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THE INFLUENCE OF THERMOELECTRIC PHENOMENA ON THE TOOL WEAR IN CASE OF CUTTING

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Abstract: It is a well-known fact that thermoelectric currents, reaching even the scale of ampere, develop during chip formation in the workpiece-tool-chip-machine system. The impact of these currents on tool wear in intermittent cutting, end-milling was examined with a qualitative mathematical model, in which wear is described by an autonomous non-linear differential equation. It was established by milling experiments using P35 carbide conducted on the C45 quality steel workpiece that it is optimal with respect to the wear of the tool behaving as a natural thermoelement that the thermovoltage is compensated with an external power source. According to the model, the thermoelectric system behaves in a chaotic way in certain cases. Further research is necessary to decide if this is only a special characteristic of the model or the model shows the actual processes.
Keywords: Cutting, Electrical current, Wear, Face-Milling

1. INTRODUCTION

The first really exhaustive measurement of cutting temperature that we know of was performed by Küsters[1] after several preliminary researches. He used the thermocouple method and managed to show through detailed examinations that temperature distribution on the tool surface contacting the chip or the workpiece is not even. As a result, the temperature measured on the tool can be considered an average, regarding which Lowack conducted extensive research [2] and isolated the workpiece and the tool from the machine in thermoelement measurements [3]. In the meantime, naturally, the assumption arose that the thermoelectronic currents developing on the tool as a result of chip formation can be significant and, according to the measurement published by Küsters, these currents can exceed 5A value. This was also confirmed by Opitz [4]. The heat effect of such current can even influence wear [5]. Ellis and Barrow found that the tool life decreased in the case of insulated tools [6]. Based on the extensive research conducted by Dubrov et al [7], if the electrical circuit of the tool-workpiece was interrupted, the tool life increased significantly, to 1.3-2.9 times the original.

Shan és Pandley [8] conducted wear tests with various cutting and electrical circuit conditions to examine the issue. They found that the efficiency of the insulation in a given tool-machine combination depends on the cutting parameters and the electric parameters of the tool-workpiece-machine system. The fact that the impact of electric current was evaluated by various researchers differently, depending on the conditions of cutting, prompted further research. Uehara et al [9] built an analogous electronic model to study the local currents developing in the chip root (Figure 1). Measurements simulating various cutting conditions confirmed the often contradictory findings of previous researches, i.e. that the isolating effect of the tool may vary depending on the actual conditions of cutting. The Peltier-effect influences the temperature on the contact surface of the tool, thus, wear as well.

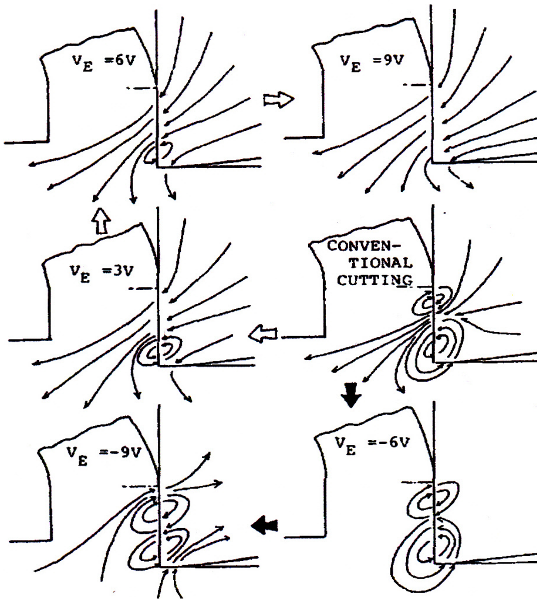

Figure 1. The impact of external voltage on internal whirling currents (Ueada et al [13]).

Besides all these, however, it can be concluded that although the heat impact of the sometimes significant electric current obviously influences the temperature of the contacting surfaces of the tool-workpiece-chip system, a rather moderate interest is found in literature in this topic. This fact lead to the idea of concluding a qualitative analysis based on the experimental findings of Csobod L. [10] regarding the thermoelectric currents developing in the chip root and the impact of externally fed electric current.

