euspen's 25th International Conference & Exhibition, Zaragoza, ES, June 2025
www.euspen.eu

The effect of passive time upon cutting power and material removal rate in micro endmilling of RSA6061-T6

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Abstract

During micro endmilling process, the determination of the cutting power is the product of the specific cutting energy and the material removal rate. Micro endmilling operation is a process where material removal occurs intermittently and can be analyzed under two conditions: engaged cutting and non-engaged cutting. In engaged cutting, more than one tooth of the cutter is acting in the cutting zone; and in non-engaged cutting, only one tooth of the cutter is acting in the cutting zone so that when this tooth leaves the cutting zone it takes a short period of time for the other tooth to enter the cutting zone again. Thus, in non-engaged cutting, it must be considered that there are two periods occurring during the removal process: cutting time (active) and idle time (passive). For analysis purposes, this passive time may result in a deviation of the cutting power value from the value spent by the process. In this paper, a quantitative analysis of the process for determining the cutting power values for the non-engaged cutting condition in micromilling of an ultrafine grain aluminum alloy (RSA 6061-T6) will be performed. A 0.8 mm diameter carbide micro edmilling tool will be used in a machining center. Thus, it will be experimentally demonstrated that the passive time should not be considered for the purpose of calculating the material removal rate. The method demonstrated that when this passive time is considered for the purpose of calculating the cutting power, the estimated value can be up to 40% lower than the value effectively measured by dynamometer. On the other hand, the comparative analysis of the experimental and theoretically calculated values, based on the material removal rate without taking into consideration the passive time, demonstrates that the estimated cutting power value reaches equivalent values. The work also shows that non-engaged cutting can present advantages in terms of energy consumption and tool life.

Cutting Power, micromilling, material removal rate, RSA6061-T6

1. Introduction

Milling is a machining operation in which material removal occurs through the rotational movement of a multi-cutting-edge tool known as a milling cutter. The milling cutter has cutting edges symmetrically arranged around an axis, and the rotational movement of the tool, combined with the feed motion of the workpiece, generates the desired shape on the workpiece surface. This process allows for the machining of various surfaces and shapes [1]. Milling is a versatile material removal process that enables the machining of complex surfaces and various shapes, making it essential in multiple industrial sectors.

There are different types of milling, such as peripheral and face milling, which can be either up milling or down milling. In peripheral milling, machining occurs mainly on the cylindrical surface of the tool, while in face milling, machining is performed on the front surface of the tool [2]. Milling can also be classified as full-slot milling, partial-slot milling, or face milling, depending on the cutting thickness and tool feed.

It is important to highlight that the cutting thickness varies according to the type of milling and can be influenced by the direction of the workpiece feed relative to the cutter's rotational movement. In up milling, the cutting thickness gradually increases until reaching a maximum value, whereas in down milling, the cutting thickness decreases until reaching a minimum value.

The components of the machining force in milling vary constantly due to the dynamics of the process, with continuous changes between lateral material flow (ploughing) and material shearing occurring throughout the process [3]. For high machining quality, the component in the cutting speed direction—known as the cutting force—is one of the most important factors to analyze. To ensure a higher production rate and that the cutting tool withstands the applied forces, understanding this force in rotary processes must be enhanced [4].

The cutting energy can be determined from the cutting force, which represents the work performed by the tool in the instantaneous cutting direction. The time derivative of this energy corresponds to the cutting power consumed at a given moment during the machining process. Mastering and controlling this parameter brings several advantages, such as regulating the heat generated on the workpiece surface and the cutting tool, preventing excessive machine tool or tool stress, and optimizing energy consumption in the operation. Cutting power, derived from the cutting force, can be determined in two ways: the first is based on the cutting force and cutting speed, and the second is based on the specific cutting pressure and material removal rate. The specific pressure and material removal rate method is generally the most used in milling operations. The objective of this paper is assessing the effect of passive time upon cutting power and material removal rate in micro endmilling.

