ON THE OPTIMIZATION OF CUTTING PROCESS BY APPLYING MACHINABILITY TESTS

Nivaldo Lemos Coppini, ncoppini@uninove.br
Universidade Nove de Julho, Av. Francisco Matarazzo, 612

Júlio Cesar Dutra, jc.dutra@uninove.br
Universidade Nove de Julho, Av. Francisco Matarazzo, 612 and Centro Universitário da FEI

Elesandro Antonio Baptista, elesandro@uninove.br
Universidade Nove de Julho, Av. Francisco Matarazzo, 612

Emerson Carlos dos Santos, emerson.carlos@tedrive.com.br
Universidade Nove de Julho, Av. Francisco Matarazzo, 612

Abstract. *It is well-known that machinability is a technological property of materials, thus being not totally adequate to characterize them. One of the problems in using the results of machinability tests to characterize a material is that the results will not likely to be extrapolated. In addition, there are many machinability criteria available, but no one normalized. Several parameters may be found in the literature. Sometimes the criteria are based on cutting edges life, measurements of cutting forces, workpiece surface roughness, to name a few. All these aspects reinforce what was mentioned above. In previous works, the authors proposed an intrinsic property to characterize materials called machining strength. As an intrinsic property, the machining strength is quite adequate to characterize the higher or lower resistance a material presents when being cut and its usefulness is shown similar to that of other intrinsic properties of materials, for example hardness of materials. However, one of the strategic factors of competitiveness in cutting process production, which has usually been used by industries, is the final cost of the workpiece. This should be as low as possible. Consequently, the authors suggest a shop floor procedure to determine the minimum cost per piece as a machinability criterium to be applied for cutting process optimization and not easy-to-cut materials. To achieve this, the original minimum cost per piece based on the previous planned process parameters must be compared to the minimum cost obtained from new parameters chosen by considering the characteristics of the cutting process scenario. This will only be possible to occur if actual dates are kept on line with the cutting process running. The authors concluded that, even when the new cutting parameters pointed out by any characteristic of a given process (roughness, cutting force, machine tool power, etc.), the optimization will be considered in terms of the lowest cost determined. The results, as mentioned above, are not adequate to be extrapolated.*

Keywords: *Machinability, Optimization, Cutting Process*

1. INTRODUCTION

Destro (1995) and Coppini (1995) published the first and original results obtained during Destro's Doctoral Thesis development, in which it was proposed and revealed a new intrinsic material property named machining strength. In continuing this work, they published a second paper proposing a way to measure this property by means of an index called CI (Coppini Index) honoring Destro's advisor. This intrinsic material property was proposed to develop and characterize materials and to be used specifically by material makers, replacing machinability normally used for these purposes. At this time, the test to determine the IC was based on measurements of the feed force under the wear evolution influence. More recently, Coppini et al. (2009) developed a simpler test to determine the CI, based on the tool wear weight of the sample after cutting under standard cut conditions. As it is better if CI is a non-dimensional number, its value is calculated by the relationship between the tool wear weight and the weight of the total chip removed from the sample.

However, machinability is, nowadays, used by material makers and all types of industries that work with cutting process. Many reasons will be shown to demonstrate that the use of machinability to develop and or characterize materials is not convenient, but the most important is that, frequently, the results are not transferable. This occurs because machinability is a technological property, thus it is dependent on many factors of influence and not only on material characteristics.

The aim of this work is to propose how to use machinability as a standard test to optimize cutting process in shop floor industries during the process running, putting forward the characterization of cutting materials by determining their Machining Strength. It is not the purpose of the present paper to deal with Machining Strength subject. As a matter of fact, this subject was developed as target from other works (Coppini *et al*., 2009).

2. MACHINABILITY

Machinability is a technological property of materials, thus it is not an intrinsic one. A material machinability index is therefore usually measured compared to another one adopted as a standard (Diniz *et al*, 2009). It is regarded as a technological property because of its dependence on numerous variables related with machining parameters and, even worse than that, it shows a very deep dependence on shopping floor conditions and its manufacturing scenario. For this reason, when a long or a short machinability test is performed using one specific manufacturing scenario, the results will not be possible to be transferred to another one with a desirable high reliable condition. Parameters such as feed rate, depth of cut, cutting speed, cutting fluid, machine characteristics, different tool suppliers, to name a few, in case they are changed from the test to the actual application, there will surely be a significant different result.

