Int J Adv Manuf Technol (2010) 51:79–86
DOI 10.1007/s00170-010-2616-4

ORIGINAL ARTICLE

Surface roughness prediction in turning of femoral head

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Received: 8 September 2009 / Accepted: 8 March 2010 / Published online: 1 April 2010

Abstract This paper is dealing with the development of a surface roughness model for turning of femoral heads from AISI 316L stainless steel. The model is developed in terms of cutting speed, feed rate and depth of cut, using response surface methodology. Machining tests were carried out with TiN–Al_2O_3–TiC-coated carbide cutting tools under various conditions. First-order and second-order models predicting equations for surface roughness have been established by using the experimental results. The established equation shows that the depth of cut was the main influencing factor on the surface roughness. It increased with increasing the depth of cut and feed rate, respectively, but it decreased with increasing the cutting speed. In addition, analysis of variance for the second-order model shows that the interaction terms and the square terms are statistically insignificant. The predicted surface roughness of the samples was found close to the experimentally obtained results within a 95% confident interval.

Keywords Femoral head · High-speed machining · Surface roughness · Taguchi method

Notation and abbreviation

C	Constant
d	Depth of cut
DF	Degree of freedom
f	Feed rate (mm/rev)
F	F value resulting from analysis of variance
MS	Mean square
SS	Sum of mean square
P	Level of significance
R_a	Average roughness
R_{aT}	Predicted average roughness
v	Cutting speed
x_1	Logarithmic transformation of cutting speed
x_2	Logarithmic transformation of feed rate
x_3	Logarithmic transformation of depth of cut
$\widehat{y}$	Estimated response of the surface roughness
ε	Random error
$\widehat{\eta}$	True response of the surface roughness

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1 Introduction

In modern industry, the goal is to manufacture low cost and high quality products in a short time. Automated and flexible manufacturing systems are employed for that purpose along with computerised numerical control (CNC) machine tools that have become very common in factories and are capable of achieving high accuracy and very low processing time. Turning is the first and most common method for cutting, especially for the finished machined parts [1, 2]. In machining of parts, surface quality is one of the most specified customer requirements where major indication of surface quality on machined parts is surface roughness. Surface roughness is one of the main results of process parameters such as tool geometry (i.e. nose radius, edge geometry and rake angle) and cutting conditions (feed rate, cutting speed, depth of cut, etc.) [3]. Furthermore, it is a significant design specification that is known to have considerable influence on properties such as wear resistance and fatigue strength. The quality of the surface is a factor of importance in the evaluation of machine tool productivity. Hence, it is important to achieve a consistent tolerance and surface finish. When surface finish becomes the main criteria in the quality control department, the productivity of the metal cutting operation is limited by the surface quality. Recent investigation has shown that increasing the cutting speed can help to maximise productivity and, at the same time, improves surface quality [4]. All this new advanced technology, which has been developed and become better in the last decades, made strange and complex surfaces like hip joint femoral heads able to be designed and manufactured. When manufacturing spherical femoral heads, it is necessary to be ensured by methods of diamond machining that their functional surfaces have diameters of 32.0, 28.0 or 22.2 mm, with non-sphericity <0.5 µm and roughness, R_a, <0.2 µm [5]. However, the relevant manufacturing process has to achieve a surface quality close to the above strict limits so the final procedure could be more efficient and easier. According to this investigation, the method of high-speed machining (HSM) was introduced in the manufacturing of spherical femoral heads.

The aim of this research is to present the use of proper cutting conditions, through high-speed turning, in order to determine the appropriate surface roughness of the femoral heads of hip implants. Furthermore, an existing theoretical model was used to make such predictions in function of operation conditions. The response surface method (RSM) is practical, economical and relatively easy to use. Experimental data were applied to build a mathematical analysis for first- and second-order modelling by a regression method.

In the next sections, the model for the surface roughness prediction of AISI 316L stainless steel with the aid of statistical methods will be presented. By using the RSM and the 2^3 factorial designs of experiments, first- and second-order models have been developed with a 95% confidence level.

