Archives of Materials Science and Engineering
Volume 39
Issue 1
September 2009
Pages 21-28
International Scientific Journal published monthly by the World Academy of Materials and Manufacturing Engineering

New approach for applications of machinability and machining strength

N.L. Coppini [a,*], J.C. Dutra [b], E.C. dos Santosa [a]
[a] Universidade Nove de Julho, Av. Francisco Matarazzo, 612, Água Branca, São Paulo, S.P., 05001-100, Brazil
[b] Universidade Nove de Julho and Centro Universitário da FEI, Brazil
* Corresponding author: E-mail address: ncoppini@uninove.br

Received 29.01.2009; published in revised form 01.09.2009

ABSTRACT

Purpose: The purpose of this paper is to present and discuss the machinability and machining strength concepts under a new viewpoint concerned with both their applications and how to measure then. Despite of the fact that to develop easy to cut steel is a very important task, this work take under consideration entire application of these properties for any kind of materials in terms of how aggressive it can be against the tool material.

Design/methodology/approach: A new approach to measure machining strength property is proposed. The reliability of the proposed test was based on experimental data from the literature. The best way to apply machinability index and machining strength index is put forward. Otherwise, at this moment, the authors are doing experimental laboratory research to evaluate the best way to organize appropriate samples to attend different kind products for respective materials makers'.

Findings: It was possible to conclude that machinability must be used by means of comparative tests as close as possible to shopping floor conditions. The main application is to select the best steel to be used for a specific cutting process workpart.

Research limitations/implications: The main limitation is that the entire new viewpoint presented is very new for the materials makers. The authors must spread the ideas presented here to check the actual materials makers' resistance or acceptance of their applications.

Originality/value: The proposed test is very simple and more reliable than that one already published. On the other hand, machining strength is a material intrinsic property. For this reason, it is best employed during easy to cut materials development and measured by a Coppini Index (CI) based on standard tests. As a material intrinsic property it is not related to a standard material. Machinability is supposed to be appropriated for process optimization and not for materials development or characterization.

Keywords: Machinability; Machining strength; Cutting process

Reference to this paper should be given in the following way:

N.L. Coppini, J.C. Dutra, E.C. dos Santosa, New approach for applications of machinability and machining strength, Archives of Materials Science and Engineering 39/1 (2009) 21-28.

MATERIALS MANUFACTURING AND PROCESSING

1. Introduction

Destro and Coppini, [1] in 1993, published the first and original results obtained during the Destro's Doctoral Thesis work development [2] 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 viable way to measure this property by means of an index called

CI (Coppini Index) honouring Destro's advisor. As one can see ahead in this work, that proposed test to CI determination showed to be very complicated and not adequate to be used by materials makers. This is because the test is based on feed force measurements and for that it needs sophisticated instruments as a dynamometer. These considerations must be understood in the viewpoint of the materials makers and their difficulties and costs limits to adopt this kind of procedure.

The purpose of this paper is to present and discuss the concepts of materials machinability and machining strength under a new approach of their applications and measurements.

1.1. Machinability

Machinability is a technological property of materials, but, not an intrinsic one. A material machinability index is therefore usually measured compared to another one adopted as a standard. [4]. It is regarded as a technological one because of its dependence on numerous variables related with machining parameters and, worst than that, show a very deeply dependence on the shop floor and its manufacturing scenario. For this reason, when a long or short machinability test is made using one specific manufacturing scenario, the results will not be possible to be transferred to another scenario with a desirable high reliable condition. Parameter as: feed rate, depth of cut, cutting speed, cutting fluid, to name a few, if they change from the test to the actual application, for sure, could be large differences.

A material may be commonly considered to have poor machinability because of its uneasiness to obtain an acceptable surface finish. In these circumstances, comparisons to other materials prove to not exist, but machining practice may be carried out until a satisfactory surface finish is achieved. This kind of problem is a typical occasion to use the machinability concepts, because the tests must be done in shop floor, 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, cutting force [5, 6, 7 and 8], surface finishing [9], productivity, geometrical and thermal characteristics [10]. The number of papers that can be found in the literature is very high. The subject is so attractive that is possible to find including models to predict the Machinability [11]. 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 [5]. Furthermore, this test has to be performed with a standard material, doubling the aforementioned difficulties.

