MACHINING STRENGTH: HOW TO MEASURE THIS NEW INTRINSIC MATERIAL PROPERTY

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Abstract. *This new property has been studied to characterise the resistance a material exhibits when machined, which may be considered as a typical material behaviour. The idea is that it must be an intrinsic material property measured by an index number that could characterise its machining strength more appropriately. The main use of this new property is to help metal/metallurgical industries to develop, select and perform as-received material quality control tests dependent only upon its intrinsic characteristics. The determination of this index number (called CI – Coppini Index as an honor made by Destro to his doctoral thesis advisor) was supposed to come from a relatively easier test to be performed when compared with Destro's proposal. The first proposal to determine was put forward by exploring the cutting process parameters, such as the evolution of wear upon the application of a feed force. By using a dynamometer, this feed force was measured during the workpiece turning whilst the tool wear was evaluated. A standard workpiece of the material to be characterised was prepared to receive a series of diameters to be cut in sequence. This way to measure the index number was unfortunately not so simple. Now the authors are trying to develop a simpler way to determine the index number to characterise the machining strength; a second idea is now being analysed: it is to determine it by the relationship between the removed mass of chip from a standard material workpiece to be characterised and the lost material one from the tool due to its wear in a turning operation. Previous tests showed that this procedure is promising. It was firstly based on wear measurements found in the literature. The purpose of this paper is to present the results of two sets of experiments in which two life criteria were established to measure both the sample and tool mass. The first criterion, was based on the failure of the tool, i.e., the sample was cut by turning operation until the complete destruction of the tool cutting edge, and the number of steps was not fixed. The second criterion, was to fix the number of steps to be cut in turning operations. In both criteria, the constant cutting speed was the same. It was possible to conclude that this new method to measure such index number presents more reasonable results to be applied in a foreseeable future. However, more experimental procedures must be done to have a more reliable and accurate way to measure the machining strength index.*

Keywords*: Machining Strength, Intrinsic Materials Property, Cutting Process.*

1. INTRODUCTION

Coppini and Destro (1993) published the first and original results obtained from Destro's doctoral thesis development (Coppini and Destro, 1995) in which it was proposed and revealed a new intrinsic material property named machining strength. On 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) honoring Destro's advisor. As one can see ahead in this paper, that proposed test to the *CI* determination showed to be very complicated and therefore not adequate to be used on a daily basis. This is because the test is based on feed force measurements and requires sophisticated instruments such as a dynamometer, not adjusted to machine-shop conditions (practical circumstances). These considerations must be understood in the viewpoint of industrial applications, their difficulties and cost limits when adopting this type of procedure.

A second idea is now being analyzed: it is to determine the *CI* by the relationship between the removed mass of chip from a standard sample of material to be characterised and the removed material one from the tool thanks to its wear on a turning operation. The first test to ensure this proposal showed that this procedure is promising; it was made based on wear measurements found in the literature.

The purpose of this paper is to present the results of two sets of experiments in which two life criteria were established to measure both the sample and tool mass. The first criterion was based on the failure of the tool, i.e., the sample was cut by turning operation until complete destruction of the tool cutting edge whilst the second one was to fix the number of steps to be cut on the turning operation. It was possible to conclude that this new method presents a reasonable result to be applied in a foreseeable future.

2. LAST DEVELOPMENT IN MACHINING STRENGTH

This item presents the last experiments developed with the aim at verifying the relationship between the removed chip mass from the sample and the one from the tool which was lost because of its wear on turning operation. It also shows that such experiment is a fairly good alternative to measure the machining strength property.

2.1. Machinability

Machinability is considered by the authors as a technological property of materials because its machinability index is usually measured by comparison to another one adopted as a standard (Diniz *et al.*, 2011). Thus, it is dependent on numerous variables related to machining parameters and, worse than that, shows a profound dependence on the machine-shop conditions and its manufacturing scenario. For this reason, when a long or short machinability test is performed, using one specific manufacturing scenario, the results are not possible to be translated to another with good reliability. Parameters such as feed rate, depth of cut, cutting speed, and cutting fluid, to name a few, if they change from testing conditions to real or practical ones, different results are likely to happen.