2 Procedures and methods

2.1 Surface roughness model

In the last years, a number of researchers have used the aforementioned method for surface roughness [6–16]. For example, Sahin and Motorcu [7, 8] and Lin et al. [12] used the RSM for predicting surface roughness. Also, Hasegawa et al. [6] and Gopal and Rao [11] investigated the use of RSM in developing a surface roughness prediction model. Petropoulos et al. [9] found a pronounced effect of tool wear on the R_a and R_{max} values of surface roughness by statistical analysis.

An exponential empirical model for surface roughness as a function of cutting speed V (metres per minute), feed f (millimetres per revolution) and depth of cut d (millimetres) was suggested in the form:

$$R_{aT} = CV^n f^m d^p \varepsilon \tag{1}$$

where R_{aT} is the surface roughness (micrometres), C, n, m and p are constants and ε is a random error [7]. Equation 1 may be written as a linear combination by performing logarithmic transformation in order to facilitate the determination of constants and parameters, i.e.

$$\ln R_a = \ln C + n \ln V + m \ln f + p \ln d + \ln \varepsilon \tag{2}$$

which may represent the following linear mathematical model:

$$\widehat{\eta} = \beta_0 x_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 \tag{3}$$

where $\widehat{\eta}$ is the true response of the surface roughness on logarithmic scale, x_0=1 (a dummy variable), and x_1, x_2 and x_3 are logarithmic transformations of cutting speed, feed rate and depth of cut.

The linear model of Eq. 3 can be written in terms of the estimated response as

$$\widehat{y} = y - \varepsilon = b_0 x_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 \tag{4}$$

where $\widehat{y}$ is the estimated response of the surface roughness on a logarithmic scale, and y is the measured response on a logarithmic scale. In this equation, ε is the experimentally random error, and the b values are the estimates of the β parameters.

The second-order model also is useful when the second-order effect of V, f and d and the two-way interactions amongst V, f and d are significant. The second-order model can be obtained from the equation of the first-order model as

$$\widehat{y} = y - \varepsilon = b_0 x_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 + b_{11} x_1^2 + b_{22} x_2^2 + b_{33} x_3^2 + b_{12} x_1 x_2 + b_{23} x_2 x_3 + b_{13} x_1 x_2 \tag{5}$$

where the b values, b_0, b_1, b_2, b_3..., etc., are to be estimated by the method of least squares. In the above equation, $\widehat{y}$ is the estimated response on a logarithmic scale. In the present study, the parameters of Eqs. 4 and 5 have been estimated by using a Minitab® computer package.

2.2 Experimental design

To develop a second-order model, a number of cutting variables, based on the design of experiments methodology, must be considered [17, 18]. Eight experiments representing

2^3 factorial designs were taken into consideration, which have another 21 points in the middle, edges and faces of the representation cube, as shown Fig. 1. Taking also into account three different levels for each variable (see Table 1), experimental conditions for 27 experiments are finally obtained, as shown in Table 3. The transforming equations for each of the independent variables are the following:

$$x_1 = \frac{\ln V - \ln(356)}{\ln(440) - \ln(356)}$$
$$x_2 = \frac{\ln f - \ln(0.08)}{\ln(0.12) - \ln(0.08)} \quad (6)$$
$$x_3 = \frac{\ln d - \ln(0.15)}{\ln(0.20) - \ln(0.15)}$$

where x_1 is the coded value of the cutting speed of the tool corresponding to its natural value of v, x_2 is the coded value of the feed rate corresponding to its natural value of f and x_3 is the coded value of the depth of cut corresponding to its natural value of d.

