Hindawi Publishing Corporation
Advances in Materials Science and Engineering
Volume 2016, Article ID 7372132, 14 pages
http://dx.doi.org/10.1155/2016/7372132

Research Article

Optimizing Cutting Conditions for Minimum Surface Roughness in Face Milling of High Strength Steel Using Carbide Inserts

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Received 7 December 2015; Revised 3 March 2016; Accepted 6 March 2016

Academic Editor: Fernando Lusquiños

A full factorial design technique is used to investigate the effect of machining parameters, namely, spindle speed (N), depth of cut (a_p), and table feed rate (V_f), on the obtained surface roughness (R_a and R_t) during face milling operation of high strength steel. A second-order regression model was built using least squares method depending on the factorial design results to approximate a mathematical relationship between the surface roughness and the studied process parameters. Analysis of variance was conducted to estimate the significance of each factor and interaction with respect to the surface roughness. For R_a, the results show that spindle speed, depth of cut, and table feed rate have a significant effect on the surface roughness in both linear and quadratic terms. There is also an interaction between depth of cut and feed rate. It also appears that feed rate has the greatest effect on the data variation followed by depth of cut. For R_t, the results show that the table feed rate is the most effective factor followed by the depth of cut, while the spindle speed had a significant small effect only in its quadratic term. The conditions of minimum R_a and R_t are identified through least square optimization. Moreover, multiobjective optimization for minimizing R_a and maximizing metal removal rate Q is conducted and the results are presented.

1. Introduction

Increasing product quality, delivery time, and productivity of the machined parts are the main challenges of metal-based industry. There has been increased interest in optimizing machining conditions to satisfy manufacturing requirements including the most prominent one, which is surface finish. Surface quality is considered as one of the most important criteria in manufacturing engineering. The performance and quality of a product are directly associated with surface integrity achieved by final machining, which is reflected in having small tolerance and minimum surface roughness, R_a. High productivity and throughput are directly correlated with high speed machining, which can be achieved by computer numerical controlled (CNC) milling technology. The automated and flexible manufacturing systems are employed for that purpose along with CNC machines that are capable of achieving high accuracy with very low processing time. Surface roughness is a key factor of surface quality, since it assumes an essential effect on wear resistance, ductility, tensile, and fatigue strength for machined parts.

Raju et al. [1] modeled and optimized the surface roughness in relation to the cutting parameters for 6061 aluminum alloy processed by end milling with high speed steel (HSS) and carbide tools under dry and wet conditions. A multiple regression analysis using analysis of variance was conducted and a second-order mathematical model of the cutting parameters was suggested. The predicted surface roughness (R_a) from the model is compared to the values measured experimentally. It is reported, in this study, that feed rate is a dominant parameter and the surface roughness increases rapidly with increasing feed rate and decreases with increasing spindle speed, whereas the effect of depth of cut is not regular.

Pimenov [2] investigated the effect of feed, cutting speed, and tool wear of a T5K10 carbide tool on the roughness of flat surfaces, produced by face milling, of steel 45. The

Table 1: Chemical composition for high strength steel material.

C	Si	Mn	Ni	Cr	Mo	V	S	Cu	P	Al	Fe
0.356	0.221	0.728	2.697	1.030	0.617	0.103	0.005	0.176	0.010	0.006	Balance

work analyzed the nature of the microprofile of changes in machined surfaces based on increasing the wear surface on the tooth flank. He showed that the roughness R_z grew from 15 to 30% for the chosen cutting conditions with growth in the flank wear (V_b) from 0 to 3.1–4 mm. The increase in feed at a constant cutting speed led to an increase in the roughness; however, increasing cutting speed at constant feed led to a decrease in roughness. It was shown that, with an increase in the flank wear on the flank surface, the frequency of peaks and troughs of the profilograms of the microprofile of machined surface was decreased.