2. Methodology

Due to the combination of the feed motion of the milling table motion and the rotational movement of the cutting tool, the chip thickness varies instantaneously. This results in a commashaped chip structure along the path where the milling cutter tooth passed and removed material, as illustrated in Fig. 1.

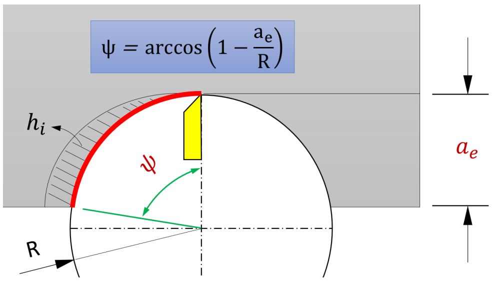

Figure 1. Partial front milling: cutting cinematics.

Where, a_e is the width of cut, and f_z is the feed per tooth. Figure 1 illustrates the variation in chip thickness (h_i). The surface area is considered the machining zone. Due to the successive movements of the cutting tool, the uncut chip surface consists of an external cutting length, generated during the cutting moment, and an internal cutting length, produced by a previous cut. However, both lengths actively interact with the tool. Therefore, the effective cutting length can be considered as the contact region defined by the engagement angle (ψ), of the machining zone. This angle is determined at the intersection point of successive cuts up to the maximum chip thickness.
For chip thickness variation, the following equation can be used:

$$h_i = f_z . sin\psi_i . sen\chi_r \tag{1}$$

Due to the instantaneous chip thickness variation, the chip thickness in milling process can be represented as the average variation in chip thickness, as shown in Eq. (2), referred as the mean chip thickness.

$$\bar{h} = \frac{1}{\psi - 0} \int_0^{\psi} f_z . sin\psi_i . d\psi = \frac{f_z . a_e}{\psi . R} \tag{2}$$

where,

$$cos\,\psi = 1 - \frac{a_e}{R} \;; \qquad \psi : rad$$

Once the mean uncut chip thickness is determined, it becomes possible to estimate the volume (V_L) which is the product of mean chip thickness, the depth of cut and the cutting length. Thus, for $\chi_r = 90°$:

$$V_L = \bar{h} . a_p . (\psi . R) = f_z . a_e . a_p \;; \qquad \psi : rad \tag{3}$$

However, the material removal rate can also be determined as the ratio between the volume of material removed and the feed time, as shown in Equation (4). The relationship between the feed length and the feed time is known as the feed rate (V_f).

$$Q = \frac{a_e . a_p . L_f}{t_f} = a_p . a_e . V_f \tag{4}$$

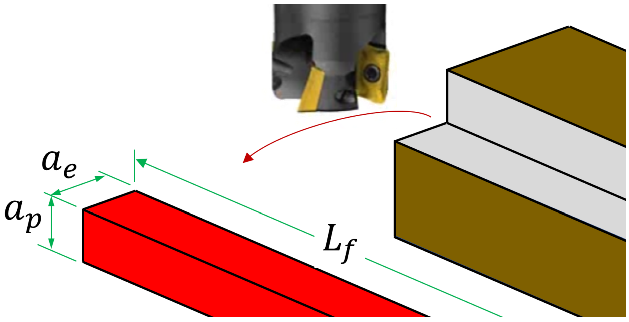

Figure 2. Illustration showing the milling process with a position angle of 90º.

The volume of material removed is calculated according to the structure of a rectangular parallelepiped, the product of the working penetration, the machining depth and the total displacement in the feed direction, as shown in Fig. 2
However, non-engaged milling results in a delay before the cutter tooth enters the machining zone after the prior tooth exits. Since the tool does not remove material during a certain period, this time should be disregarded in the effective calculation of the material removal rate. Figure 3 illustrates the movement of one complete tool rotation in which the milling is not engaged, showing a period of idle movement (passive time). The cutting time refers to the duration in which the cutter tooth passes through the machining zone, removing material, while the passive time is the interval the cutter tooth takes to complete its motion before the next tooth enters the machining zone to remove another layer of material:

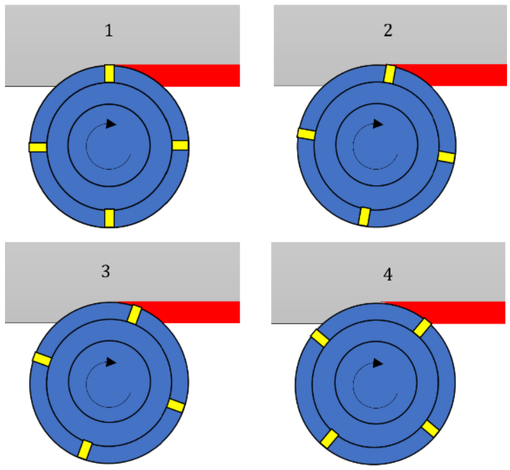

Figure 3. Illustration of discordant partial milling with idle time for four teeth endmill.

Considering the conventional method for calculating the material removal rate, for a complete tool rotation, Q is given by the ratio of the volume of material removed in one rotation (two chips formed: $2V_L$) to the elapsed time for this rotation ($t_f = 2t_c + 2t_p$), where t_c is the cutting time and, and t_p is the idle time. Thus, Q is estimated by the following equation:

$$Q = \frac{2V_L}{t_f} = \frac{2V_L}{2t_c + 2t_p} = \frac{V_L}{t_c + t_p} \tag{5}$$

It can be observed in Equation (5) that the time during which no material removal occurred is masking the results, causing Q to have a lower value than the actual one. Therefore, if the cutting process includes idle movement, the total elapsed time cannot be used in the calculations of the material removal rate. Thus, to determine the effective material removal rate in a non-engaged milling process, the idle time must be excluded from the equation, as shown in Equation (6). Knowing that the uncut chip volume is given by $\bar{h} . a_p . L_c$ [5] and that the ratio between the cutting length and the cutting time is the cutting speed, we have:

$$Q_e = \frac{V_L}{t_c} = \frac{\bar{h} . a_p . L_c}{t_c} = \bar{h} . a_p . V_c \quad (6)$$

4. Experimental procedures

Micromilling tests were carried out using a Hermle C800U CNC machining center. This machine tool has 18 kW total power, 24000 RPM maximum spindle speed and 0.5 µm positioning error. Spindle speed (n=20000 RPM) and depth of cut (ap=50 µm) were kept constant. Cutting conditions are shown in Table 1. No cutting fluid was used in the cutting tests. Two-flute carbide endmills with 0.8 mm diameter, without coating, from Swisstool® were used. Tool geometry valus are shown in Table 2. The workpiece is made of the aluminum alloy RSA 6061-T6– average grain size of 1 µm. This ultrafine grain material was used to avoid anisotropic effect of the microstructure captured by tool force signals and to attenuate signal noise. The machining strategy adopted was the partial cut, in order to facilitate chip removal from cutting zone. First, a channel was machined with the same size of the micromill diameter. Then, the tool was moved laterally in the x-direction to carry out the machining tests with cut width smaller than the micro endmill diameter (partial cut) (Fig.4). The workpiece fixture mounted on the piezoelectric dynamometer (9256C2 from Kistler). The data acquisition system for the cutting forces consists of a charge amplifier 5233A (no filter used), a multifunction I/O device (USB-6216 from National Instruments), and the program Labview™ V.7.1.

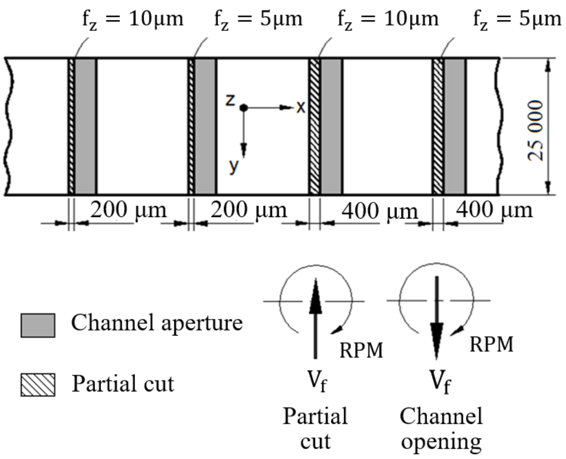

Figure 4. Machining strategy and cutting conditions.