2.3 Experimental work

The workpieces, manufactured in a CNC lathe OKUMA Lb 10II, were made of AISI 316L steel, with a hardness of about 79 HRB and properties as shown in Table 2. Medically, the use of stainless steels like 316L, although with high Fe content, renders them non-compatible with magnetic resonance imaging and to be poor fluoroscopic materials. In spite of their limitations and a myriad of materials that have been chosen (like titanium), stainless steels are still favoured, as evidenced by the fact that seven out of the eight implants, approved by the US Food and Drug Administration, are made of stainless steels [19]. In cited literature, there are a number of publications which deal with the turning process of stainless steel. For example, Voronenko [20] and Tekiner and Yesilyurt [21] examined the machining of austenitic stainless steels and the appropriate cutting parameters. Furthermore, Paro et al. [22], Xavior and Adithan [23] and Dhar and Kamruzzaman [24] investigated surface roughness and tool wear of turning such materials. According to these researches, in low cutting speeds, i.e. between 40 and 90 m/min, the surface roughness came close to 2–3 μm. When the cutting speed increases up to 264 m/min, the surface quality becomes better, and its roughness value decreases to less than 1 μm. Additionally to the aforementioned researches come Noordin et al. [25] and Ciftci [26], who use coated carbide tools for these manufacturing processes, resulting to less tool wear and better surface quality for higher cutting speeds. Finally, Chang and Tsai [27], Outeiro et al. [28] and Maranhão and Paulo Davim [29] investigated the cutting forces and residual stresses not only experimentally but also through numerical simulation. These materials are considered to be difficult to machine, because of specific properties such as high mechanical and micro-structural sensitivity to strain and stress rates. Moreover, their low thermal conductivity leads to bad heat conduction at the tool tip and, locally, to very hot points. Regarding to the use of coolants, 316L better results in tool wear, and piece roughness are achieved when external coolant (emulsion 4–5% of a mineral oil in water) is used [30]. Furthermore, the development of new materials for cutting tools, such as

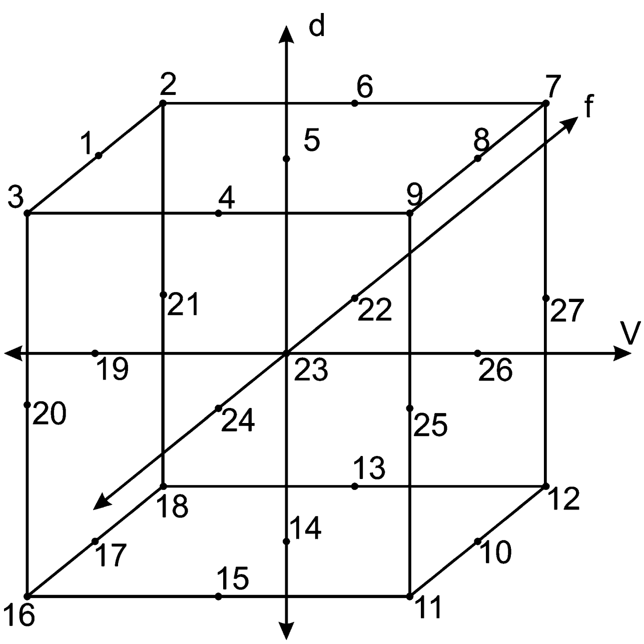


Fig. 1 Central composite design for three factors

Table 1 Level independent variables

Factor, coding (unit)	Low (−1)	Centre (0)	High (1)
Cutting speed, v (m/min)	264	352	440
Feed, f (mm/rev)	0.06	0.08	0.12
Depth of cut, d (mm)	0.1	0.15	0.2

Table 2 Material properties

Material properties	AISI 316L stainless steel
Physical	
Density	8 g/cm^3
Mechanical	
Hardness, Rockwell B	79
Tensile strength, ultimate	560 MPa
Tensile strength, yield	290 MPa
Elongation of break	50%
Modulus of elasticity	193 GPa
Poisson's ratio	0.29

TiN-coated cemented tungsten carbides, has also led to better control of the material removal process [31–33]. Therefore, a coated tool from SECO specification: DNMG 110402-M3 with TP 2000 coated grade was used for the manufacturing process. This cutting tool has a rhombic shape with cutting edge angle 55°, and it is intended for general turning on steels and alloyed steels, as it is coated with four layers of Ti $(C, N) + Al_2O_3 + $ Ti $(C, N) + $ TiN. The rake angle mounted in the toolholder is γ=−5° and inclination angle is λ_s=−9.5°. The tool cutting edge angle is κ=93°.