A material may be commonly considered to have poor machinability because of its uneasiness to obtain an acceptable surface finish. Machining practice may be carried out until a satisfactory surface finish is achieved. This kind of problem is one among several of typical examples of hindrance to use machinability concepts, because the tests must be done in shopping floor conditions, in the same scenario of the material actual application for production with high quality and adequate surface finishing.

Several criteria and tests have been developed to quantify machinability. The criteria, among others, are based on tool life (Coelho et al., 2008), cutting force (Li, 2006), and surface finishing (Thamizhmanii, 2007). The number of papers found in the literature is very high. The subject is so attractive that it is possible to find even models to predict the Machinability (Al-Ahmari, 2007). The most frequently used and accepted ones are based on life tool with time-consuming tests, which is also painstaking and expensive with a wide variety of cutting speeds. Furthermore, following the machinability established concepts, these tests have to be performed with a standard material, doubling the aforementioned difficulties. It is probably because of these that machinability tests have not been standardized until today.

3. THEORETHICAL FOUNDATIONS

For the last years many papers have been published about cutting process optimization (Lee, 2000), (Meng, 2000). Different propositions have been made, for instance: optimization of turning operations with considerations on production or machining theory; optimization related to milling operations; optimization related to tool failure and economics viewpoint.

On the other hand, the authors have done investigations about cutting optimization in which their results are adequate to be applied for the concept of machinability under the point of view proposed here. These results are described in the following paragraph.

According to the aim of the present work, it is suggested that Taylor life equation coefficients, x and K, (Baptista, 2004) must be determined in shopping floor conditions just when the cutting process is running for one machine-tool-workpiece specific system, and the machinability concept proposed should be applied to optimize it. This procedure uses two different cutting speeds (v_{c1} and v_{c2}) and their respective cutting edge lives (T_1 and T_2). The cutting edge lives must be determined using the same tool life criterion. v_{c1} is the cutting speed selected by the process planner and it is what is normally used, nowadays, in practically all cutting process industries. The selection of this cutting speed is made by using tool makers catalogues or process planer accumulated experience. There is no reason for this cutting speed to be the best one, because in the catalogues, for the simple reason that the scenario of the cutting process costumer may not be contemplated. If the process planner never optimizes the selected speeds, one’s experience will not probably also be taken into account to the optimized values.

So, after the T_1 determination, cutting speed v_{c1} must be changed by v_{c2} and, using the same tool life criterion, T_2 must be determined by the same procedure. The new value of v_{c2} is given by the Equation (1). If v_{c1} is already a very high speed for the machine, tool and piece system, v_{c2} must be lower than v_{c1}, or on the contrary, it must be higher.

To determine the value of x, it is enough to replace the values of the cutting speeds and their respective lives in Equation (2). By knowing the value of x, it is possible to calculate the value of coefficient K from Equation (3).

$$v_{c2} = (\pm 1.2) \times v_{c1} \tag{1}$$

$$x = \frac{\log(T_1.T_2^{-1})}{\log(v_{c2}.v_{c1}^{-1})} \tag{2}$$

$$K = T_1.v_{c1}^{x} \tag{3}$$

Finally, with x and K coefficients, it is possible to determine K_p (total machining cost per piece), from Equation (4).

$$K_p = C_1 + \frac{\pi.d.l_f}{60.1000.f.v_c} C_2 + \frac{\pi.d.l_f.v^{(x-1)}}{1000.f.K} C_3 \tag{4}$$

where:

C_1= independent cost on cutting speed, [R$];
C_2= operational cost, [R$];
C_3= tool cost, [R$];
d= part or tool diameter, [mm];
l_f= feed length, [mm];
f= feed, [mm/rot].

C_2 can be calculated by:

$$C_2 = S_h + S_m \tag{5}$$

and C_3 by:

$$C_3 = K_{ft} + \frac{t_{ft}(S_h + S_m)}{60} \tag{6}$$

where:

K_{ft} = cutting edge cost, [$];
t_{ft} = time to change the cutting edge, [min];
S_h = operator salary and rights per hour, [$/hour]
S_m = all the costs related to the machine tool, [$/hour].

