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Study of different cutting strategies for sustainable machining of hardened steels

C.Vila[a,]*, José V. Abellán-Nebot[a], H. R. Siller-Carrillo[b]

[a]Department of Industrial Systems Engineering and Design, Universitat Jaume I, Campus de Riu Sec, Castellón, 12006, SPAIN
[b]Escuela de Ingeniería y Ciencias, Instituto Tecnológico y de Estudios Superiores de Monterrey, Monterrey NL, 64849, MEXICO

Abstract

This paper studies the power consumption of different cutting strategies in face milling operations in order to evaluate the efficiency of each cutting strategy. The experimental procedure evaluates the machine-tool efficiency by estimating cutting forces and measuring the power consumption. After modeling the efficiency of the machine-tool at different states (idle, fast movement and cutting at different conditions), the cutting strategies and cutting parameters are analyzed and compared in terms of sustainability (CO_2 emissions) and quality (surface roughness). The optimal cutting strategy to ensure a predefined quality specification is also derived.

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Keywords: Sustainable machining; Hardened steels; Cutting strategies.

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1. Introduction

Currently, there is a growing social commitment towards the development of systems and manufacturing strategies with minimal environmental impact permitting enforcement of sustainable manufacturing. Preliminary environmental studies for machine-tools in material removal processes (e.g. turning, milling) indicate that more than 99% of the environmental impacts are due to the consumption of electrical energy [1,2]. Therefore, reducing electrical energy consumption of manufacturing processes not only benefits the manufacturers economically but also improves their environmental performance.

Within manufacturing technologies, specifically in the field of machining processes, numerous research studies have been directed towards minimizing the energy consumed in the operation developing efficient production strategies while maintaining product quality [1,3]. For example, at tool path planning level, there is usually a preferred orientation of a workpiece on the machine-tool (the orientation of the tool path and workpiece-setup is defined with respect to the feed drive axis) and, for that orientation, a preferred tool path to remove the desired material.

Choice of tool path is very critical for efficient application of the milling process. The tool path determines the axial depth of cut thereby controlling the maximum cutting force while machining. The definition of the tool path controls the productivity by way of cycle time and it is usually handled by computer aided manufacturing (CAM) systems. The tool path direction along with direction of spindle rotation also controls the chip removal direction.

Several studies have been conducted to optimize tool paths for reduction of forces, improving edge quality, reducing tool or part deflection and reducing cycle time losses. Rangarajan and Dornfeld [4] studied the effect of the

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* Corresponding author. Tel.: +34-964-728-185; fax: +34-964-728-170.
E-mail address: vila@uji.es

orientation of tool paths with respect to the machine-tool feed drives to try to reduce the cycle time losses and balances the loads on the feed drives. Kong et al [5] showed that an efficient cutting strategy can often result in substantial savings in energy to produce the same part feature with no loss of cycle time. At the micro-planning level specific energy of material removal (J/cm^3) is inversely proportional to the material removal rate (MRR). This implies that higher removal rates will be more efficient [6]. In this field, Kara et al [2] presented an empirical approach to characterize the relationship between unit energy consumption and process variables. Eight different CNC turning and milling machines were selected for investigation and they showed that generic models for predicting energy consumption in machine-tools can lead to develop potential energy saving strategies during product design and process planning stages.

In this paper, a theoretical and experimental study of energy consumption in machining hardened steels is conducted considering different cutting strategies. For the sake of simplicity, this study is focused on face milling operations although the same methodology can be conducted to analyze the environmental impact of different cutting strategies in other machining operations such as pocketing, end milling, slotting, and so on. The main goal of the study is to characterize the face milling process in terms of sustainability (CO_2 generation) and quality (surface roughness) in order to select optimum cutting strategies under quality constraints.

