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The application of tool deflection knowledge in process planning to meet geometric tolerances

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Abstract

Machine tool deflections due to cutting forces can result in dimensional errors on workpieces. The problem is most severe when flexible tools such as end mills are used. When dimensioned features are specified with tolerances, process planning should examine the compromise between achieving high productivity rates and meeting dimensions within the specified tolerances. The use of geometric dimensioning and tolerancing permits interaction between size and position and makes bonus tolerances available. The errors occurring in end milling are first examined and modelled using regression methods. A procedure is proposed for selecting optimal feed rates that ensure that tolerances can be met. The process is demonstrated in machining a slot using the down milling mode. The use of a tolerance analysis chart clarifies the results of the test in relation to the tolerance standards. The need to consider the transient errors at the exit of the cut is demonstrated.

Keywords: Tool deflection error; Transient State error; Geometric tolerances

1. Introduction

In modern machining practice, there are competing pressures for productivity and part accuracy. It has been pointed out [1] that a 50% increase in tool life would lead to a 1.5% reduction in production cost whereas a 20% increase in productivity would lead to a 15% reduction in production cost. Greater gains are clearly available by increasing metal removal rates but this in turn creates problems in holding accuracy on parts since an increase in metal removal rates, particularly if achieved through higher chip loads, leads to greater cutting forces. In a CIRP keynote paper [2] that deals with machining errors, it is reported that, "deflection of the machine due to cutting forces dominates the error budget". End milling is a particular machining process that has received a lot of attention in the context of tool deflection [3–7]. End mills are comparatively flexible tools that deflect easily, regardless of the rigidity of the machine in which they are used. Moreover, the magnitude, application point and direction of the resultant cutting force change with the rotation of the tool. There is thus an inherent and unavoidable periodic variation in the cutting force that is partly responsible for the dimensions that result on the cut surface. In addition, in selecting machining conditions, it is easy to stray into combinations of feed and speed that induce machining instabilities such as chatter that further affect surface finish and dimensions.

A number of methods have been proposed to deal with tool deflection. A recommendation to use the shortest possible tool for the greatest rigidity is obvious. Feed rate regulation has also been proposed [8–10]. However, a feed rate reduction may result in the tool operating at a level below its potential and frequent changes in feed rate may result in an inconsistent surface quality [11]. Another proposed method is tool path compensation. Watanabe et al. [12] developed an adaptive control system on an NC machine that altered the tool path to compensate for surface errors. Suh et al. [5] investigated a tool path correction method based on an instantaneous deflection model whilst Yang et al. [11] proposed a tool deflection compensation method based on tool tilting. Law et al. [13] presented a method that predicts contour

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accuracy as a result of tool deflection and compensates for the error. Compensation methods such as these can reduce the errors occurring while maintaining the initial process conditions for maximum productivity but there is little work reported that considers machining errors in the context of process planning to meet specified part tolerances. The machining of complete part features often requires a combination of steady state cutting and transient cutting conditions where the cutting geometry changes. An example of the latter occurs at the entry and exit of cuts. Force variations in these instances pose problems in holding tolerances over the whole of a feature's surfaces.

Geometric dimensioning and tolerancing (GD&T) has been in use for many years as an alternative to traditional coordinate dimensioning. It is a method used to control variations of a part from its specified size and form to meet part functionality or interchangeability requirements. In particular, it introduces methods that link the size and position of features from datum surfaces. It offers the prospect of bonus tolerances on position when the size of features is targeted at one of the limits of size with the use of a material modifier. Instead of simply searching for a compensation methods to reduce the error of a cut surface, the wider problem is to consider actual part requirements at the process planning stage, to examine the tolerances that are required to be achieved, to evaluate the opportunities offered through the interaction between size and position and to recommend process conditions that can meet the tolerances specified.

This paper considers the errors that occur in the end milling process and evaluates the process planning decisions for a simple part containing a feature specified with GD&T that is to be machined by end milling. The need to take a complete view of the machining requirements is demonstrated.