As seen above, and the notorious downfalls of these tests to quantify the machinability index, the authors will further present some examples to use this property to be rationalised and even focused on its purpose.

1.2. Machining strenght

Machining strength is an intrinsic material property that represents the difficulty a material presents when it is machined. It can be expressed by the CI (Coppini Index). Destro [2, 3] proposed in 1995 that the CI value may be determined by a standard test on a specimen as shown in Figure 1. It allows that bars with different diameters be used with standardised values to determine the referred index in function of these values, as can be seen, as an example, in Table 1.

The CI Value may be obtained by:

$$CI = \frac{\sum_{i=1}^{N} F_{fi}}{N} \tag{1}$$

where:

F_{fi} is the feed force measured by a dynamometer in each i-esimal scaling [N];

N is the number of scalings of the specimen.

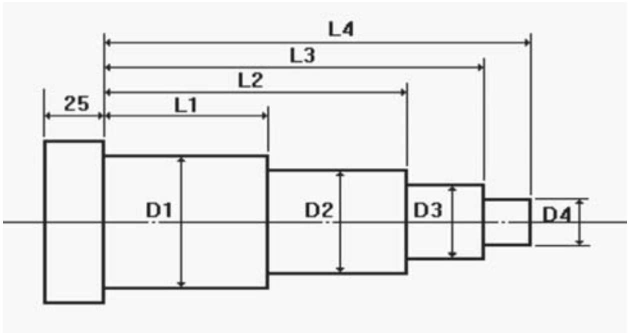

Fig. 1. Typical Specimen in determining Coppini Index.

Therefore, the CI Value may be understood as an average of measured feed forces throughout the test and brings itself the tool wear. The feed force measurement was chosen because of its lower influence on tool wear when compared with cutting force or other components of the cutting force [4].

Considering the aspects investigated by Destro, [1, 2, 3] the authors present a new approach, simpler and more efficient for the determination of CI Index and discuss the main applications of this property called Machining Strength.

1.3. Theoretical foundation

During last years many papers were published about cutting process optimization [12, 13, 14, 15]. All sort of way were used for propositions, for instance: optimization of turning operations with considerations about production or machining theory; optimization related to milling operations; optimization related with tool failure and economics viewpoint.

The authors developed cutting optimization studies that are adequate to be applied for the concept of machinability, it was necessary to consider the concepts of tool life and strategic cutting speeds possible to be applied in different machining conditions to optimize the process in shopping floor conditions (manufacturing scenario) and when machining parts during days work production. For this reason, the coefficients from Taylor life equation, x and K, [16] must be determined. This procedure uses two different cutting speeds and their respective cutting edge lives; the last ones being obtained during the process and the production of parts in which a given machining process is to be optimized. Taylor coefficient values may then be determined by using Equations (2) and (3):

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

$$K = T_1.v_{c1}^{x} \quad (3)$$

It is possible to determine from these coefficients the manufacturing cost per part, the cutting speeds of minimum cost, maximum production, and minimum cost limit, when using Equations (4) to (7):

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

$$v_{cmc} = \left\{ \frac{K.(S_h + S_m)}{60.(x-1).\left[K_{ft} + \left(\frac{S_h + S_m}{60}\right) \times t_{ft}\right]} \right\} \quad (5)$$

$$v_{cmcLim} = \left\{ \frac{K.(S_h + S_m)}{60.(x-1).K_{ft}} \right\}^{\frac{1}{x}} \quad (6)$$

$$v_{cmxp} = \sqrt[x]{\frac{K}{(x-1)\cdot t_{ft}}} \quad (7)$$

Where:
(K_p) is the cost of manufacturing per part ($);
(C_1) is the cost independent from cutting speed [$];
(d) is the part or tool diameter [mm];
(l_f) is the feed [mm];
(f) is the feed per rotation [mm/turn];
(C_2) is the total cost of a man and a machine [$/h];
(C_3) is the total cost of tool and to change it [$];
(T) is the cutting edge life of a given tool [min];
(x) e (K) are Taylor life coefficients;
(S_h) is the salary per man and fringe benefits [$/hour];
(S_m) is the machine salary [$/hour];
(K_{ft}) is the cost of a tool cutting edge [$];
(t_{ft}) is the period of time to change and adjust the edge tool [min].

