

Minimization of energy and surface roughness of the products machined by milling

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Abstract. Metal cutting represents a large portion in the manufacturing industries, which makes this process the largest consumer of energy. Energy consumption is an indirect source of carbon footprint, we know that CO₂ emissions come from the production of energy. Therefore high energy consumption requires a large production, which leads to high cost and a large amount of CO₂ emissions. At this day, a lot of researches done on the Metal cutting, but the environmental problems of the processes are rarely discussed. The right selection of cutting parameters is an effective method to reduce energy consumption because of the direct relationship between energy consumption and cutting parameters in machining processes. Therefore, one of the objectives of this research is to propose an optimization strategy suitable for machining processes (milling) to achieve the optimum cutting conditions based on the criterion of the energy consumed during the milling. In this paper the problem of energy consumed in milling is solved by an optimization method chosen. The optimization is done according to the different requirements in the process of roughing and finishing under various technological constraints.

1. Introduction

The reduction of greenhouse gas emissions, mainly CO₂ responsible for 80% of the greenhouse effect due to industrial countries is now a global issue highlighted by the Kyoto agreement. This agreement led the community to reduce its energy consumption [1].

In the case of machine tools, the energy required for the machining represents a very small part compared to that required by the machine. On these machines, there are a number of possible manners to reduce the energy consumption, for example by using regulators and controllers to adapt to a specific task, but also by using energy-saving units. However, these approaches often include major investments, particular the acquisition of new machinery [2].

From another point of view, a considerable energy saving can also be achieved with optimized cutting conditions on existing machines taking into account the limits of performance of the machine, of the cutting tool and the material machined. These limits are taken from laws cutting and expressed as a function of cutting conditions (cutting speed, feed per tooth and depth of cut). These are known as optimization constraints and they limit the research area of optimal conditions.

The optimization of cutting conditions takes an important place in the industrial scientific research in order to respond to three objectives: improving the quality of manufactured products, reducing production costs and reducing the energy consumed. In previous studies, the optimization of cutting conditions was made using a variety of optimization criteria. The first study was made by WW Gilbert



[3] in 1950, from that date several studies were performed in the same sense [4-6]. Therefore, these methods may not be robust for some problems because of the nonlinearity of the objective functions and numerous constraints. To remedy these problems, the researchers made use new methods for optimizing cutting conditions [7- 12].

However, the methodology used in this work is based on using a new optimization technique, the hybrid genetic algorithm - sequential quadratic programming, to reduce the energy consumed in milling.

2. Cutting process model

2.1. Decision variables

In the construction of the optimization problem, three decision variables are considered: cutting speeds V_c , feed rate f and depth of cut a

2.2. Objective function

2.2.1. First objective function

Assuming that the volume of material removed is V , Specific energy consumed can be given as a follow

$$SCE = \frac{60BhL}{Va_e a_p} \left[(P_0 + P_m) \left(\frac{1}{f_u} + \frac{1}{nzf_z} \right) + \frac{[(1+b)\pi d F_c]}{60 * 1000 z f_z} \right] \quad (1)$$

2.2.2. second objective function

In finishing, the roughness of the machined surface can be predicted by:

$$R_a = k v_c^{x_1} f^{x_2} a^{x_3} \quad (2)$$

2.3. Constraints

Some constraints that affect the selection of optimal cutting conditions will be considered

2.3.1. Parameter bounds

Due to the limitations on the machine and cutting tool and due to the safety of machining, the cutting parameters are limited with the bottom and top limit.

$$\text{Spindle rotation speed:} \quad N_{\min} \leq N \leq N_{\max} \quad (3)$$

$$\text{feed per tooth:} \quad f_{z \min} \leq f_z \leq f_{z \max} \quad (4)$$

$$\text{Depth of cut:} \quad a_{\min} \leq a \leq a_{\max} \quad (5)$$

2.3.2. Limitation on the cutting power

The power required to cut should be below a limit power [13]

$$P_m \geq \frac{P_c}{\eta} \quad (6)$$

In milling, the average value of the cutting power is given as follows:

$$P_c = \frac{V_c F_c}{6120} \quad (7)$$

Where F_c is the average peripheral cutting force in kgf . It is given as follows [13]:

$$F_c = C_{zp} B Z d^{b_z} a^{e_z} f_z^{u_z} \quad (8)$$

2.3.3. Arbor strength

The spindle is subjected to a tensional force of the action of the cutting resistance. Therefore, the values of the cutting parameters should ensure that the shaft is safe from the point of view of force [13]:

$$F_c \leq \frac{0.1k_b d_a^3}{0.8L_a + 0.65\sqrt{(0.25L_a)^2 + (0.5ad)^2}} \quad (9)$$

3. Example of application

The application example concerns the machining of an aluminium alloy on a milling machine tool.