Several criteria and tests have been developed to quantify machinability. Among others, they are based on tool life, cutting force (Coelho *et al.*, 2008; Bagetti *et al.*, 2008; Li *et al.*, 2006; Arrazola *et al.*, 2009), surface finish (Thamizhmanii *et al.*, 2007), productivity, geometrical and thermal characteristics (Hossain *et al.*, 2008). The number of papers found in the literature is considerable and so attractive that it is even possible to find models to predict it (Al-Ahmari, 2007). However, the most frequently used and accepted concepts of machinability are based on tool-life with time-consuming tests, which are not only painstaking but also expensive with a wide variety of cutting speeds (Coelho *et al.*, 2008; Boothroyd and Knight, 2006). Furthermore, these tests have to be performed with a standard material, increasing the aforementioned difficulties. These machinability characteristics have motivated the authors to propose this new property.

2.2. Machining strength – concept and measurement

2.2.1. First proposal to measure *CI*

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* (*C*oppini *I*ndex). The first test to measure the *CI* was proposed by Coppini and Destro (1995). He proposed that the *CI* value would be determined by a standard test on a specimen as shown in Fig. 1. This specimen permits that different diameters be used as standardized values to determine the referred index, as can be seen in Tab. 1. The *CI* value may be obtained by:

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

in which:
F_{fi} is the feed force measured by a dynamometer in each step *i* of the scaling showed in Fig. 1 [N];
N is the number of specimen scaling.

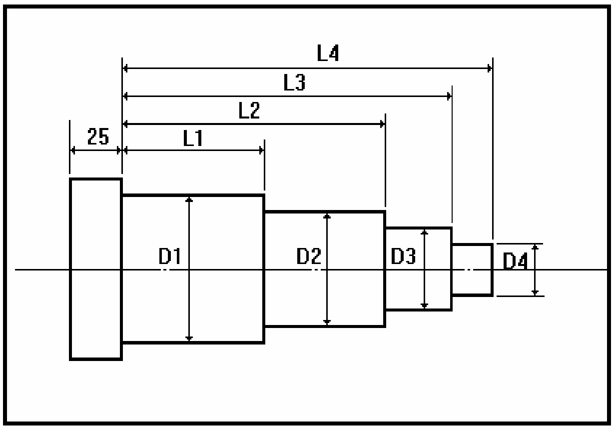

Figure 1. Typical specimen in determining the Coppini Index.

Therefore, the *CI* value may be understood as an average of the measured feed forces throughout the test and brings itself the tool wear evolution influence. The feed force measurement was chosen because of its lower influence on tool wear when compared to the cutting force or other components of the cutting force (Diniz *et al.*, 2011).

Table 1. Diameter values and machining lengths of specimens for test (Coppini and Destro, 1995).

Diameter	Diameter Class (all dimensions in mm)												
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

Despite of being laborious, this way to measure the *CI* is, surely precisely and adequately enough to be used in laboratories where scientific approaches are normally required.

2.2.2. Second proposal to measure *CI*

Considering the aspects investigated by Destro (Coppini and Destro, 1993; 1995) a new test was proposed to measure the *CI* index and also identify its sensibility (Coppini *et al.*, 2009). The idea was to propose a simpler and more feasible test to be applied in industrial conditions, specifically directed to metallurgical or mechanical sectors. Thus, Eq. (2) was proposed for the *CI* determination, where (m_{tool}) is the global mass of the material removed from the tool because of its wear and (m_{cp}) is the mass of chip removed for it is the main responsible for the tool material wear:

$$CI = \frac{m_{tool}}{m_{cp}} \tag{2}$$

The suggested specimen would have dimensions and geometries more convenient to each material producer. For example, a steelmaker specialized in rolled or drawn 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 (Matsumoto *et al.*, 2008). Figure 3 shows the result of a test-life performed in both AISI 630C (conventional) and AISI 630BMS (bettered machining strength) steels. Their chemical compositions (weight percent) are seen in Tab. 2. The machining conditions are from the tests performed by Matsumoto *et al.* (2008), which were:

feed rate f = 0.19 mm/turn;
depth of cut a_p = 0.7 mm;
cutting speed v_c = 50 m/min;
tool material = high-speed steel.

Table 2. Chemical composition of AISI 630C (conventional) and AISI 630 BMS (bettered machining strength) stainless steels (Matsumoto *et al.*, 2008).