Pusavec et al. [3] studied alternative cooling/lubrication conditions compared to conventional machining of Inconel 718 and its relation to chip breakability. Genetic algorithms (GA) were used to evaluate and optimize the machining process in terms of tool-life, machined surface quality, chip breakability, productivity, and power consumption.

Felho and Kundrak [4] introduced a new method to calculate both the profile (2D) and surface (3D) parameters of theoretical roughness in the face milling of plain surfaces. This new method was based on an expediently developed CAD model and used a professional program for the roughness evaluation. Cutting experiments were performed on 42CrMo4 specimens in order to validate the accuracy of the model. The results have revealed that the method was able to predict surface roughness with good accuracy.

Rawangwong et al. [5] conducted a study on the surface roughness of a semisolid AA 7075 machined by face milling, using CNC milling machine with 63-millimeter diameter fine type carbide tool with twin cutting edge. The process factors were the speed, feed rate, and depth of cut. The results showed that the factor affecting surface roughness was the ratio of feed rate to the cutting speed while the depth of cut had no effect.

Kivak [6] used analysis of variance (ANOVA), Taguchi method, and regression analysis to investigate the effects of the machining parameters on surface roughness and flank wear for milling of Hadfield steel with PVD TiAlN- and CVD TiCN/Al_2O_3-coated carbide inserts under dry milling conditions. Several experiments were conducted using full factorial design with a mixed orthogonal array on a CNC vertical machining center. The process variables were the cutting tool, cutting speed, and feed rate. It was concluded that the feed rate was the dominant factor affecting surface roughness, while cutting speed was the dominant factor affecting flank wear.

Rawangwong et al. [7] investigated the effect of main machining factors on the surface roughness of nodular cast iron FCD 400 face milled by carbide tools. The etching experiments were done using semiautomated milling machine Obraeci Strojie brand FGV 32 model. The factors studied were the speed, feed rate, and depth of cut. The experiments illustrated that the factors affecting surface roughness were feed rate and cutting speed with tendency for reduction of roughness values at lower feed rate and greater cutting speed.

Abbas [8] presented a performance comparative analysis, involving the criteria of surface roughness (R_a, R_t, and R_z) during high strength steel's turning operation, between the conventional and wiper inserts. The main parameters considered in this study were the speed of cutting, the feed rate, and the depth of cut. The results showed the significance of cutting depth and feed rate in the reduction of surface roughness. It was reported that the quality of the surface derived with the wiper carbide insert had significant improvement in comparison to the conventional carbide insert. The maximum improvement of 3.5 times between the wiper insert and conventional insert was achieved at a cutting speed of 75 m/min.

The current work focuses on providing a comprehensive study on the effect of machining process parameters, namely, feed fate, cutting speed, and depth of cut, on the surface roughness, through a DOE full factorial design for face milling of high strength steel using carbide tools. Four levels for each process parameter are investigated. Analysis of variance (ANOVA) will be used to determine the effects of the machining parameters on surface roughness and to develop a mathematical model through regression analysis that best describes the variation within the experimental data.

2. Materials and Methods

This research study aims to investigate the effect of main factors on the surface roughness of high strength steel in face milling process using CNC milling machine and carbide inserts. Emco Mill Concept 45 CNC vertical milling machine equipped with Sinumeric 840-D with technical specifications including a speed range of 50–10,000 rpm and feed rate 0–10 m/min was used. Workpiece samples are high strength steel with the chemical composition shown in Table 1. The heat treatment given to the material involved austenitizing at 900°C for 5 hr, followed by air cooling, heating at 880°C for 5 hr, quenching in oil, tempering at 590–600°C for 8 hr, and then air cooling. The resulting hardness achieved was HRC 41–43. The surface area of each sample is 40 × 70 mm and height 60 mm. The cutting tool with carbide inserts model face mill with tool holder Sandvik R245-063Q22-12M and Sandvik carbide coated inserts R245-12 T3M-PM4240 was used. The diameter of the cutter is 63 mm with 5 edges. This type of milling cutter was designed for high metal removal and mirror surface finish. It is designed with enhanced corners to reduce burr formation and frittering of

Table 2: The cutting parameters and their levels used in the factorial design experiment.

