COMPUTATIONAL METHOD FOR CALCULATION OF THE SPECIFIC CUTTING ENERGY

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Abstract. *The Specific Cutting Energy (SCE) is an intensive quantity that characterizes the cutting resistance offered by a given workpiece material. This paper presents a computational routine that optimizes the calculation of the SCE from the integral of milling force and workpiece volume data. Initially the routine corrects amplitude distortions of the force signal and windows it precisely on machining time. Then, the SCE is obtained by integrating numerically the cutting force, considering the cutting speed, chip volume and machining time. For method validation, experimental results from eight milling conditions and two workpiece materials were compared to the models of Kienzle, Taylor, ASME, AWF and Sandvik, presenting deviations up to 18,5%.*

Keywords*: milling, specific cutting energy, computational methods*

1. INTRODUCTION

Machining is one of the most important manufacturing processes. Parts manufactured by others processes usually require further operations before the product is ready for its application. Machining operations can be applied to both metallic and non-metallic materials, such as polymers, wood, ceramics, and composites. Nowadays in the industrialized countries, the costs related with machining sum over 15% of all manufacturing processes. For this reason, machining is very important for the modern manufacturing industries (Davim, 2008).

The evaluation of the machinability based on SCE is of great importance since it deals with one of the most important physical quantities originated in the machining phenomenology. Other indexes are also relevant when analyzing the machinability, such as cutting force, cutting temperature, machining time, tool wear, and others (Rodrigues, 2007).

The SCE has a straight relationship with the machining results. High values generate high rates of heat transfer and high residual stresses in the workpiece, which may lead to a poor surface integrity of product, while low values result in less damage to the part, indicating quality and efficiency of the cutting tool (Ersoy e Atici, 2004).

The SCE is defined as the effective consumed energy to remove a unitary volume of workpiece material. It is considered a good index of machinability of materials and allows understanding the whole cutting process (Polini and Turchetta, 2004). The SCE for a general case is given by Eq. (1).

$$u = \frac{F_c.v_c}{h.b.v_c} \tag{1}$$

in which F_c is the cutting force [N], h is the cutting thickness [mm], b is the cutting width [mm], and v_c is the cutting speed [m/min]. Usually, the SCE is given in J/mm^3. The SCE is a concept not only used in machining, but also very useful for forming processes (Shaw, 2004). In machining, it is possible to estimate the cutting forces which determine the structural needs of the machine and influence in the geometric and dimensional quality of the product. According to Ersoy and Atici (2004), the SCE can be also used to determine the power required by the machine tool.

Several factors influence on the force and SCE, such as the type of material being machined, the cutting tool, cutting conditions, and cutting operations. The knowledge of these factors is important for appropriate planning of the machining process. The machining parameters such as depth of cut, feed rate, cutting thickness and cutting area are inversely proportional to the SCE, and the feed rate and cutting thickness are the most sensitive of them.

Some workpiece material properties also influence on SCE, like hardness, chemical composition and shear strength. Harder materials tend to increase the SCE, as well as certain alloy elements, such as P and S reduce the SCE for easing the cut, due to the lower shear strength.

This paper presents a computational procedure to optimize the experimental determination of the SCE, by integration of the cutting force obtained through machining, volume data of the workpiece and the cutting parameters.

2. MATERIALS AND METHODS

2.1. Methods of SCE calculation

There are several theories based on experimental results for the empirical calculation of the SCE using turning process, such as those purposed by Shallbroch, Kronenberg, Vieregge and Opitz and Victor. Taylor studied the dependence of the SCE with the area and shape of the cut section. After many tests, the researcher presented analytical formulae for gray cast iron, white cast iron and mild carbon steel, respectively (Ferraresi, 1970).

$$u = \frac{88}{f^{0.25} a_p^{0.07}} \tag{2}$$

$$u = \frac{138}{f^{0.25} a_p^{0.07}} \tag{3}$$

$$u = \frac{200}{f^{0.07}} \tag{4}$$

in which f is the tool feed and a_p is the depth of cut.

The ASME - *American Society of Mechanical Engineers* - also researched the SCE. With a selection of data from cutting power and chip removal rate, it was possible to estimate a representative expression of the data, Eq. (5).

$$u = \frac{C_a}{f^n} \tag{5}$$

in which f is the tool feed and n is 0.2 for steels and 0.3 for cast iron, C_a is a constant of the material. The use of other materials and tools is possible using patches (Ferraresi, 1970).

The AWF - *Ausschuss für Wirtschaftliche Fertigung*, the German Production Association, as well as ASME, presents a table of the SCE obtained from tests for various materials, Eq. (6).

$$u = \frac{C_w}{f^{0.477}} \tag{6}$$

in which C_w is a material's constant and f is the tool feed (Ferraresi, 1970).