2. THE ELECTROTHERMAL MODEL OF THE CHIP ROOT

The well-know 'classical' formula of cutting temperature is

$$\Theta_e = C_v v^x \tag{1}$$

where C_v and x are constants. This then is usually extended by various technological parameters. Actually the x exponent itself also depends on cutting speed, which can be resolved by using different values in the various temperature ranges [11]. Kalászi [12] also showed that thermovoltage is also influenced by the structural transformation that may occur in contacting materials in the thermoelement measurements of cutting speed, which shall be considered in the evaluation of the results.

Naturally, it is a dynamic process that also depends on time, which, after the initial transient stage, approximates to a constant value in the continuous cutting of a material of constant diameter and this value is usually described with formula (1). In intermittent cutting such as face milling, the transient stage of the process is important, where the application of empirical formula

$$\Theta_e = C_v v^x \exp\left(-\frac{\tau}{t}\right) \tag{2}$$

has proven useful [11]. Here t means time, τ is the time constant characteristic of the transient process, e.g. τ =1.95s in the case of steels of moderate C-content [11].

The temperature field on the surface of the cutting tool develops as a combined result of the following three processes.

a. the fast deformation of the material in the chip root and the friction on the surface of the tool.
b. the temperature developing on the surface of the tool increases by $\Delta\Theta_w$ value as a result of wear, which is also connected to the power of the friction force
c. the temperature field developing on the contacting surfaces of the workpiece, the tool and the chip creates a special electric potential field on the surface of the tool and whirling currents develop, as shown by Figures 1 and 2. This results in a further increase $\Delta\Theta_i$ of temperature.

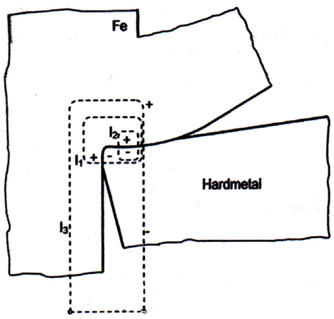

Figure 2. Currents in the chip root

Naturally these three processes are interrelated, which needs to be taken into account in actual measurements. Thus, the so-called cutting temperature that can be determined by various measurement methods is

$$\Theta = \Theta_m + \Delta\Theta_w + \Delta\Theta_i \tag{3}$$

Mostly new, not yet worn tools are used to determine formulas (1) and (2), so the results do not contain the $\Delta\Theta_w$ value. Increment $\Delta\Theta_i$, however, is obviously a part of the Θ_e value determined by measurement, which supports the assumption

$$\Theta_e = \Theta_m + \Delta\Theta_i, \tag{4}$$

This is the so-called cutting temperature, which means a specific average value on the working surface of the tool, which makes the rake face maximum warmer and the flank land temperature lower. Thus, a $\Delta\Theta_f$ temperature difference has a meaning for the flank land. So the temperature of the flank land is

$$\Theta_f \approx \Theta_m + \Delta\Theta_w + \Delta\Theta_i - \Delta\Theta_f \tag{5}$$

Naturally, formula (2) shall be used instead of (1) for intermittent cutting.

Assumptions for thermo-current calculations:

R_f resistance between the tool flank and the workpiece contact depends on the degree of wear:

$$R_f = \frac{c_R}{W} \tag{6}$$

Cutting temperature increases in proportion to wear:

$$\Delta\Theta_w \approx c_W W \tag{7}$$

and c_W is constant.

The temperature difference between the rake face and the flak land is:

$$\Delta\Theta_f \approx c_f \Theta_f (1 + c_{f1} W) \tag{8}$$

where c_f and c_{f1} are also constants.

Finally, $\Delta\Theta_i$ temperature increase, which develops as a result of i_f thermoelectric current is

$$\Delta\Theta_i \cong c_i \frac{i_f^2}{R_f} \tag{9}$$

where c_i is constant.

With regard to the qualitative analysis of the impact of electrical circuits, the constants listed above can be estimated from the data that has been published in cutting literature regarding the temperature of the tool flank and the impact of wear on temperature.

The electric field/paths shown in Figure 1 were summarized in three circuits in Figure 3: $i_1=i_f$: current through the rake face and the flank land; i_2: internal current on the rake face; i_3: current through the tool, the chip and the machine.