Designation	Process parameter	Level 1	Level 2	Level 3	Level 4
A	Spindle speed (rpm)	500	750	1000	1250
B	Depth of cut (mm)	0.25	0.50	0.75	1.00
C	Feed rate (mm/min)	50	75	100	125

Figure 1: Test rig for machining the workpieces.

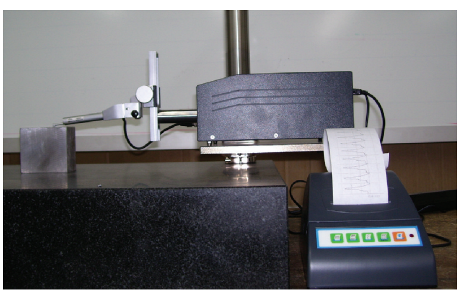

Figure 2: Test rig measuring the surface roughness.

the component. This type of cutter is suitable for face milling applications in all types of materials such as steel, stainless steel, cast iron, aluminum, and heat resistant and titanium alloys. The test rig for machining workpieces is shown in Figure 1. The surface roughness measuring device for evaluating the surface topography is model TESA Rugosurf 90-G and is shown in Figure 2.

The test plan was carried out through 64 test specimens, group (A), and repeated for producing replicates in group (B). Each group was divided into 16 groups. Every four groups are subjected to one common machining spindle speed. Groups 1–4, 5–8, 9–12, and 13–16 were processed using spindle speed machining of 500 rpm, 750 rpm, 1000 rpm, and 1250 rpm, respectively. Each group has been machined using four levels of cutting depth (0.25, 0.50, 0.75, and 1.0 mm) and each depth was processed using four levels of table feed rates (50, 75, 100, and 125 mm/min). To apply the above conditions, CNC milling machine equipped with Sinumeric 840-D was used. The surface roughness tester TESA was used to measure the surface roughness parameters, R_a and R_t, where R_a is arithmetic average deviation of the assessed profile and R_t is maximum height of the profile. The machined surfaces were duplicated for each set of cutting conditions. Three readings of surface roughness were measured on each surface and the average was recorded in the Appendix for groups (A) and (B).

3. Experimental Design

Full factorial design is a comprehensive technique that requires a large number of experiments and yields a detailed description of all system relations and interactions. In this research, full factorial design was used to build the experiment with three independent variables (factors) and four levels for each. Table 2 summarizes the variables and their levels. Analysis of variance (ANOVA) was conducted to test the significance of the factors and their interaction with a confidence level of 95%. Least squares method was used to build second-order multiple regression models. Minitab 17 was used to run the DOE analysis.

4. Results and Discussion

Figures 3(a) and 3(b) represent the effect of table feed rate on R_a for different depth of cuts at spindle speed 500 rpm in (a) and 1000 rpm in (b). Preliminary observation of these curves indicates that the surface roughness values (R_a) increase with increasing table feed rate for both rotational speeds. Comparing the effect of rotational speeds for two values of depth of cuts, of 1.0 and 0.25 mm, can be seen in Figure 4. For a depth of cut of 1.0 mm, the value of surface roughness (R_a) at spindle speed 1000 rpm is higher compared to the 500 rpm. Opposing conclusion can be made for the 0.25 mm depth of cut, where the value of R_a is higher at spindle speed 500 rpm compared to the 1000 rpm. This draws towards the possibility of a saddle (minimax) point existing among the different machining conditions tested. This will be clearly verified in the surface plots presented in the next section. More detailed analysis will be conducted through analysis of variance in the following section.

