WIRELESS MONITORING OF A METAL CUTTING TECHNOLOGICAL PROCESS IN AN INDUSTRIAL ENVIRONMENT, AFFECTED BY ELECTROMAGNETIC NOISE

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Abstract. In industrial settings which imply metal cutting with machine tools, these tools can be seen as high-intensity and density electromagnetic noise generators, thus causing errors to wireless transmissions. The authors present an experimental and partially analytic study regarding the extraction, conditioning and transmission of the signal produced by a cutting tool during the processing of different materials, by this, emphasizing the limitations of the radio channel.

Keywords: wireless transmission, electromagnetic noise, metal cutting

1. Introduction

This paper consists in the following: an overview of the physical phenomena which evolve during the process; an overview of the testing schemes, the experimental results interpretation and conclusions.

2. The basic physical phenomena

The monitored electrical signal is a result of the cutting process – specifically between the cutting tool (the drill bit) and the material. The phenomena which were observed in relation to the electrical signal extraction are:

- the electric potential at the contact between the tool and the processed material, given by $U = k \cdot S$ (where k is the conversion constant, measured in V/m^2, and S is the surface, measured in m^2);
- the thermoelectric phenomenon, which consists in a thermocouple potential, which depends on the cutting regime temperature, that is $U = k \cdot \Delta T$ (where k is a constant, in V/°C, and ΔT is the temperature, in °C) [1, 2, 3].

The level of these signals varies between a few µV to hundreds of µV. The two signals are generated on different impedances. The contact effect gives information regarding the quality of the cutting contact surface (wear or damage). This effect is useful sharpness assessment for identical cutting tools. The thermoelectric effect generates information regarding the quality of the tool cutting area (the lip), as well as the cut material.

These electrical signals require correct extraction of the signal and an electronic conditioning up to tens of mV, so as to maintain compatibility with the acquisition level.

3. Monitoring the contact voltage

The experiment for extracting the signal was performed under the following conditions:

- direct line of sight, at a distance of 5 m;
- input signal possibly received at: 5 – 20 µV (or 50 µV) amplified by a factor of 10^3;
- amplifier immunity of 80 dB.

The following parameters were determined:

- the noise density error;
- linearity coefficient of the transmission channel, provided that the noise is generated at different intensity thresholds;
- amplifier immunity of 80dB.

The parameters mentioned above were determined by using the following technological model, presented in Figure 1, which represents the analogue system for extracting and processing the electrical monitoring signal.

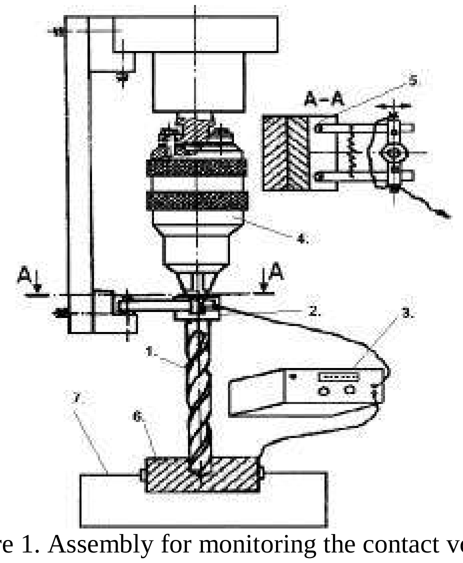


Figure 1. Assembly for monitoring the contact voltage during drilling

The thermal potential and the contact potential are influenced by the cutting regime, the cutting tool dimensions, the thermocouple material, the cutting liquids, and the state of wear of the cutting tool. The model in Figure 1 consists of:

1. the cutting tool (the drill bit);

2. the signal brush-type collector fixed on the non-cutting sector of the tool;
3. the small signal preamplifier;
4. the tool drive chuck;
5. the collector, technical details;
6. the test material;
7. the blocking gear.

The technological process for metal cutting is the process of drilling.