This paper is organized as follows. First, Section 2 presents theoretical models to estimate cutting forces, power consumption and surface roughness in face milling operations. Section 3 presents the experimental study to analyze the actual power consumption in face milling operations of hardened steels. The study models the machine-tool behavior when the machine-tool is idle, under fast feed movements, and milling under different cutting conditions. Furthermore, an empirical surface roughness is derived. Section 4 studies the power consumption and the specific energy of material removal required at different cutting strategies and cutting parameters considering the actual machine-tool behavior. As a result, an optimal cutting strategy and cutting parameter combination is defined. Finally, Section 5 presents the conclusions of the paper.

2. Theoretical models

2.1. Cutting force

In order to analyze the power consumption for each cutting strategy, the cutting force required for a given machining operation should be evaluated. For a face milling operation, the spindle speed (N) and the feed rate (V_f) are evaluated as:

$$N\ (rpm) = \frac{V_c \cdot 1000}{\pi \cdot D_e} \tag{1}$$

$$V_f\ (mm/min) = z \cdot f_z \cdot N \tag{2}$$

where V_c is the cutting speed in m/min, z the number of cutting flutes and D_e is the effective cutting diameter in mm which can be obtained as

$$D_e\ (mm) = D_c + \frac{2 \cdot a_p}{tan\, \kappa_r} \tag{3}$$

and D_c is the cutting diameter, a_p is the axial depth of cut and κ_r is the cutting edge angle. The specific cutting force can be evaluated as:

$$k_c (N/mm^2) = k_{c_1} \cdot\ {h_m}^{-mc} \cdot \left(1 - \frac{\gamma_0}{100}\right) \tag{4}$$

where k_{c1} is the cutting force in the cutting direction needed to cut a chip area of 1 mm² that has an average thickness (h_m) of 1 mm and uses a cutting-tool with a rake angle of 0. The k_{c1} value depends on the workpiece material and can be obtained from cutting-tool data. In face milling, the average thickness is obtained as:

$$h_m(mm) = \frac{sin(\kappa_r)\cdot 180\cdot a_e\cdot f_z}{\pi\cdot D_c\cdot arcsin(\frac{a_e}{Dc})} \tag{5}$$

where a_e is the radial depth of cut. Therefore, the cutting force can be evaluated as:

$$F_c\ (N) = k_c \cdot A \tag{6}$$

where A is the chip area which is:

$$A(mm^2) = h_m \cdot \frac{a_p}{sin(\kappa_r)} \tag{7}$$

2.2. Material removal rate

The material removal rate is evaluated as:

$$Q(cm^3/min) = \frac{a_p \cdot a_e\cdot V_f}{1000} \tag{8}$$

2.3. Cutting power and net power requirement

The cutting power is evaluated as:

$$P_c(kW) = \frac{Q\cdot k_c}{60\cdot 10^3} \tag{9}$$

and the net power requirement is:

$$P_{cons}(kW) = \frac{P_c}{\eta} \tag{10}$$

where η is the machine-tool efficiency.

2.4. Specific energy of material removal

The specific energy of material removal is evaluated as:

$$E(kJ/cm^3) = \frac{60\cdot P_{cons}}{Q} \tag{11}$$

2.5. CO_2 generation

The energy emission factor in Spain is considered as 0.404 kg CO_2 / kW·h [7].

2.6. Surface roughness

According to cutting theory, the surface roughness Ra is evaluated as:

$$R_a = \frac{f_z^2}{32\cdot r_e} \tag{12}$$

where r_e is the cutting-tool radius.

3. Experimental procedure

An experimental procedure is conducted in order to evaluate the machine-tool consumption in two situations: i) non-operation (idle) and ii) linear movements at different feeds. Furthermore, the machine-tool efficiency is evaluated by conducting several face milling operations under different cutting parameter combinations.

