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Mathematical modeling of surface roughness for evaluating the effects of cutting parameters and coating material

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ABSTRACT

The work presented in this paper examines the effects of cutting parameters (cutting speed, feed rate and depth of cut) onto the surface roughness through the mathematical model developed by using the data gathered from a series of turning experiments performed. An additional investigation was carried out in order to evaluate the influence of two well-known coating layers onto the surface roughness. For this purpose, the experiments were repeated for two CNMG 120408 (with an ISO designation) carbide inserts having completely the same geometry and substrate but different coating layers, in a manner that identical cutting conditions would be ensured. The workpiece material machined was cold-work tool steel AISI P20. Of the two types of inserts employed; Insert 1 possesses a coating consisting of a TiCN underlayer, an intermediate layer of Al_2O_3 and a TiN outlayer, all deposited by CVD; whilst Insert 2 is PVD coated with a thin TiAlN layer ($3 \pm 1\,\mu m$). The total average error of the model was determined to be 4.2% and 5.2% for Insert 1 and Insert 2, respectively; which proves the reliability of the equations established.

1. Introduction

In machining processes, it is necessary to attain the desired surface quality in order to produce parts providing the required functioning. The surface quality also defines some mechanical properties of the product, such as wear resistance. Being such a considerable quality, surface quality is influenced by various parameters. It will be costly and time consuming to acquire the knowledge of appropriate cutting parameters. At this point, surface roughness prediction will be helpful, which is mostly based on cutting parameters (cutting speed, V; feed, f; depth of cut, a) and sometimes some other parameters.

Since improvement of surface quality can be hindered by tool wear, resistance of the tool against thermal and mechanical loads should be taken into consideration. Looking from this aspect, an ideal tool should possess the properties of good wear resistance, high mechanical strength and high thermal stability. As well as substrate material, coating process and coating material are of high significance in accomplishing these objectives. CVD (chemical vapor deposition) and PVD (physical vapor deposition) technologies are employed to obtain a thin (about 3–12 μm) but hard coatings. Each of these two technologies provides different qualities for the tools resulting from their process temperatures and process flexibility different from each other.

Özel et al. (2005) conducted a set of analysis of variance (ANOVA) and performed a detailed experimental investigation on the surface roughness and cutting forces in the finish hard turning of AISI H13 steel. Their results indicated that the effects of workpiece hardness, cutting edge geometry, feed rate and cutting speed on surface roughness are statistically significant; besides, the effects of two-factor interactions of

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the edge geometry and the feed rate, and the cutting speed and the feed rate are also important. They reported that especially, small edge radius and lower workpiece hardness increased surface roughness in their experiments. The work of Davim and Figueira (2007), concerning the machinability evaluation of cold-work tool steel (D2) using statistical techniques, presented that the most influential factors for surface roughness are feed rate and cutting time, with percentage of contributions of 29.6% and 32.0%, respectively. Mufioz-Escalona and Cassier (1998) stated that the increase of the feed rate and the depth of cut results in a decrease in the critical cutting speed, which is defined as the cutting speed value above which poor quality and/or performance do not take place. Referring to their study, tool nose radius does not influence critical cutting speed significantly. They also established surface roughness equations and demonstrated that surface finish is more directly affected by: in first term feed rate; secondly, tool's nose radius; finally, by the cutting speed.