Figure 2 illustrates the Maximum Efficiency Interval which is constituted by both the minimum cost cutting speeds and maximum production cutting speed. Also shows the maximum Machine speed that can be higher or lower than the maximum production speed, depending on the time to change the tool cutting edge.

When the time to change the cutting edge is nearly zero, the maximum production speed will be higher than the maximum machine speed. In this way, it will represent, along with the minimum cost limit speed, the Interval of Machine Maximum Efficiency [17].

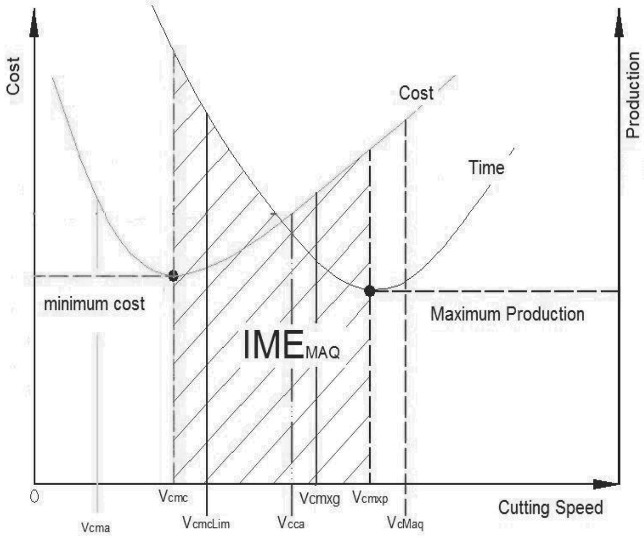

Fig. 2. Interval of Maximum Efficiency and all the strategic speeds compatible with several manufacturing conditions. [17]

Finally, Figure 2 shows strategic speeds according to different manufacturing conditions. Thus:

- v_{cma} is the minimum admissible cost speed, which is used in situations where there is machine idleness. It represents cost saving with tools. It can be calculated considering the new tool life obtained when the idleness time is considered. It takes in account the fact of during the idleness time, both the operator and machine, must be charged according the costing system utilized by de industry;

Table 1.
Diameter values and machining lengths of specimens for this test. All values are in mm.

Diameter	Diameter Class											
Length	K	KL	M	ML	N	NL	P	PL	Q	QL	R	RL	S
D1	20	25	30	35	40	45	50	55	60	65	70	75	80
L1	86	68	56	48	42	37	33	30	28	26	24	22	21
D2	18	23	28	33	38	43	48	53	58	63	68	73	78
L2	96	74	61	51	44	39	35	32	29	26	24	23	21
D3	16	21	26	31	36	41	46	51	56	61	66	71	76
L3	109	82	66	55	47	41	36	33	30	27	25	23	22
D4	14	19	24	29	34	39	44	49	54	59	64	69	74
L4	126	91	71	59	50	43	38	34	31	28	26	24	22

- v_{cmc} is the minimum cost speed, used when lowering costs is the principal aim and the period of time to change tool is very long. It can be calculated using the equation 5. Very long time to change the tool could be understand as impossible today, considering the flexibility of machines, and specific apparatus to change tools. Otherwise, included in that time, are all the passive times related to clean the work machine area and to make the tool adjusts considering all the position correction made before to change the tool ;
- v_{cmclim} is the minimum cost limit speed, to be used when the lower possible costs is in question and the period of time to change tool is short or zero. It can be calculated by the equation 6. This is the opposite case compared with v_{cmc}. The time could be very short to zero or zero when the flexibility is considered in a scenario of just time procedure. In this case, is possible to occur that one batch of pieces be cut whit one single tool. Another possible situation occurs when the change of tools comes from tool magazines;
- v_{cca} is the maximum admissible cost speed, to be used when the cost per part is higher than the minimum cost. The concept involved in this case is related with the scenario in which the industry want to minimize cost, but she has a tolerable cost to be used higher then minimum cost, enough to allows a production improvement. The v_{cca} value, can be calculated imputing into the equation 4 the tolerable cost defined by the industry and using trial and error procedure;
- v_{cmxg} is the maximum throughput speed, to be used in manufacturing scenarios based on restriction theories[18, 19]. Goldratt [19, 20] comments that throughput can be understood as all the money that enters in the company less everything that was paid to its suppliers. That would be the money that the company generated. The money paid to the suppliers is the money generated by other companies.

