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Experimental analysis of dimensional error vs. cycle time in high-speed milling of aluminium alloy

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Abstract

Manufacturers of machined aluminium parts are among the principal users of high-speed milling. The excellent machinability of aluminium allows this technology to be used with severe cutting conditions, and at the same time permits the machining of complex shapes. There are many factors influencing the quality of manufactured aluminium parts and the economics of the manufacturing process, but little corresponding data is available, making process planning enormously difficult.

The aim of the work presented in this article is to experimentally analyse the influence of some of these factors, specifically the feed rate, the type of interpolation and the toolholder, on the dimensional accuracy of the product and the cycle time. Design of experiments (DoE) is used to determine which experiments have to be conducted to obtain a mathematical model that relates the mentioned factors with the responses.

The results show that the toolholder has considerable influence over dimensional accuracy and that the type of interpolation appreciably affects the cycle time. Details of the first-order interactions between factors have been included.

Keywords: High speed machining; Dimensional error; Cycle time; Tool path

1. Introduction

The machining of aluminium alloys is one of the largest fields of high-speed machining applications. The sectors most commonly employing this technology are the aeronautic sector and the moulds and dies industry, especially in the manufacturing of blow moulds which, being more and more demanding and competitive, require greater dimensional accuracy and surface finish and, at the same time, a reduction in costs and in manufacturing time [1]. Such a requirement is normal if we consider how the effectiveness of mould manufacturing affects the entire development cycle of new products and the technology used to manufacture the moulds is therefore an essential link in the production line [2].

Numerous and varied factors of high-speed milling influence the quality of the final part and its manufacturing economy [3]. Among these factors are the part and tool materials, the shape of the tool and the toolholder, the cutting conditions, the behaviour of the machine tool and the control performance, the type of interpolation used in generating CNC programmes and the use of refrigerants.

Individually analysing the effect of each of these factors on the final result has generated much interest. Various research projects have recently been conducted in which one of the previously mentioned factors has been correlated with mould surface roughness: Vivancos et al. [3] and López de Lacalle et al. [4] for steel machining, and Coelho et al. [5] for aluminium alloys machining. However, only a few research projects have analysed the relationship between these factors and dimensional accuracy [6], and the influence of these same factors on cycle time has been analysed in very few cases [7], almost all of which have been focussed on steel machining. Another key objective of

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recent research has been the optimisation of cutting conditions in high-speed machining, and in this field a great variety of work can be found: Kaldos et al. [8], based on aluminium alloys machining, and Chien and Tsai [9], Juan et al. [10] and López de Lacalle et al. [11], based on steel machining.

The purpose of this article is to analyse the influence of a set of factors (including some of those mentioned previously) on two of the parameters, which although considered important by mould manufacturers [2], have been researched far less: dimensional error and cycle time.

2. Manufacturing conditions

In order to minimise the cutting time of the manufacturing processes and obtain dimensional accuracy in accordance with product specifications, the most suitable manufacturing conditions for each operation must be carefully selected [12].

While, generally, only the cutting conditions (feed rate, depth of cut, cutting speed) are taken into account, each element involved in the machining process has some influence on the final result of that process.

The machine, and in our case the machining centre, is the basic element of the process. There are many types of machining centres with a variety of characteristics: power, workspace dimensions, spindle speed, travel speed on axes, number of axes and tool magazine capacity, among others.

However, other aspects related to machining centre behaviour are not as easily quantifiable and yet are also very important for the final result: the dynamic behaviour of the machine and the thermal expansion of the spindle. The latter, unavoidable due to the rising temperature of the functioning machine, can lead to dimensional errors in the part. To control it, some machine tools have temperature-controlled spindles, but warm-up is recommended in all cases to assure that expansion occurs before the manufacturing process begins, not during it, so that the entire production takes place under the same conditions.

The cutting tool is another key machining element. The term "high-speed milling" is generally used to describe end milling with a small diameter tool, less than or equal to 10 mm, at a high rotation speed, superior to 10,000 rpm [13]. Under these conditions, and given the high propensity for vibration, tool rigidity is a critical issue. This problem can be solved or minimised using a suitable toolholder. It is also important to control the tool wear and to replace the tool when the parameter to measure that wear (VB, for example) exceeds a specific value.

Numerical control is another important element in machining. Control features provide options for accurate machining and functions like look-ahead or feed-forward, considered very important in high-speed machining [14]. With regard to the machine tool and control, the type of position sensor must also be taken into account, given its significant influence on the quality of the final part.

Another element closely related to control is the NC programme. The type of interpolation used for tool path generation introduces variety, and although linear interpolation is used in most situations, when milling sculptured surfaces, the possibility of using circular or polynomial interpolations should be considered to reduce the size of the programmes and improve the dimensional accuracy. Not all controls are capable of processing polynomials, however, so in many cases the dilemma is limited to linear and circular interpolation. Between the two options, the solution most often adopted is the first.

Crucial to the creation of the NC programme is the CAM system. Currently, the majority of commercial CAM systems have high-speed machining options, which provide more suitable machining strategies for this technology. However, some research has also allowed the cutting parameters to be calculated [15], as the majority of CAM systems are based on programming the geometry and not on selecting the cutting parameter, which requires a larger amount of information about materials and tools.

This list of aspects capable of varying the results is far from exhaustive. A much longer list could be drawn up, taking into account all the factors involved in manufacturing, from the expertise of the machinist to the quality of the CAD model or the maintenance of the machine. Although it would be a very interesting starting point, drawing up such an exhaustive, comprehensive list is not one of the aims of this research.

It is obviously difficult to analyse all the factors mentioned, and for this reason the present research is limited to those factors that, according to various authors [16,17], are most representative and have the greatest effect on cycle time and dimensional accuracy. The factors considered in the analysis are:

- The type of toolholder, since good tool balance is critical to avoiding premature failure of the tool and to obtaining a good surface finish.
- The cutting conditions and, specifically, the programmed feed rate, which is the parameter that, in this case, ensures that the process is high-speed milling.
- The type of interpolation used to create the programmes, distinguishing specifically between linear and circular interpolation.

In addition to these variable factors, there are some other factors that can be considered as fixed factors by using the same configuration in all the experiments, for instance, the tool used, the execution mode, the controller type, the thermal expansion of the spindle (controlled through warm-up) and tool wear (for which a maximum value is established to indicate when it should be replaced). The effect of tool vibration can also be minimised by using a not very long tool with a large enough diameter to assure rigidity.