Choudhury and Srinivas (2004) formulated a mathematical model for flank wear, and concluded the cutting velocity (speed) and the index of diffusion coefficient to be the most significant factors, followed by the feed and depth of cut. Palanikumar and Davim (2007) developed a mathematical model to predict the tool wear when machining Glass Fibre Reinceforced Plastic Composites and obtained a %95 confidence level in a range of parameters. Within V, f, a and workpiece fibre orientation, V was the most influential one. Lee et al. (1998) conducted statistical and sensitivity analysis to examine various force ratios and recommended one of these ratios (feed force/tangential force) to be the input variable beside V, f and a, for a more precious tool wear monitoring. Sikdar and Chen (2002) studied on finding a correlation between cutting forces and the 3 dimensional flank wear surface in turning and presented mathematical models using various cutting parameters (V, f, a). Their results showed that an increase in flank wear surface area causes all cutting forces to have higher values. They also concluded that although the tangential force is the greatest one, after the fail period of the tool begins, the rates of increase of axial and radial cutting forces are higher than that of the tangential cutting force. Choudhury and Kishore (2000) developed a mathematical model correlating ratio of feed force to cutting force and flank wear height. V, f, a and also diameter of workpiece (D) were used in these models. Feed rate, depth of cut and D increased flank wear almost linearly, whilst the cutting speed having the most increasing influence, affects the flank wear in a parabolic manner. Kwon et al. (2004) proposed a model providing a relationship between surface roughness and tool wear. They concluded that this model can serve for a better utilization of tool in a way that tools can be employed to the fullest extent until they do not achieve the required surface quality. Abouelatta and Mádl (2001) carried out an investigation focusing on the correlation between surface roughness and cutting vibrations. They inferred from the results that the maximum height roughness parameter R_t depends greatly on the cutting speed. Şahin and Motorcu (2005) established first-order and second-order equations (in which the independent variables are logarithmic transformations of speed, feed rate and depth of cut) using response surface methodology in order to predict surface roughness in machining mild steel and reached a conclusion that the main influencing factor on surface roughness is the feed rate. They also deduced from the variance analysis that the interaction terms and square terms for second order model are statistically insignificant. Some works have been done to establish a model between the cutting conditions and surface roughness in milling operations as well (Baek et al., 1997; Öktem et al., 2005; Özçelik and Bayramoğlu, 2006). Mansour and Abdalla (2002) created a surface roughness model for the end milling EN32 (a semi-free cutting carbon case hardening steel with improved merchantability). Besides concluding that an increase in either the feed rate or the axial depth of cut increases the surface roughness, whilst an increasing cutting speed decreases the surface roughness; based on the model created, they constructed contours of surface outputs in planes containing cutting speed and feed rate at a certain depth of cut in order to enable the selection of the proper combinations to increase the metal removal rate without sacrificing the quality of the surface finish.

In the present work, for the purpose of analyzing in what direction and intensity the cutting parameters influence the surface roughness in turning cold-work tool steel AISI P20, a mathematical model was developed. The second objective of the work was to research the effect of two well-known coating layers. In order to achieve this, identical experiments were performed for each of the coating layers, both of which are present on inserts having the same geometry and substrate. The model demonstrated its reliability with at most 5.2% total average error.

2. Experimental work

The machine tool employed was a turning lathe of 5.5 kW having a rotational speed range of 90–200 m/min and a feed rate range of 0.03–0.25 mm/min. The experiments were carried out in dry cutting conditions.

Since the machine tool is of conventional type, desired cutting speeds are not able to be achieved precisely. Correspondent cutting speeds were equalized at different workpiece diameters to the extent that rotational speed ratios permit.

The workpiece material was cold-work tool steel AISI P20. The material was supplied in fully annealed condition, having a diameter of 70 mm and a length of 300 mm. Due to the presence of nickel, this steel, having been used in a hardened and tempered condition for plastic dies of medium size, offers an excellent depth of hardening and good machinability even when hardened and tempered. The chemical composition and hardness value of the workpiece material are given in Table 1.

Two CNMG 120408 (with an ISO designation) carbide inserts, having completely the same geometry and substrate but different coating layers, were employed.

Table 1 – Chemical components and hardness value of workpiece material

ISO/DIN	AISI	C	Mn	Cr	Mo	V	Si	Hardness
1.2738	P20	0.37	1.40	2.00	0.20	–	0.30	52–54 HRC

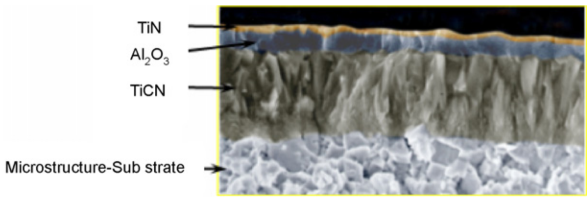

Fig. 1 – Coating layers of Insert 1.

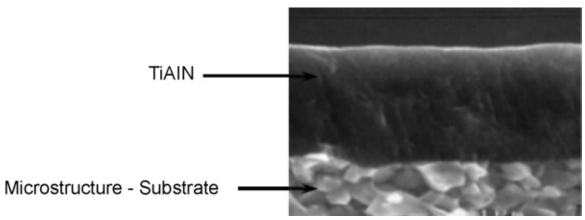

Fig. 3 – Coating layer of Insert 2.

Insert 1 possesses a coating consisting of a TiCN underlayer, an intermediate layer of Al_2O_3 and a TiN outlayer, all deposited by CVD (Fig. 1). This insert is suitable for high speed finishing of cast iron and steel. Geometrical properties of Insert 1 are depicted in Fig. 2.

