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Integrated optimization model for cutting data selection based on maximal MRR and tool utilization in continuous machining operations

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ABSTRACT

The search for increased productivity can be interpreted as the increase of material removal rate (MRR). Namely, increase of feed, depth of cut and/or cutting speed. The increase of any of these three variables, will increase the tool wear rate; therefore decreasing its tool life according to the same tool life criteria. This paper proposes an integrated model for efficient selection of cutting data for maximal MRR and maximal tool utilization. The results show that, it is possible to obtain a limited range of cutting parameters from where the CAM Programmer can select the cutting data assuring both objectives.

Introduction

The selection of the cutting parameters in a machining operation is a key step to achieve high productivity. Once the work piece material, the operation and the tool are chosen, the selection of three main variables is requested: depth of cut, feed and cutting speed. The time required by the CAM (Computer Aided Manufacturing) Programmer to obtain optimal values may need several iterations; therefore the use of an integrated optimization model for cutting data selection can help the CAM Programmer to reduce the development time of the NC program.

Different optimization criteria can be used in order to maximize production rate [1–3], minimizing cost [4], maximizing material removal rate [5], or maximizing tool life [6]. In other words, to maximize the amount of parts machined per hour, minimize the total production cost of a part, maximizing the material removal per time unit, or maximize the time in which a tool can be used until it reaches an established wear criteria. Thereby, the optimal cutting data depend on several related parameters, have several constraints and potentially multiple simultaneous optimization criteria. Thus it is difficult to reach a balance between them [7].

The aim of this paper is to show a developed model that will assist in the selection of the cutting data for a selected material removal rate (MRR), assuring at the same time the maximal use of the tool for a continuous machining operation. Therefore, the optimization criteria selected are the maximization of MRR and tool utilization.

In industrial operations, where a high percentage of raw material needs to be removed from the blank while keeping the machining time to a minimum, MRR is an extensively used metric. MRR is a function of feed (f), depth of cut (a_p) and cutting speed (v_c), presented in Eq. (1). The depth of cut is commonly defined to be constant for a certain situation f has an upper limitation related to the maximal mechanical load that can be applied on the tool, thereby defining a mechanical barrier. v_c has an upper limitation related to the maximal thermal load that the tool can withstand, thereby defining a thermal barrier. Therefore, the chosen cutting tool sets limitation on f and v_c for a certain work piece material. Fig. 1 shows an example of the initial cutting data work frame in terms of feed and cutting speed for a certain a_p and cutting tool. Fig. 1 also includes the mechanical and thermal barrier for the maximal f and v_c, respectively, that shall be used during the operation.

Another constraint is that the cutting tool must be changed at specific points in order to not disrupt the surface finish of the work piece. Therefore the cutting data must be selected also in order to be able to reach the tool change point without exceeding the tool life and to utilize the tool to its maximum extent.

It is important to find the balance between the two criteria of MRR and tool utilization. In case of reducing MRR, it might be possible to extend the tool life until the operation is finished,

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Nomenclature

Variables

a_p depth of cut [mm]
α, β, γ, C_t Taylor tool life equation constants
f feed [mm/rev]
k_c specific cutting force [N/mm^2]
$n_{\max}$ maximal spindle speed [rpm]
η machine efficiency
P_c cutting power required [kW]
$P_{\max}$ maximal power provided by the machine [kW]
Q_i specified MRR-level [cm^3/min]
r nose radius of the cutting tool [mm]
R_a average surface roughness [mm]
T tool life [min]
t_k machining time for the kth operation [min]
t_m effective machining time [min]
v_c cutting speed [m/min]

Abbreviations

CAM computer aided manufacturing
ETL expected tool life [min]
MRR material removal rate [cm^3/min]
RTL remaining tool life [% of ETL]
UTL utilized tool life [% of ETL]
V_B tool wear (Flank wear) [mm]

avoiding for example a tool change; or in case of increasing MRR, reducing the machining time of the operation, reducing the tool life as well.

Status in CAM programming

The initial cutting data used is selected by the CAM Programmer using both old know-how and tool supplier recommended data. In modern CAM systems, there is still a lack of guidance for the CAM Programmer to define the best possible cutting data and points along the tool trajectory, where the tool shall be changed with regard to the amount of time that a cutting tool can be used (tool life) and the amount of time that the tool is actually used (tool utilization). As highlighted by previous studies [8], there is a need on the CAM programming system to have an estimated value of the tool life left on the cutting tool during the creation of the CAM program.