The main factors that influence the electrical potential during cutting, apart from materials, are the cutting regime and the cutting tool dimensions. The cutting regime is described by the cutting rate *v*, the cutting feed *s* and the drill bit size *t*. The cutting tool dimensions refer to the cutting angle and the diameter *d*.

For the cutting of the high-grade rolled steel OLC45 with hard-cutting alloys P30 mechanically fixed (SMPR 150612-P30) and with a drill bit from high-speed steel "Rp3", the following influences of the cutting factors on the thermovoltage are obtained, as presented in Figure 2.

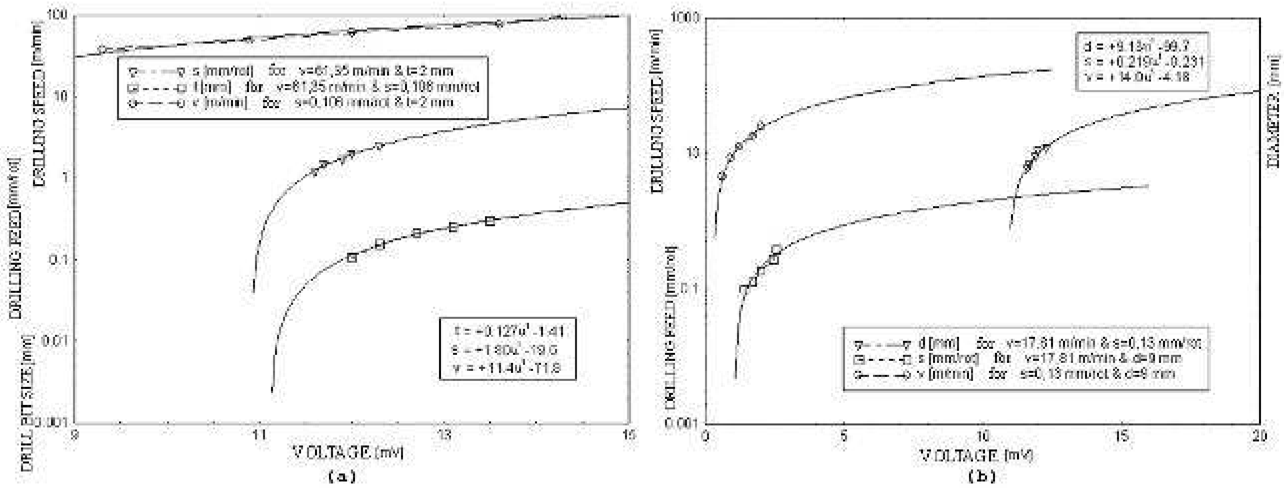


Figure 2. The influences on thermovoltage
(a) the drill bit, the cutting rate and feed for OLC45 SMPR 150612-P30;
(b) the diameter, the cutting rate and feed for OLC45 for a drill bit Rp3-type

The sets (*v*, *s*, *t* and *v*, *s*, *d*) summarize these influences, by using the following relations, with *U*, as thermovoltage, expressed in mV [4, 5]:

$$U(v, s, t) = 11 + 0.3v + 0.18s + 2.62t \quad (1)$$

$$U(v, s, d) = 4 + 0.023v + 1.52s + 0.036d \quad (2)$$

Because the value of the contact voltage is much smaller than that of the thermovoltage, a DC amplifier with high input sensitivity and high gain is required in order to measure and process the signal accordingly. The amplifier used for enhancing the contact voltage, presented in Figure 3, displays the following characteristics [6]:

- input level for the operating signal from 2 – 50 μV;
- 60 dB gain;
- levels of gain in two stages: 10 and 100;
- noise rejection factor: 80 – 90 dB;
- a noise-free supply (a 9 V battery) used for the preamplifier.

The electric potential was measured during the process of metal cutting and the data containing the observed parameters was:

- (a) stored locally (transmitted through a shielded cable with the length below 2 m);
- (b) simultaneously transmitted through an RF wireless channel to a computer for storage and analysis.