Table 1. Experimental cutting conditions for micro endmilling tests.

Micromilling			
5	5	10	10
400	200	400	200
$f_z5\ a_e400$	$f_z5\ a_e200$	$f_z10\ a_e400$	$f_z10\ a_e200$

Table 2
Geometry of the micro endmill.

	α_2	α	λ	χ_r	r_ε [µm]	r_e [µm]
Tool	15°	17°	30°	90°	5	3.287

5. Results

Figure 5 presents the results of the machining force components in a partial face milling operation from the beginning to the end of the process. It can be observed in Fig, 5 that, after reaching the maximum chip thickness (point A)—which corresponds to the moment when the second tooth of the milling cutter exits the machining zone—there is a decay period in the dynamometer reading along with an idle movement of the tool, as no material removal occurs during this interval. After this interval (from point A to point B), the first tooth of the milling cutter re-enters the machining zone (point B). When the first tooth comes into contact with the workpiece, the forces begin to increase progressively as the chip thickness increases.

Thus, the distance between points B and C represents the time during which chip formation occurs. When the first tooth reaches the maximum chip thickness (point C), the chip is expelled from the workpiece due to the rotational motion of the cutting tool, and at this exact moment, no further material removal occurs. Consequently, the forces start to decay again (from point C to point D). After the idle movement, a new milling cycle begins, from point D to point E, carried out by the second tooth of the milling cutter. These cycles then repeat successively until the end of the milling operation.

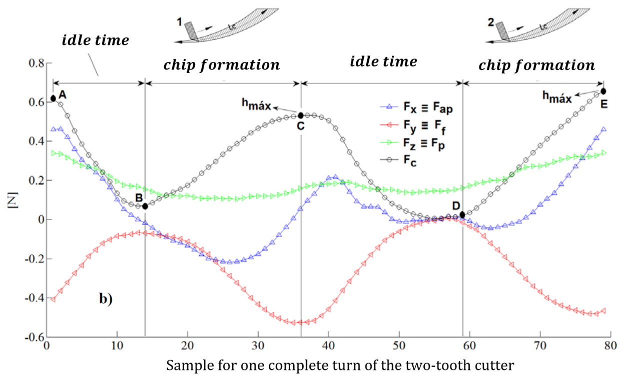

Figure 5. Machining Force Components in Partial Face-Facing Micro Milling of a Cutter Turning in Which Forms 2 Chips: Vc= 50 m/min, fz = 5 µm/dente, ae = 0,4 mm, ap = 50 µm, R = 0,4 mm, ψ = 60º e Z = 2. Modified from Militão Dib et al. (2018).

By shifting the force signals from all cycles to a common origin, it was possible to obtain an average force line for the cutting force. For each condition, an average line was determined, and based on this line, calculations were performed for the cutting power as a function of the cutting force and cutting speed, the specific cutting pressure, and both the conventional and effective material removal rates.

An analysis of the various representations of cutting power is shown in Fig. 6, which depicts the cutting power consumed in chip formation ($P_{c_{real}}$:thick solid line), The cutting power increases with the rise in cutting thickness due to the greater effort required from the cutting tool to remove a larger volume of material. The real cutting power was determined by the product of the cutting force measured by the piezoelectric dynamometer and the cutting speed. The calculation method that most closely matched the variation of this cutting power was the one based on the average cutting force ($P_{c_i} = \overline{F_c}.V_c$:). On the other hand, when calculating the power based on the conventional and effective material removal rates ($P_{c_i} = \overline{k_s}.Q\ e\ P_{c_i} = k_{s_i}.Q_e$, the values showed a small discrepancy. The power estimated using the constant and the slope of the regression line exhibited a significant difference from the real values.