In general, the creation of a CAM program is a time consuming process and several iterations and re-runs are needed along the process, including real tests on the machine, until the optimal cutting data is found.

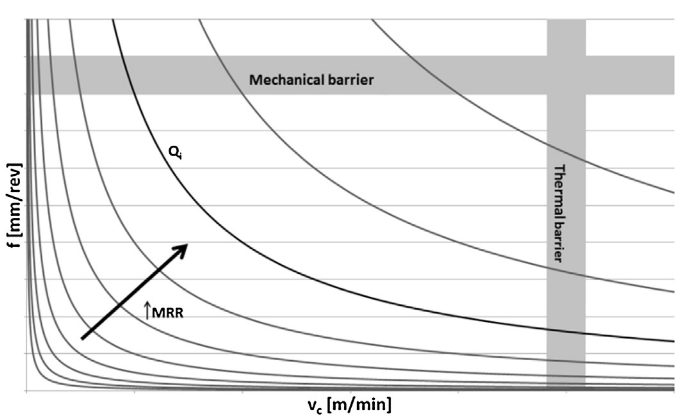

Fig. 1. Initial cutting data work frame for a certain tool defined by a mechanical barrier for the maximal feed and a thermal barrier for the maximal cutting speed. Family of iso-MRR curves considering constant depth of cut a_p = 2 mm, including specified MRR-level as Q_i = 640 cm^3/min on the bold curve. Each iso-MRR represented doubles the value of the previous iso-MRR.

Integrated optimization model

The selection of cutting data values will vary depending on different variables such as the work piece and cutting tool material, the selected cutting operation, the selected tool change points and the aimed MRR.

The mathematical model described in this section is able to calculate, first expected tool life (ETL), second utilized tool life (UTL) and thirdly remaining tool life (RTL) of a tool during a metal cutting operation. The use of a model can help to predict [9], in this case the tool wear. By using this model, it is possible to select the cutting data and its optimization with respect to the previously mentioned criteria of MRR and tool utilization.

Iso-MRR curves

The material removal rate (MRR) on a turning operation is the volume of material that is removed per minute and given as:

$$\mathrm{MRR}(v_c, f) = v_c f a_p \quad (1)$$

where v_c denotes the cutting speed, f is the feed and a_p is the depth of cut. In this work a_p is considered to be constant, therefore MRR is a function of v_c and f.

The iso-MRR curve is the line in which the MRR value is maintained constant. The iso-MRR curve is obtained in a $\{v_c, f\}$ graph by finding the cutting data combinations $\{v_c, f\}$ that satisfy the condition

$$\arg_{v_c, f} \mathrm{MRR}(v_c, f) = Q_i \quad (2)$$

where Q_i is a specified MRR-level.

Fig. 1 shows a family of iso-MRR curves for a fixed value of a_p and different values of Q_i. Each iso-MRR represented doubles the value of Q_i of the previous iso-MRR. Note that there are several combinations of $\{v_c, f\}$ values that, for a constant depth of cut, will generate the same material removal rate value. But the different combinations of those parameters will result in different tool life. A cutting tool supplier often provides a recommended set of cutting data. Normally, for a rough operation, the used values will be the highest recommended by the cutting tool supplier and for a specific operation-work piece material-tool combination. The recommended cutting data may however not be the most suitable for a specific machining operation, depending on many factors, such as the intended tool path including its complexity and length.

As previously mentioned, to find the most beneficial operating point for the cutting tool, the expected tool life and utilized tool life must also be taken into account.

Tool wear, tool life and tool utilization

It has been considered that during a cutting operation, the tool will not present an early failure during the operation, neither brittle nor thermal failure due to either high cutting forces or high temperatures, as mentioned in the Introduction section. Instead, the tool wears off gradually until the flank wear reaches its selected tool wear limit (V_{Bn}). Tool life can be described as the amount of time that a tool can be used until the flank wear has reached the tool life criteria [10], as shown in Fig. 2. The diagram shows the influence of v_c on T, where a lower value of v_c increases T.