The wireless transmission consists of an acquisition network configured with specific software (WN Explorer) and based on processing with LabVIEW (Figure 4) [7, 8]. The application in LabVIEW supports precise readings, up to 6 decimals for the data acquired with WN modules placed 10 meters apart. There were no direct obstacles in the line of sight, but there were lateral obstacles consisting of machine tools.

The block diagram of the acquisition application developed in LabVIEW is presented in Figure 5. By using the two data storage modes (a and b, presented previously), the quality of the RF channel (electromagnetic noise generated by industrial devices, adjacent channel interference, noise generated by the environments parameters, etc.) can be determined by comparison between the locally stored and the transmitted data [9].

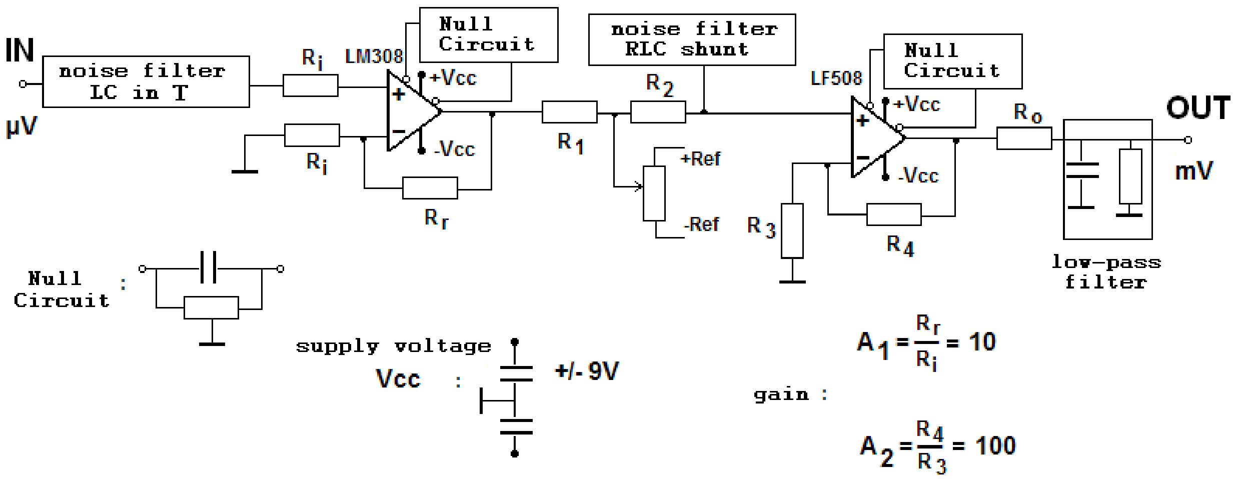


Figure 3. The DC amplifier schematic diagram

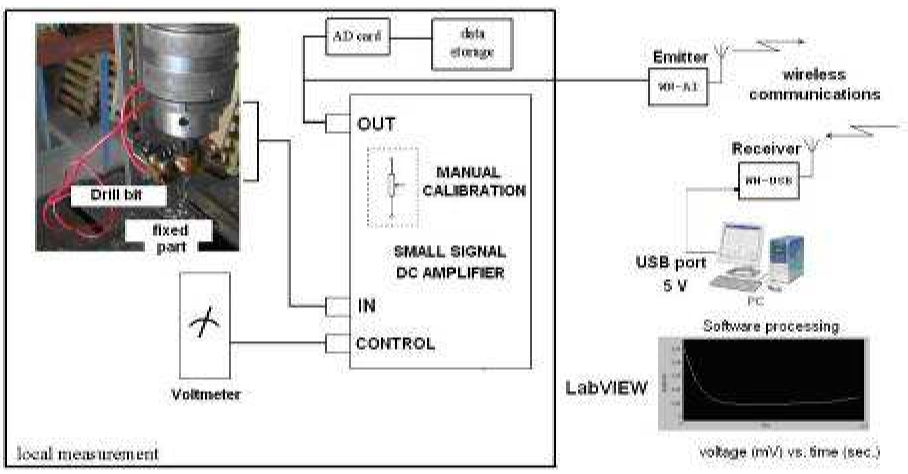


Figure 4. The system for monitoring the contact voltage with WN modules (schematic diagram)