Figure 1 shows the curves from the expressions used to calculate the SCE aiming at comparing the proposed formulations. The different slopes are due to different exponents of the feed (Ferraresi, 1970).

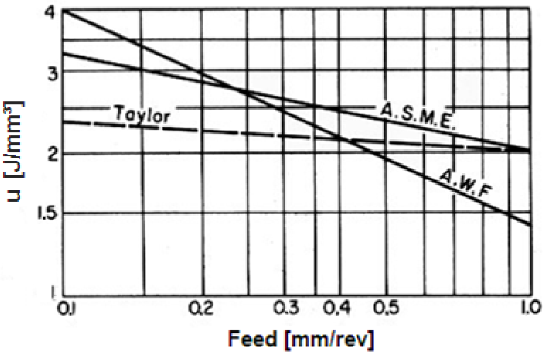


Figure 1. SCE versus tool feed (modified from Ferraresi, 1970).

Seeking a simple and precise formulation, Kienzle in 1951 suggested the Eq. (8) which uses the cutting thickness for determining SCE. Through practical tests, it is possible to show the graphic of the SCE for a given tool-workpiece pair, as seen in Fig. 2. The Kienzle formula is considered one of the most important finding about SCE.

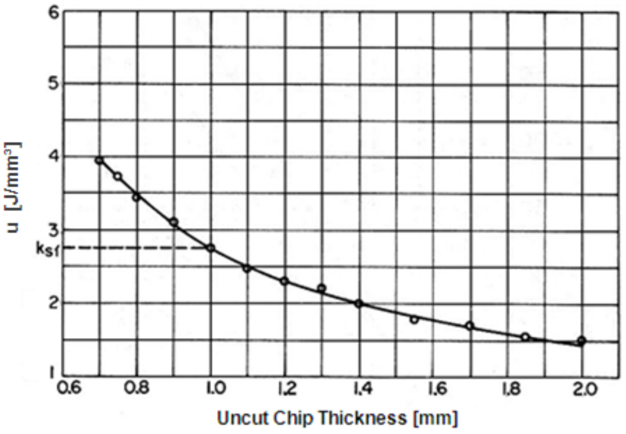


Figure 2. SCE as a function of the cutting thickness (modified from Ferraresi, 1970).

$$\log(u) = \log(k_{s1}) - z.\log(h) \tag{7}$$

$$u = \frac{k_{S1}}{h^z} \tag{8}$$

in which k_{s1} is a material's Constant for a cutting section of 1 mm² and z is the slope of the straight line, which can be observed when using logarithmic scales in the graph of Fig. 2 (Ferraresi, 1970).

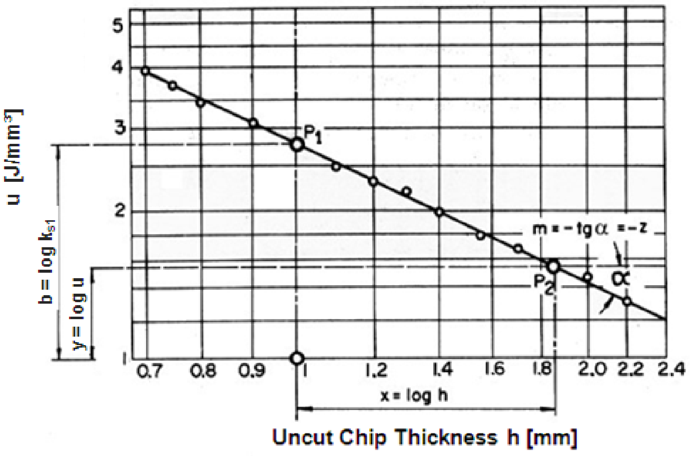


Figure 3. SCE as a function of the cutting thickness in dilogarithm scale (modified from Ferraresi, 1970).

More current methods for calculating the SCE can be found in manual guides of tool manufacturers. Sandvik Coromant (2003) has presented a formula for milling aiming at determining the SCE considering different cutting parameters and workpiece materials, Eq. (9).

$$u = k_{c1} \times h_m^{\text{-mc}} \tag{9}$$

in which k_{c1} is the specific cutting force [N/mm^2], h_m is the average chip thickness [mm] and *mc* is the non-dimensional factor of increase in specific cutting force as a function of chip thickness.