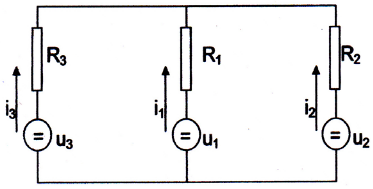

Figure 3. Circuits in cutting

As broadly known, the electromotive force is nearly proportionate to temperature, so if Θ_f is known, u_1 can be calculated with formula

$$u_1=E_f=c_E\,\Theta_f \tag{10}$$

where c_E is the Peltier constant regarding the actual material pair, whose value is known from the authors' own measurements [10].

Voltage $u_2=E_t$ develops on the rake face of Θ temperature, so

$$u_2=E_t=c_E\,\Theta\approx c_E\,(\Theta_f+\Delta\Theta_f) \tag{11}$$

Voltage marked with u_3 in Figure 3 only needs to be considered in the special case if an external source of current also works between the tool and the workpiece, as happens in milling experiments presented in this paper. Otherwise $u_3=0$.

The strength of the electric current going through the tool flank can be calculated from the circuits shown in Figure 3. Disregarding the details

$$i_f=i_f'-i_f''-i_f''', \tag{10}$$

and

$$i_f'=\frac{E_f}{c_R+\dfrac{R_mR_tW}{R_m+R_t}},\qquad i_f''=\frac{R_mW}{c_R+R_mW}\cdot\frac{E_f+\Delta E}{R_t+\dfrac{R_mc_R}{c_R+R_mW}},\qquad i_f'''=\frac{R_tW}{c_R+R_tW}\cdot\frac{E_t}{R_m+\dfrac{c_RR_t}{c_R+R_tW}} \tag{11}$$

The temperature calculated with these formulas can be used for the calculations of tool wear, for which the following differential equation can be used [13]

$$\frac{dW}{dt}=\frac{v}{W}\left(A_a+A_{th}\exp-\frac{Q}{R\Theta_f}\right) \tag{12}$$

where v is cutting speed, Q is the activation energy of wear, R is the universal gas constant, A_a and A_{th} are constants. It can be seen that there is a positive feedback in the relationship of W wear, which is, in our case, VB flank wear, and Θ_f temperature. It is advisable to regard W wear as an independent variable in the numerical solution as this influences R_f resistance (6), $\Delta\Theta_f$ (8) and $\Delta\Theta_i$ (9) heat increment and i_f current strength (10). Δt will be the dependent variable in the differential version of equation (13) in accordance with formula

$$\Delta t=\frac{\Delta W}{dW/dt}, \tag{13}$$

by which function W(t) can then be determined numerically.

It is an important fact that we also have a positive feedback here.

3. CUTTING EXPERIMENTS

The machine used in the experiment was a UF221 type horizontal axis milling machine (Figure 4), on which a vertical axis head was mounted. The machine was in a moderately used condition in a factory maintenance workshop. The tool was a face mill, in which a cutting tip was inserted ($\gamma_o=6^\circ$, $\kappa=70^\circ$, $\varepsilon_r=90^\circ$, P35 carbide).

C45 and C60 quality steels were cut during the experiment. Cutting technology: feed 100mm/min and f=0,105mm/edge, depth of cut a=2,5mm, without cooling, cutting speed: v=298,3m/min. Consequently, the tool was cutting for t_o=10,057s during one turn of the mill.

Based on the preliminary experiments, the duration of cutting was 4.15min pure cutting after the machining of 5 layers L=500mm (Figure 5), and this means N=23728 cutting cycles. The axis of the mill was isolated from the other parts of the machine, thus, various external voltage could be switched to the tool from a battery (12V). The external current driven through the chip root is superimposed on the current generated by the thermovoltage and either added up to it