4.1. ANOVA Results for R_a. Using Minitab 17 multiple regression option, the data were fit into a cubic model. However, the results showed a high level of multicollinearity between the cubic terms (third-order terms) and linear terms, even with coded data. To avoid this problem, the cubic terms were removed from the model. The adequacy of the model fit, measured by the coefficient of determination (adjusted R-squared), was reduced from 82% to 79% due to removing the cubic terms.

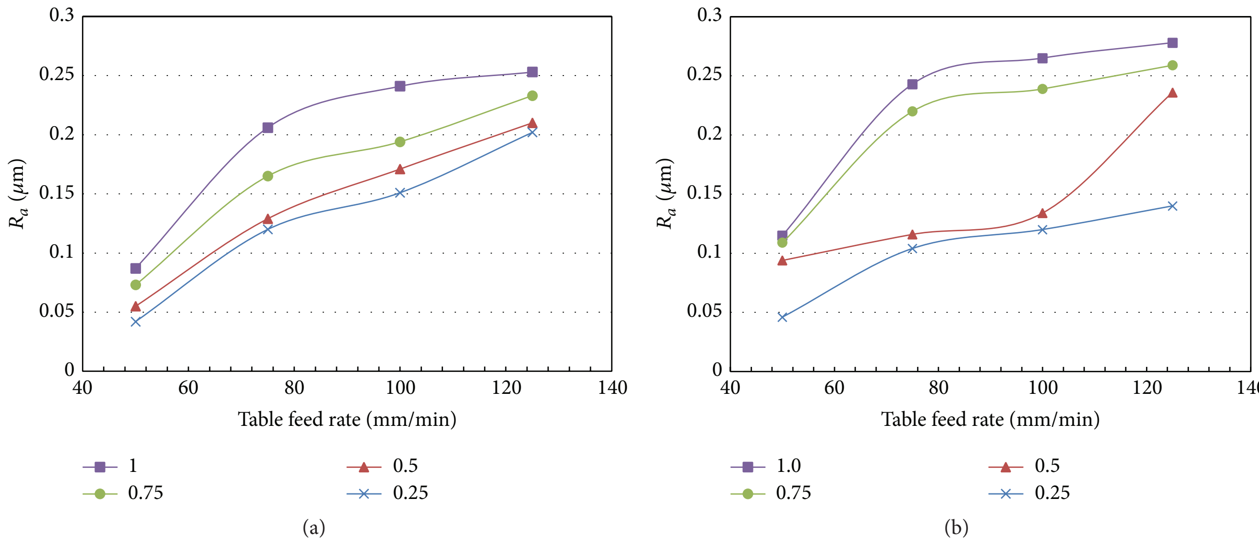

FIGURE 3: The effect of table feed rate on R_a for different depth of cuts (mm) at 500 rpm in (a) and 1000 rpm in (b).

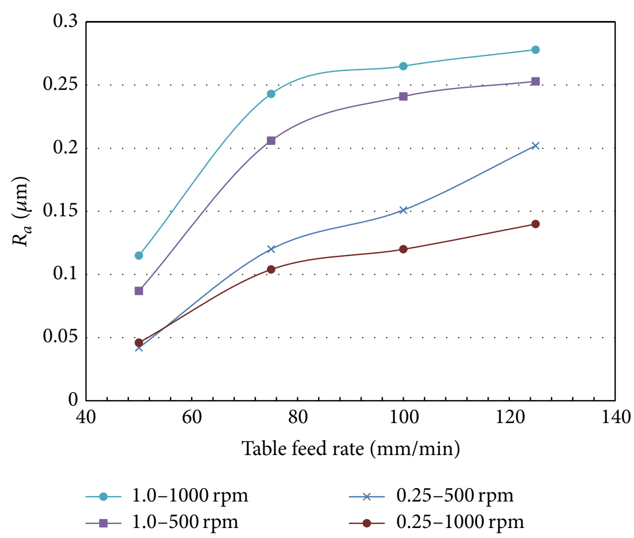

FIGURE 4: Effect of table feed rate on R_a for two values of depth of cut, of 1.0 and 0.25 mm, for two rotational spindle speeds of 500 and 1000 rpm.