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 BMS	0.07	16.0	4.5	3.4	0.003	0.016	0.022

Considering the proposed test as an alternative to measure the machining strength, the cutting edge tool life measured by the total cut length, L_c, measured by Matsumoto's test (1,582,000 mm), Fig. 2, was used. The cutting edge tool life *T* could be calculated by:

$$T = \frac{L_c}{v_c} = \frac{1{,}582{,}000}{50} = 31.64\,\text{min} \tag{3}$$

The volume of chip removed V_{cp} in these conditions was calculated by:

$$V_{cp} = a_p fL_c \tag{4}$$

By imputing the respective values in Eq. (4) results

$$V_{cp} = 0.7 \times 0.19 \times 1{,}582{,}000 \tag{5}$$

And finally the volume of removed chip was:

$$V_{cp} = 210{,}406\ mm^3 \tag{6}$$

The mass of removed material could then be calculated by:

$$m_{cp} = \rho_{cp} V_{cp} \tag{7}$$

where ρ_{cp} is the density of the tested steel.

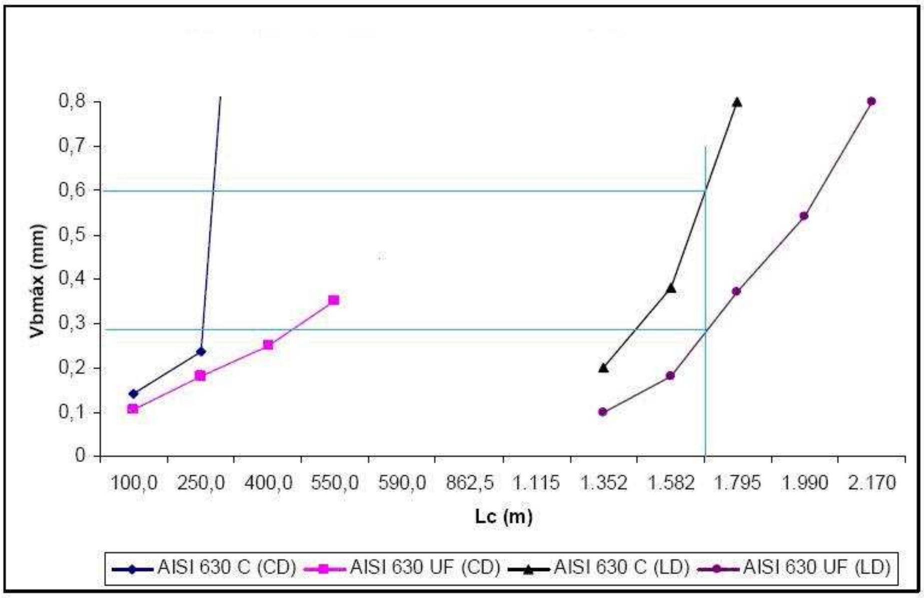

Figure 2. Flank wear for the cutting lengths in tests of short (CD) and long durations (LD) (Matsumoto *et al.*, 2008).

To calculate the overall mass of removed material from the tool because of wear action (m_{cp}), an approximation was based on a simplifying hypothesis, which is shown in Fig. 3: the triangle *ABC* represents the area of material removed from the tip of the tool because of its wear. This area belongs to an orthogonal plan to the cutting edge.

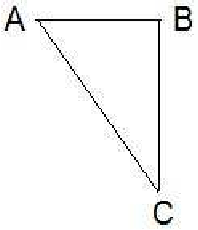

Figure 3. Schematic representation of a tool tip, showing the final wear area over an orthogonal plan to the cutting edge.

$A\hat{C}B$ angle is the relief angle of the tool and, according to Matsumoto *et al.* (2008), it is 6^o. Side *BC* represents the V_b wear. Therefore:

$$\overline{AB} = \overline{BC} \times tg6^o \tag{8}$$

Or

$$\overline{AB} = 0.11\overline{BC} \tag{9}$$

As the depth of cut was 0.7 mm, the approximate value of V_{tool} of wear material removed from the cutting edge tool may be calculated by Eq. (9). In other words, the area of the triangle *ABC* may be multiplied by this depth of cut as a third dimension of the triangle along the cutting edge. As *BC* = V_b, this gives:

$$V_{tool} = \frac{[0.11VBVBa_p]}{2} \tag{10}$$

and the tool wear mass may be calculated by:

$$m_{tool} = \frac{[0.11 \times 0.7 \times VB^2 \times \rho_{ferr}]}{2} \tag{11}$$

where ρ_{tool} is the density of the tool material (high-speed steel). From Eq. (11) results:

$$m_{tool} = 0.04 \times \rho_{tool} \times VB^2 \tag{12}$$

Densities of both sample and tool can be considered to be very similar, so $\rho_{cp} \approx \rho_{tool}$. According to Eq. (2), the value of the machining strength *CI* of these steels may be calculated by:

$$CI = 0.04 \times VB^2 / 210{,}406 \tag{13}$$

And finally,

$$CI = 1{,}90.10^{-7} VB^2 \tag{14}$$

It can be seen from Fig. 2 that *VB* = 0.6 for AISI 630 C steel and 0.28 for AISI 630 BMS steel. Thus, the values of machining strength of these steels are:

$$CI_{630C} = 68.4 \times 10^{-9} \tag{15}$$

and

$$CI_{630BMS} = 14.9 \times 10^{-9} \tag{16}$$

These results showed that the proposal was promising.