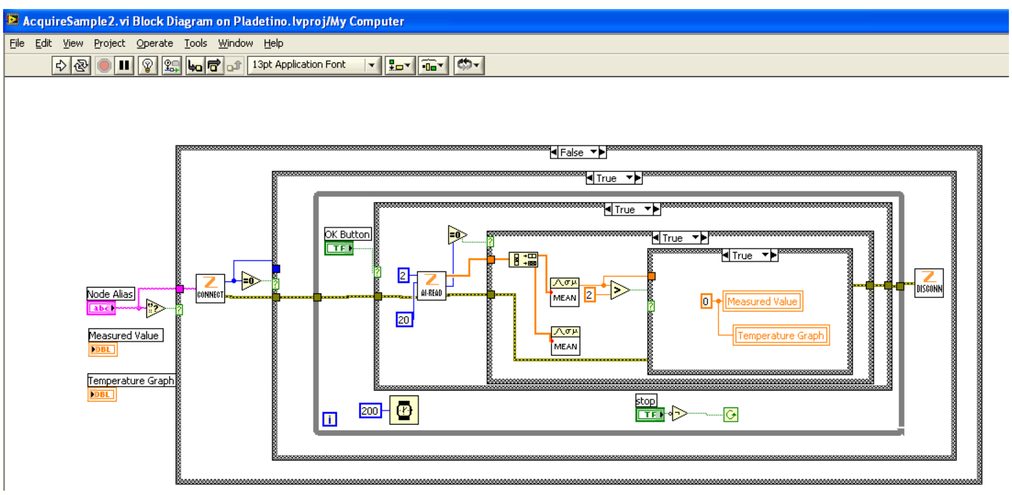
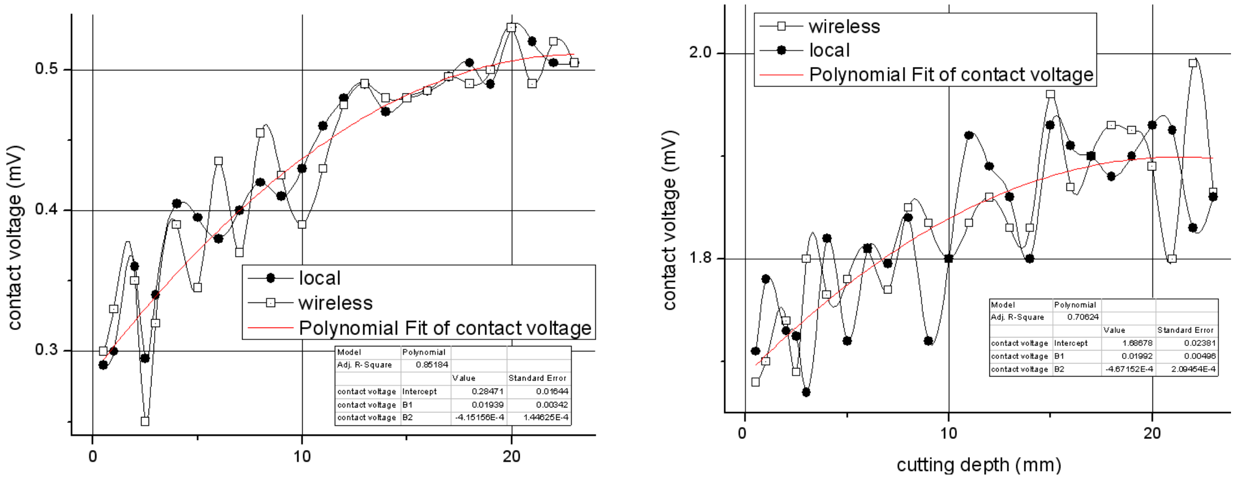