2.2. Methodology proposed by this work

The SCE was calculated using the cutting force. Retaking the Eq. (1) and considering the depth of cut a_p and feed rate f instead of the cutting thickness h and cutting width b (for composing the cutting section), the denominator of the equation equals the material removal rate (MRR), Eq. (10).

$$u = \frac{F_c.v_c}{a_p.f.v_c} = \frac{F_c.v_c}{MRR} \tag{10}$$

Multiplying the Eq. (10) by cutting time t_c, we have the total volume removed V_{rem} in the denominator and the impulse of cut I_c multiplying the cutting speed v_c in the numerator.

$$u = \frac{F_c.v_c.t_c}{MRR.t_c} = \frac{v_c.F_c.t_c}{V_{rem}} = \frac{v_c.I_c}{V_{rem}} \tag{11}$$

The impulse of cut is given by the integral of the cutting force, which is the vector sum of force in direction x and y, Eq. (12)

$$u = \frac{v_c}{V_{rem}} \int_0^{t_c} \left(F_x^{\,2} + F_y^{\,2}\right)^{1/2} dt \tag{12}$$

in which $\left(F_x^{\,2} + F_y^{\,2}\right)^{1/2}$ [N] is the cutting force F_c, v_c [m/min] is the cutting speed, t_c [s] is the cutting time e V_{rem} [mm³] is removed chip volume by the milling process. The Simpson's 1/3rd Rule was chosen to solve the integral of Eq. (12), better detailed in Eq. (13).

$$\int_b^a f(x)dx \approx \frac{b}{3}\left[f\left(x_0\right) + 4f\left(x_1\right) + 2f\left(x_2\right) + 4f\left(x_3\right) + ... + 4f\left(x_{n\text{-}1}\right) + f\left(x_n\right)\right] \tag{13}$$

in wich f(x) is any function, a and b are the integration limits, and b is the integration step ($x_{n+1} - x_n$). The Simpson's 1/3rd Rule employs a second degree polynomial to obtain the approximate value, because it considers three points in each subinterval of integration. Thus, this method allowed obtaining the value of SCE adequately once it requires only the function values at each point without needing the function of cutting force during machining.

Unlike the traditional formulations, this methodology uses an integral that considers all the forces in the period of time instead of using a mean value for the cutting force. This ensures a better accuracy of the method, since the fluctuation of force is considered. The computational routine was developed according to Fig. 4.

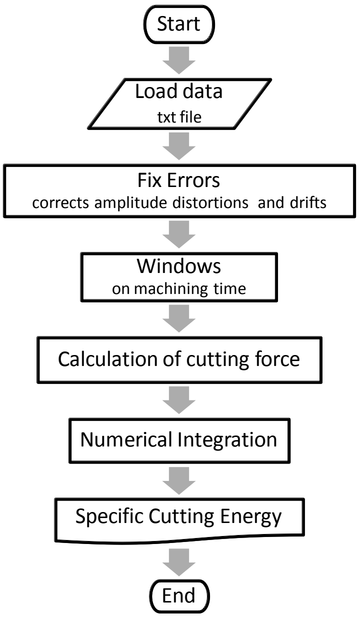


Figure 4. Flowchart of computational procedure for calculating the SCE.

2.3. Machining tests and workpiece

The trials were carried out in a CNC vertical machining center Romi Discovery 560, with 10,000 rpm maximum spindle speed and 11 kW power. For cutting force data acquisition a Kistler 3-component piezoelectric dynamometer 9257BA and amplifier 5233A coupled to an acquisition system National Instruments® were used.

All tests were performed adopting dry and down-milling condition, with 2.0 mm radial depth, 100 and 589 m/min cutting speeds, 0.5 and 3.0 mm depth of cut and 0.05 and 0.20 mm/tooth feed per tooth. All cutting parameters were combined to each other generating eight milling conditions by means of 2^3 factorial design.

Low carbon steel 0.15%C (200 HV) commercially named COS AR 60 provided by USIMINAS-Cubatão was used. The carbide inserts code R390-11 T3 08M-PM 4220 coated with Al_2O_3 and ISO P15 grade, and tool-holder code R390 025A25 11L with two indexable inserts and 25 mm diameter from Sandvik Coromant were used.

3. RESULTS AND DISCUSSION

The calculation methods for SCE abovementioned in the section 2.1 i.e. Taylor, ASME, AWF, Kienzle, and Sandvik Coromant models were chosen for comparison, because they require cutting parameters used in this work and tabulated data relative to the workpiece's material, even though in some cases approximations were used, mainly related to the chip shape. Thus, the input data for models were extracted from Ferraresi (1970) and Sandvik Coromant (2003).

Using the results of the SCE obtained, it was possible to generate SCE curves as a function of the material removal rate for all models used (Fig. 5). The material removal rate was chosen because it is representative of both cutting speed and feed per tooth, in other words, of the most influential factors in SCE.

