SURFACE ROUGHNESS PREDICTION DEPENDING ON WORKPIECE TEMPERATURE AND MATERIAL REMOVAL RATE IN DRY MILLING

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Abstract: As it is well known, almost entire quantity of mechanical work generated in the milling process is converted into heat, and an important quantity of heat is eliminated together with removed material. The aim of present paper is to present an alternative solution for the usual surface roughness modelling by using as input parameters for roughness prediction a dry milling generated factor as workpiece temperature and a productivity criterion as material removal rate (MRR). It was also determined the relationship between workpiece temperature and the material removal rate when 42CrMo4 steel was machined in dry milling conditions. In order to determine the workpiece temperature, an infrared thermography method was used while for surface roughness prediction a regression model was successfully applied. Regarding the relation between workpiece temperature and material removal rate, it was determined that for a constant value of cutting speed, the workpiece temperatures values were enclosed in a certain domain of values while material removal rate could be increased.

Key words: surface roughness prediction, workpiece material temperature, infrared thermography method, material removal rate.

1. INTRODUCTION

The development of the cutting processes demand the optimization of the machining, by trying to produce chipper, quicker and, of course, at higher precision. The most common quality parameter analysed in machining is the workpiece surface roughness. The surface roughness is affected by the factors involved and developed in cutting process as cutting parameters, cooling strategies (Jiang Feng, 2010), tools wear, cutting forces and temperatures generated in machining (Colak et al., 2007; Öktem et al., 2006a; Ozcelik and Bayramoglu, 2006; Ozcelik et al., 2005). Beside the influence of these factors, the surface roughness is also affected by the tool diameter increasing because workpiece temperature will decreasing and an important quantity of heat will be concentrated at the tool-chip interface (Kiryushin et al., 2008).

The surface roughness prediction was usually studied using (Zain et al., 2011) analytical and experimental modelling or based on artificial intelligence as fuzzy logic, neuronal network or genetic algorithms (Öktem et al., 2006b; Ozcelik et al., 2005).

Studying the surface roughness through workpiece temperatures is a viable solution and can be recommended because the temperatures generated in machining induce a thermal expansion of workpiece superficial layer. The workpiece volume increasing leads to important deviation of the surface and important damage of the surface integrity. Thus, controlling the generated temperature and workpiece temperature can prevent its influence and can become a decisive factor for roughness surface improving. An optimal value of temperature can improve the machined surface quality by increasing the material machinability.

Regarding the influence of the material removal rate, as productivity criteria, on surface roughness it can be added that is needed to increase the productivity and obtain the same surface quality or an improved one. Therefore, finding a relationship between the workpiece temperature and material removal rate can be an important factor in machined surface quality improving and productivity increasing.

The workpiece temperature is influenced not only by the cutting parameters and cooling strategies but also by the material chemical composition, material physical-mechanical properties and by the workpiece volume. Usually, the workpiece temperature analysing has been studying through the influence of the cutting parameters. The cutting parameter having the most important influence on the workpiece temperature generation is the cutting speed (V_c) (Fang et al., 2005), (Kikuchi, 2009), (Richardson et al., 2006). Besides cutting speed the next cutting parameter having also an important influence on the workpiece temperature is the feed rate (f_z), because the increase of the feed rate will determine the decrease of the workpiece temperature (Avram and Brabie, 2011; Richardson et al., 2006). Besides these two main cutting parameters, the workpiece temperature can be also influenced by the axial cutting depth (a_a) whose decrease determines the increase of the workpiece temperature (Fang et al., 2005), (Kikuchi, 2009). Also, it can be added that the tool diameter increase (Kiryushin et al., 2008) and the increase of cutting interruptions in milling machining will determine the decrease of the workpiece temperature (Kountanya, 2008).

The maximum of the workpiece temperature values occur at the exit of cutting tool from machining (Inasaki et al., 2002), (Kountanya, 2008), (Teramoto et al., 2006).

As it was mentioned, in the case of milling process, the workpiece temperature was mostly determined and analysed depending on cutting parameters. An alternative solution consists in determination of the relation between workpiece temperature and material removal rate.