Small cylindrical parts with diameter 30 mm and length 28 mm with a conical hole were used to manufacture the spheres of femoral heads. They were supported on lathe from their hole with a specific device in order to materialise the manufacturing procedure (Fig. 2).

According to the international standards, ISO 7206–Part 2 the roughness measurement takes place in accordance with the principles given in ISO 468. The spherical articulating surfaces of metallic and ceramic components shall have R_a values not greater than 0.2 µm, using a cut-off value of 0.05 mm [34]. Following these restrictions, the only way to measure the surface profile of all balls was the use of an atomic force microscope (AFM). The cantilever is the surface sensor of an AFM (see Fig. 3). A new cantilever commonly has a tip with radius of about 10 nm. When the cantilever comes close to the surface of a sample, the tip interacts with the surface atoms, which apply a very weak force on the cantilever. This force is measured by the laser detection system (that explains why the microscope is called 'Atomic Force Microscope'). To measure a surface profile, the cantilever is moved parallel to the surface. At the same time, the controller tries to keep the force on the cantilever tip constant by adjusting the distance between the cantilever and the sample, making the cantilever to move perpendicular to the surface. This movement is recorded, and it resamples the surface profile. For measuring not only a single profile line but for example a rectangular area, this area is divided into several scan lines, which are combined to reproduce a three-dimensional surface profile. This operation principle enables the AFM to detect even atomic steps on the surface, while the lateral resolution is directly related to the cantilever tip radius [35].

This technique was used for two reasons. Firstly, we have to measure very low and accurate values of roughness, and secondly, it is quite a good method for measuring spherical surfaces, as it can measure a very small surface, i.e. 50×50 µm, considering it as a flat portion of the sphere. The surface roughness was predicted by measurements, which were made at five different points of each sphere. Each measurement was revised three times, in order to eliminate the fault factor. This procedure was repeated for a number of places along the profile, where the heights of the lays and the feed marks variation have significant importance for the surface quality. The results of four measurements, as they have been taken from the software of the AFM, are shown in Fig. 4.

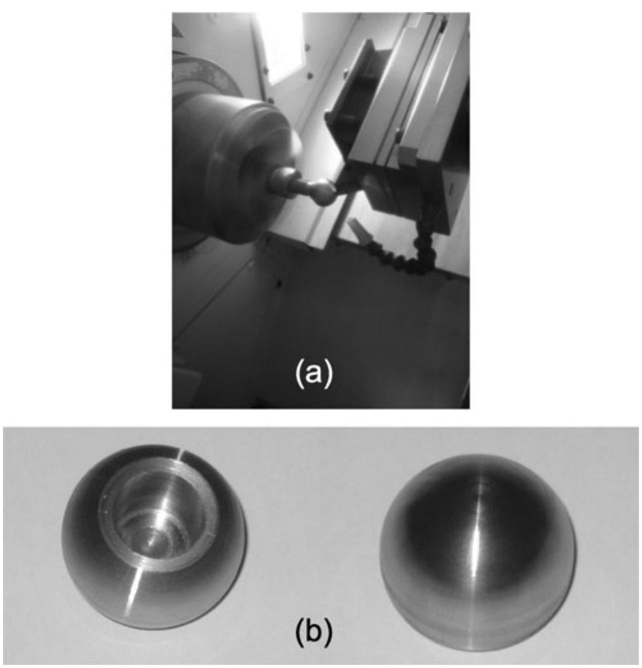


Fig. 2 **a** The part during the machining and (**b**) the final result

3 Results and discussion

3.1 Second-order model

The second-order model was postulated in obtaining the relationship between the surface roughness and the machining independent variables. The model is based on the response surface design. The model equation is given by

$$
\begin{aligned}
\widehat{y} = {} & 0.327928 - 0.000137531x_1 + 0.808961x_2 - 1.15409x_3 \\
& -0.00000073357x_1^2 - 4.15124x_2^2 + 5.53333x_3^2 \\
& +0.000991942x_1x_2 + 0.00147054x_1x_3 \\
& +2.42659x_2x_3
\end{aligned}
\tag{7}
$$

This equation shows that the surface roughness increased with increasing of the feed rate, but it decreased with increasing the cutting speed and depth of cut. The depth of cut has the most dominant effect on surface roughness value. The results of the measured and predicted values and residual error for surface roughness are shown in Table 3.