Equation (4) is a typical one that denotes the existence of a minimum point. Thus, the derivative of cost K_p related to cutting speed equals to zero, resulting on the value of lowest cost, which allows to calculate the minimum cost cutting speed v_{cmc}, as shown in Equation (7). During this calculation, based on data from shopping floor conditions, it is essential to take into account that the resulted value of v_{cmc}, must be in the interval of $[0,99\ v_{c1}, 1,01 v_{c2}]$. This interval represents the validity interval used for the experimental determination of x and K. If v_{cmc} is not in this interval, a new interval must be used.

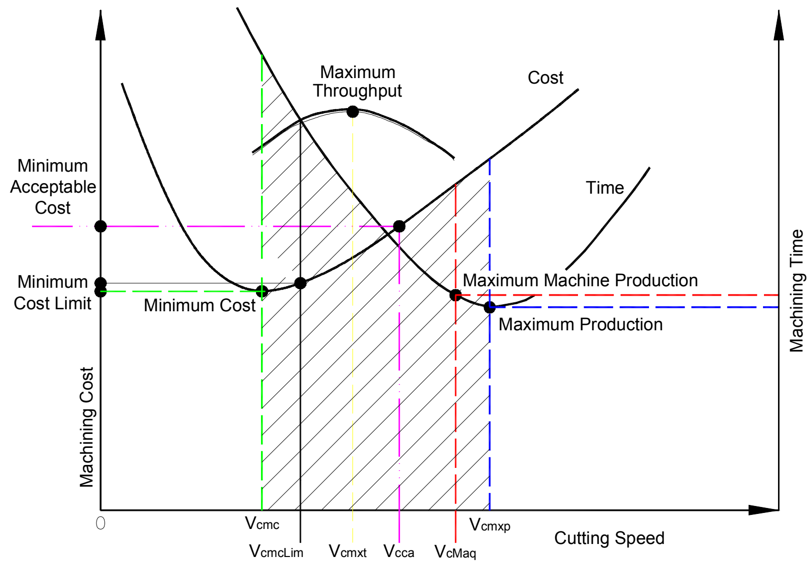
$$v_{cmc} = \left\{ \frac{K.(S_h + S_m)}{60.(x-1).\left[K_{ft} + \left(\frac{S_h + S_m}{60} \right) \times t_{ft} \right]} \right\}^{\frac{1}{x}} \tag{7}$$

As mentioned above, the authors consider that all optimization procedure must be done in shopping floor conditions and during the process running considered as well as the specific scenario target of the optimization procedure. Therefore, they developed some specific optimized cutting speed to each one of these scenarios.

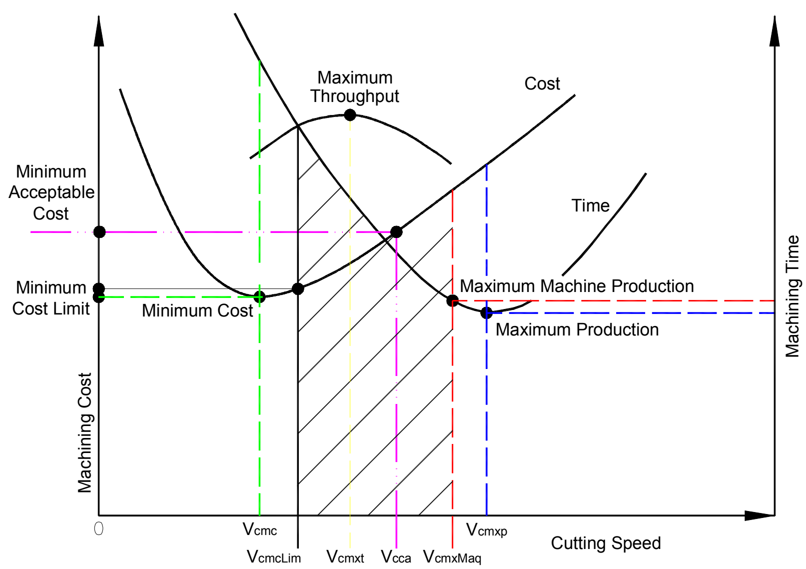
It is possible to identify in Figure 1 these cutting speeds that may be used as a reference to cutting process optimization. Each one is specifically defined and determined to assist a particular manufacturing scenario. The right side of Figure 1, one has:

- v_{cmxp} – maximum production cutting speed – the use this cutting speed is recommended in scenarios were all machine tools are bottle necks, i.e., the maximum production of those workpieces are needed, independent from how much the cost is. For times to change the cutting edge equal to zero or very close to zero, v_{cmxp} becomes very high and higher than v_{cmxMaq}. In this case, the last cutting speed must be used. (Diniz et al, 2009)
- v_{cmxMaq} – is the larger cutting speed available in the machine tool to cut a specific workpiece, and it must be used as aforementioned. (Baptista, 2004);
- v_{cmxt} – maximum throughput cutting speed – to be used when Theory of Constraint (TOC) is being applyed to balance a production line (it can be an alternative relating to v_{cmxp}) (Souza et al, 2006);

- v_{cca} – minimum cost acceptable cutting speed – to be used for idle machine tools. It means that scenario allows the reduction of cutting speed under minimum cost cutting speed to save tool life and, respectively, tool costs, once the operator and machine tool costs must be paid even when the machine tool is off (Grivol, 2005);
- v_{cmcLim} – minimum cost limit cutting speed - to be used when the time to change the cutting edge is zero or close to zero. In this case, the Maximum Efficiency Interval becomes [v_{cmcLim}, v_{cmxMaq}], because v_{cmxp} will be very high and higher than v_{cmxMaq} (Baptista, 2004);
- v_{cmc} – minimum cost cutting speed – to be used when the cost/benefit ratio must be the target (Diniz et al, 2009);
- v_{cma} – maximum cost accepted cutting speed – to be used when it is possible to accept to cut the workpiece with a higher cost than the minimum one, because this is accepted by the market, so it is possible to improve the productivity without so much high cost as that for maximum production conditions (Baptista, 2004).



(a)



(b)

Figure 1. Cutting speed references for each manufacturing scenario (Coppini et al, 2008) (a) Maximum Efficiency Interval. (b) Maximum Efficiency Interval Machine (Baptista, 2004).

In the present work only v_{cmc} is being suggested to be used, because the cost/benefit per piece is the target for the scenario optimization. However, any scenario and its respective cutting speed may be used as a machinability criterion to optimize the shopping floor cutting conditions. It is enough to calculate the cost per piece for each scenario in the same way that is shown below when it was used the minimum cost scenario.

4. MACHINABILITY AS A PROCEDURE FOR PROCESS OPTIMIZATION

This work proposes to use the machinability concept as a procedure for process optimization, so the machinability criterion can be the relationship between the minimum cost and a machinability index *MI*, given by:

$$MI = \left(\frac{K_{pP} - K_{pOp}}{K_{pP}} \right) \times 100 \tag{8}$$

where the K_{pP} and K_{pOp} are, respectively, the cost per workpiece for the "*P*lanned cutting conditions" and "Optimized cutting conditions". If *MI* is positive, then the optimized cutting conditions are better than the planned one; on the contrary, it is worse. The *MI* value will denote how much better or worse the optimized condition is.

5. DISCUSSION

The procedure was proposed to be applied in shopping floor conditions during cutting process evolution when its optimization is to be demanded. The first thing to do is to determine K_{pP} during cutting process evolution in shop floor. This must be made by using Equations (1) to (7).

Then, it will be the moment of providing technical changes in the process to be optimized. These changes can be anything in the sense of improving the process, such as:

- changing the tool by another with better characteristics, and/or;
- changing the tool supplier, and/or;
- changing the tool to another one to increase the depth of cut as well as to improve productivity considering machine power availability, and/or;
- changing the tool to get better surface finishing, and/or;
- changing the piece material properties, e.g. by applying heat treatment, and/or;
- changing feed rate and depth of cut to have more convenient chip removal, and others.

After technical changes and only when all the aspects of quality are adopted will it be the moment to determine K_{pOp} also during cutting process evolution in shop floor. This must also be done by using Equations (1) to (7). It is important to highlight that during the data collection of tool lives for the respective cutting speed, the workpiece is to be produced normally, i.e., the "experience" is not being done in laboratory and with the interruptions and additional costs of the process. With the values of K_{pP} and K_{pOp}, the machinability index could be calculated by Equation (8).

