AN INVESTIGATION OF SPECIFIC ENERGY ON THE CHIP FORMATION PROCESS USING AN INSTRUMENTED CHARPY TEST MACHINE

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Abstract. *In 1901, August Charpy proposed a test to measure the energy when notched specimens were fractured under high strain rates. In the same way, chip removal by machining processes involves elastic and plastic deformations and fracture, also under high strain rates. Considering these aspects, a conventional Charpy test machine was instrumented to evaluate the specific cutting energy in the chip formation process. An encoder positioned on the pendulum rotation shaft supplies the precise angular displacement. Cutting tools were fixed on a piezeletric dynamometer, which measures the* F_x, F_y *e* F_z *forces components, and then fixed on the Charpy machine structure. With all these instrumentations, the specific energy could be evaluated. The influences of the depth of cut, chip breaker, corner radius and insert coating on the specific cutting energy were investigated. This work presents some of the first results of specific energy using an instrumented Charpy test machine. The Al2024 aluminum alloy, on supplied condition, was used as workpiece material. It was adopted the cutting speed of about 170 m/min. The specific energy values resulted in the range from 0.640 to 1.15 J/mm*^{3}*. Generally the main results indicate that specific energy decreases with increase in depth of cut, use of chip breaker, uncoated insert and larger corner radius.*

Keywords. *specific cutting energy, chip formation.*

1. Introduction

The specific cutting energy (CSe) is one of the most important physical parameters in metal cutting. Although other parameters, such as force, temperature and tool wear are also important, many results found in scientific study of chip formation mechanism can only be explained throughout the use of SCe.

During the cutting process, the total energy spent per unit time can be determined multiplying the cutting force F_c by the cutting speed v_c (assuming that other forces are negligible). However, if this is divided by material removal rate, that is, the product between cutting thickness h, cutting width b and cutting speed, results in Eq. (1).

$$u = \frac{F_c \cdot v_c}{h \cdot b \cdot v_c} = \frac{F_c}{h \cdot b} \quad \left[\frac{J}{m^3}\right] \text{ or } \left[\frac{W}{m^3/s}\right] \text{ or } \left[\frac{N}{m^2}\right] \tag{1}$$

Shaw (1995) stated that SCe is an intensive quantity, which characterizes the resistance offered by a particular material to the cutting or shear process. It can be similar to the tensile stress and hardness that characterize the resistance to plastic strain. Based on that, according to Cohen (1989), the SCe can also be divided into four components:

- shear energy per unit volume, u_s;
- friction energy per unit volume, u_f;
- kinetic (momentum) energy per unit volume, u_m;
- surface energy per unit volume, u_a.

The energy per unit volume u_s resulting from shear process can be estimated replacing the energy per unit time necessary to shear the workpiece material by the total energy u, in Eq. (1). Thus,

$$u_s = \frac{F_z \cdot v_z}{h \cdot b \cdot v_c} \qquad \left[\frac{J}{m^3}\right] \tag{2}$$

where $v_z = v_c \cdot \cos\gamma/\cos(\phi - \gamma)$ is the shear speed and F_z is the shear force. It is estimated that the shear energy per unit volume represents more than 75% of the total energy.

The energy per unit volume due to friction effect u_f is consumed on the passage of chip throughout the rake face of tool. This component is related to the cutting speed and it can be expressed according to Eq. (3).

$$u_f = \frac{F_T \cdot v_{cav}}{h \cdot b \cdot v_c} \qquad \left[\frac{J}{m^3}\right] \tag{3}$$

where $v_{cav} = v_c \cdot \mathrm{sen}\phi / \cos(\phi - \gamma)$ is the chip flow speed on the tool rake face and F_T is the friction force on chip-tool interface. The momentum energy per unit volume u_m necessary to accelerate the chip is generally neglected, but it becomes especially important when using high speed machining. This component can be written as:

$$u_m = \frac{F_m \cdot v_z}{h \cdot b \cdot v_c} \qquad \left[\frac{J}{m^3}\right] \tag{4}$$

where $F_m = \rho \cdot v_c^2 \cdot h \cdot b \cdot \delta \cdot \mathrm{sen}\phi$ is the momentum force, ρ is the density of workpiece material and δ is the shear strain. Nevertheless, the energy per unit volume u_a necessary to produce an uncut new surface is provided by Eq. (5).

$$u_a = \frac{2T}{h} \qquad \left[\frac{J}{m^3}\right] \tag{5}$$

where T is the surface energy of workpiece material and h is the undeformed chip thickness. Concluding, for applications on cutting, the total energy per unit volume required to cut a material can be approximated by:

$$u \cong u_s + u_f \qquad \left[\frac{J}{m^3}\right] \tag{6}$$

Equation (6) is only valid for cases where cutting speed is not over 900 m/min. Thus, for cutting speeds higher than that, the part of momentum energy must be included.