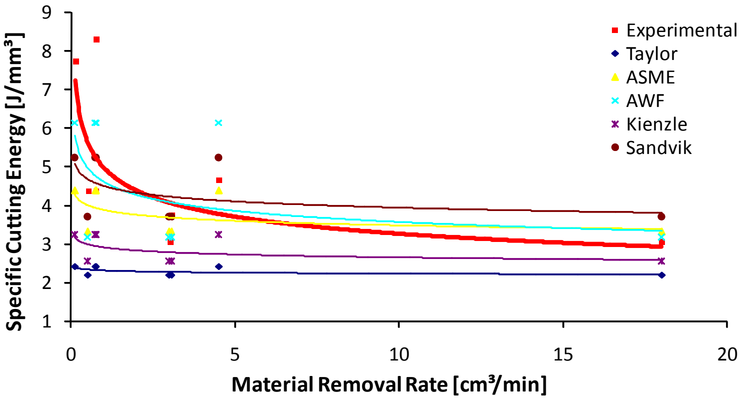


Figure 5. Comparison of the SCE models for COS AR 60 steel.

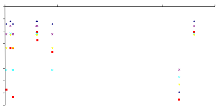
The experimental values of SCE generated by this work showed a behavior similar to other models. Only when small material removal rates were applied the experimental curve showed a stronger growth than the others. Note that the curve generated by this work was closer to that of the calculation methods of Sandvik Coromant, ASME, and AWF.

By examining the obtained curves, it is possible to verify that the size effect phenomenon is more pronounced for the proposed model and less pronounced for other methods of calculating the SCE. This difference in behavior may lie in the fact that other models are strongly based in the tool feed and, in some cases, in the depth of cut (less significant in the SCE), while the proposed model takes into account, besides tool feed (most influential factor), the cutting speed (a more significant effect than the depth of cut).

Another analysis refers to the effect of chip thickness on SCE. The comparative empirical methods of the proposed model were formulated for a range of workpiece materials, considering the constant chip thickness. This may be the cause of the differences between the models, except for the one of Sandvik Coromant, which considers a variable chip thickness, as well as the milling process performed by this work.

Besides the difference resulting from the variation in chip thickness, some models drawn from Ferraresi (1970), such as ASME, AWF, and Kienzle were fed with tabulated data, approximated to the workpiece's materials. Taylor's method, in turn, takes into account only the cutting tool feed, and the model constants are used in medium carbon steels. This broad application of the Taylor's method, not specifying for example characteristics such as hardness, strength or chemical composition of parts, may also have led to greater differences between the results.

With the validation of the obtained values, it becomes possible to create a model for calculating the SCE for the materials and cutting parameters used in this work. Figure 6 shows the interpolation of experimental results of the SCE as a function of feed speed for COS AR 60 steels.



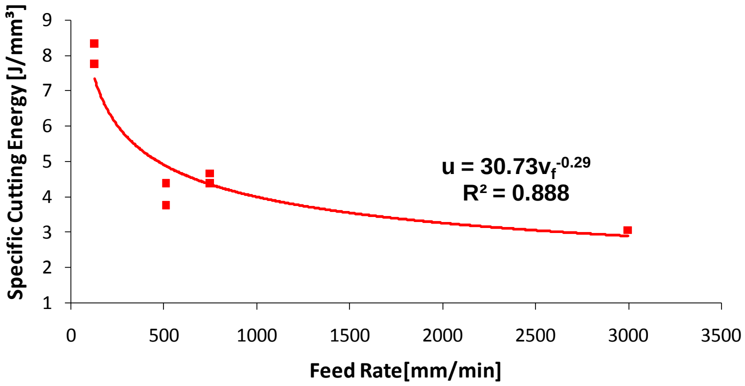


Figure 6. SCE as a function of feed speed of the tool.

The fit of the curve considering the feed speed, such as the material's removal rate above mentioned, represents a behavior of the SCE, for incorporating the major factors, which are tool feed and cutting speed. Analyzing the expression generated when fitting the points, the negative exponent of the feed speed (-0.29) also determines the degree of curvature of the curve, because the higher the value, the more the curve is asymptotic to the Y axis, indicating the sensitivity of the material to the size effect and maximizing the SCE with the decrease of the feed speed.

4. CONCLUSION

Based on the experimental results for validation of the methodology for calculating the SCE, the following conclusions can be drawn:

1. The computational algorithm optimized the calculation of the SCE, showing agility and ease in calculations, allowing its application in several machining processes. Thus, the methodology makes SCE an index of easy calculation where the machinability of materials or the machining strategies can be quickly compared.
2. The methodology formulated showed good agreement with the methods for calculating the SCE originated from the scientific and technical literature, even when different machining processes are considered. Compared with Taylor, ASME, AWF, Kienzle, and Sandvik's models, the results showed similar patterns with deviations lower than 18.5%, varying according to the cutting conditions, thus showing the good accuracy of the method.
3. The equation proposed for SCE showed a good fit (R=0.889), allowing the calculation of SCE by using only the feed speed. Such calculations can be used with good precision for the parameter range and geometries employed in the experiment for the COS AR 60 steel.

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