According to (Sandvik Coromant, 2010), the material removal rate value can be determined by using the following equation:

$$Q = \frac{f_z \cdot n \cdot z \cdot a_a \cdot a_e}{1000}, \qquad (1)$$

where: Q represents the material removal rate [cm^3/min], f_z is the feed rate [mm/tooth], a_e is tool radial engagement [mm], a_a is the axial depth of cut [mm], n represents the spindle speed [rpm] and z is number of tool teeth.

From the analysis of the material removal rate equation, it can be observed that material removal rate parameter is a comprehensive parameter and expresses a direct relationship between cutting parameters (cutting speed, feed rate, axial depth of cut and tool radial engagement). Also, the material removal rate can be connected to machined surface roughness as productivity criteria.

The present paper analyses based on experimental investigations the surface roughness depending on workpiece temperature and material removal rate. In order to determine the workpiece temperature values, an infrared thermography method was used while for surface roughness prediction a regression model was succesfuly applied.

2. EXPERIMENTAL ANALYSIS

2.1 Experimental conditions

The experimental investigations were performed on a three axes milling centre according to cutting conditions presented in Table 1. The experimental trials were based on a 3^3 factorial design of the following parameters: cutting speed (V_c), feed rate (f_z) and tool radial engagement (a_e). The axial cutting depth (a_a) was the only cutting parameter kept constant having a value equal to 0.5 mm.

All the experiments were realized in dry up and down milling conditions using a 50 mm milling tool with one square insert mounted on it in order to avoid the influence of inserts different wear. Because the admissible flank wear of the inserts has to be until the maximum value of 0.35mm (Thepsonthi et al., 2009) every experiment was executed using a new cutting edge of the insert.

Table 1. Cutting parameters used in experimental investigations

Item	a_e [mm]	V_c [m/min]	f_z [mm/z]
1	2.5	150	0.1
2	15	275	0.17
3	23.5	500	0.2

The tool insert was coated with the following layers: MT-T_iCN, Al_2O_3, T_iN, whose main geometric parameters were as follows: entering angle (Kr) equal to 90°, rake angle (γ) equal to 20 ° and clearance angle (α) equal to 15°.

Regarding the surface roughness value, it was measured after each trial with the help of a portable Mitutoyo roughness device. The measuring force was equal to 4mN while measuring speed was set to 0.8 mm/s. Each surface roughness value used in statistical analysis was an average of five values of the machined surface roughness.

The temperature of the workpiece surface was recorded by using the Flir A325 infrared camera with a recording speed of 30 frames/s. The detector was calibrated based on the “black body” theory, and the interest surface was painted with a thermo-resistant paint (up to 650° C). The scope of the surface painting was to avoid the influence of surface emissivity on temperature measurement.

During experiments, between the IR camera and measured surface, a distance equal to 200 mm was constantly kept (Figure 1).

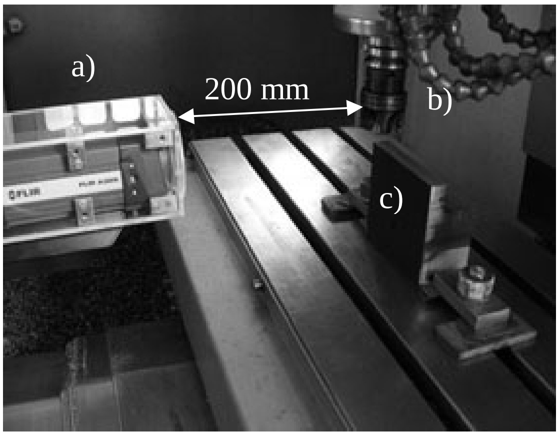


Fig.1. Experimental arrangement
a) IR camera b) cutting tool c) workpiece

Compared to other methods, the infrared thermography is a non-invasive and a “surface” method, which correlates the thermal energy emitted by the workpiece with its temperature. In order to ensure an ideal positioning, the IR camera was covered by a plexiglas box having a germanium lens mounted between the IR detector and cutting zone. The germanium lens was chosen because its property to induce a minimal influence on the IR measurement. Besides this it also protects the infrared detector against the removed material.