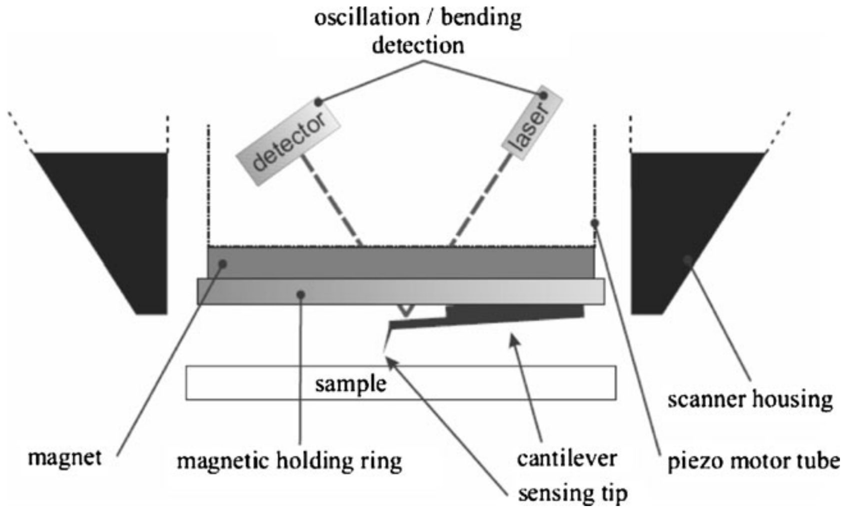


Fig. 3 Schematic drawing of the bottom (sensing) part of an atomic force microscope scan head

The experimental values were found very close to the theoretically predicted values, as indicated in Table 3. It is indicated that the models constructed are able to provide accurate prediction of the surface roughness from the cutting process.

The analysis of variance was used to check the adequacy of the second-order model. The variation between the groups of cutting parameters represents systematic variation due to the effect of the forces. The between-groups variation is often called as the effect variance, and the within-groups variance is often called as error variance. In statistical terms, the analysis will demonstrate whether the groups differ significantly or not. If a result is statistically significant, it tells that the group means are too different to have been given by chance. Two levels of significance, $p<0.05$ and $p<0.01$,