Insert 2, PVD coated with a thin TiAlN layer ($3 \pm 1\,\mu$m), has an extremely hard submicron substrate having high fracture toughness. Since PVD coatings can be deposited at considerably lower temperatures, toughness of the substrate does not decrease considerably contrary to that in CVD coating technique. The coating provides compression stresses in the upper coating layer and only a very small tensile stress below the coating, in the upper layer of the substrate (Fig. 3). Under high speed conditions, TiAlN forms a thin Al_2O_3 layer on the cutting edge, reducing friction, protecting the insert from further oxidation and also excessive wear by decreasing heat conduction. Geometrical properties of Insert 2 are depicted in Fig. 4.

Individual experiments were conducted using 3 various cutting speeds, 3 various feed rates and 3 various cutting depths. The cutting parameters used were as below:

Cutting speed (V, m/min) = 120/160/200.
Feed rate (f, mm/rev) = 0.12/0.18/0.22.
Cutting depth (a, mm) = 1/1.5/2.

In each experiment, one parameter was altered whilst the other two kept constant.

3. Results and discussion

In the experiments an unused cutting edge was employed for each cutting speed–feed rate–cutting depth combination and surface roughness values (R_a, μm) were measured for each of these combinations.

Using all possible combinations, 54 experiments (27 for each tool) were conducted. The surface roughness values (R_a) obtained from these experiments, for both Insert 1 and Insert 2, are depicted in Table 2.

3.1. *Development of the surface roughness model*

Considering the surface roughness values as output, and cutting parameters as inputs; it is possible to attain a linear, second order (quadratic) or exponential equation expressing the relationship between the output and inputs.

3.2. *Linear model*

The dependent variable R_a can be conceived as a linear combination of the independent variables, namely cutting speed, feed rate and cutting depth. Therefore, the equation will be as below:

$$R_a = k_0 + k_1 V + k_2 f + k_3 a_p \quad (1)$$

When a regression analysis is employed applying the least squares method to the experimental data in order to obtain the coefficients of this equation, the following two equations (one equation per tool) are attained:

$$R_{a(\text{Insert 1})} = 0.034038 - 0.004951V + 12.571053f + 0.106111a_p$$
$$(R^2 = 0.93 \quad \text{and} \quad R_a^2 = 0.92) \quad (2)$$

$$R_{a(\text{Insert 2})} = 0.533368 - 0.001138V + 9.882895f + 0.235778a_p$$
$$(R^2 = 0.94 \quad \text{and} \quad R_a^2 = 0.93) \quad (3)$$

3.3. *Second order model*

It can be assumed that the equation below demonstrates the relationship between the dependent variable R_a and the independent variables cutting speed, feed rate and cutting depth.

$$R_a = k_0 + k_1 V + k_2 f + k_3 a_p + k_4 V^2 + k_5 f^2 + k_6 {a_p}^2 + k_7 Vf + k_8 V a_p + k_9 f a_p \quad (4)$$

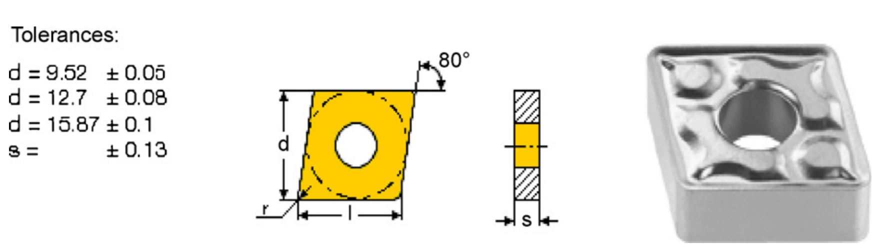

Fig. 2 – Geometrical properties of Insert 1.

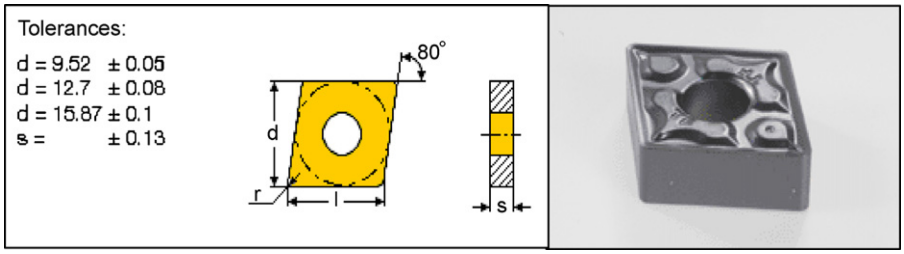

Fig. 4 – Geometrical properties of Insert 2.