The material chemical composition and thermal properties are presented in Table 2 and Table 3.

Table 2. Chemical composition of 42CrMo4

C	Mn	Si	P	S	Cr	Mo
(%)	(%)	(%)	(%)	(%)	(%)	(%)
0.42	0.78	0.22	0.013	0.007	1.09	0.226

Table 3. Thermal properties of 42CrMo4 steel

Thermal expansion (10^{-6}/ºC)	Thermal conductivity (W/m-K)	Specific heat (J/kg-K)
12.3	42.7	473

The analysis of the workpiece temperature value was performed by using the Research IR software. A rectangular element (Figure 2) was chosen for the temperature values analysis because had the following properties: it can include the entire cutting zone and it can be also configured to output the maximum values of the analysed temperature.

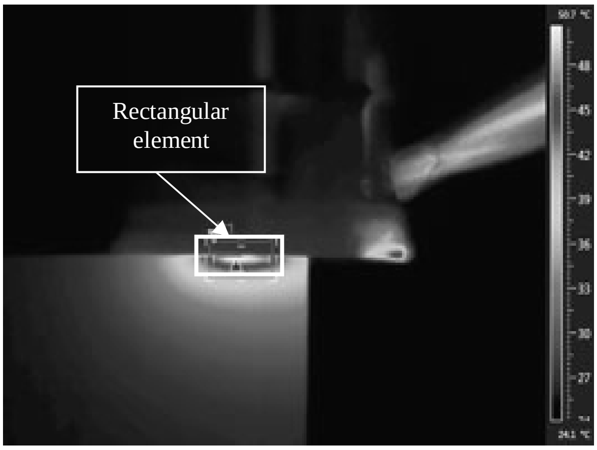


Fig. 2. The IR image of the face milling machining (V_c= 500 m/min, f_z=0.2 mm/tooth, a_a= 0.5 mm)

2.2 Experimental results. Discussions

The maximum of the workpiece temperature values were graphically represented depending on the cutting length in **FIGURE 4**.

From the graphic analysing the following three areas of temperature variation could be distinguished: first area corresponding to entrance of cutting tool in machining, where the workpiece temperature presents an important increase in a short period of time (T1); the second area corresponding to workpiece machining, where the temperature values presents a constant evolution (T2); the third area corresponding to cutting tool exit from machining, where the temperature reaches the maximum values from workpiece machining (T3).

Therefore, from these three temperature areas, only temperature values from T2 area were use in analysis, because during this area the generated temperature had a relative constant value.

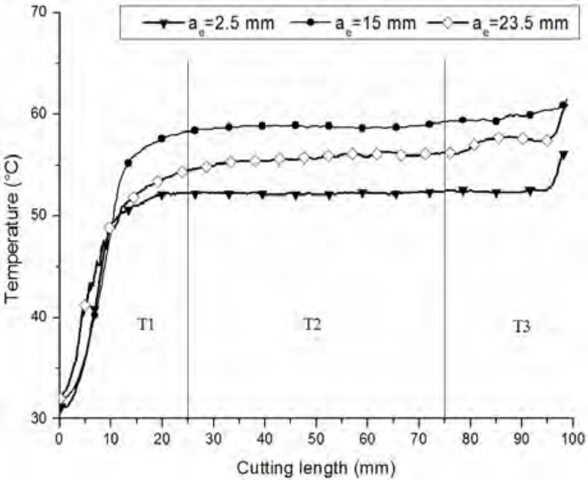


Fig. 4. Variation of workpiece temperature depending on cutting length for different a_e values

In order to predict the surface roughness depending on temperature values and material removal rate, the relation between workpiece temperature and the material removal rate was analysed.

The temperature and material removal rate values obtained during experimental trials, for down milling conditions, are presented in the Table 4.

