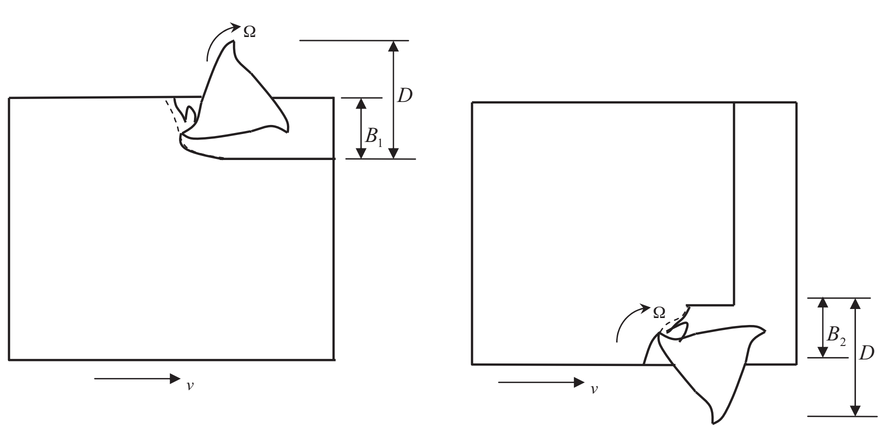

Fig. 3. The two end-milling modes (a) Up end-milling. (b) Down end-milling.