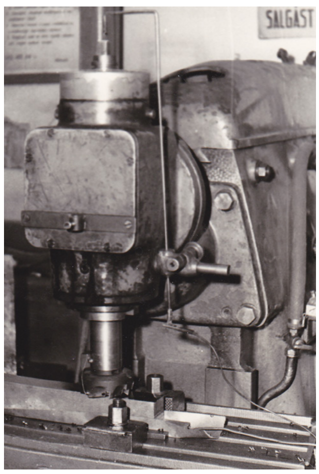

Figure 4. Milling machine with a workpiece

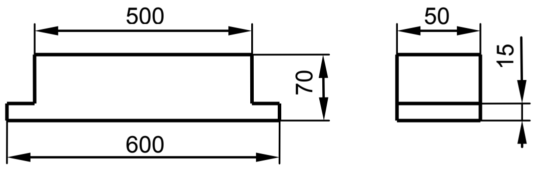

Figure 5. Experimental workpiece

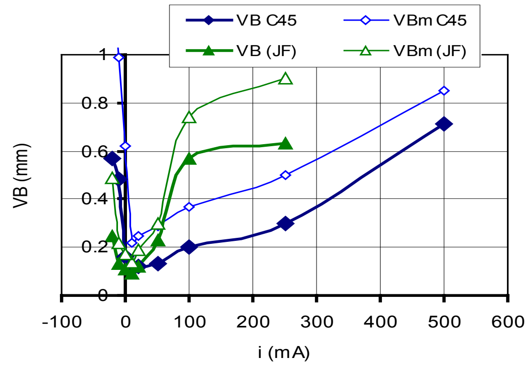

Figure 6. Tool wear in various external currents

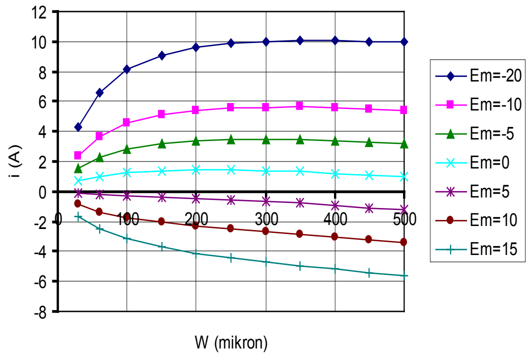

Figure 7. Calculated i_f current as a function of wear at various external E_m voltage (W=VB, R_m=2m □)

or was offset by it depending on the direction of the current. The results of cutting experiments are shown by Figure 6. Based on two series of measurements the optimum is to be found nearly at the same external current.

4. CALCULATIONS WITH ELECTROTHERMAL CHIP MODEL

Figure 7 shows the i_f current going through the contacting surface of the tool flank and the workpiece at various E_m external voltage sources as a function of W=VB wear calculated by formula (10). Using the fact that the duration of a cutting cycle is by far shorter than the time of wear measurable in minutes, the simplified assumption that W=VB=constant during a particular cycle can be used. This way the W_j=y(W_j) increment of wear can be calculated for various W_j values (60, 100, 150 …m), which then can be numerically determined. This is shown by Figure 8 in the case when E_m=0, i.e. with no external current used. Using this function and formula (13) wear can be calculated even at increasing wear for the various E_m values, which is shown by Figure 9 (E_m=0, A_a=8.10^{-6}m, A_{th}=200m, Q=152kJ/mol, τ=1,95ms). The qualitative modelling of the electrothermal processes of the chip root lead to similar results as those found by the experiments. According to measurements, the optimum is not at E_m=0mV, i.e. not at normal cutting circumstances. An external voltage source, which can compensate the impact of the thermo element, is necessary for this.

Examining the cutting process, calculations revealed interesting anomalies of the electric current during a single turn of the mill. As it can be seen in Figure 10, the current seems to be stable from about the middle of the cycle, i.e from 6s time, but it fluctuates with a decreasing amplitude before that. The figure only shown the peaks of the calculated fluctuations of the current, thus, a funnel-shaped graph can be seen.

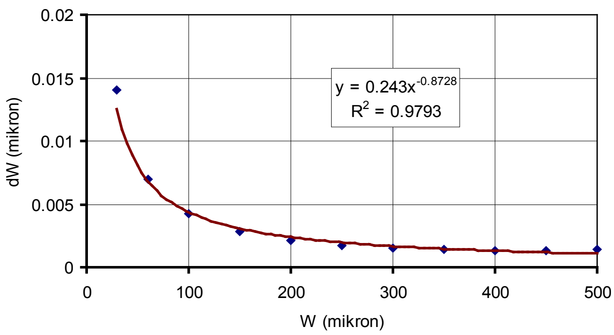

Figure 8. dW(W) increase of wear in a single cutting cycle (E_m=0, R_m=2$\mu\Omega$)