ANOVA results of the model are presented in Table 3. P values less than 0.05 indicate a significant term. Insignificant terms were then removed from the model one by one starting with terms that have the greatest P value, unless it is a part of higher level term or interaction (Zhang and Chou [9], Fydrych and Rogalski [10], and Ding et al. [11]). The ANOVA results of the reduced model are given in Table 4. The percentage contribution column is calculated for each term as the percentage of the term's adjusted sum of squares to the total adjusted sum of squares. It provides a rough but effective estimation to the relative importance of each model term (Montgomery [12]).

The results show that spindle speed, depth of cut, and table feed rate have a significant effect on the surface roughness (R_a) in both linear and quadratic terms. There is also an interaction between depth of cut and feed rate. However, looking at the percentage contribution column, it appears that factor C (table feed rate) has the greatest effect on the data variation followed by factor B (depth of cut).

Figure 5 shows the residual plots for the response R_a. Apparently, the residuals show no pattern and are distributed randomly against the fitted values and observation order. The normal probability plot and histogram show the normality of the residuals. The normality was tested using

Table 3: ANOVA for R_a.

Source	DF	Adj. SS	Adj. MS	F-value	P value
Regression	10	0.476642	0.047664	47.92	0
A	1	0.005935	0.005935	5.97	0.016
B	1	0.102187	0.102187	102.74	0
C	1	0.317063	0.317063	318.79	0
$A * A$	1	0.01274	0.01274	12.81	0.001
$B * B$	1	0.017414	0.017414	17.51	0
$C * C$	1	0.011724	0.011724	11.79	0.001
$A * B$	1	0	0	0	0.999
$A * C$	1	0.002544	0.002544	2.56	0.112
$B * C$	1	0.00683	0.00683	6.87	0.01
$A * B * C$	1	0.000205	0.000205	0.21	0.65
Error	117	0.116365	0.000995		
Lack-of-fit	53	0.116245	0.002193	1174.66	0
Pure error	64	0.000119	0.000002		
Total	127	0.593006			

Table 4: ANOVA for R_a after removing insignificant terms.

Source	DF	Adj. SS	Adj. MS	F-value	P value	% contribution
Regression	7	0.473893	0.067699	68.2	0	
A	1	0.005935	0.005935	5.98	0.016	10.0
B	1	0.102187	0.102187	102.95	0	17.2
C	1	0.317063	0.317063	319.42	0	53.5
$A * A$	1	0.01274	0.01274	12.83	0	2.1
$B * B$	1	0.017414	0.017414	17.54	0	2.9
$C * C$	1	0.011724	0.011724	11.81	0.001	2.0
$B * C$	1	0.00683	0.00683	6.88	0.01	1.2
Error	120	0.119114	0.000993			
Lack-of-fit	56	0.118994	0.002125	1138.02	0	
Pure error	64	0.000119	0.000002			
Total	127	0.593006				
Model summary						
R-sq.: 79.91%; R-sq. (adj.): 78.74%; R-sq. (pred.): 77.39%						

Anderson-Darling normality test and the results proved that the residuals are normally distributed with AD value = 0.545 and P value = 0.158 (P value < 0.05 shows nonnormality) as shown in Figure 6.

Model adequacy measures, reflected in the values of the coefficients of determination (R-squared, adjusted R-squared, and predicted R-squared), show reasonable levels of model adequacy. With respect to adjusted R-squared, the model explains about 80% of the variation in the data. The value of 77% of the predicted R-squared is very close to the adjusted R-squared, which proves that the model is not overfit and has a good predictability.