2.2.3. Third proposal to measure *CI*

Based on the results above, an experiment was prepared to measure the *CI* index. Samples from AISI 316L stainless steel with 51 mm diameter and 200 mm length were prepared for the machining strength tests. Four samples were annealed at 1200^{o}C for 2 hours to have an average grain size ten times higher than the other four samples which were maintained in the as-received condition, i.e., they had a smaller average grain size. The chosen temperature and time were calculated after studying grain growth kinetics (Burke, 1949) and using previous results of grain growth phenomena for this steel to permit the calculation of K and n (Stanley and Perotta, 1969):

$$D = kt^n \tag{17}$$

where *D* is the grain size [μm], *k* [μm^{-n}] and *n*, constants, and *t*, time [*min*].

By assuming that the structure of grain boundaries is similar when this phenomenon takes place, Burke (1949) proposed that the effective boundary curvature radius may be related to their grain diameter. In this way, it was possible to put forward the ideal grain growth law:

$$D^2 - D_0^2 = kt \tag{18}$$

where D_0 is the initial grain size [μm] and k may be expressed by:

$$k = k_0 \, exp(\frac{-Q}{RT}) \tag{19}$$

where k_0 is a pre-exponential constant, Q [$kJ.mol^{-1}$] is the activation energy for grain growth, R is the general constant of gases (8.314 $J.mol^{-1}.K^{-1}$), and T is the absolute temperature [K]. Grain size for the specimens was determined by ASTM-E-112 (1982). At least 50 fields were counted by a circle test method. The average number of intercepts was 38, which is in accordance to the aforementioned standard. This grain size was used in Eq. (17), and the result may be used in Eq. (18) and (19), so it becomes:

$$D^2 = 12^2 + [5.173.10^6 \, exp(\frac{-184.9.10^3}{8.314.T})].t \tag{20}$$

For a 2 hour period, to achieve a grain size approximately ten times larger than the initial one, Eq. (20) gives 1200°C. In this way, four samples were annealed at 1200°C for 2 hours. After that, they were all quenched in water to avoid precipitation of sigma phase. This was a strategy adopted to test the *CI* sensitivity. 8 samples were then submitted to the Machining Strength tests, 4 of which in the initial condition (12 μm grain size) and the others in the annealed condition with an average grain size approximately ten times bigger.

A series of Rockwell *G* hardness tests were performed in the samples to be machined (150 *kgf* load and a spherical indenter of 1.58 *mm* (1/16”)). The results can be seen in Tab. 3. On average, hardness values of samples with larger grain sizes are lower than the ones from samples with small grain sizes.

Table 3. Rockwell *G* hardness values obtained from as-received and annealed samples.

Sample	**Condition**	**HRG**
1	As-received	73±11
2	As-received	74±11
3	As-received	72±10
4	As-received	71±11
5	Annealed	64±2
6	Annealed	61±2
7	Annealed	51±3
8	Annealed	51±4

The specimens mentioned above were prepared by turning operation in order to obtain a 50-*mm* diameter and 200-*mm* length; 50 *mm* of its length was used to hold the specimen on the lathe. The tests were performed on an Okuma© lathe with 15 kW power.

A carbide tool class M, from Sandvik© Coromant TNMMG 16 04 04 MF was selected for this preliminary test; the selection was based on the fact that it has both an average wear resistance and toughness. This type of tool is supposedly interesting to be used as a standard for the *CI* determination. The other machining conditions were set as:

Cutting Speed = 300 $m.min^{-1}$
Feed Rate = 0.15 $mm.rot^{-1}$
Depth of Cut = 1.0 mm (used in each step during turning cycle)
Feed Length = 150 mm (used in each step during turning cycle)

The criterion used to change both the tool and sample was to run the cylindrical turning process cycle until it was possible to identify the tool being prone to fail, keeping the cutting speed constant. Because of this, the number of steps was not constant, as can be seen further in Tab. 4. The results from the machining strength tests may be seen in Tab. 3; the *CI* is at its right side. Samples with larger grain sizes showed a lower machining strength whilst the *CI* varied from 0.45 to 1.76. Note that because these numbers are so small, they appear without their decimals. On the other hand, specimens with smaller grain sizes showed a higher machining strength whilst the *CI* varied from 0.34 to 4.38. Although some results presented some discrepancies, it is believed that they are due to the number of steps taken in the test, which was unusually high. This will be explored further.