The SCe is a very useful concept not only for machining using single-point tools and grinding processes, but also for forming processes (Shaw, 1995). In grinding, the particular significance of the SCe lies in the fact that any proposed mechanism of abrasive-metal interaction must be able to account for its magnitude and dependence on the process parameters (Malkin, 1989).

Evaluation of cutting forces can be of primary necessity in machine tool designs, requirements of power to machine a particular workpiece and to determine the machine tool structure. It can also be important to the processes, since it influences the dimensional and geometrical quality of the workpiece. Also, according to Shaw, in metal cutting, the specific energy does not significantly vary with the cutting speed and depends only on tool rake and undeformed chip thickness. It has shown a behavior inversely proportional to the undeformed chip thickness in Eq. (7).

$$u = \frac{1}{h^n} \tag{7}$$

According to the author, this formulation is valid only for h > 25 μm. The n value depends on machining operation and is equal to 0.2 for processes that use single-point tools, 0.3 for rough grinding and 0.8 to 1 for finish grinding. It was also noted by the author that the cutting speed presents some paradoxes when related to the SCe concept. The increase of the cutting speed causes two effects on SCe values: increase the strain rate that consequently will increase SCe; increase the workpiece material ductility by thermal effect that will cause the reduction of SCe (Shaw, 1996). The contribution of each effect will depend on the cutting speed, which determines the strain rate and the thermal effects.

Specific energy allows understanding the rupture and plastic deformation mechanisms inherent to cutting processes. About ¾ of total energy is associated with shearing in primary zone and ¼ remaining is due to secondary zone at the chip-tool interface. Essentially, the energy consumed on the cut is converted to heat and parts of this heat are transferred to chip, workpiece and tool approximately 90%, 5% and 5%, respectively.

By analyzing the cutting phenomena, it is possible to understand because n exponent is different and depends on cutting processes in the Eq. (7) for SCe proposed by Shaw. In finish grinding, the ratio of cutting edge radius and the undeformed chip thickness is sometimes so large that the chip formation model proposed by Merchant for orthogonal cutting becomes unsuitable. The tool effective rake is so negative that the material removal process can be more precisely classified as that generated as an extrusion. This theory has been confirmed in experiments of hard steel turning (AISI 1550 - 60 HRc) with cutting speed between 66 and 120 m/min, feed rate between 0.025 and 0.2 mm/rev, and depths of cut between 0.5 and 2 mm, Fig. (1).

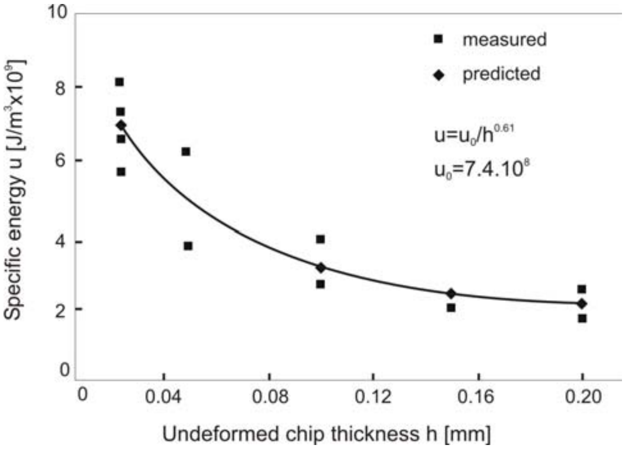


Figure 1. SCe related to undeformed chip thickness on orthogonal cutting (Elbestawi et al., 1996).

In these experiments, it was noted that undeformed chip thickness values can be compared to values applied on abrasive processes. Due to cutting edges on ceramic tools, with tool rake between –6° and –26° and 1.2mm corner radius, the process is similar to grinding. This way, it can be estimated that SCe in chip formation with single-point tool and high speed cutting processes have been approximated to abrasive processes. This occurs mainly because of highly negative tool rake and large edge radius, compared to the undeformed chip thickness.