Equation (1) is the regression equation for R_a given by the reduced model. The optimum R_a (minimum R_a) is given by the values $A = 1250$ rpm, $B = 0.447$ mm, and $C = 50$ mm/min. Figure 7 shows the optimization for R_a :

$$R_a = -0.1452 + 0.000255A - 0.2140B + 0.003876C - 0.000000A^2 + 0.1866B^2 - 0.000015C^2 + 0.000935B * C. \quad (1)$$

Figures 8–10 show the surface plots of R_a versus two of the processing parameters while fixing the third parameter at

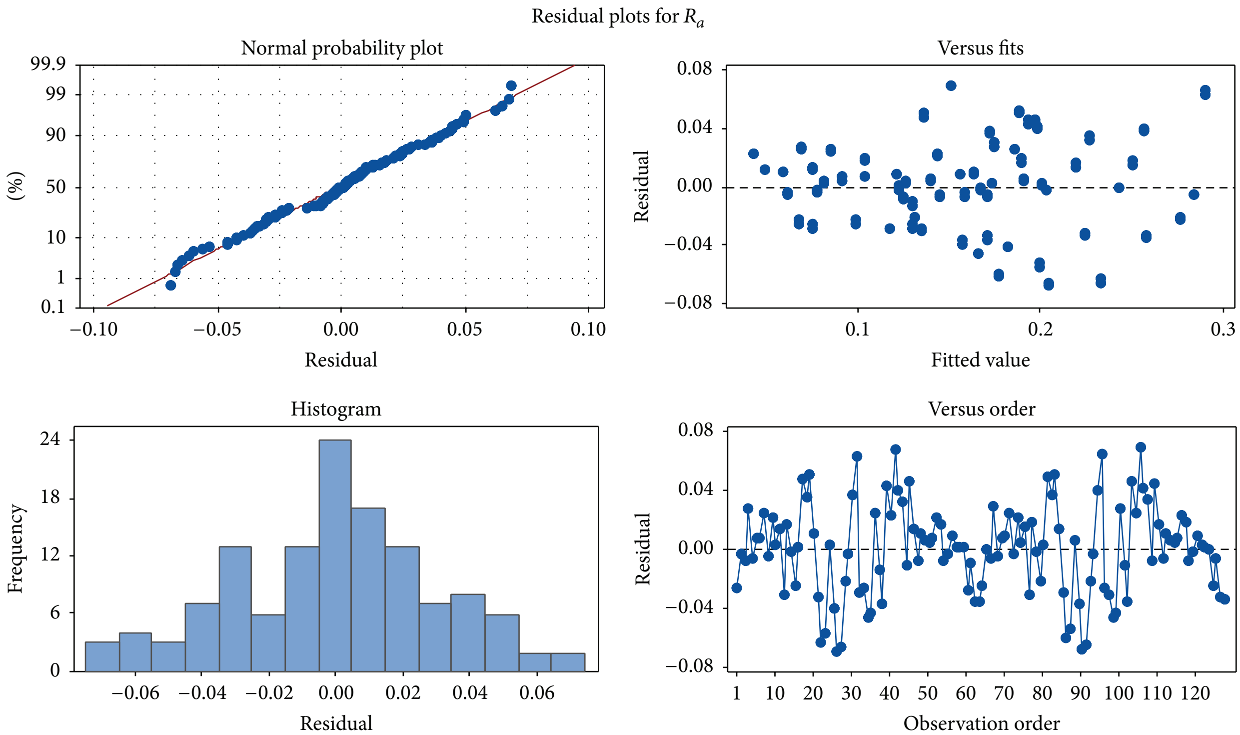

Figure 5: Residual plots for the response R_a.