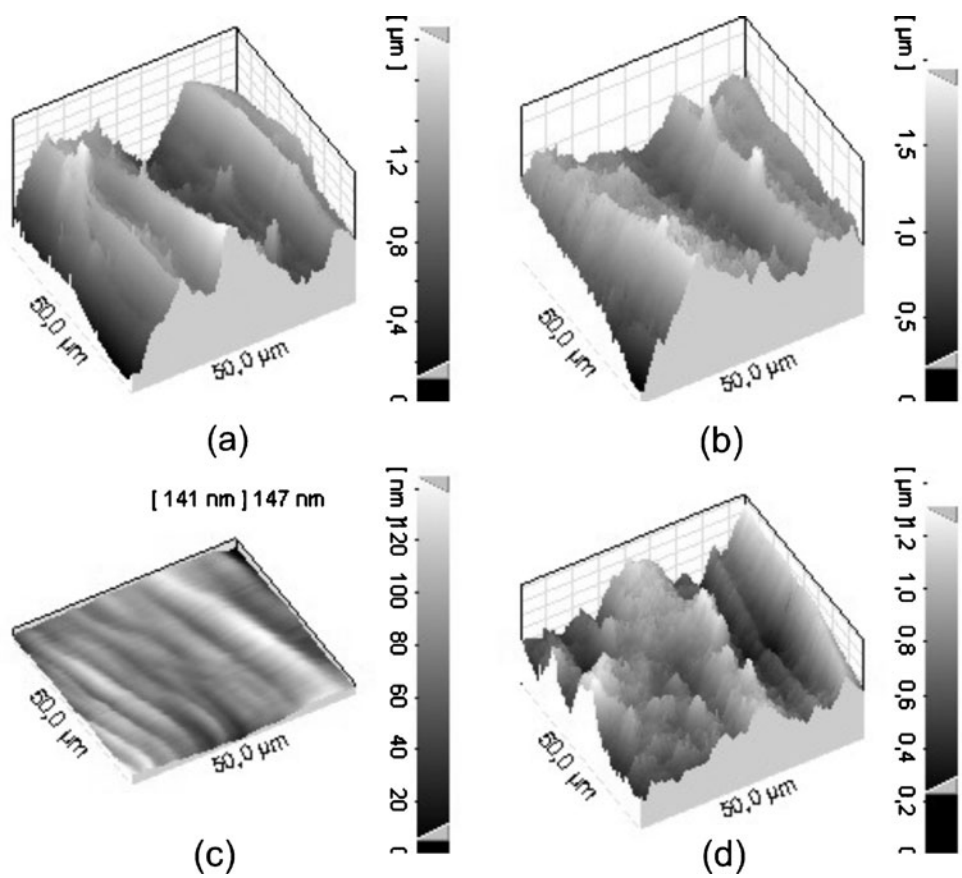


Fig. 4 Surface topography of manufactured femoral heads (**a**) with 356 m/min cutting speed, 0.06 mm/rev feed rate and 0.2 mm cutting depth, (**b**) with 440 m/min cutting speed, 0.06 mm/rev feed rate and 0.2 mm cutting depth, (**c**) with 440 m/min cutting speed, 0.06 mm/rev feed rate and 0.1 mm cutting depth and (**d**) with 356 m/min cutting speed, 0.08 mm/rev feed rate and 0.1 mm cutting depth

Table 3 Experimental conditions, results and results of residual error for surface roughness