Table 2 – The surface roughness values (R_a, μm) concerning the workpieces machined using Insert 1 and Insert 2

Tool	Feed rate (mm/rev)	Depth of cut (mm)								
		V = 120 m/min			V = 160 m/min			V = 200 m/min		
		1	1.5	2	1	1.5	2	1	1.5	2
Insert 1	0.12	0.869	1.091	1.104	0.816	0.859	0.873	0.766	0.785	0.864
	0.18	1.620	1.628	1.632	1.391	1.420	1.452	1.284	1.371	1.428
	0.22	2.576	2.582	2.629	1.998	2.029	2.086	1.766	1.929	1.973
Insert 2	0.12	0.824	0.860	0.984	0.802	0.888	0.939	0.692	0.786	0.834
	0.18	1.112	1.270	1.379	1.287	1.546	1.560	1.284	1.324	1.509
	0.22	1.845	1.981	2.232	1.681	1.722	1.901	1.572	1.783	1.883

If the regression analysis utilizing least squares method is performed, the two equations below are established:

$$R_{a(\text{Insert 1})} = 2.228504 - 0.018730V - 4.875512f + 0.216281a_p + 0.000071V^2 + 79.888889f^2 - 0.058000a_p^2 - 0.057226Vf + 0.000621Va_p - 0.204825fa_p$$

$$(R^2 = 0.98 \quad \text{and} \quad R_a^2 = 0.97) \tag{5}$$

$$R_{a(\text{Insert 2})} = -0.155678 + 0.007654V - 1.737500f + 0.046754a_p - 0.000017V^2 + 33.916667f^2 + 8.22E - 14a_p^2 - 0.013904Vf - 0.000567Va_p + 1.613596fa_p$$

$$(R^2 = 0.95 \quad \text{and} \quad R_a^2 = 0.93) \tag{6}$$

3.4. *Exponential model*

Surface roughness as a dependent variable can be expressed by employing the independent variables consisting of cutting speed, feed rate and cutting depth in an exponential form. Then the equation will be as follows:

$$R_a = k_0 + k_1V + k_2f + k_3a_p + k_4V^2 + k_5f^2 + k_6{a_p}^2 + k_7Vf + k_8Va_p + k_9fa_p \tag{7}$$

The surface roughness model built upon a similar least square regression is presented below:

$$R_{a(\text{Insert 1})} = 2.228504 - 0.018730V - 4.875512f + 0.216281a_p + 0.000071V^2 + 79.888889f^2 - 0.058000a_p^2$$

Table 3 – Total average errors for each tool (underlined values are the smallest total average errors among those of the 3 models)

V (m/min)	*a* (mm)	Insert 1			Insert 2		
		Linear (%)	Second order (%)	Exponential (%)	Linear (%)	Second order (%)	Exponential (%)
120	1	11.29	5.74	8.50	11.80	8.95	10.33
160	1	5.55	4.68	2.74	4.56	1.80	3.16
200	1	10.75	3.50	2.30	3.93	6.49	3.93
120	1.5	8.65	5.12	8.80	7.50	5.06	6.97
160	1.5	5.95	2.98	3.56	6.93	7.17	6.62
200	1.5	7.15	5.18	2.20	1.82	2.30	2.76
120	2	8.28	5.28	8.76	8.81	7.76	9.33
160	2	6.39	1.27	4.94	1.15	3.4	3.19
200	2	7.32	4.05	3.55	2.96	4.47	2.90
Total average error		7.926	4.199	5.038	5.496	5.248	5.465