6. EXAMPLE TO CONFIRM THE PROPOSED MODEL

Just to confirm the validity of the proposed model, one cutting process scenario was simulated. It was supposed that the machine tool used to cut the workpiece is an idle lathe. During the planning process, the cutting conditions and its parameters were: feed rate f = 0.25 mm/rot; depth of cut l_f = 46 mm; workpiece diameter d = 26.8 mm; tool cost by cutting edge K_{ft} = \$3.20; idle time per workpiece ti = 2 min; tool cutting edge t_{ft} = 7 min. The operator salary S_h = 0 \$/hour and the cost of machine tool per hour S_m = 33 \$/hour. Based on tool makers catalog, the planer selected 210 m/min as a cutting speed.

During the process running, in shopping floor conditions, two cutting speeds were used to measure the corresponding tool cutting edge lives on line with the workpiece production: the first one was v_{c1} = 175 m/min and the second was v_{c2} = 210 m/min. The tool cutting edges lives were, respectively, T_1 = 23.40 min and T_2 = 10.97 min. With these values and using Equations (2) and (3), it was possible to calculate the tool life Taylor Equation coefficients *x* and *K* as shown below in Expressions (9) and (10):

$$x = \frac{\log(T_1.T_2^{-1})}{\log(v_{c2}.v_{c1}^{-1})} = \frac{\log\left(210/175\right)}{\log\left(10.97/23.40\right)} = \frac{\log 2.135}{\log 1.2} = 4.16 \tag{9}$$

$$K = T_1 . v_{c1}^{x} = 23.4 \times 175^{4.16} = 5.02 \times 10^{10} \qquad (10)$$

From x and K values in Equation (7), it is possible to calculate the Maximum Efficiency Interval given by the minimum cost and maximum production cutting speeds, respectively, 190 m/min and 1.016 m/min. As the lathe is an idle one, it is better to work with the minimum possible cost.

The process supervisor decided to introduce changes to optimize the cutting conditions. Firstly, he introduced a more flexible tool hold 1.8 $ more expensive than the other one, but with significant reduction in the change cutting edge tool from 7 to 2 min; secondly, he adopted the minimum cost cutting speed, say 190 m/min. Finally, he optimized the unproductive time from 2 to 1.7 min by workpiece. These changes presented cost per workpiece reduction from K_{pP} = 184.3 $ to K_{pOp} = 148.4 $ calculated by using Equation (4). Equation (7) allows to calculate the Machinability Index as follows:

$$MI = \left(\frac{K_{pP} - K_{pOp}}{K_{pP}} \right) \times 100 = \left(\frac{184.3 - 148.4}{184.3} \right) \times 100 = 19.5 \qquad (7)$$

Therefore, the process supervisor succeeded in around 20% of improvement in terms of cost reduction of the process and even better, it was possible for him to demonstrate how much the improvement was for any case he needs to demonstrate.

7. FINAL CONSIDERATIONS

As discussed before, it is possible to make the following final considerations:

- Machinability is not a convenient property to characterize materials. So it is not recommended to be used by material makers for developing and characterizing the so called easy-to-cut materials; for this purpose, the authors suggest that it is much better to use Machining Strength because it is an intrinsic material property;
- Machinability is very convenient to be applied to optimize cutting process because it is a technological material property and the optimization refers to the process itself;
- Introduction of better technical conditions to improve the cutting process characteristics must be followed by cost analysis to prevent losses; for this reason, the authors suggest minimum cost production to determine and to calculate the machinability index to be used during the optimization procedure. However, it can be used another cutting speed to calculate the cost by workpiece if the cost is not the target of optimization;
- The proposed optimization procedure based on machinability index is more effective if the minimum production cost could be determined from shop floor data measurements when compared with data from toolmakers catalogue;
- After changing technical conditions, the minimum cost can be higher than before. In this case, an analysis must be done to determine if it is convenient or not to pay more for the change;
- To confirm the proposed way to optimize the cutting process, an example was presented by creating an imaginary scenario very likely to be real and it was introduced some technical changes. The proposed model proved to be adequate.

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