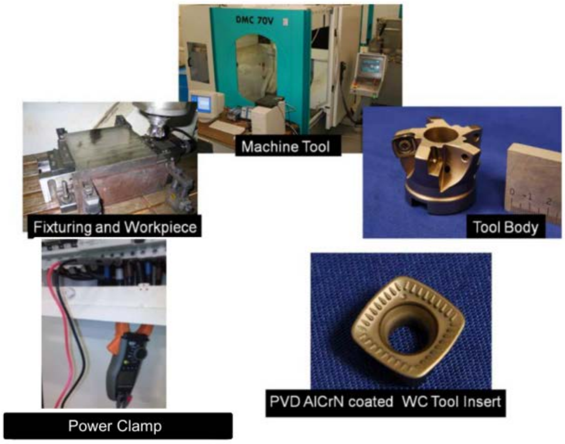

Fig. 1. Experimental set-up. Machine-tool, cutting-tool, fixture, workpiece and power clamp.

3.1. Experimental setup

The experimental setup is shown in Fig. 1. A power clamp is installed on the machine-tool power unit and a workpiece of AISI D3 hardened steel is mounted on a fixture using 4 screws. The cutting-tool is a Ø52 mm face mill composed of 5 carbide inserts with PVD AlCrN coating and the machine-tool is a vertical machining center Deckel Maho DMC70V. The rake angle of the insert is 13 degrees and the cutting edge angle is 12.6 degrees. Compressed air is used to cool the cutting edge while machining. Power clamp measures are recorded on an internal memory and then transferred to a PC using a Bluetooth transmission. In order to ensure that the hardness of the workpiece is constant throughout the part, hardness measurements are conducted using a mobile Leeb hardness tester at different locations over the surface. The hardness of the workpiece measured was 60±2 HRc throughout the part. To inspect surface roughness, a profilometer Mitutoyo Surftest 301 was used.

3.2. Machine-tool power consumption: idle and linear movements

In order to characterize the power consumption of the machine-tool, different movements and machine-tool states were considered. Table 1 shows the power consumption measured by the power clamp for the following states: i) idle, the machine-tool consumption is due to the hydraulic system of the refrigeration system, PLC, monitor and display unit, etc.; and ii) under linear movements on X- and Y-axis at different feeds.

Table 1. Machine-tool power consumption when idle or under linear movements.

Machine-tool state	N (rpm)	Vf (mm/min)	Pcons (kW)	Machine-tool state	N (rpm)	Vf (mm/min)	Pcons (kW)
#1. Idle	--	--	6.55	#1. Idle	--	--	6.54
#2. Linear mov (X-axis)	367	2,000	6.69	#2. Linear mov (Y-axis)	367	2,000	6.66
#3. Linear mov (X-axis)	367	5,000	6.73	#3. Linear mov (Y-axis)	367	5,000	6.7
#4. Linear mov (X-axis)	367	10,000	6.85	#4. Linear mov (Y-axis)	367	10,000	6.82
#5. Linear mov (X-axis)	367	20,000	7.2	#5. Linear mov (Y-axis)	367	20,000	7.24

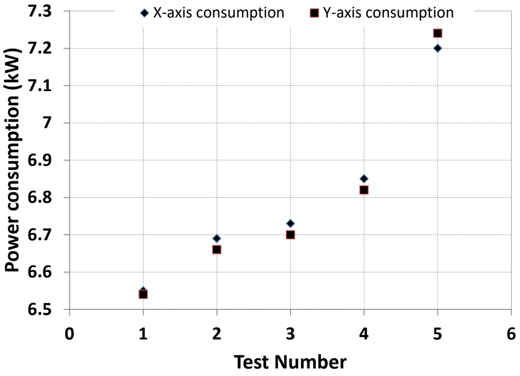

Fig. 2. Power consumption when moving on X- or Y-axis at different feeds.

Fig. 2 shows the power consumption at 4 different feeds according to X- or Y-axis movement. For the range of feed movements analyzed and according to the figure, it can be concluded that there is no relevant difference between the power consumption when moving in X- and Y- axis and the differences on power consumption are due to the feed movement itself.