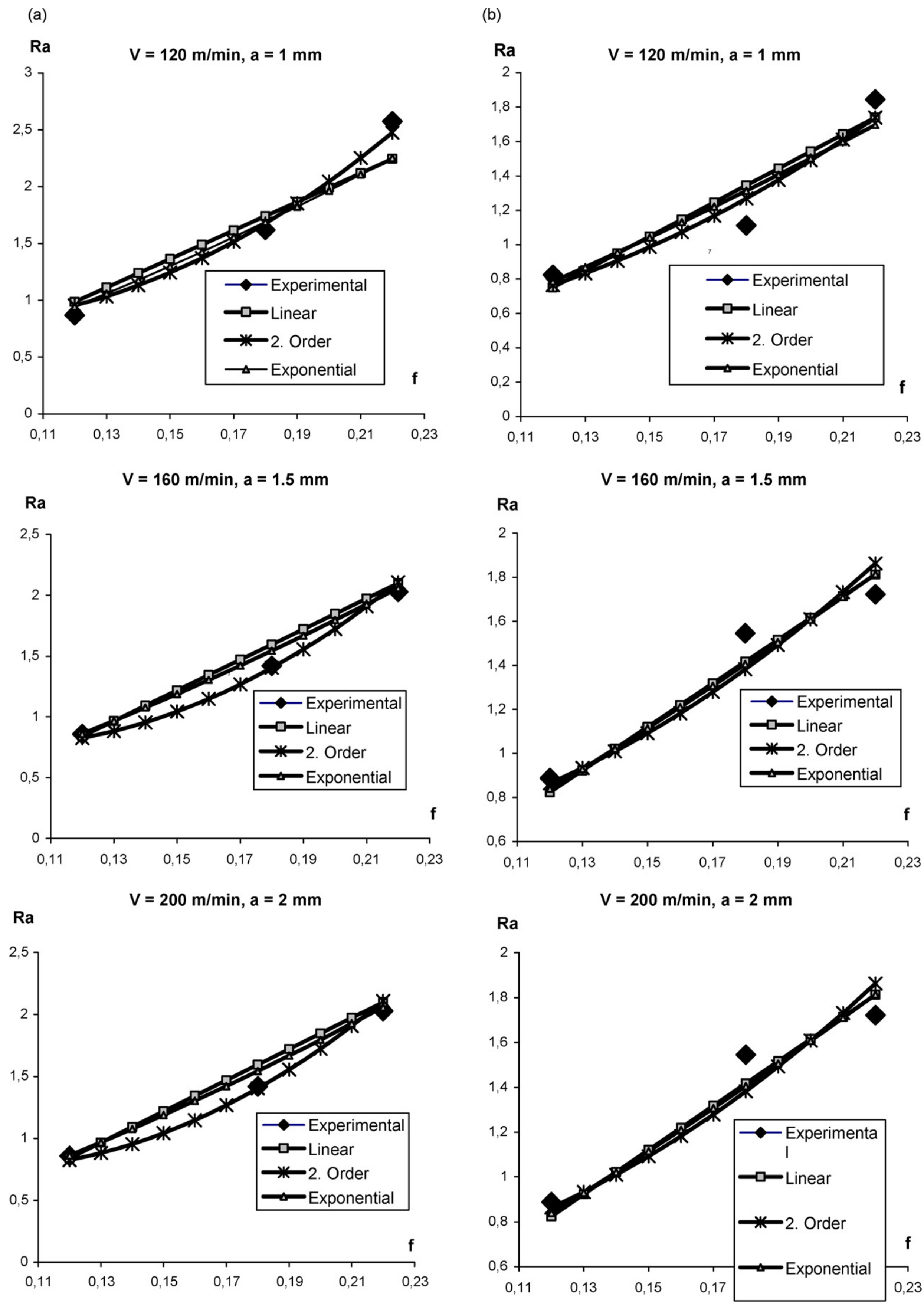

Fig. 5 – Comparison of regression models with the experimental R_a results: (a) for Insert 1; (b) for Insert 2.

$$-0.057226Vf + 0.000621Va_p$$
$$-0.204825fa_p (R^2 = 0.98 \quad \text{and} \quad R_d^2 = 0.97) \qquad (8)$$

$$R_{a(\text{Insert 2})} = -0.155678 + 0.007654V - 1.737500f + 0.046754a_p$$
$$-0.000017V^2 + 33.916667f^2 + 8.22E - 14a_p^2$$
$$-0.013904Vf - 0.000567Va_p$$
$$+1.613596fa_p (R^2 = 0.95 \quad \text{and} \quad R_d^2 = 0.93) \qquad (9)$$

3.5. *Selecting the most reliable model*

The values calculated using all the equations generated for 3 surface roughness models were compared with the experimental measurements, for the purpose of discovering the most suitable model (Table 3).