In Tab. 4, m_{tool-i} is the mass of the tool before turning while m_{tool-f} is its mass after turning; n is the number of turning steps achieved in each sample; and m_{cp} is the removed mass from the sample after n steps. The results show, on average, that the machining strength values, measured by the *CI*, are 2.25 and 1.13 for small and large grain sizes, respectively, which means that it was more difficult to machine specimens with small grain sizes than specimens with large grain sizes. This is due to the number of grain boundaries. In the first case, because of the fact that small grain sizes mean that these specimens have more grain boundaries per unit volume and therefore impede the movement of dislocation, causing a pile-up of dislocations. On the other hand, large grain sizes have fewer grain boundaries per unit volume so there will be lesser pile-up of dislocations.

Table 4. *CI* values for the as-received and annealed specimens (third proposal).

#	Tool Edge Number	Condition	M_{tool-i} [g]	M_{tool-f} [g]	$(.10^{-4})$ δm_{tool}	n	m_{cp} [g]	$.10^{-6}CI$	$.10^{-6}CI$ Average / σ	CI_{ar}/CI_{an}
1	3	As-received	7.1104	7.1044	60	9	1369.19	4.38	2.25 / 2.14	1.99
2	3	As-received	7.1044	7.1038	6	13	1784.77	0.34		
3	1	As-received	7.1128	7.1121	7	10	1484.21	0.47		
4	3	As-received	7.1038	7.0986	52	9	1369.19	3.80		
5	4	Annealed	7.1215	7.1187	28	11	1591.82	1.76	1.13 / 0.54	
6	4	Annealed	7.1187	7.1179	8	13	1784.77	0.45		
7	2	Annealed	7.1096	7.1075	21	13	1784.77	1.18		
8	4	Annealed	7.1179	7.1159	20	13	1784.77	1.76		

Assuming that there is a substantial plastic deformation before the removal of chip on the machining test – which is very plausible for the chosen material, the movement of dislocations may explain the machining easiness found in these specimens, particularly because the chosen material was both very ductile and easily work hardened. It is then clear that the number of grain boundaries was probably the main cause for the difference found between the machining strengths in these two groups of specimens whereas tool wear was guaranteed by the work hardening of this material.

However, the number of steps seems to be important in the test and consequently, their results. This may be seen by analysing samples 2, 3 and 6. Although their results are unusually low, the number of steps may have caused the low value of wear of the tool. A further improvement in this work was then to fix the number of steps to be used in the machining strength tests, allowing their results to be compared more accurately. In this sense, when this is performed in a company, it will be necessary to do a preliminary test to discover the necessary number to compare the results more accurately. The following conclusions based on the results and discussions of this third proposed test may be drawn:

- the test is fairly adequate to measure the *CI*;
- machining strength is higher when there are more grain boundaries in stainless steels or when its grain size is small;
- the *CI* values showed to be sensitive enough to present distinct values of machining strength in solid solutions with different number of grain boundaries;
- the machining strength test may be performed to discover the minimum number of steps in order to get more accurate results.

3. NEW TEST FOR THE *CI* DETERMINATION

This item deals with a fourth and new test proposed to measure the *CI*.

3.1. Discussions about the third test

It is interesting to discuss in more depth the results presented in Tab. 4. The aforementioned conclusions were based on the fact that the results were obtained after practical tests, so they must be considered as true. For this reason, the average values were obtained by considering all the data involved in the calculation for the determination of the *CI* values.

The cutting edges of the tool number 3 showed higher wear values when the number of steps was lower and equal to 9. However, when this number was higher (10 and 13), the wear values were lower. In the case of the as-received specimens, it does not seem to be possible to analyse their results altogether because two of them showed high *CI* values and the other two low *CI* values. On the other hand, when considering the results of the annealed samples, it is possible to discard the wear value of 0.45 because of its discrepancy when compared to the others. To complicate the matters, the differences found in the hardness test between these specimens do not help to explain these discrepancies. Thus, it is possible to conclude only that the as-received specimens present more variability whilst the annealed samples showed more consistent results from a statistical point of view.