Table 4. Temperature and material removal rate values obtained for down milling conditions

Down milling (DM)					
No	a_e	V_c	f_z	Q	T2
	mm	m/min	mm/tooth	cm^3/min	°C
1	1	1	1	0.119	58.6
2	1	1	2	0,203	54.9
3	1	1	3	0,239	62.4
4	1	3	1	0,398	116.2
5	1	3	2	0,677	90.3
6	1	3	3	0,796	99.7
7	2	1	1	0,716	59.9
8	2	1	2	1,218	61
9	2	1	3	1,433	56.2
10	2	2	1	1,313	69.1
11	2	2	2	2,233	79.9
12	2	2	3	2,627	85
13	2	3	1	2,388	104.4
14	2	3	2	4,06	101.4
15	2	3	3	4,776	97.8
16	3	1	1	1,122	52
17	3	1	2	1,908	60.1
18	3	1	3	2,244	56.7
19	3	2	1	2,057	77.1
20	3	2	2	3,498	80.2
21	3	2	3	4,115	69.3
22	3	3	1	3,741	109.2
23	3	3	2	6,36	99
24	3	3	3	7,482	96.9

The temperature and material removal rate values obtained during experimental trials, for up milling conditions, are presented in the Table 5.

Table 5. Temperature and material removal rate values obtained for up milling conditions

Up milling (UM)					
No	a_e	V_c	f_z	Q	T2
	mm	m/min	mm/tooth	cm^3/min	°C
1	1	1	1	0.119	52
2	1	1	2	0,203	56.1
3	1	1	3	0,239	62.2
4	1	3	1	0,398	120.8
5	1	3	2	0,677	112.6
6	1	3	3	0,796	113.6
7	2	1	1	0,716	61.1
8	2	1	2	1,218	56.3
9	2	1	3	1,433	67.9
10	2	2	1	1,313	85
11	2	2	2	2,233	74.5
12	2	2	3	2,627	90.2
13	2	3	1	2,388	115
14	2	3	2	4,06	80.1
15	2	3	3	4,776	112
16	3	1	1	1,122	60
17	3	1	2	1,908	62
18	3	1	3	2,244	56.6
19	3	2	1	2,057	88.7
20	3	2	2	3,498	81.5
21	3	2	3	4,115	66.7
22	3	3	1	3,741	118.5
23	3	3	2	6,36	110.3
24	3	3	3	7,482	105.4

The relation between workpiece temperature and material removal rate has been graphically represented for a cutting speed value equal to 150 m/min in Figure 3, and equal to 500 m/min Figure 4. For a particular cutting speed value, the workpiece temperature oscillates in a finite domain, while the material removal rate value can be increased.

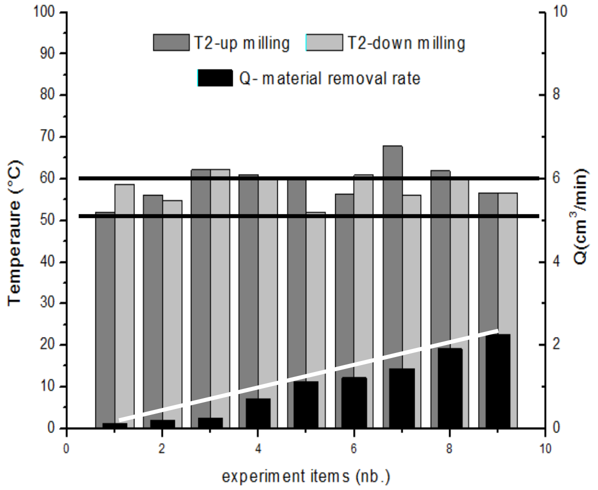


Fig. 3. The workpiece temperature values and material removal rate when V_c= 150 m/min

The domains where workpiece temperature oscillated were as follow: between 52°C -62°C for cutting speed equal to 150 m/min and between 95°C -115°C for cutting speed equal to 500 m/min, while the material removal rate values increase from 0.3 to 2 cm^3/min for the first domain, or 0.8 to 7 cm^3/min for the second domain.