A computer program was written for the comparison mentioned above. Besides the cutting parameters (cutting speed, feed rate, cutting depth), the experimental surface roughness results were entered as inputs. The outputs of the program were the surface roughness values computed by means of the predictive equations established above and the corresponding percentage errors of predictions. Surface roughness (R_a) values were calculated for each cutting speed, feed rate and cutting depth values. The percentage values presented in Table 3 are the mean values of 3 errors calculated for 3 various feed rates at the cutting speed and cutting depth given on the corresponding row.

As understood through Fig. 5a and b and Table 3, the exponential model provides smaller errors for Insert 1 for some cutting parameter combinations. However, considering the total average errors, it is clear that the second order model represents the most consistent approach. Similarly for Insert 2, although linear model gives better results in some cases, second order model is again the most appropriate one with its total average error being the smallest.

3.6. *Effects of cutting parameters and coating layers on surface roughness*

There is no doubt that the data gathered through the experiments possesses some errors and this fact affects the models

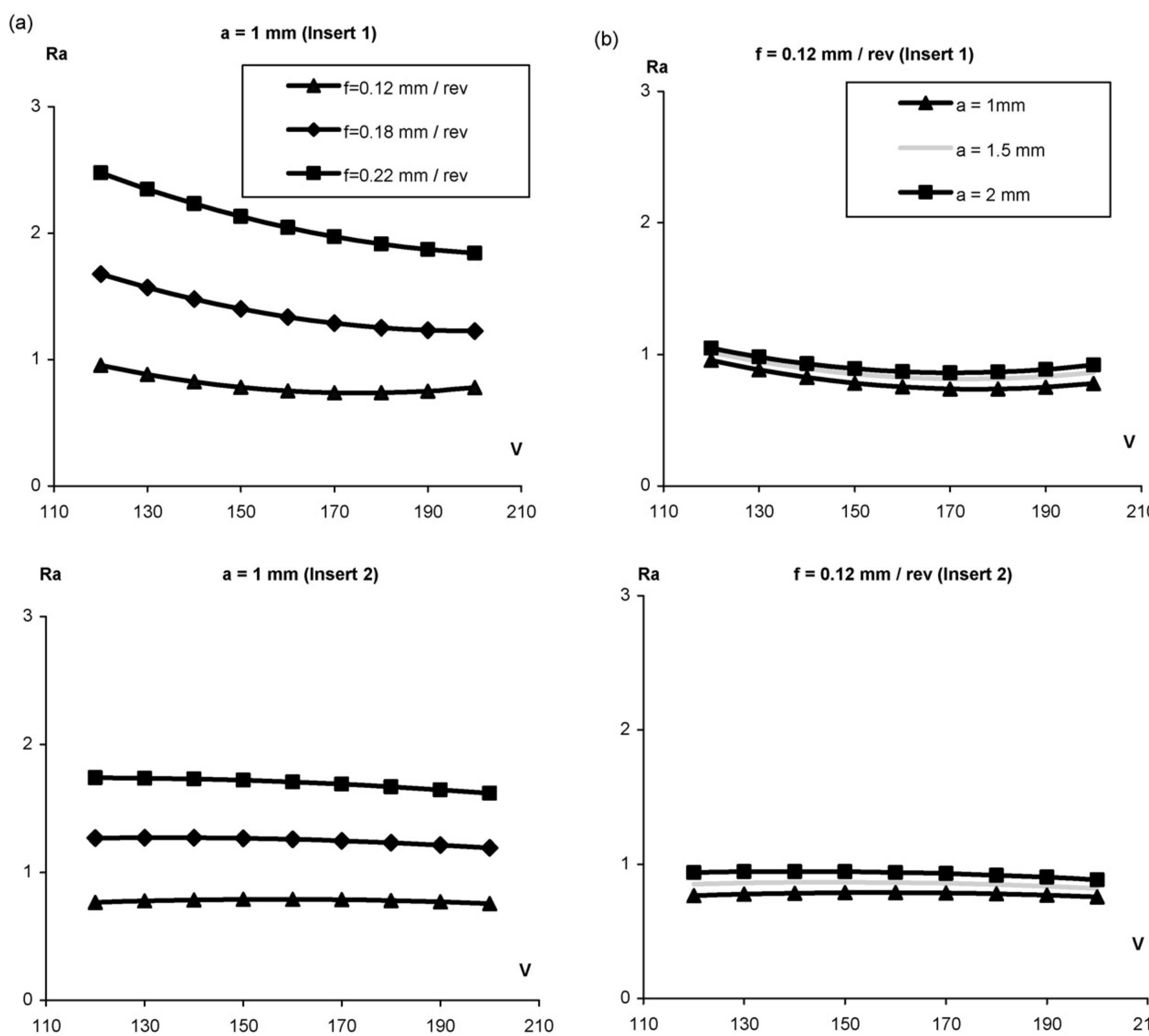

Fig. 6 – Effect of cutting parameters on R_a for Insert 1 and Insert 2: (a) effect of V at various feed rates (a = 1 mm); (b) effect of V at various depths of cut (f = 0.12 mm/rev).