The resultant force between cutting edge and workpiece material determines the size of elastic-plastic strain zone, as well as, the direction that it establishes, in the same direction of resultant force. The chip formation mechanism proposed by Shaw in 1972, by considering only one abrasive particle (with rake angle very negative, small depth of cut at the same magnitude of the edge radius), illustrates the size effect of SCe, being much greater on grinding processes than on normal single-point cutting processes.

When dealing with very small chips, the increase of SCe can be a result of some reduction on the probability of finding microstructural defects caused by the decrease on size of elastic-plastic strain zone. The decrease of dislocations capable of freely moving may generate an increase of SCe (Schroeter, 1999).

Therefore, the size effect theory was proposed to explain the increase in flow stress with smaller undeformed chip thickness. However, it was already possible to verify the presence of high dislocation densities in the shear zone, by transmission electron microscopy of fine grinding chips. This would seem to cast serious doubt on the size effect theory (Malkin, 1989).

Nevertheless, in finish grinding, a great volume of material must be deformed under SCe to generate little chip effective volume. This indicates that SCe increases fast with decreasing of undeformed chip thickness in grinding than on cutting processes with single-point tool. Because of that, the n value is higher. Table (1) shows some representative specific energy for grinding and cutting processes.

Table 1. SCe for carbon mild steel (Shaw, 1995).

Process	**Undeformed chip thickness [µm]**	**SCe [J/mm^3]**	**n value**
Cutting	250	2.1	0.2
Rough grinding	25	13.8	0.3
Finish grinding	1.25	68.9	0.8 - 1.0

According to Malkin (1989), grinding experiments performed on high carbon content steels resulted in some relation between material removal rate and SCe. Several sizes of abrasive grains were used and all results fall on the same curve. At slow removal rates, SCe is extremely big, but it rapidly decreases with increase on removal rate and reach a minimum value of approximately 13.8 J/mm^3. This magnitude is still very big when compared to normal single-point tool cutting processes. The author suggests a separation of the SCe into three parts: chip formation u_{ch}, plowing deformation u_{pl} and sliding u_{sl} components, as presented in Eq. (8).

$$u = u_{ch} + u_{pl} + u_{sl} \tag{8}$$

The specific chip formation energy is the minimum grinding energy required to remove material. It seems that specific chip formation energy on grinding is not sensitive to alloying and metal work process. Hot-worked low carbon steels and hardened alloy steels present the same minimum grinding energy.

Plowing energy is expended by deformation of workpiece material without removal. It is normally associated with side flow of material from the cutting path. The plowing mechanism occurs in an initial part of cut. The depth of cut varies from zero to a maximum value at the end of cut. An elastic contact is made initially, but its generated energy is assumed to be negligible. After that, deformation plastic (plowing) occurs.

Several experiments have been carried out aiming to study the plowing process. Depths of cut with triangular-based or square-based pyramidal tool are fixed to simulate abrasive cutting points. The set can be performed with tool orthogonally or obliquelly positioned in relation to cutting direction. Sharpness of the cutting edge and rake angle are some factors that influence the plowing energy.

In grinding, the sliding occurs because of wear-flat areas with striated markings in grinding direction. This indicates that a part of the energy expended by grinding is due to flattened grain sliding against the workpiece. Therefore, there is a consumption of energy due to flattened tips on the abrasive grains without removing any material.

2. Experimental work

2.1. Evaluation of the instrumentation error

Initially, a previous test was conducted selecting a particular set of parameters and repeating the test several times. This test would have to yield the same value, except for the instrumentation random error. The results found are presented in Table (2).

Table 2. Results of test conducted with the same set of parameters: 150.7 m/min cutting speed, 0.50 mm depth of cut, 0.8mm corner radius and uncoated insert with chip breaker.

Test Number	Energy (pendulum) [J]	Volume [mm^3]	Specific Energy [J/mm^3]
1	22.15	30.42	0.728
2	24.97	30.64	0.815
3	27.04	32.65	0.828
4	25.88	33.23	0.779
5	24.99	32.80	0.762

Mean: 0.782 J/mm^3
Standard deviation: 0.04 J/mm^3
Interval of 95% confidence for the mean: 0.035 J/mm^3

The results indicate that the mean value of SCe for condition tested is 0.782 ± 0.0175 J/mm^3 with 95% of confidence. This indicates a statistical error of about 4.48% in relation to the mean, for the SCe of this aluminum alloy, with 95% of confidence.