The characteristics of the machine tool used are summarized in Table 1

Table 1. Characteristics of the machine [13].

| Characteristics | Symbol | Values |
|---------------------------------------|--------------------|--------|
| Motor power | $P_m (kW)$ | 5.5 |
| Efficiency | η | 0.7 |
| allowable stress of flexion | $k_b (kgf / mm^2)$ | 14.27 |
| allowable torsional stress | $k_t (kgf / mm^2)$ | 12.23 |
| Shaft diameter | $d_a (mm)$ | 27 |
| Shaft length between supports | $L_a (mm)$ | 210 |
| Modulus of elasticity of shaft | $E (kgf / mm^2)$ | 20,387 |

3.1. Modeling of the discharge power

J. G. Li et al. [14], Shows that the measured discharge power can be installed as a polynomial second order function with the spindle speed variable as follows

$$P_u = -10^{-6}n^2 + 0.046n + 589.7$$

In the equation of the objective function we can replace $P_0 + P_m$ by $P_u * T_u$ Where T_u presents the preparation time. In our case $T_u = 18.96s$

3.2. Coefficients of the cutting force

The coefficients of the cutting force are given in Table 2

Table 2. Coefficients of the cutting force.

| C_f | x_F | y_F | u_F | w_F | q_F | k_F |
|-------|-------|-------|-------|-------|-------|-------|
| 29.0 | 1.0 | 0.75 | 0.85 | -0.13 | 0.73 | 1.2 |

3.3. Characteristics of the cutting tool

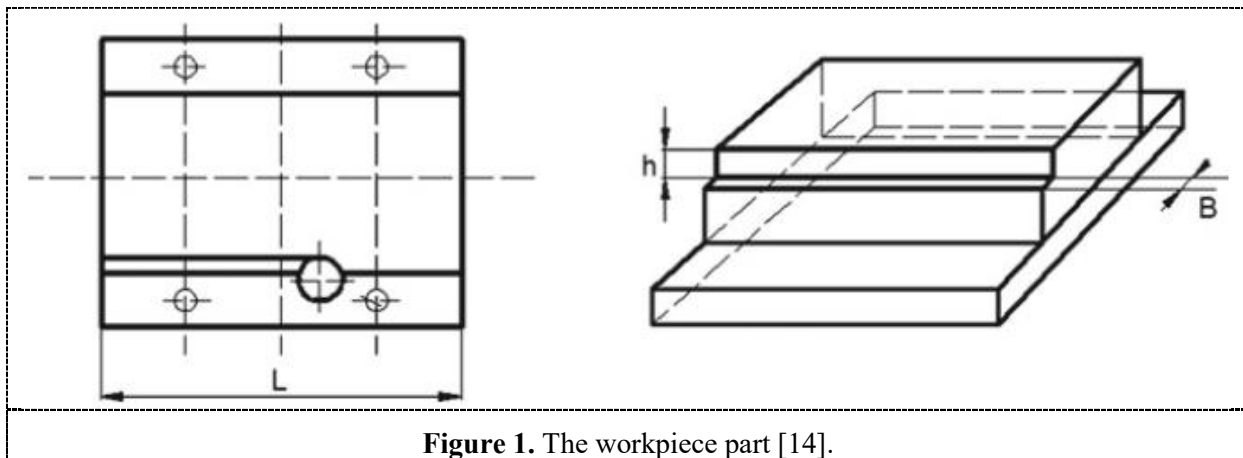
The characteristics of the cutting tool used to make the work are shown in Table 3

Table 3. Characteristics of the cutting tool.

| Material | Diameter (mm) | Number of teeth |
|----------|---------------|-----------------|
| HSS | 63 | 8 |

3.4. Machining Parameters

It is desired to machine the part shown in figure 1 of an aluminum alloy (2017A) of dimension $B=100mm$, $h=10mm$ et $l=132mm$.

**Figure 1.** The workpiece part [14].

The table 4 shows the various machining parameters:

Table 4. Machining parameters.

| Parameters | Symbol | Values |
|--------------------------------|----------------|------------|
| Spindle Speed | $n (tr / min)$ | 5000-12000 |
| Advance per tooth | $f_z (mm)$ | 0.01-0.06 |
| Lost energy coefficient | b | 1.25 |
| Shrinking speed | $f_u (mm / s)$ | 1600 |
| Depth of cut | $a_p (mm)$ | 0.5-2 |
| Width of cut | $a_e (mm)$ | 50 |
| Constant of roughness | k | 1.001 |
| | x_1 | 0.0088 |
| | x_2 | 0.3232 |
| | x_3 | 0.3144 |

4. Results and discussion

4.1. Single objective minimization

The results obtained with the method hybrid genetic algorithm-sequential quadratic programming is listed in Table 5 and Table 6.