established. Especially because the machine employed is a conventional lathe, cutting speed adjustment was restricted by the rotational speed ratios of the machine tool. But decreasing diameter of the workpiece being machined and rotational speed ratios were adjusted such that the difference between desired and actual cutting speeds would be at most ±5%.

In order to determine a surface roughness value, at least 3 measurements were performed each starting from a different point of the measured region, and the mean of the measurements was calculated. Thus, probable observation errors were kept relatively small.

3.6.1. *Effects of cutting speed, feed rate and cutting depth*

Theoretically, surface roughness is a function of feed rate and nose radius. But in practice; cutting speed, cutting depth and tool wear have influence on surface roughness as well. Since the inserts employed in the experiments possess identical nose radius values, the effect of nose radius was not investigated in this study. In addition, because the wear does not reach high enough levels to affect the surface roughness in 120 s (the flank wear V_B reached only from 0.068 mm (V_{B30}) to 0.074 mm (V_{B120}) for Insert 1 and from 0.055 to 0.059 mm for Insert 2), the effect of tool wear was neglected. In this context V_{B30} is the flank wear after 30 s where V_{B120} is the wear after 2 min.

The effects of cutting parameters according to the experiments conducted can be summarized as follows:

- As seen from Fig. 6a, feed rate has the greatest effect on surface roughness. This situation can be explained by the decrease in cutting forces resulting from the decrease in feed rate. Smaller cutting forces cause less vibration and provide better surface finish.
- Another factor to consider is cutting speed. Examining Fig. 6a, it is understood that an increase in cutting speed improves surface quality. This result supports the argument that high enough cutting speeds reduce cutting forces together with the effect of natural frequency and vibration, giving better surface finish (Sturesson et al., 1997).