No. of cut	Speed (m/min)	Feed (mm/rev)	Depth (mm)	x_1	x_2	x_3	Measured R_a	Theoretical R_aT	Ln R_a	Ln R_aT	Residual (R_a-R_aT)	Sum of squares of $(R_a-R_aT)^2$
1	265	0.12	0.1	−1	1	−1	0.323	0.317	−1.12959	−1.14942	0.019831	0.0003933
2	265	0.08	0.1	−1	0	−1	0.292	0.297	−1.23214	−1.2125	0.019641	0.0003858
3	265	0.06	0.1	−1	−1	−1	0.289	0.283	−1.24191	−1.26307	0.021163	0.0004479
4	356	0.12	0.1	0	1	−1	0.295	0.287	−1.22248	−1.24805	0.02557	0.0006538
5	356	0.08	0.1	0	0	−1	0.280	0.264	−1.27297	−1.33148	0.058519	0.0034244
6	356	0.06	0.1	0	−1	−1	0.266	0.248	−1.32363	−1.39589	0.072256	0.0052209
7	440	0.12	0.1	1	1	−1	0.237	0.249	−1.4411	−1.39105	0.050053	0.0025053
8	440	0.08	0.1	1	0	−1	0.215	0.223	−1.53789	−1.50282	0.035069	0.0012298
9	440	0.06	0.1	1	−1	−1	0.176	0.204	−1.73917	−1.58786	0.15131	0.0228946
10	440	0.12	0.15	1	1	0	0.319	0.307	−1.14413	−1.1803	0.036163	0.0013077
11	440	0.08	0.15	1	0	0	0.317	0.276	−1.14833	−1.28727	0.138947	0.0193062
12	440	0.06	0.15	1	−1	0	0.251	0.255	−1.38363	−1.3647	0.01893	0.0003583
13	356	0.12	0.15	0	1	0	0.330	0.339	−1.10967	−1.08098	0.028691	0.0008232
14	356	0.08	0.15	0	0	0	0.321	0.311	−1.13528	−1.16658	0.031308	0.0009802
15	356	0.06	0.15	0	−1	0	0.303	0.293	−1.19292	−1.22918	0.036262	0.0013149
16	265	0.12	0.15	−1	1	0	0.349	0.362	−1.05268	−1.01521	0.037478	0.0014046
17	265	0.08	0.15	−1	0	0	0.307	0.338	−1.18036	−1.0844	0.095966	0.0092095
18	265	0.06	0.15	−1	−1	0	0.307	0.321	−1.18254	−1.13628	0.046261	0.0021401
19	265	0.12	0.2	−1	1	1	0.460	0.436	−0.77689	−0.83126	0.054367	0.0029558
20	265	0.08	0.2	−1	0	1	0.411	0.406	−0.88876	−0.90036	0.011599	0.0001345
21	265	0.06	0.2	−1	−1	1	0.410	0.387	−0.8916	−0.94958	0.057978	0.0033614
22	356	0.12	0.2	0	1	1	0.405	0.419	−0.90469	−0.86958	0.035108	0.0012326
23	356	0.08	0.2	0	0	1	0.369	0.386	−0.99786	−0.95078	0.047084	0.0022169
24	356	0.06	0.2	0	−1	1	0.344	0.365	−1.06615	−1.00754	0.058602	0.0034342
25	440	0.12	0.2	1	1	1	0.393	0.393	−0.9331	−0.93337	0.000268	7.173E−08
26	440	0.08	0.2	1	0	1	0.348	0.357	−1.05651	−1.02943	0.027077	0.0007332
27	440	0.06	0.2	1	−1	1	0.345	0.334	−1.06566	−1.09596	0.030301	0.0009181

are typically employed in statistics. These mean that the probability of getting that result is less than 5% and 1% perceptively. These numbers are really positive for us to believe that the obtained result is a true reflection of an actual difference [36, 37]. The results of the analysis of variance for the second-order model are shown in Table 4. Because of the large p value in square and interaction, which means confidence less than 95%, the model is adequate. Therefore, first-order model was formed for the prediction of the surface roughness value.

3.2 First-order model

The first-order model for surface roughness was postulated, based on Eq. 3. The following formula may be obtained by the four constant parameters:

$$\widehat{y} = 0.191813 - 0.000347291x_1 + 0.764683x_2 + 1.2363x_3 \tag{8}$$

Equation 8, describing the roughness model, can transform using Eq. 6 into the following form:

$$R_a = 13.1176 \cdot V^{-0.001639} f^{1.8859} d^{4.2974} \tag{9}$$

This result shows that the depth of cut has the most significant effect on surface roughness, followed by the feed rate and, finally, the cutting speed. Namely, the cutting speed has a little effect on machining of stainless steel. Simply, this equation indicates that the surface roughness decreases with increasing the cutting speed and decreasing the depth of cut and the feed rate. This can also be seen easily in the graph of Fig. 5.

Also, the first-order model was tested by a thorough analysis of variance as shown in Table 5.

From this Table it is obvious that the cutting conditions play an important role to the first-order model, as the F factor is high enough and the p factor is less that 0.01, which means the confidence is over 99%. Checking the coefficient F value for the depth of cut, it was found that it

Table 4 Analysis of variance for second-order model

Source	DF	Seq SS	Adj SS	Adj MS	*F*	*p*
Regression	9	0.097381	0.097381	0.010820	24.23	0.000
Linear	3	0.095234	0.094038	0.031346	70.20	0.000
Square	3	0.001401	0.001401	0.000467	1.05	0.398
Interaction	3	0.000746	0.000746	0.000249	0.56	0.650
Residual error	17	0.007591	0.007591	0.000447		
Total	26	0.104971				