3.3. Machine-tool efficiency

In order to identify optimal cutting strategies and parameters, the machine-tool efficiency should be evaluated under different cutting conditions. Although power consumption can be estimated according to the formulae given at Section 2, power losses due to motor drivers, transmission systems and deviations between theoretical and actual cutting forces (variations of hardness, tool wear, chip formation issues, etc.) will increase the actual power consumption. In order to estimate the relation between theoretical and actual power consumption at different cutting conditions, a design of experiments is conducted.

The experiments are face milling passes at different cutting-tool parameters, and the actual power consumption is measured at each parameter combination. The efficiency of the machine-tool is then estimated comparing the actual power consumption and the theoretical one. Since the application studied is face milling operation of hardened steels, the machining operation is conducted at lower depth of cuts for finishing cutting passes and high radial depth of cut to increase productivity. Thus, both axial and radial depth of cut are fixed to 1 mm and 31.25 mm, respectively. The cutting parameters studied are cutting speed and feed per tooth, whose recommended ranges are for this particular application, 60-100 m/min and 0.05-0.15 mm, respectively. The face milling operations are conducted in X- and Y-axis. The experimental results are shown in Table 2. Note that the results are expressed as power consumption increase from the machine-tool idle state.

Table 2. Design of Experiments for evaluating machine-tool efficiency.

Cutting direction	Vc (m/min)	fz (mm/tooth)	MRR (cm3/min)	ΔPc (kW)	ΔPcons (kW)	η
X	60	0.05	2.87	0.33	0.61	0.54
X	60	0.15	8.61	0.78	0.98	0.8
X	100	0.05	4.78	0.55	1.05	0.53
X	100	0.15	14.35	1.30	1.35	0.96
Y	60	0.05	2.87	0.33	0.82	0.4
Y	60	0.15	8.61	0.78	1.22	0.64
Y	100	0.05	4.78	0.55	1.14	0.48
Y	100	0.15	14.35	1.30	1.83	0.71

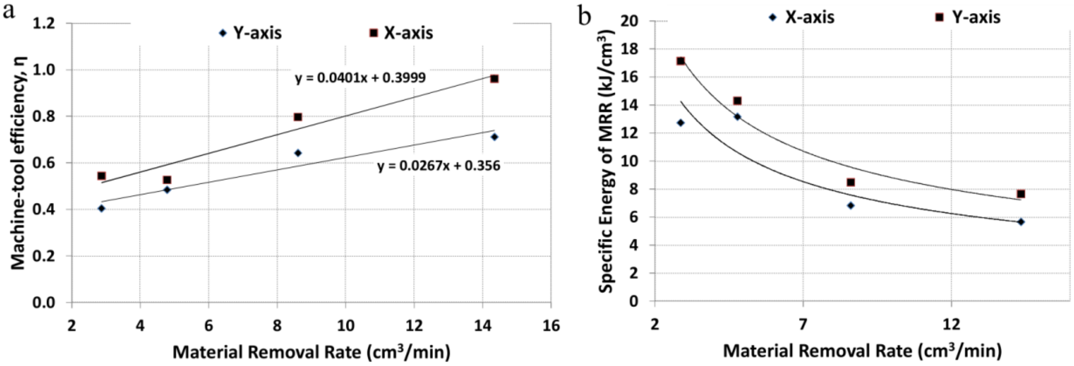

Fig. 3. (a) Machine-tool efficiency vs material removal rate for X- and Y-axis movements; (b) relationship between specific energy of material removal and material removal rate.

The results are graphically represented in Fig. 3. As it can be seen, the machine-tool efficiency is related to the material removal rate. This is due to an energy loss that, in relative terms, is more significant at lower power consumptions. Both cutting operations in X- and Y-axis present a similar behavior. Fig. 3-b shows the specific energy of material removal when cutting in X- and Y-axis. As it can be expected, at higher material removal rates the specific energy decreases which means higher material removal rates are always more efficient for removing a specific volume of material. Fig. 3-b also shows that the efficiency is higher when cutting in X-axis since at the same cutting speed and feed, lower specific energy is required.