2.2. Experimental tests

The experimental tests were carried out in an Instrumented Charpy Machine (ICM) using cutting speed of 170 m/min. This equipment was adopted to provide measurements of energy throughout angular displacement and force measurements during the chip removal process. An angular optical encoder (10,000 points per revolution) and piezelectric dynamometer Kistler 9257BA were installed on machine for measuring the specific cutting energy.

The workpieces of Al2024 aluminum alloy (118 HB hardness), used on supplied condition (solution and hardened by preciptation), were fixed at the center of gravity of the pendulum. This allowed material was used only for investigating the influence of tool parameters on SCe. The details of the design, modeling and implementation of the instrumentation, as well as, the equipment operation and measurement of SCe can be found in Rodrigues (2003).

Tools were positioned in a device on the machine structure. All tests used tool rake angle set up at 7° and square inserts of 12 mm with 4 mm thickness. Other parameters are showed in Table (3), together with the factors used in the ANOVA (Analysis of Variance). Figure (2) shows a typical model of the chip breaker geometry used.

Table 3. Factors and levels for ANOVA application on specific cutting energy.

Factors	Levels	Specifications		
Corner radius [mm]	3	0.8	1.2	1.6
Depth of cut [mm]	3	0.2	0.4	0.6
Tool geometry	2	Chip breaker		No chip breaker
Coating	2	TiN		No coating

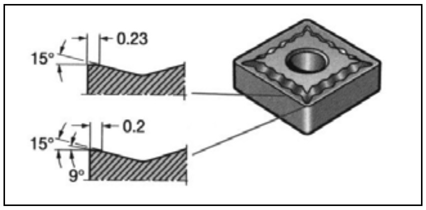
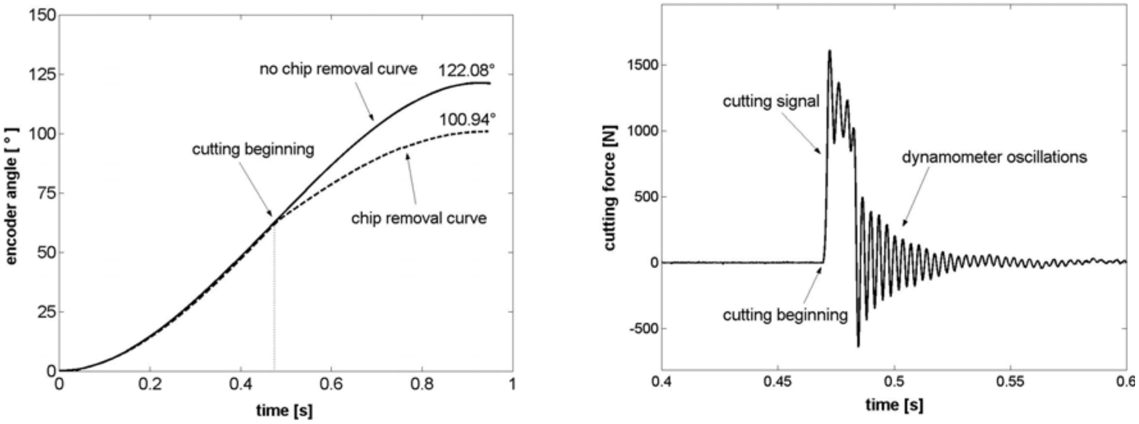


Figure 2. Typical model of chip breaker geometry tested.

Considering these variables, it was used a Full Factorial Design of experiment with one replication, in a total of 72 experiments, aiming the ANOVA technique.

3. Results and discussions

Figure (3) shows typical curves obtained from the Instrumented Charpy Machine. Two ways were used to calculate the SCe: by the difference between angular displacement of the pendulum and also by numerically integrating the force versus displacement (time) curve. The volume of material removed divides these values yielding the SCe. Results found by these two different ways agreed very well and the first one was used to the analysis; the other was used to double check, avoiding rough errors.



(a) (b)

Figure 3. (a) Angle of Charpy pendulum and (b) cutting force measurement. Conditions were: 0.6 mm depth of cut, 1.6 mm corner radius, no coating and no chip breaker on the tool.

With the tests performed, the first analysis was the ANOVA, considering the factors. Table (4) presents the results.

Table 4. ANOVA results from the tests with Instrumented Charpy Machine.