Table 5 Analysis of variance for first-order model

Source	DF	Seq SS	Adj SS	Adj MS	*F*	*p*
Cutting speed	3	0.016631	0.016631	0.008315	19.64	0.000
Feed rate	3	0.009824	0.009824	0.004912	11.60	0.000
Depth of cut	3	0.068779	0.068779	0.034390	81.22	0.000
Residual error	23	0.009737	0.009737	0.0004234		
Total	26	0.104971				

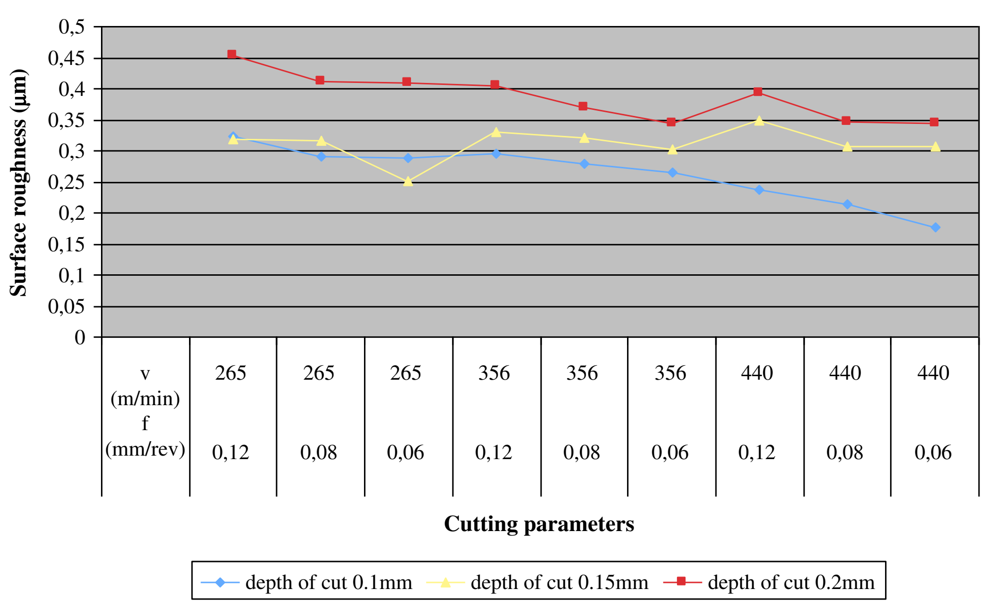
is approximately eight times larger than the same values of the other conditions (see Table 5). However, the other two are quite in the same range. A comparison between the results and the data from the cited literature is not possible, because of the variations and the cutting conditions that were used. However, a qualitative comparison can be made. For example, Puertas Arbizu and Luis Perez [38] found that the effect of the feed rate and the depth of cut have a negative effect on the surface roughness average, using a factorial design. Feng [39] found that the feed rate, the tool nose radius, the work material and speeds and the tool point angle have a significant impact on the observed surface roughness, using the fractional factorial experimentation approach. A higher cutting speed results in a smoother surface, by using the Taguchi method [40].

4 Conclusions

Factorial design of an experiment, based on the Taguchi's method, can be successfully employed by using TiN–Al_2O_3–TiC-coated tools in machining of 316L stainless steel. The following remarks may be drawn:

- First-order and second-order model predicting equations for surface roughness have been developed using RSM.
- The established equations clearly show that the depth of cut was a main influencing factor on the surface roughness. It increased with increasing the depth of cut and the feed rate, respectively, but it decreased with increasing the cutting speed. Among the other parameters, the feed rate was found to be more insensitive than the cutting speed.
- The variance analysis for the second-order model shows that the interaction terms and the square terms are statistically insignificant.
- The predicted values and the measured values are fairly close, which indicates that the developed surface roughness prediction model can be effectively used to predict the surface roughness from the cutting process, within a 95% confident interval for both cases.
- Using HSM, we can manufacture femoral heads easier, faster and the surface quality is close or sometimes even better than the international standard limits.

Fig. 5 Surface roughness in correspondence to cutting parameters



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