Figure 5. The block diagram for the acquisition application

In order to observe and highlight the errors in the communication channel, repeated measurements using identical conditions were conducted. The results are presented in Table 1 and in Figure 6. For OLC45 with drill bit from Rp3, from a diameter of 9 mm and a speed of 630 rpm, results a cutting rate of 17.81 m/min, and a feed of 0.13 mm/rot. For OL50 with drill bit from Rp5, from a diameter of 11 mm and a speed of 224 rpm, results a cutting rate of 7.74 m/min and a feed of 0.1 mm/rot. The cutting angle is similar for both materials, a value between 116º and 118º. Therefore, by knowing the drill bit diameter, the cone height can be easily computed. For OLC45 with Rp3 drill bit, the cone height is 2.6 mm and for OL50 with Rp5 drill bit 3.15 mm.



a.) b.)

Figure 6. The influence of the cutting depth on the contact voltage during the cutting
a.) OLC45 with drill bit from Rp3; b.) OL50 with drill bit from Rp5, using the two methods

Table 1. The contact voltage (after amplification) for drilling with OLC45 and OL50 by direct method and wireless method

Cutting depth (mm)	Contact voltage for OLC45, local measurement (mV)	Contact voltage for OLC45, wireless transmission (mV)	Contact voltage for OL50, local measurement (mV)	Contact voltage for OL50, wireless transmission (mV)
0.5	1.71	1.68	0.29	0.3
1	1.78	1.7	0.3	0.33
2	1.73	1.74	0.36	0.35
2.5	1.725	1.69	0.295	0.25
3	1.67	1.8	0.34	0.32
4	1.82	1.765	0.405	0.39
5	1.72	1.78	0.395	0.345
6	1.81	1.81	0.38	0.435
7	1.795	1.77	0.4	0.37
8	1.84	1.85	0.42	0.455
9	1.72	1.835	0.41	0.425
10	1.8	1.8	0.43	0.39
11	1.92	1.835	0.46	0.43
12	1.89	1.86	0.48	0.475
13	1.86	1.83	0.49	0.49
14	1.8	1.83	0.47	0.48
15	1.93	1.96	0.48	0.48
16	1.91	1.87	0.485	0.485
17	1.9	1.9	0.495	0.495
18	1.88	1.93	0.505	0.49
19	1.9	1.925	0.49	0.5
20	1.93	1.89	0.53	0.53
21	1.925	1.8	0.52	0.49
22	1.83	1.99	0.505	0.52
23	1.86	1.865	0.505	0.505

The measurements were performed in two stages. The first stage, known as cone feed, consists of 5 steps, from 0 mm until the cone height is reached. The second stage consists of 20 steps, each of 1 mm, starting from the point where the drill bit fully penetrated the material. This second stage is known as the complete cut. The experimental results are presented in Figure 6. The influence of the cutting depth (in mm) on the contact voltage, expressed in mV (after amplification), is approximated with the following relations for the two materials:

$$U_{\mathrm{OLC45}}(h) = -4.67\cdot 10^{-4}h^2 + 0.0193h + 0.16 \quad (3)$$

$$U_{\mathrm{OL50}}(h) = -4.151\cdot 10^{-4}h^2 + 0.0193h + 0.2 \quad (4)$$

Under normal processing conditions, the relations 3 and 4 follow a second order polynomial characteristic (Figure 6), for OLC45 with Rp3 (rel. (3)) and OL50 with Rp5 (rel. (4)). The free terms from the two formulas define the cutting tool type, that is Rp3 for OLC45 and Rp5 for OL50. The slopes describe the material being processed (i.e. OLC45 and OL50).