3.2. Results and discussion

After the previous results and discussions, the authors decided to perform a new set of experiments by changing the cutting tool edge life criterion: the number of steps was set at nine, different from the previous experiments in which the test came to a halt when the cutting tool showed signs of typical wear or signs of burned tip of the cutting edge. This decision was taken for tests to be performed by repeating exactly all the others cutting parameters used before. Tab. 5 shows the results from this new set of experiments.

Table 5. *CI* values for the specimens as-received and annealed for current test.

#	***Tool Edge Number***	***Condition***	m_{tool-I} ***[g]***	m_{tool-f} ***[g]***	$(.10^{-4})$ δm_{tool}	***n***	m_{cp} ***[g]***	$10^{-6}.CI$	10^{-6} ***CI Average / σ***	CI_{ar}/CI_{an}
1	2	As received	7.1196	7.1178	18	9	1369.19	1.31	3.45 / 4.77	2.91
2	4	As received	7.1241	7.1227	14		1369.19	1.02		
3	1	As received	7.1247	7.1235	12		1369.19	0.88		
4	3	As received	7.1248	7.1103	145		1369.19	10.6		
5	2	Annealed	7.1211	7.1196	15		1369.19	1.10	1.19 / 0.20	
6	3	Annealed	7.1266	7.1248	18		1369.19	1.31		
7	1	Annealed	7.1266	7.1247	19		1369.19	1.39		
8	4	Annealed	7.1254	7.1241	13		1369.19	0.95		

It is possible to compare the results between Tab. 4 and 5. It may be observed that when the number of steps was set to nine, the results showed more regularity. However, the last value showed a very large discrepancy in the as-received specimens. On the other hand, the values measured for the annealed specimens behaved more regularly. These results permit to speculate that the as-received specimens presented more heterogeneity in both mechanical and metallurgical properties than the annealed ones.

Further analysis of these results showed that by establishing a life criterion of the cutting edge based on a constant number of steps resulted in values more regularly behaved. It can be seen that the best results were found when the largest value for as-received sample was disregarded. There is no doubt that the *CI* value of 10.60 is notoriously different from the others and seems to be an accidental value or the presence of a different mechanism of tool wear.

One of the reasons for such variations of wear may be the necessary knowledge of the physical behavior of the sheared workpiece material at the cutting edge for an understanding of wear mechanisms (Brookes, 1992). These mechanisms may lead to cracking, chipping, burning and to provoke adherence of workpiece material on the tool, causing significant variations that take place between one specimen and another used on the tests. Another important factor is the magnitude of the cutting speed, which may cause a softening effect because of the high temperature involved in high cutting speeds and consequently the tool wear mechanism. Another hypothesis to be investigated in a work to be done in the near future is related to the possibility of the operating conditions, specially at very high cutting speed which may have led to a situation threshold among different mechanisms of wear, such as mechanical abrasion and/or large plastic deformation due to the prevailing temperatures in the region of the cut. This could explain the discrepant values found, even with all parameters being held constant throughout the tests. To investigate these phenomena, it is therefore necessary to use other characterisation techniques, for example a scanning electron microscope, which is to be used in another upcoming paper.

To answer the questions above, it is therefore necessary to perform more tests because the machining process behaviour showed a considerable dispersion of results, at least for the cutting edge criterion based on tool failure. This shall be done in the near future, including a closer investigation of the wear mechanisms of hard materials, namely the tool wear mechanisms that took place in these tests.

4. FINAL CONSIDERATIONS

The present paper permits the following final remarks:

1. The test for the determination of the *CI* proposed in a previous work and reformulated in this paper is simpler and more viable than the one presented by Destro and Coppini (1993; 1995) because it is based on simpler instruments and a non-intrusive approach to the machining process;
2. More tests with other cutting conditions and more reliable results must be done, to see how sensitive the *CI* index is to compare materials with different machining strength values;
3. The results were more homogenous for the annealed specimens than the as-received ones;

4. After achieving more reliable results and an adequate test to measure *CI*, to be properly standardized, the new material property machining strength could be very useful for quality control sector to foresee the easiness of cutting material in industries in general and also to develop easy-to-cut material for steelmakers.

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7. RESPONSIBILITY NOTICE

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