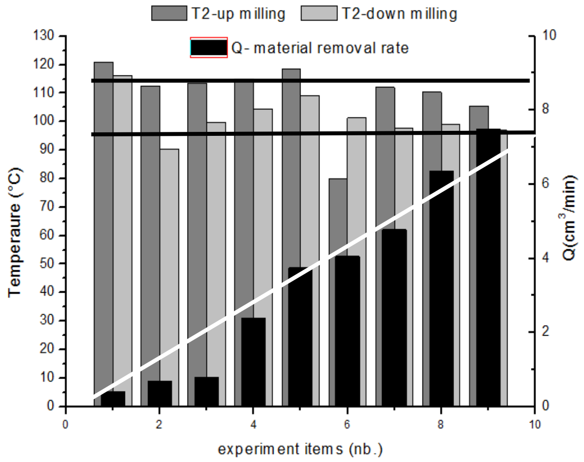
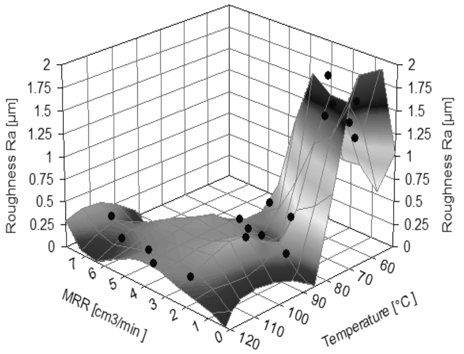
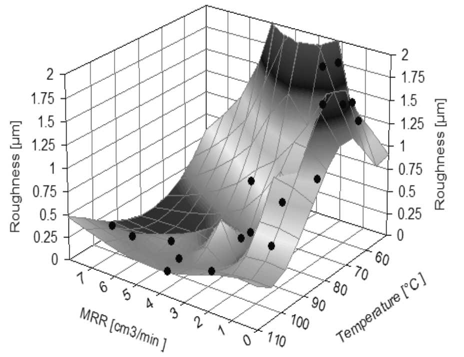


Fig. 4. The workpiece temperature values and material removal rate when V_c= 500 m/min

Therefore, it can be affirmed that for a particular workpiece temperature domain the material removal rate can increase without radically changing the workpiece temperature. Thus, the material removal rate value can be increased as long the necessary roughness value is obtained. In order to revile the influence of removed material and temperature on roughness value, the tridimensional graphics are presented in Figure 5.



a.down milling conditions



b.up milling conditions

Fig. 5. The influence of workpiece temperature and material removal rate on surface roughness

By analysing the results presented in Figure 5 was observed that the roughness value can be predicted by knowing the temperature value and material removal rate. In this manner it can be determined the best productivity by increasing the material removal rate value for an improuved surface roughness. Thus, in the case of dry up milling, when workpiece temperature reaches 85°C, the surface roughness value decreases up to 0.25 µm while material removal rates has values between 2-7 cm^3/min. In the case of dry down milling, the surface roughness value decrease up to 0.25 µm when workpiece temperature reaches 90°C, while material removal rates has values between 5-7 cm^3/min.

2.3 Surface roughness prediction

The surface roughness values were predicted depending on material removal rate and workpiece temperature with the help of Table Curve Expert software. The surface roughness regression equations were obtained for different cutting directions (up or down milling). The machining directions were separately analysed and for each equation, R^2 and adjusted R^2 were obtained. Generally R^2 indicates the variation between the measured values and predicted ones.

The regression model obtained for the surface roughness, in case of down milling, was:

$$Ra= -19.5902948-82.8009215*x -10260000/y+ 0.01163915* x^2 + 42.08116674/y^2 + 402233.3855* x/y + 0.043783489 *x^3 - 4916.87537/y^3+0.10954589* x/y^2+18.72913081 *x^2/y. \quad (2)$$

where: x was material removal rate and y was workpiece temperature.

The obtained model was analysed with ANOVA and the results are presented in Table 5.