4. Wireless channel analysis

The initial errors were compared to the errors obtained by averaging and approximation, with results shown in Table 2.

Table 2. Comparison between the initial non-linear errors and the errors obtained by averaging and approximation

Acquisition method	Steel type	Maximum error (mm)	Initial error (%)	Maximum initial error (%)	Error averaged and aprox. (%)	Max. error averaged and aprox. (%)
Direct	OLC 45	2	2.32	5.7	0.92	3.67
	OL50	1	3.02	6.2	1.91	3.3
Wireless	OLC 45	2	1.91	5.7	0.8	1.37
	OL50	1	3.38	7.9	1.37	3.46

The comparative analysis of the electric signals obtained by local measurements (Figure 7) and by measurement through the wireless channel (Figure 8) leads to several results. The two stages of the comparative analysis were:

- establishing the cutting process evolution equation by local measurement;
- establishing the cutting process evolution equation through the wireless channel.

These equations describe the best approximations for the string of experimental data. Therefore, for local and wireless channel measurements, by using the experimental data from Table 1, the following equations result:

$$y_L = -0.00007x^3 + 0.0021x^2 - 0.0062x + 1.74 \quad (5)$$

$$y_R = 0.000004\cdot x^3 - 0.0005x^2 - 0.0201x + 1.68 \quad (6)$$

$$y_L = 0.000003x^3 - 0.0005x^2 - 0.0203x + 0.282 \quad (7)$$

$$y_R = -0.000005x^3 - 0.0002x^2 - 0.0175x + 0.281 \quad (8)$$

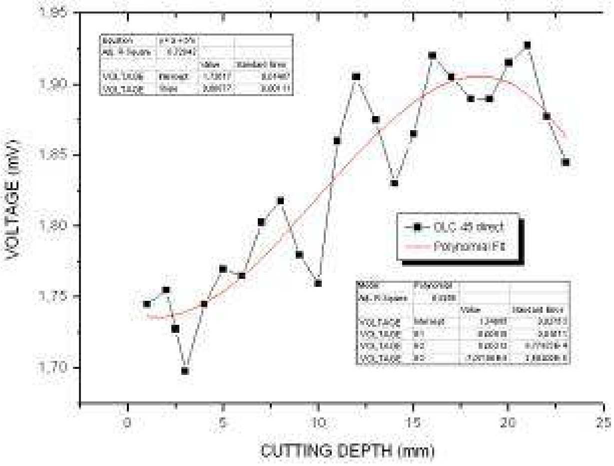


Figure 7. The average characteristic of the contact voltage for cutting OLC45 (local data storage)

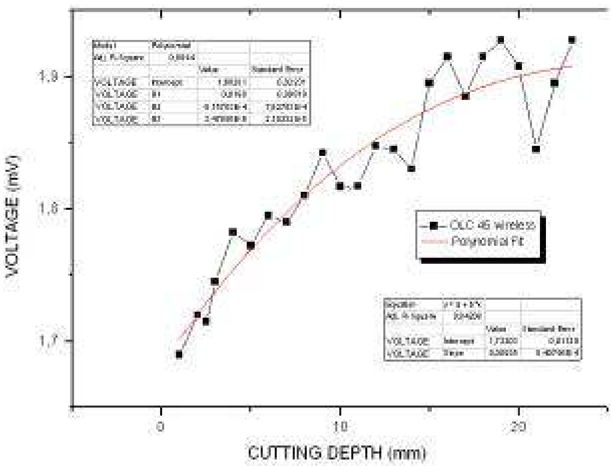


Figure 8. The block diagram for the acquisition application

The pair of equations y_L and y_R reproduces the two cutting processes: y_L represents the contact voltage obtained through local measurements, y_R the contact voltage received wirelessly, and x represents the cutting depth. The equations (5) and (6) represent the cutting with Rp3 drill bit for OLC45 material. The equations (7) & (8) represent the cutting with Rp5 drill bit for OL50.