The authors showed that, the total throughput can be calculated according with equation 8. So this equation will be used to determine the maximum throughput speed as follows:

$$TT = \frac{\left[PV_u - MP_u - \left(\frac{l_f \cdot \pi \cdot d \cdot v_c^{(x-1)} \cdot K_{ft}}{1000 \cdot K \cdot f} \right) \right] \cdot T_{disp}}{\left(\frac{l_f \cdot \pi \cdot d}{1000 \cdot f \cdot v_c} \right) + t_i + \left(\frac{l_f \cdot \pi \cdot d \cdot v_c^{x-1} \cdot t_{ft}}{1000 \cdot f \cdot K} \right)} \qquad (8)$$

Where:
TT = total throughput [$];
PV_u = total sales price [$];
MP_u = cost of the material for all the pieces of the batch;
T_{disp} = available time for the production of the specified batch of pieces [min].

Throughput (TT) in equation 8 is function of the cutting speed (v_c). The maximum point of this function can be obtained by TT differentiation in relation to v_c and by the solution of equation "derivative equal to zero".

The equation, in this case, does not allow obtaining an analytic expression for the maximum throughput cutting speed. However, in specific situations it is possible to attribute values to the different parameters that compose the equation and, by the use of numeric processes for determination of equations roots, to obtain the numeric value cutting speed of maximum throughput (v_{cmxg}).

To illustrate the proposed approach it will be considered as example, the turning process with the following parameters: feed rate f = 0,25 mm/rot; Taylor's tool life equation coefficients x = 4,16; K = 5,02x1010 (validity speeds interval 175-210 m/mim, with tolerance of ±10%); feed length l_f = 46 mm; sales price per piece PU_u = R$ 7,00; T_{disp} = 480 min; material cost per piece MP_u = $3,00; piece diameter d = 26,8 mm; tool cost acquisition K_{ft} = $3,20; unproductive time t_i = 2 min; tool edge changing time t_{ft} = 0,58 min. Using the software Maple® and being substituted these values in the Equation (8), is obtained the throughput curve against cutting speed shown in the figure 3. The maximum value of the throughput is of R$ 920.00 per day, for a v_{cmxg} = 233 m/min.

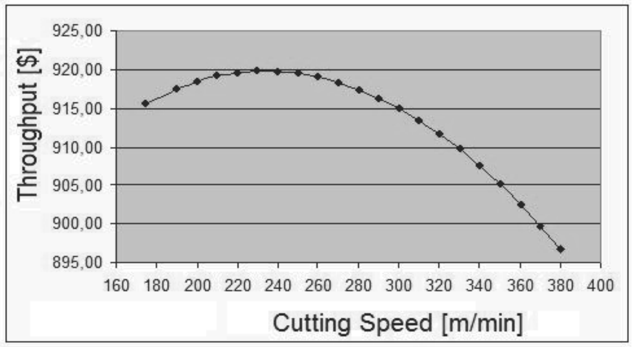

Fig. 3. Total Throughput in function of cutting speed.

- v_{cmxp} is the maximum production speed, to be used in scenarios that demand the maximum production possible. It can be calculated using the equation 7. It can happen, in function of the machine and cutting parameters, that the maximum production speed becomes higher then maximum cutting speed machine v_{cMaq}. The main factor responsible for this is the time to change the tool edge. For this reason when the maximum production speed being higher then the machine maximum speed, the definition of the IME must be considered as shown in figure 2;
- v_{cMaq} is the machine maximum speed, to be used in situations that demand both maximum production and a short period of time to change tool. It's value can be calculate taking in account the geometry and cutting parameters involved during cutting process applied to produce a specific piece.

The cost per part for each different situation may be calculated by Equation (4), replacing the respective value of **v** by the corresponding cutting speed.