Source	Degrees of Freedom	Sum of Squares	Mean Square	F-value	P-value
Depth of cut	2	0.361446	0.180723	23.30	0.000
Coating	1	0.019208	0.019208	2.48	0.120
Corner radius	2	0.008099	0.004050	0.52	0.596
Tool geometry	1	0.000001	0.000001	0.00	0.989
Error	65	0.504183	0.007757		
Total	71	0.892937			

The ANOVA table indicates that only the factor "depth of cut" can have a significant influence on the SCe. It yielded a very low probability, compared with the experimental error, ~0% and 4.48% respectively. This statement can be confirmed by Figure (4) where the SCe is plotted against each of the main factors.

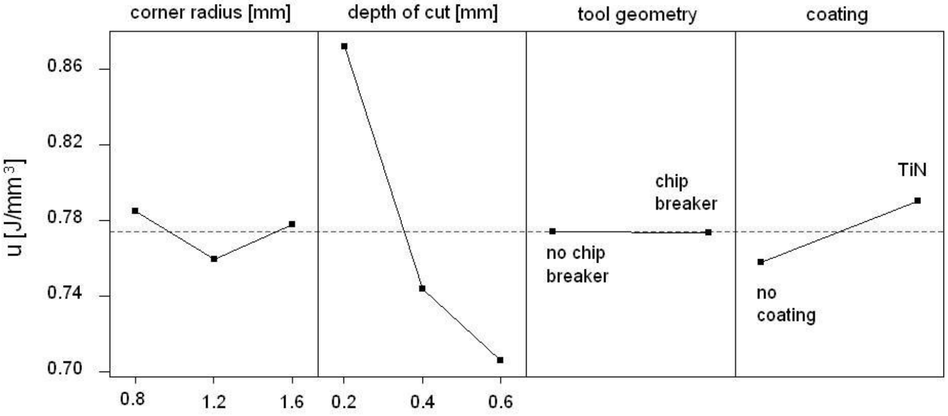


Figure 4. General behavior of SCe against the main factors.

Figure (4) confirms that the depth of cut plays an important role on SCe and it decreases as the depth of cut increases. The application of coating on inserts seems to cause increase on the SCe. This also confirms practical facts observed by machine operators that when cutting aluminum alloys, the use of coating does not improve tool peformance and causes adherence of workpiece material. Therefore, the experiments were capable of detecting this fact, indicating the increase of SCe when using coated tools. Machine operators also find better cutting conditions for aluminum alloys when using polished rake face, which will have to be investigated with the Charpy Instrumented Machine.

Contrastingly, the use of chip breaker provides very little modifications on the values of SCe, at least with the model tested in this work. It seems worth investigating, since the use of chip breaker shows a slight decrease in the SCe. It appears that sharper chip breaker will lead to low SCe, which will be object of new studies.

Like the chip breaker, the corner radius showed little differences, relatively to the experimental error, at least within the values tested. It seems to have a lower value at radius of 1.2 mm, but the differences were of the same magnitude of the experimental error.

This indicates that no significant variations were found with the different corner radius used. The combinations of all factors in groups of two, and their interactions, did not show significancy, therefore, their analyses were not considered here.

With the statistical analysis accomplished, with isolated or combined factors, it was attempted to obtain a simple linear mathematical model, which could represent the behavior of SCe as a function of the main factors only: depth of cut a_p and corner radius r_ε.

$$u = 0.729 - 0.083 \cdot a_p - 0.0035 \cdot r_\varepsilon \tag{9}$$

The model indicates a greater influence on the depth of cut. The equation tries to predict the values of SCe as a function of the main factors, within the range tested. The SCe values cannot be extrapolated and the intermediated values of the main factors are assumed to be linear, which may not be the case, as can be seen in Figure (4) for the depth of cut. At the end, Eq. (9) is only a rough indication of the SCe value.

In general, the literature about manufacturing presents several results of SCe for aluminum alloys, under a great number of conditions and machining operations. These measurements were, generally, performed in machine tools, and calculations considered cutting speed, force, and material removal rate. Grinding processes are those with higher number of results on SCe measurements.

Figure (5) shows a comparison between the average value found at the present work with some other obtained by several authors for aluminum alloys in conventional machining operations, like milling and turning and single-point tools. They were obtained from tables, equations and graphs in the references, based on experimental data. It can be noticed that SCe results show a large range due to the number of uncontrolled factors involved in the measurements.