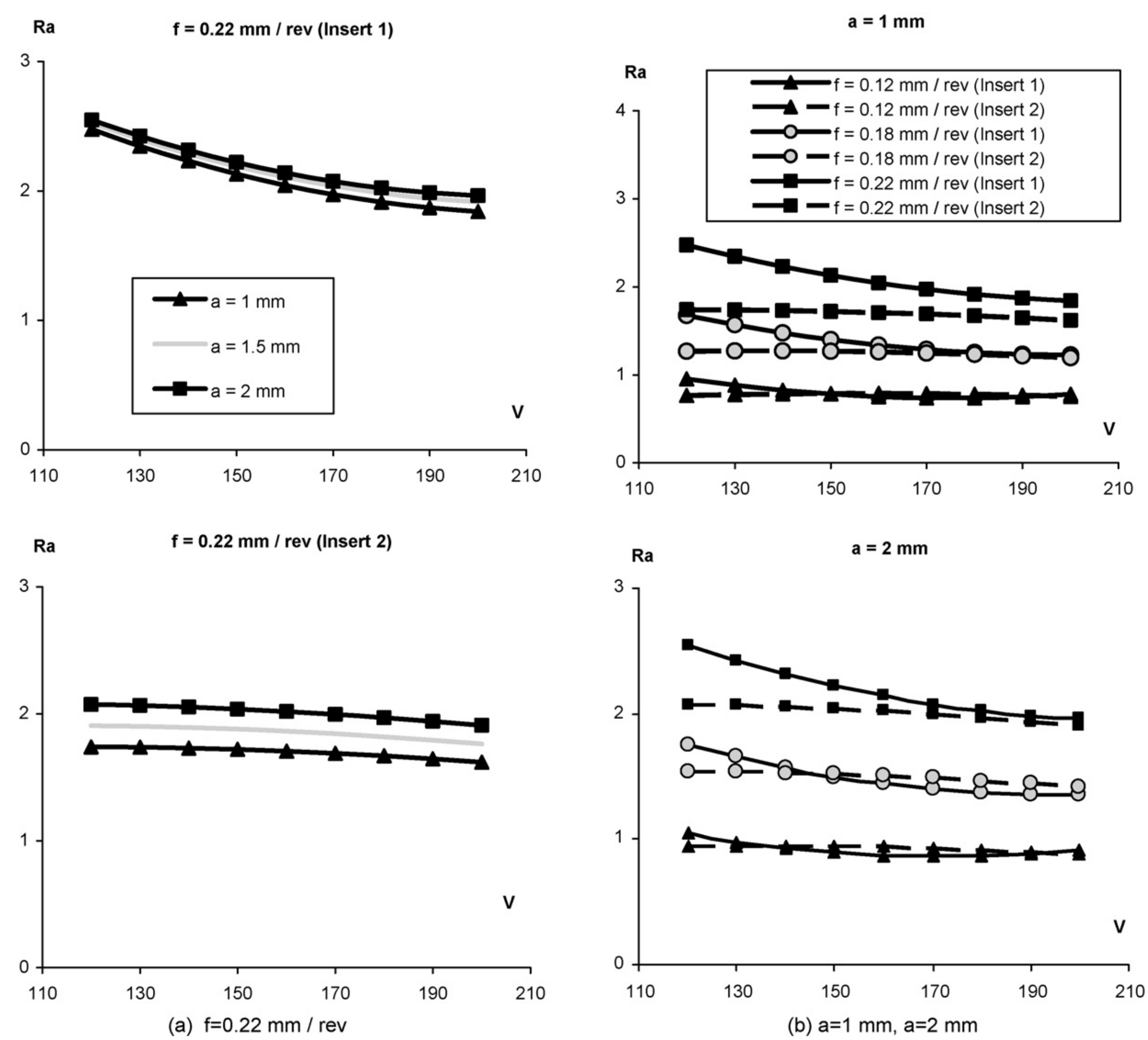

Fig. 7 – Effect of coating layers on R_a: (a) effect of V at various depths of cut (f = 0.12 mm/rev for Insert 1 and Insert 2, respectively); (b) effect of V at various feed rates (for a = 1 and 2 mm, respectively).

- Fig. 6a also represents the fact that best surface quality values are achieved where the low feed rates and high cutting speeds coincide.
- As obviously comprehended from Figs. 6b and 7a, cutting depth has an insignificant effect on surface roughness. Even after a 100% increase in cutting depth, no considerable change was noticed.

3.6.2. *Effects of coating layers*

The effects of coating layers on surface roughness is depicted in Fig. 7b by two graphs, one for 1 mm and the other for a 2 mm of cutting depth. The graphs demonstrate the following facts:

- Although the improvement obtained through the use of higher cutting speeds can be observed clearly when employing Insert 1, lower surface roughness values are achieved when employing Insert 2.
- For Insert 1, surface roughness demonstrates three different behaviors (Fig. 7b, Graph 1). In the first stage of the graph ($V = 110$–160 m/min), since the vibration originating from the high cutting forces decreases with the reducing cutting resistance due to the increasing workpiece temperature, R_a shows a decreasing tendency. In the following stage, surface roughness remains almost constant. However, after reaching a cutting speed of 190 m/min, R_a starts increasing. It results from the excessive cutting temperatures causing galling and rapid tool wear.
- For Insert 2, roughness curve exhibits almost no variations in shape (Fig. 7b, Graph 2). It can be attributed to the higher toughness of the insert and the heat shield effect of the coating. Higher toughness prevents the negative effects of the vibration at lower cutting speeds, whilst the PVD TiAlN coating protects the tool from rapid wear at higher cutting speeds.

4. Conclusions

In the paper presented here, a mathematical model of cutting parameters was generated for the purpose of predicting surface roughness. Two types of inserts (Insert 1 and Insert 2) having the same geometry and substrate but different coating layers were used in the experiments and the effects of two coating layers as well as the cutting parameters onto the surface roughness were investigated. The results obtained are as follows:

- Total average errors of 4.2% and 5.2%, respectively, for Insert 1 and Insert 2, indicate the reliability of the surface roughness model generated.
- Among the cutting parameters, feed rate has the greatest influence, followed by cutting speed. Higher feed rates lead to higher surface roughness values, whereas cutting speed has a contrary effect and cutting depth has no significant effect.
- Although the positive effect of higher cutting speeds can easily be noticed when employing CVD coated ($TiCN + Al_2O_3 + TiN$) Insert 1, surface roughness values obtained when employing PVD coated (TiAlN) Insert 2 are lower.

Considering the dissimilar behaviors of the two insert types against cutting speed, another study can be carried out concerning the tool life.

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