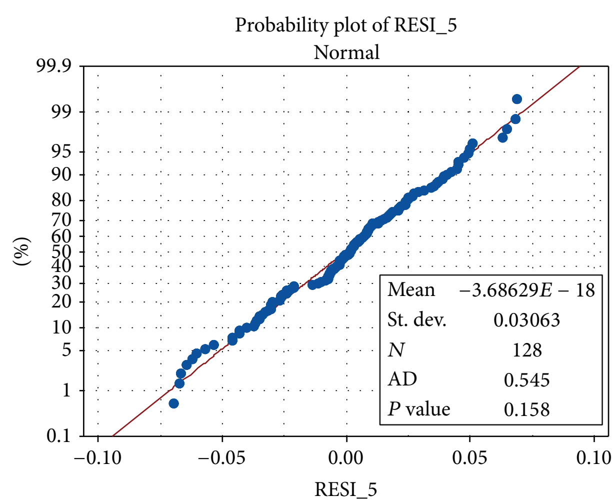

Figure 6: Anderson-Darling normality test results for R_a residuals.

its mean value. The figures show the moderate curvature nature of the relationship between R_a and the studied factors.

4.2. ANOVA Results for R_t. Running the analysis as described in Section 4.1, Table 5 shows the ANOVA final results of the model for R_t. However, the model could not be reduced due to the existence of significant third-level interaction ABC. The results show that the table feed rate is the most effective factor followed by the depth of cut on R_t, while the spindle speed had a significant small effect only in its quadratic term. Also, the interaction between the feed rate and depth of cut does exist as in the case of R_a.

Figure 11 shows the residual plots for the response R_a. Apparently, the residuals show no pattern and are distributed randomly against the fitted values and observation order. The normal probability plot and histogram show the normality of the residuals. The normality was tested using Anderson-Darling normality test and the results proved that the residuals are normally distributed with AD value = 0.425 and P value = 0.311 as shown in Figure 12.

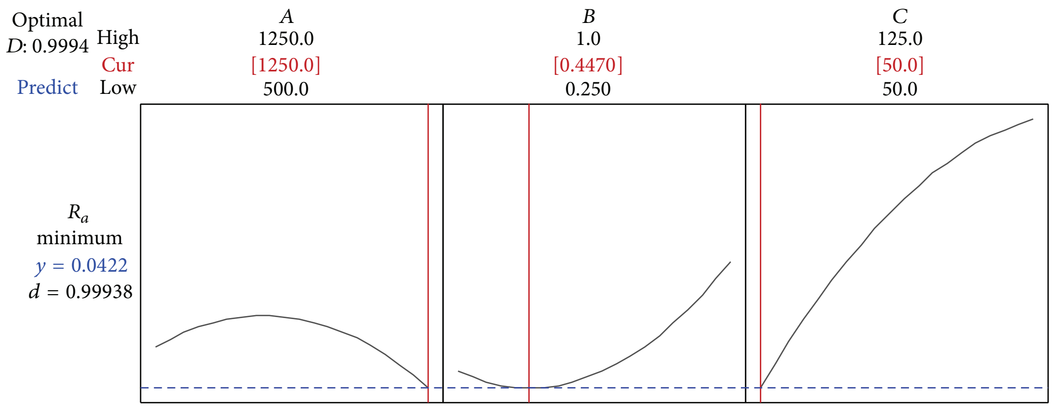

FIGURE 7: Optimization plot for R_a.

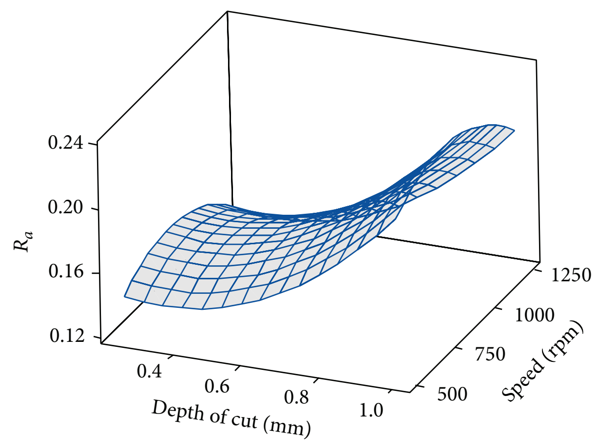

FIGURE 8: Surface plots for R_a versus spindle speed and depth of cut at a mean table feed rate of 87.5 mm/min.