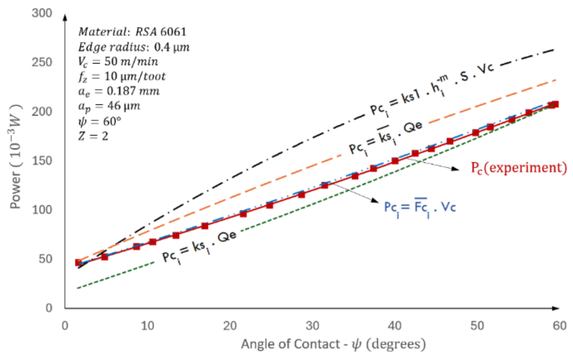

Figure 6. Cutting Power in Chip Formation in Partial Micromilling**.**

Finally, Fig. 7 presents a comparison between the cutting power calculated as a function of the conventional material removal rate ($Q = a_e . a_p . V_f$) and the effective material removal rate ($Q_e = \overline{h} . a_p . V_c$) and the actual cutting power consumed in micromilling operations with idle movements.

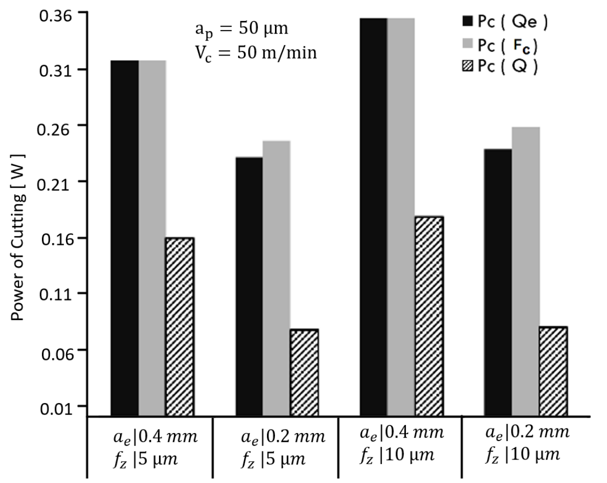

Figure 7. Comparison of actual Cutting Power $\mathbf{P_c(F_c)}$, Cutting Power as a function of conventional removed material rate $\mathbf{P_c(Q)}$ and the rate of material removed effected $\mathbf{P_c(Q_e)}$.

As observed in Fig. 7, the cutting power calculated based on the conventional material removal rate, $P_c(Q)$, showed lower values compared to the real cutting power $P_c(F_c)$. This effect is due to the time intervals in which no machining occurred. Since this idle time is considered in the calculation of the conventional material removal rate, the cutting power values tend to be lower, as Q represents the ratio between volume and elapsed time.

6. Conclusions

In this study, we investigated the actual cutting power in the micromilling process by measuring machining forces using a piezoelectric dynamometer. We conducted partial micromilling experiments to clarify and accurately determine the cutting power, considering the variation of cutting parameters. This approach allowed for a detailed analysis of different methods for calculating cutting power, contributing to a better understanding of operating conditions and their influence on the accuracy of the milling process.

The main conclusions of this study are:

- The machining parameters used in the experimental methods applied to the RSA6061-T6 material resulted in cutting forces ranging from 180 mN to 400 mN for both cutting tools. The cutting force for these experiments can be estimated using the constants = 364 N/mm² and z = 0.27. Thos Parameter are generally used to estimate the cutting force using Kienzle and Victor proposed method [6-7]

- The cutting power ranged from 60 mW to 360 mW. Based on these results, it is concluded that when the milling process is engaged (i.e., more than one cutting edge is active in the machining zone), the conventional material removal rate can be used in the cutting power calculations. However, when the cut is not engaged, the effective material removal rate should be used for accurate cutting power calculations.

- The method demonstrated that when this passive time is considered for the purpose of calculating the cutting power, the estimated value can be up to 40% lower than the value effectively measured by dynamometer.

- Since this is micromachining, the cutting power values obtained through direct power measurement in the machine's drive motor would possibly bring with them a lot of uncertainty and little accuracy in estimating the cutting power considering the passive time.

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