This method consists in sequentially executing the two methods (GA and fmincon) in such a way that the results of the genetic algorithm serve as initial solutions for the "fmincon" function of MATLAB.

Table 5. Rough Optimum Cutting Parameters.

| Parameters | $N (rev / min)$ | $f_z (mm / tooth)$ | $a_p (mm)$ | $SCE (w / mm^3)$ |
|---------------|-----------------|--------------------|------------|------------------|
| Values | 235.575 | 0.242 | 2 | 19.325 |

Table 6. Finishing cut parameters.

| Parameters | $N (rev / min)$ | $f_z (mm / tooth)$ | $a_p (mm)$ | $SCE (w / mm^3)$ | $R_a (\mu m)$ |
|------------|-----------------|--------------------|------------|------------------|---------------|
| SCE | 366.342 | 0.300 | 1.001 | 24.487 | 0.566 |
| Ra | 300 | 0.100 | 0.500 | 132.029 | 0.396 |

The study showed that the selection of cutting conditions based on the criterion of minimizing the energy consumed can lead to a reduction of 81.81% of the Energy Consumption (w / mm^3)

The study showed that the selection of cutting conditions based on the criterion of minimizing the roughness can lead to a reduction of 69.96% of the roughness (μm)

4.2. Minimizing multi objective of the finishing operation

The optimization performed for a multi-objective minimization of finishing operations, it is done by the method of NSGA II which gives us the curve in figure 2 this curve presents the Pareto Front:

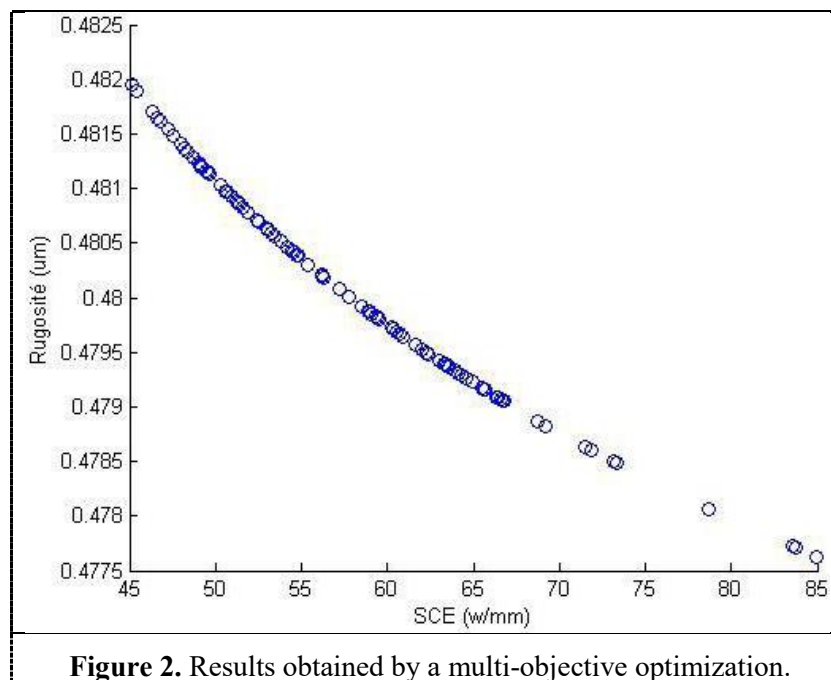


Figure 2. Results obtained by a multi-objective optimization.

The curve of the Pareto front shows that energy consumption and roughness have an inverse proportionality, whilst in each case one wants to increase the quality of surface the consumption of energy increases because the good state of surface requires a high spindle speed Of a small depth of cut.

The machining requirements are the main factors in choosing a combination of objectives.

5. Conclusions

The objective of this work concerns the establishment of a methodology to reduce energy consumption during milling operations and consequently the production of carbon dioxide CO₂. This methodology takes into account the development of modeling tools and efficient use of optimization methods.

The main contribution of our study is located in the proposed of a new optimization method hybrid genetic algorithm - sequential quadratic programming, adapted to the characteristics of the turning process, in order to obtain optimum cutting conditions that minimize the energy consumed.

The multi-objective analysis allows us to simultaneously optimize two objectives. With multi-objective optimization a set of non-dominated solutions has been found (the "front of Pareto"), solutions among which one cannot decide if one solution is better than another to take account of our objectives: Energy Consumption and roughness.

6. References

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