For instance, the equation 9 allows to calculate the cost for the scenario of maximum throughput.

$$K_{pmxg} = C_1 + \frac{\pi.d.l_f}{60.1000.f.v_{cmxg}} C_2 + \frac{\pi.d.l_f.v_{cmxg}^{(x-1)}}{1000.f.K} C_3 \qquad (9)$$

2. Materials and methods

The method used in this work is an exploratory one. A review on the literature over machinability and machining strength was considered and procedures for the use of these properties are presented and discussed to rationalize their practical implications and applications. A new test is proposed; however, its accreditation is based on experimental data taken from the literature, which permits to foresee preliminary tests to what is proposed. Own results to test these suggestions is to occur in the near future. Another aspect to be considered related with materials and methods is that the author developed a lot of optimization models for each manufacturing scenario and in the present paper all the results are being applied.

3. Results

3.1. Application of machinability concept

Considering machinability as a technological property of materials and, therefore, dependent on different parameters connected to the machining process, the authors propose that this property be based on the following remarks:

- to not use machinability tests for the development of easy to cut materials;
- to not use machinability tests to optimize the piece material because the material is naturally chosen during its project and is somewhat fixed;
- the standard of machinability must be the system machine, tool and part, determined by the process planning and must be optimized using the machinability tests;
- consider the manufacturing scenario to apply the optimization procedure. The test must attend the scenario condition, in other words, if the surface finishing is the problem, so the machinability test must be focused to this parameter. Another tool geometry, or another cutting fluid, or another relation between radio edge and feed rate, must be choose to rich the best surface roughness possible;
- always use the machinability index as mentioned above as a relationship of costs obtained for the last and the new conditions found after optimization. Lower costs are very often the competitive strategy factor for the industries that want to survive in the market.

The following example helps to understand this proposal: if the manufacturing scenario is both the minimum cost and short (or zero) period of time to change tool, not taking into account the production of parts per hour, the cost determined for minimum cost limit speed may be used to determine the machinability index, as follows:

- Determine x_A and K_A coefficients from Taylor life equation for the condition A (process planning read, but not optimized), by using Equations (2) and (3);
- Calculate the minimum cost limit speed, v_{cmclim} , and then calculate the value of the respective cost, K_{pLimA}, according to Equations (3) and (5), valid for this scenario;
- Promote alterations in the process to optimize it: changing feed, the depth of cut, changing tool, etc. so that this new condition B is now regarded as being optimized and to be achieved;
- Repeat the first two steps above for the new optimize cutting conditions;
- Calculate the machinability index, as follows:

$$MI = \frac{K_{pLimA}}{K_{pLimB}} \times 100 \qquad (8)$$

If MI is higher than 100, the situation A is more adequate than B, and vice-versa.

The same procedure must be used for any other scenarios that intend to optimize the process, taking into account costs for each of the characteristic cutting speeds, as already seen in the theoretical foundation. It is important to observe that this proposal makes a great deal on lower cost condition, independent from the analysed manufacturing scenario, for this competitive factor is generally preponderant over others. However, it is not impossible that a certain condition of productivity may be used, by using MI dependent on this factor.

3.2. Application of machining strength concept

Machining strength is proposed for the development of easy to cut material. Its application is relevant to ferrous materials, more specifically steels. This is because these materials are normally very resistant to be cut and chemical additions are made to develop new easy to cut steels. Otherwise, it can be successfully applied to develop any kind of ease to cut material.

Different from what was proposed by Destro [2] (see theoretical foundation), the authors consider that Coppini Index (CI) must be the result of the relationship between the global mass of tool material removed under all the wear action (m_{ferr}) and the mass of material removed from the piece (m_{cp}) responsible for the tool material waste. Such mass must be measured during the test, which may even be performed by the material producer that intends to develop or characterize its produced materials based on machining strength and specially to produce easy to cut materials. Alternatively, these tests can be performed in laboratory facilities from research institutes and universities.

The calculus of CI is:

$$CI = m_{ferr}/m_{cp} \qquad (9)$$

The suggested specimen must have dimensions and geometries more convenient to each material producer. For example, a steel maker specialized in rolled or drawing bars, with a wide variety of diameters, may choose cylindrical turning tests by simply standardizing specimens to be tested and the test conditions adequate to the analysed material.