2. Characterisation of tool lateral deflections in end milling

To anticipate the surface error on a part feature at the process planning stage, prediction of the cutting forces is required. The factors that influence the cutting forces are work material, tool geometry and process conditions. Surface errors are determined by tool deflection normal to the cut surface, which in turn is linked with the normal component of the resultant cutting force F_N and the tool work flexibility. Fig. 1 shows an end mill in a cut where d_A is the axial depth of cut and d_R is the radial depth of cut. There has been a considerable amount of work on the topic of forces in milling. Mechanistic cutting force models were first developed by Tlusty and MacNeil [14]. This approach computes the instantaneous force on incremental sections of the helical cutting edge, based on the specific cutting force of the work material and the frontal area of the chip being removed at that increment. The overall instantaneous force is found by summing the incremental contributions. Other approaches have also been developed and a detailed review is presented in [15]. In terms of linking forces with dimensional accuracy, Budak and Altintas [16] examined tool deflection and indicated how metal removal rates could be optimised while maintaining workpiece accuracy. These authors also used a mechanistic cutting force model and commented that the maximum difference between predicted and measured forces was about 15% for both up milling and down milling. The approach taken in the present work is simpler in that a regression equation is used to link the normal force with the process variables. This is slightly less accurate than the mechanistic model but does not alter the process planning considerations.

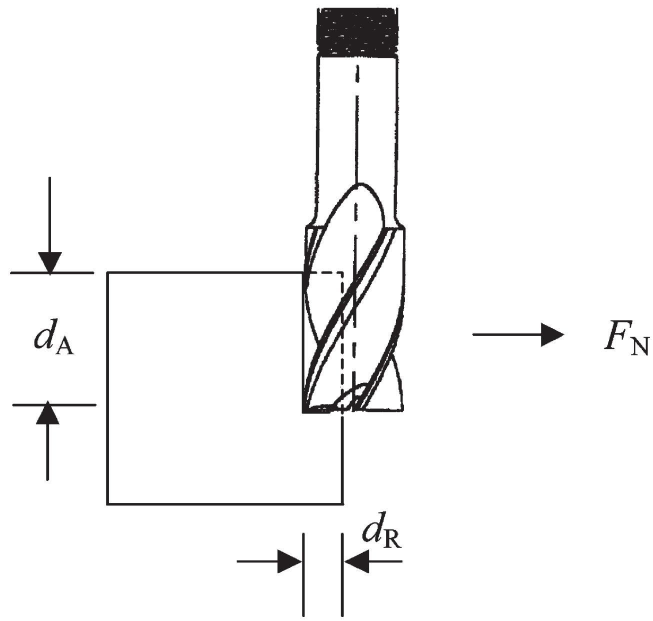

Fig. 1. Side view of end mill in cut.

Fig. 2 shows the surface errors obtained in an end

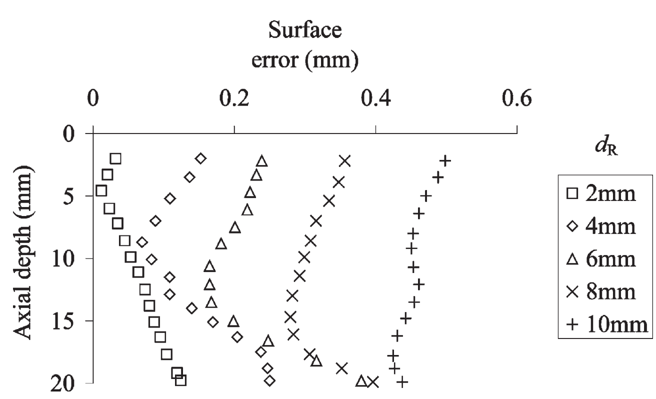

Fig. 2. Errors in down milling with increasing radial depth of cut (d_A = 20 mm, F = 200 mm/min, N = 400 rpm).