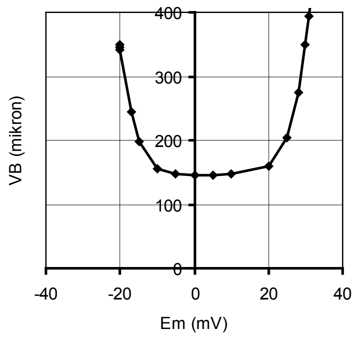

Figure 9. The impact of external E_m voltage on wear (R_m=2$\mu\Omega$)

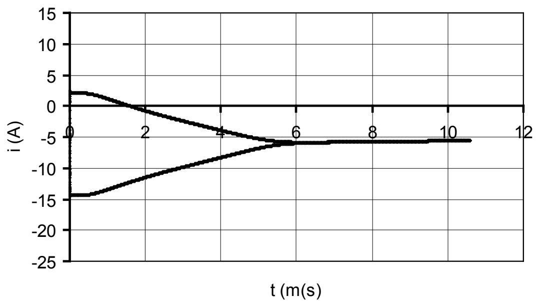

Figure 10. Current fluctuation in E_m=20mV, R_m=1mΩ

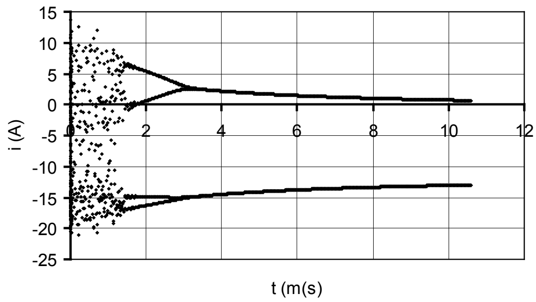

Figure 11. Current fluctuation in the case of E_m=25.07mV, R_m=1mΩ

However this withering bifurcation, which can be called regular, turns completely chaotic at the beginning of the cutting phase (Figure 11) if E_m external voltage is moderately increased, then a regular, four-cycle fluctuation occurs, which then changes to a two-cycle fluctuation.

Based on the available data it cannot yet be decided with certainty if this phenomenon is the "own product" of the mathematical model or it is a specific characteristic of the electro-thermal processes occurring in the chip root. It is a fact that the cycle time of the wave equals the time scale applied in calculations in the case of regular alternation, however, this is not so under chaotic conditions. On the other hand, it also needs to be considered that the model was prepared considering the actual temperature conditions developing in the chip root. In order to decide the open questions further research is necessary.

5. SUMMARY

A mathematical model was prepared for the qualitative examination of the thermoelectric processes of the chip root. This model considers the characteristics of the temperature field developing on the contacting surfaces. The results of the calculations can be summarised as follows:

- significant currents may circulate in the chip root;
- these currents depend on the wear of the tool and this dependence is mutual;
- according to calculations supported by experiments, it is optimal with regard to the wear of the tool if an external power source compensates the thermoelectric current.
- based on the mathematical model, the system behaves in a chaotic way under several conditions, however, it can only be estimated if this is down to the modelled system itself.

Further research is necessary to decide this question.

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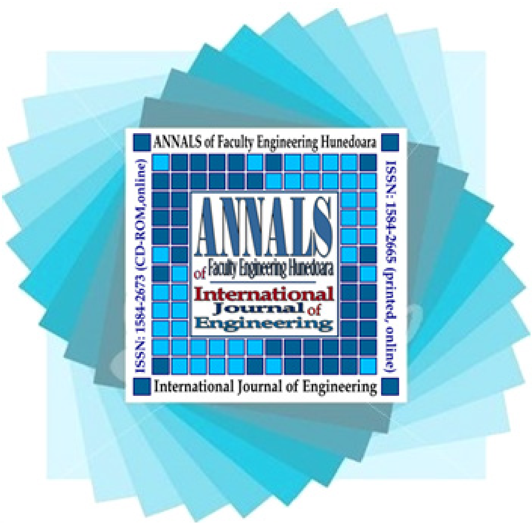

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