3.4. Surface roughness

Since the application analyzed is finishing face milling operations, a surface roughness model is required to optimize cutting parameters. Section 2 shows a theoretical model for face milling, however, at very low feed rates as those used in face milling operations of hardened steels, the theoretical expression deviates from actual values and, thus, empirical models may be required. In order to analyze this deviation and model the surface roughness, a short design of experiments presented in Table 3 was conducted. The actual surface roughness was measured three times using a profilometer Mitutoyo Surftest 301. Fig. 4 shows the actual values and the theoretical model from Section 2 to show the deviation and the necessity of an empirical model.

Table 3. Design of Experiments for evaluating surface roughness.

V_c (m/min)	f_z (mm/tooth)	Ra (μm)	V_c (m/min)	f_z (mm/tooth)	Ra (μm)	V_c (m/min)	f_z (mm/tooth)	Ra (μm)
60	0.05	0.45; 0.28; 0.3	80	0.05	0.39; 0.41; 0.38	100	0.12	1.74; 1.98; 1.82
60	0.08	0.37; 0.54; 0.49	80	0.12	0.84; 0.82; 0.68	100	0.15	2.36; 2.29; 1.87
60	0.12	0.89; 0.96; 0.79	100	0.05	0.59; 0.49; 0.49	80	0.08	0.65; 0.64; 0.64
60	0.15	1.09; 1.23; 1.22	100	0.08	0.94; 1.00; 1.15	80	0.15	1.24; 0.84; 1.24

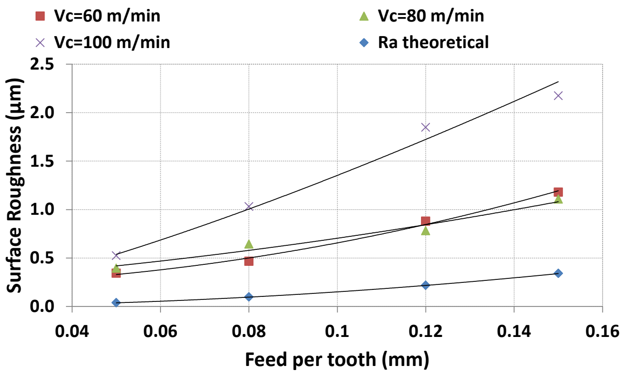

Fig. 4. Theoretical and actual surface roughness.

In order to obtain a model more accurate than the theoretical one, a statistical regression model is built considering as regressors: f_z^2, V_c, f_z and $V_c \bullet f_z$. Removing the non-significant regressors by statistical analysis, the final regression model with a R^2 adjusted value of 82.8% was obtained and it is given by the expression:

$$R_a = 0.17 \cdot V_c \cdot f_z - 3.2 \cdot f_z - 0.13 \tag{13}$$

Unlike other materials such a mild steels or aluminum, where built-up edge formation is produced at lower-medium cutting speeds increasing surface roughness, when machining hardened steels this effect is less likely to be produced and thus, low-medium cutting speeds may be recommended. Furthermore, the influence of feed per tooth on surface roughness is well-known due to the chip formation and geometric considerations. For the range of feed per tooth analyzed, the feed has a linear impact on surface roughness and there is no ploughing effect at low feed rates [8].

4. Sustainable cutting strategies and optimal cutting conditions

After previous experimental procedure, a specific process plan can be analyzed in terms of expected power consumption (i.e. CO_2 generation) in X- and Y-axis cutting direction and expected part quality (surface roughness). For illustrative purposes, a face milling operation on AISI D3 workpieces with dimensions 250 x 250 mm is analyzed. In this study, 5 different strategies were generated using a CAM software: i) contour; ii) one way (X-axis); iii) one way (Y-axis); iv) zig-zag (X-axis); and v) zig-zag (Y-axis).