Table 5. Analyse of variance (ANOVA) for down milling roughness equation

R^2	Adj R^2	Fit Std Err	F-val
0.902	0.762	0.279	8.218

Source	SS	DF	MS	F	P>F
Regr	6.44	8	0.80	21.68	0.00
Error	0.33	9	0.03		
Total	6.77	17			

The regression model obtained for the surface roughness, in case of up milling, was:

$$Ra=0.000000148151-0.000062436/x+0.01036722*x^2 -0.84621092/x^3+33.87214686*y-0.53161426*y^2 + 0.461273982 * y^3+0.652302532 *y^4-530.112774 * y^5 \quad (3)$$

where: x was material removal rate and y was workpiece temperature.

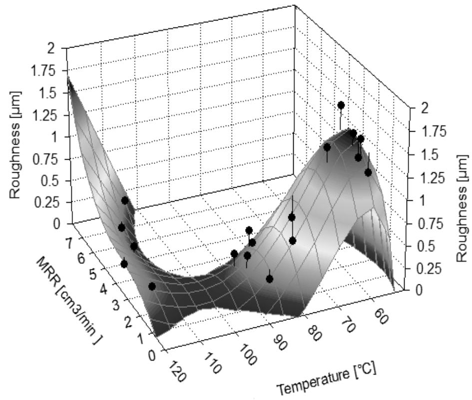
The obtained model was analysed with ANOVA and the results are presented in Table 6.

Table 6. Analyse of variance (ANOVA) for up milling roughness equation

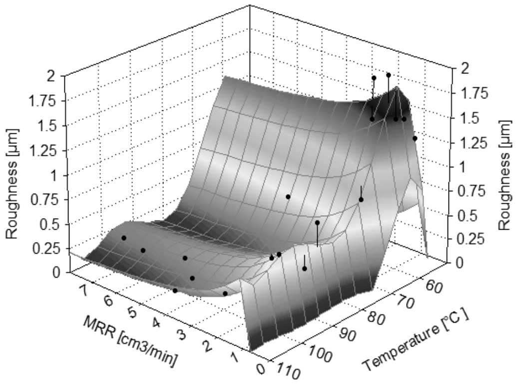
R^2	Adj R^2	Fit Std Err	F-val
0.95	0.895	0.192	21.68

Source	SS	DF	MS	F	P>F
Regr	6.44	8	0.80	21.68	0.00
Error	0.33	9	0.03		
Total	6.77	17			

Therefore, for dry down milling machining, the R^2 value is equal to 0.90 while for dry up milling is equal to 0.95. The values prove reliable estimation for the obtained predictions. According to analyse of variance, the p-values (p-value <0.05) indicates that the models are robust and adequate. For a better understanding of the predicted models, the graphical interpretations of the equations are represented in the Figure 6.



a.down milling conditions



b.up milling conditions

Fig. 6. The surface prediction depending on workpiece temperature and material removal rate

By comparing the prediction results (Figure 6) with the experimental analysis (Figure 5) it can be observed that relation between workpiece temperature, material removal rate and surface roughness was estimated almost in the same manner. Analysing the results presented in the Figure 6, the following conclusions could be draw: the surface roughness improves with workpiece temperature increasing. Besiedes this, the surface roughness can be kept with the same value while the material removal rate can have different values. For the example, in the case of down milling, the roughness values was under 0.25 µm only when the temperature was between 90 - 110°C and material removal rate had values between 2-4 cm^3/min while in the case of up milling, the surface roughness value was under 0.25 µm when workpiece temperature of 80°C and material removal rate had values between 5-7 cm^3/min material.

3. CONCLUSIONS

The analysis of surface roughness prediction based on the relation between the workpiece temperature and material removal rate, in the case of dry up and down milling, leads to following conclusions:

1.when the cutting speed value was kept constant, the workpiece temperature was enclosed in a certain domain of values. It was determined that for a certain workpiece temperature domain, the material removal rate value can be increased without radically modifying the workpiece temperature;

2.the surface roughness improves with the workpiece temperature increasing. For the same temperature, the material removal rate could be increased without modifying the surface roughness;

3.the relation between workpiece temperature (as machining generated factor) and material removal rate (as productivity criteria) can be used for surface roughness prediction.

4.the surface roughness prediction based on workpiece temperature and material removal rate can be used as an alternative analysis of machined surface roughness.

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