Cutting Tool Strategies for Multifunctional Part Configurations: Part I – Analytical Economic Models for Cutting Tools

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The optimisation problem of multifunctional cutting tools, including multistep and combination tools, has been investigated. The tools’ concepts for their physical understanding are discussed in order to provide the necessary background for the reader. Since they are not available in the literature, the necessary mathematical models for the optimisation are analysed based on constant tool speed (rpm), constant surface speed and variable speed or feed for each tool step and/or function. The integration of the mathematical models in optimisation schemes results in an analytical design tool for modelling and simulation of the advanced multifunctional tools in an early part processing stage that refines the process and tooling approaches while determining the sensitivity of these tools to the performance and production cost of individual machines. The aforementioned problem has been theoretically analysed here, while heuristic optimisation algorithms for determining the optimum cutting speed(s) and feed(s) for the multifunctional tools are presented in Part II of this paper. Experimental results and analytical examples which demonstrate the effectiveness and advantages of the proposed approach utilising the described mathematical models are presented in Part II.

Keywords: Cutting tools; Economic models; Combination tools; Multistep tools

1. Introduction

Currently, the majority of tools carry out a single function and generally are used for only one operation or are made to machine a single configuration of a part. However, the use of multifunctional cutting tools is becoming highly attractive and even necessary in single spindle manufacturing systems in order to increase productivity and/or quality and reduce cost.

The family of a multifunctional cutting tool includes both combination and multistep tools. The term combination is used for tools which are utilised in more than one distinct operation while the term multistep is applied to tools employed for manufacturing a multistep configuration in one motion. The difference between combination and multistep tools is that the former ones consist of a single or multiple geometry which perform at least two different distinct operations at consecutive time intervals. For example, the valve guide and seating in an engine block is manufactured by a generated head or plunge tool. The generated head tool is considered to be a combination tool since it bores and/or reams the guide and then in another machine motion it bores the seating. On the other hand, the plunge tool is a multistep tool since it will machine the guide and the seating in one motion. The aforementioned tools are employed not only for the advantages of either reducing the machining time and eliminating tool change time in NC machines or reducing the machining stations in a transfer line, but also for improving part quality and functionality. For example, multistep drills and/or reamers are used in order to guarantee concentricity and straightness between the different hole diameters.

The justification for use of multifunctional tools, which usually have a higher degree of complexity with respect to their geometry, tool life and reliability than the conventional tools, is often accomplished on the basis of a comparison with the conventional or single step tools. The optimum cutting conditions of the aforementioned tools are necessary not only for the evaluation of the product design and quality, but also for the determination of the part processing and required machinery based on which the production time and production cost are estimated. Availability of analytical methods for the evaluation of the previous
tools will facilitate a decision as to the use of these tools in both product and process design simultaneously. The optimisation of cutting conditions for conventional tools has been undertaken by several investigators during the past two decades [1-3] whereas, the optimisation of multifunctional tools has been totally neglected.

This research is reported in a two-part paper, the first of which analyses fundamental mathematical models (objective functions) and methodology for the determination of the optimum cutting conditions for combination, multistep and single point tools generating stepped configurations in order to reduce the production cycle time and cost and maximise the tool life and reliability. Physical constraints regarding the cutting parameters, force, power and surface finish, as they arise in the different operations, are also considered. The solution scheme (based on heuristic algorithms) for the aforementioned optimisation problem is described in the second part of the paper. The analytical results in Part I are discussed through simulation examples in Part II together with the presentation of some experimental results.

2. Formulation of the Multistep Tool Problem

The multistep tool design, usually adapted in rotated tools for the machining of stepped hole configurations, will be analysed in this section. In addition, the single point boring tools utilised on lathes for stepped bores are considered. The mathematical analysis that follows for the rotated tools can, however, be easily applied to stationary multistep tools. Multistep tools are often used to drill or ream multidiameter holes (see Fig. 1), drill and counterbore, drill and chamfer, ream and chamfer, drill and thread, etc. These tools have more than one cutting edge along their axis and can complete the part configuration in a single tool motion during which two or more tool steps are cutting simultaneously. However, the boring of stepped holes can be accomplished with a multistep boring bar or a single point tool. The single point tool can machine one-by-one all the bore diameters with the same cutting edge when it is used in a lathe.

Multistep tools are made with or without brazed tips and with indexable inserts or replaceable tool bits which require a different mathematical analysis; the wear of one indexable step does not necessarily require the regrinding or disposal of the other unworn steps on the tool as opposed to the solid or brazed tools.

The cutting conditions for the various steps in a multistep tool can differ depending on the tool’s geometry, size, material and equipment. The major reasons for the spindle rpm change to be considered in practice are: (a) to reduce the surface speed of the larger tool step in order to prevent high temperatures at the cutting zone and high wear rate; (b) to optimise the speeds of a multistep tool when there are two or more steps comprising different tool materials; and (c) for obtaining good part quality and surface finish. The tool steps can operate at the same spindle speed (rpm), same surface speed, at a different surface speed, and spindle rpm and/or at a different feed. The determination of the best operation strategy for a particular application is dependent on the tool, operation economics and the capability of the machine tool control system.

The simplest method is to use constant spindle rpm and feed, which results in a different surface speed at the various tool steps. The next consideration would be to apply a constant surface speed strategy which requires a change of the tool rpm when a larger diameter tool step is in contact with the workpiece during cutting so that the specified surface speed limit is not exceeded by any tool step. This approach is considered when there is a significant change between tool step diameters. Today’s technology can incorporate a speed or feed change within 50–100 ms in a controllable manner and this can be standardised at any time on NC machining centres with compatible control systems. The last and least desirable strategy is to operate the various tool steps at different surface speeds and spindle rpm, which is sometimes applied in practice in order to use a compromised speed for steps with a significant difference in their diameter; this method can be applied to single step tools with a large length to diameter ratio such as drills, reamers, etc. utilised in high speed machining, without the application of bushing at the entrance, where they have to enter the part at conventional (low) speeds and feeds which are then increased to the optimum