For each cutting strategy and the recommended cutting conditions range (Vc = [60-100] m/min; fz =[0.05-0.15] mm/tooth), the machining time and fast feed movements were obtained from the CAM software. According to this information and knowing the machine-tool efficiency and consumption under linear movements (previously obtained in Section 3), the expected power consumption per part for each cutting strategy is estimated. Fig. 5 (left) shows the specific energy of material removal estimated for each cutting strategy and cutting parameter combination. As it can be seen, there is a clear difference of machining efficiency for the machine-tool and application analyzed. This is mainly due to different efficiencies of the machine-tool when cutting in X- or Y-axis and the power consumption in linear movements without cutting. Clearly, the cutting strategy of one way in X axis is the most efficient cutting strategy.

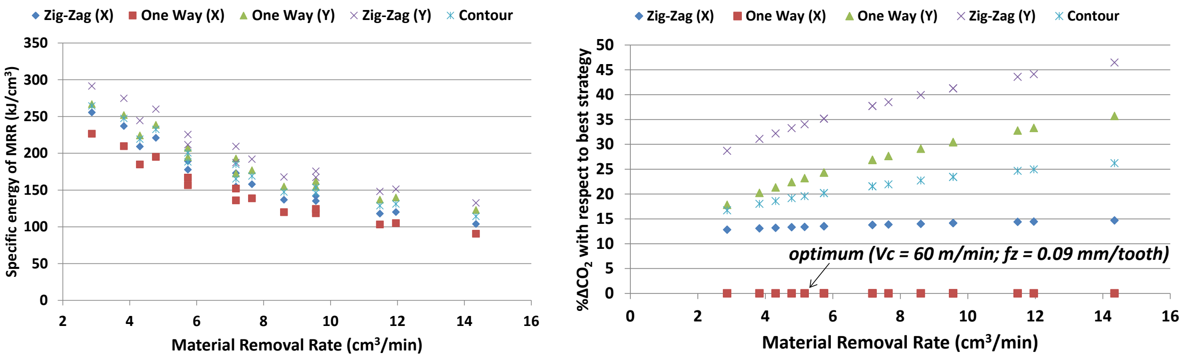

Fig. 5. Specific energy of material removal for different cutting strategies (left). Comparison of CO_2 emission for different cutting strategies and optimal cutting parameters (right).

Knowing the most efficient cutting strategy, the optimal cutting conditions are obtained selecting those that minimize the specific energy of material removal and ensure surface roughness. Assuming that for this application the surface roughness should be lower than 0.5 µm, the optimal cutting conditions are: V_c = 60 m/min and f_z = 0.09 mm/tooth, which means a material removal rate of 5.17 cm^3/min and a surface roughness of 0.5 µm. Please, note that these efficient conditions do not consider the cutting-tool wear effect, so they could be different throughout the wear of the insert in order to ensure the surface roughness constraint. In terms of CO_2 generation, the optimal cutting strategy and cutting parameters are notably more environmental friendly than other cutting strategies as shown in Fig. 5 (right). Considering the one way in X-axis as reference, any other cutting strategy for this specific machine-tool and application increases the CO_2 emission more than 12%.

4. Conclusions

This paper has presented and experimental and theoretical analysis of machine-tool power consumption at different cutting conditions and cutting strategies. The study shows how to include a short experimental procedure to model surface roughness and machine-tool behavior in terms of power consumption in order to evaluate the efficiency of different cutting strategies and cutting parameters. This approach let the process planner to choose optimal cutting conditions while minimizing the environmental impact (in terms of CO_2 emission) of the machining operation. Although the study was focused on face milling operation, a similar procedure can be applied for other machining operations. The study does not deal with other important costs or factors in terms of sustainability such as cutting-tool costs, wear effects on part quality and so on, which will be studied in future work.

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