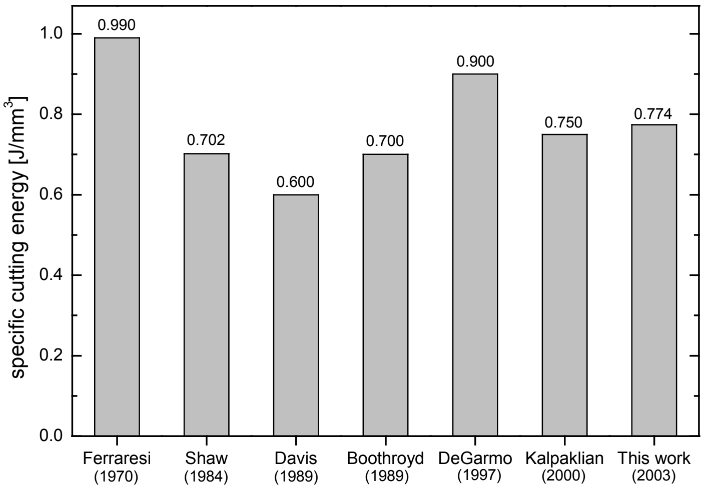
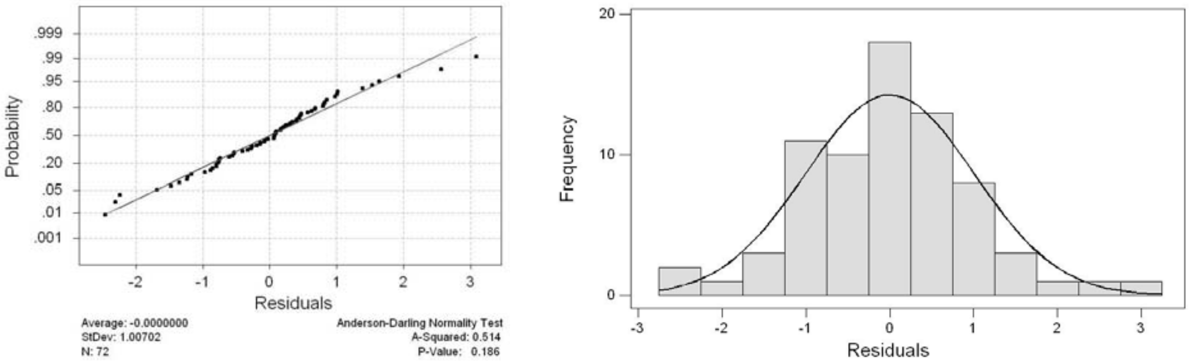


Figure 5. General results of SCe found in literature by experimental measurements in different machining operations for aluminum alloys.

Finally, the application of ANOVA assumes that the residuals are normally distributed with average zero. These conditions were checked and the results are shown in Fig. (6) with the normality test graph and the histogram, obtained by MINITAB 13.2 statistical software.



(a) (b)

Figure 6. (a) Normality test and (b) histogram of residuals.

The normality test, applied on SCe results, indicates a good possibility to apply ANOVA on the results. Probability values greater than 5% validate the use of ANOVA technique.

4. Conclusions

The present paper presented an investigation about the SCe consumed on chip formation processes by using an Instrumented Charpy Machine. This measurement method allowed obtaining absolute results of specific cutting energy (SCe) and evaluating the tools performance. According to the results obtained, the following conclusions can be reached:

- The evaluation of the instrumentation error provided a value of 4.48% of the mean when assessing the SCe of a particular set of parameters, with a confidence of 95%;

- It was possible to evaluate the chip formation SCe with good precision and sensibility using an Instrumented Charpy Machine;

- Considering all studied variables, the depth of cut presented greater influence than other parameters upon the response (SCe);

- The use of TiN coating caused an increase on the SCe, as it has been observed in real cutting conditions of aluminium alloys, although the differences found here were not statistically significant, compared to the experimental error;

- The positive chip breaker used to compare with no chip breaker presented the smallest influence on SCe compared to other factors. There was a slight decrease of SCe when using the chip breaker, which seems to indicate a trend, but there is no statistical significance at this point;

- The influence of the corner radius on SCe was small with no statistical significance too. A smaller value was found with 1.2 mm radius, which could indicate a minimum point, but there was no evidence to surely state that. The meaning and reasons for those results are still to be investigated.

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