The difference between the two methods, y_L and y_R, describes the channel error evolution for the process (ε).

For the first process (OLC45 with Rp3, ε_1) and the second process (OL50 with Rp5, ε_2) the following equations result, as seen in Figures 11 and 12:

$$\varepsilon_1 = 0.0023x^2 - 0.223x + 0.434 \qquad (9)$$

$$\varepsilon_2 = 0.0030x^2 - 0.030x + 0.055 \qquad (10)$$

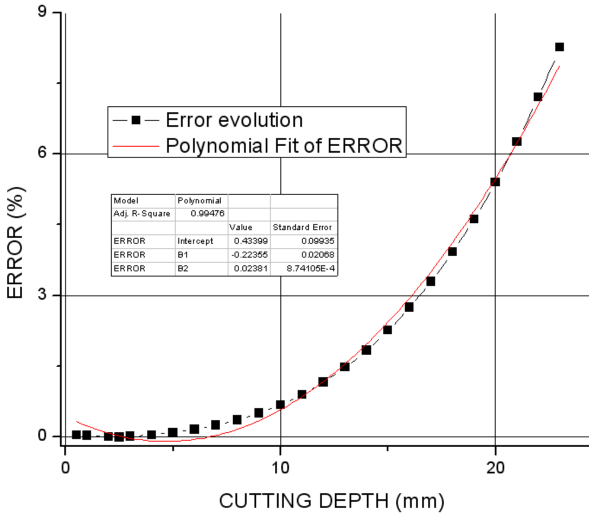


Figure 11. Channel error evolution (%) dependence on cutting depth (mm), for the cutting process with Rp3-type drill bit in OLC45 material

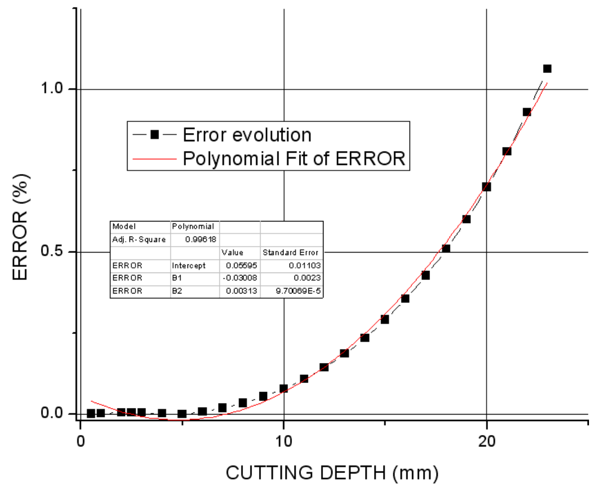


Figure 12. Channel error evolution (%) dependence on cutting depth (mm), for the cutting process with Rp5-type drill bit in OL50 material

5. Conclusions

From the error evolution, the following conclusions can be drawn:

- For small cutting depths, up to 10 mm, the data received on the wireless channel are approximately identical with the locally stored data, which implies that the wireless channel is working properly (i.e., the error is almost constant and under 1%), regardless of the cutting material and cutting tool;
- For larger depths, greater than 10 mm, the data transmitted wirelessly undergoes a process of alteration, the error exceeding 2 %. The variation in the wireless channel accuracy is affected by noise generated through the metal cutting process by the cutting tool. Therefore, it can be concluded that the wireless channel is influenced by the cutting tool dimensions;
- As the cutting depth increases, the electromagnetic noise grows exponentially with the depth of penetration, which in return limits the use of the wireless channel, as the errors can no longer be linearized. The cutting depth and wireless channel accuracy are imposed by the processing accuracy class.

Observations:

- the processes did not imply the cooling of the drilling tool;
- the experimental data are mean values for strings of data (Figures 7 ÷ 10), with a minimum of 100 values taken into account for one string.

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