In this sense, similar to what occurs to other intrinsic material properties; the machining strength may need measurement scales as well as specific tests for these scales. A typical example of this statement is the hardness test (e.g. Rockwell, Brinell and Vickers), with its scales and types of indenters.

To show the validity of this proposal, some data from the literature were taken. [21]. Figure 3 shows the result of a life test performed in AISI 630 C (conventional) and AISI 630 BMS (bettered machining strength). Their chemical compositions (weight percent) are show in Table 2.

As it was not possible to measure the mass m_{ferr} and m_{cp} at this moment, but to preliminarily test the proposal of this work, data from the long duration test, taken from Figure 3, were used to calculate them.

The machining conditions used comes from the tests performed by Matsumoto [21], were:
feed rate f= 0.19 mm/turn;
depth of cut ap = 0.7 mm;
cutting speed v_c = 50 m/min;
tool material = rapid steel.

Considering the proposed test as a way to measure machining strength, a 1,582,000 mm cutting length L_c (Figure 4) would take a duration of t_c calculated by:

$$t_c = l_c / v_c = 1{,}583{,}000 / 50 = 31.64\,\text{min} \tag{10}$$

which represents the cutting time used and the consequent life of the tool. The volume of chip V_{cp} removed in these conditions would be calculated by:

$$V_{cp} = a_p \times f \times L_c \tag{11}$$

Imputing the respective values in the equation 11, results

$$v_{cp} = 0.7 \times 0.19 \times 1{,}582{,}000 \tag{12}$$

And finally the volume of removed material from the specimen, is:

$$v_{cp} = 210{,}406\text{mm}^3 \tag{13}$$

The mass of removed material would be calculated by:

$$m_{cp} = \rho_{cp} \times V_{cp} \tag{14}$$

Where ρ_{cp} is the density of the steel being tested.

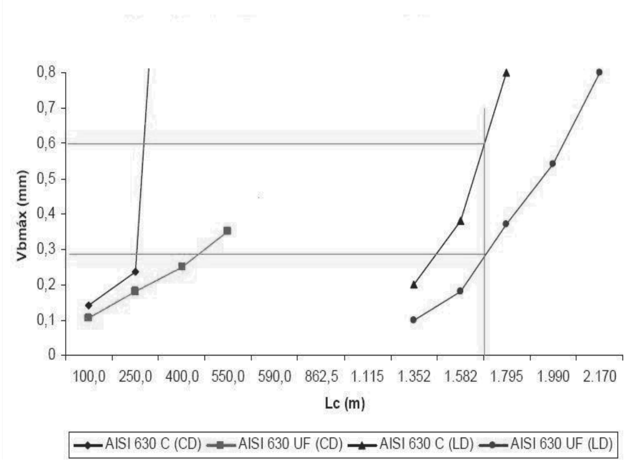

Fig. 4. Flank wear for the cutting lengths in tests of short (SD) and long durations (LD) [21].

Table 2.
Chemical composition of stainless steels AISI 630C (conventional) and AISI 630BMS (bettered machining strength). [21]

Steel	C	Cr	Ni	Cu	Ca	P	S
630 C	0.07	16.0	4.6	3.6	0.001	0.019	0.007
630 RUM	0.07	16.0	4.5	3.4	0.003	0.016	0.022

To calculate the volume of removed material of the tool because of the wear is not a simple task because the only information about tool wear, present in the literature already mentioned, is the measurement of Vb wear. Therefore, an approximation was necessary based on a simplifying hypothesis, which is shown in Figure 5. Thus, the triangle ABC in Figure 5 represents the area of material removed from the tip of the tool because of the wear. This area belongs to a orthogonal plan to the cutting edge.

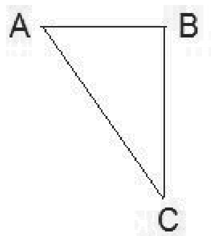

Fig. 5. Schematic representation of the tool wear area over an orthogonal plan to the cutting edge.

$A\hat{C}B$ is the relief angle of the tool and, according to Matsumoto [21], is 6^o. Leg BC represents the Vb wear. Therefore:

$$AB = BC \times tg6^o, \tag{15}$$

or:

$$AB = 0.11 \times BC \tag{16}$$

As the depth of cut is 0.7 mm, the approximate value of V_{ferr} of wear material from the tool may be calculated by equation 16. In other words, was considered the area of the triagle ABC multiplied by deph of cut as a third dimension of the triagle along the cutting edge. As BC = Vb, results:

$$V_{ferr} = [0.11 \times Vb \times Vb \times a_p]/2 \tag{17}$$

and the tool weared mass can be calculated by:

$$m_{ferr} = [0.11 \times 0.7 \times Vb^2 \times \rho_{ferr}]/2 \tag{18}$$

Where ρ_{ferr} is the density of the tool material high speed steel). From equation 18 results:

$$m_{ferr} = 0.04 \times \rho_{ferr} \times Vb^2 \tag{19}$$

Densities of the sample and tool can be considered to be very similar, so $\rho_{cp} \approx \rho_{ferr}$. According to Equation (9), the value of the machining strength CI of these steels may be calculated by:

$$CI = 0.04 \times Vb^2/210,406 \qquad (19)$$

And, finally

$$CI = 1,90.10^{-7}\, VB^2 \qquad (20)$$

It can be seen from Figure 3 that VB = 0.6 for steel AISI 630 C and 0.28 for steel AISI 630 (BMS). Thus, the values of machining strength of these steels are:

$CI_{630C} = 68.4 \times 10^{-9}$

and

$CI_{630BMS} = 14.9 \times 10^{-9}$

4. Discussion

It may be noted that CI is a pure number (dimensionless) and also has close relationship between the part material and the machining strength. Based on the examples from the literature, it is evident that AISI 630C presents a resistance 4.6 times higher than the one with additions of calcium and sulphur.

The most important contribution of this work is in the sense of making the use of the concept of machinability easier. Nowadays, as it is defined, material producers use it as a material property to compare the effect of its structure, chemical composition, and mechanical properties in the development of easy to cut materials. The authors of the present work consider that this is not the most adequate approach because machinability is a technological property, and not always a given material that presents the best machinability will have the same behaviour in the manufacturing scenario in case a process technology is changed.

The proposal is, therefore, to show to materials producers that the use of the concept of Machining Strength is to be put forward. As it is an intrinsic material property, the development or characterization of easy to cut materials will be improved in the sense of characterising it, because of its independence from process technological factors. Machining strength is dependent exclusively on the structure, chemical composition, and mechanical properties of a certain steel to be developed. The test to determine the CI Index, which will be presented in the near future, is very simple, with adequate specimens and will consist in a precision scale to measure the mass of tool removed material because the wear and compare it with the volume of removed chip, previously established.

While machining strength is based on the tool life concept, machinability can be based on tool life, cutting force, surface quality, productivity, etc. While machining strength represents intrinsically the resistance of material to be cut, machinability represents a way to optimize the cutting conditions during the machining process evolution in shop floor.

Finally, by selecting an easy to cut material characterized by CI index, machining industries can use the machinability test to improve the cutting process performance for the same selected material.

5. Conclusions

The present paper has the following conclusions:

- Machining strength is proposed for the use by materials producers in the development and characterization of easy to cut materials. It is more adequate for this aim because it is an intrinsic material property;
- Since machinability is a technological property, it should not be used in the development and characterization of easy to cut material. Its dependence on technological conditions may need to prove the results to be pointless when they are altered;
- The machining strength concept may be used by machine shops to select materials that have CIs adequate to their applications, whether they are easy to cut steels or not;
- Machinability must be used by machine shops to optimize processes in shopping floor conditions and during the manufacturing process according to the imposed technological conditions present in the manufacturing scenario;
- The test to determine the CI value, to be developed in the near future, has proved to be viable, at least preliminarily, based on data taken from the literature. To measure the tool wear material by a precision mass measure scale is better than to measure the Vb wear;
- The authors have great interest in finding materials producers and industries to develop tests in accordance to what has been proposed in this paper.

Acknowledgements

The authors wish to thank Universidade Nove de Julho and CNPq (Conselho Nacional de Desenvolvimento Científico e Tecnológico) for their indispensible support for this work. Wish also to tank Dr. Hidekasu Matsumoto and Elesandro Antonio Baptista for gentle surrender datas from their experiences.

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