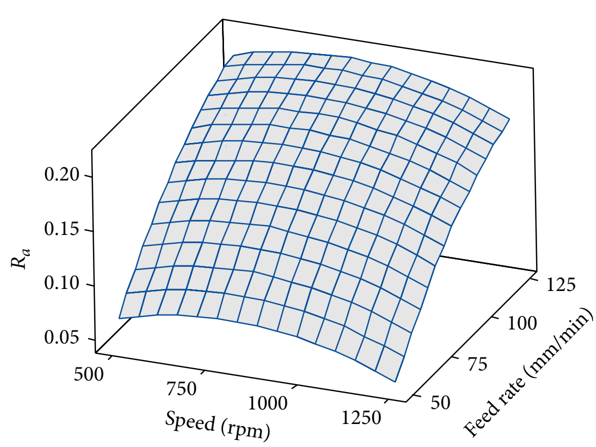

FIGURE 9: Surface plots for R_a versus spindle speed and table feed rate at mean depth of cut of 0.625 mm.

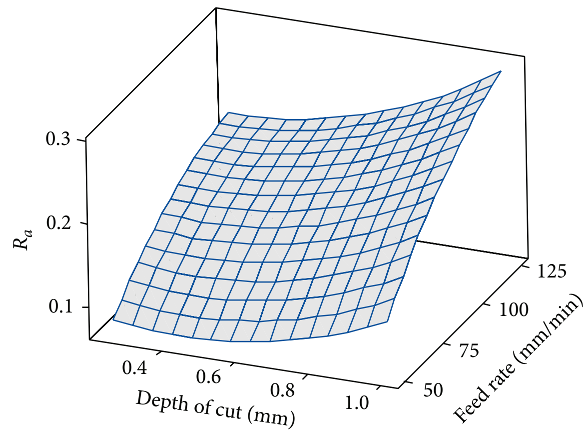

FIGURE 10: Surface plots for R_a versus depth of cut and table feed rate at a mean spindle speed of 875 rpm.

TABLE 5: ANOVA for R_t.

Source	DF	Adj. SS	Adj. MS	F-value	P value	% contribution
Regression	10	23.6589	2.3659	56.45	0	
A	1	0.0003	0.0003	0.01	0.928	0.0
B	1	4.7025	4.7025	112.21	0	16.5
C	1	14.9689	14.9689	357.19	0	52.4
$A * A$	1	0.9405	0.9405	22.44	0	3.3
$B * B$	1	0.8653	0.8653	20.65	0	3.0
$C * C$	1	1.0068	1.0068	24.02	0	3.5
$A * B$	1	0.0193	0.0193	0.46	0.499	0.1
$A * C$	1	0.1679	0.1679	4.01	0.048	0.6
$B * C$	1	0.2752	0.2752	6.57	0.012	1.0
$A * B * C$	1	0.7122	0.7122	16.99	0	
Error	117	4.9032	0.0419			
Lack-of-fit	53	4.9031	0.0925	37711.35	0	
Pure error	64	0.0002	0			
Total	127	28.5622				
Model summary						
S: 0.204714; R-sq.: 82.83%; R-sq. (adj.): 81.37%; R-sq. (pred.): 79.01%						

The coefficients of determination values are comparable to that of R_a and, hence, the same conclusions are valid. Equation (2) represents the relationship between R_t and studied factors:

$$R_t = -2.659 + 0.003758A + 1.000B + 0.04798C - 0.000001A^2 + 1.316B^2 - 0.000142C^2 - 0.002832A * B - 0.000017A * C - 0.02395B * C + 0.000034A * B * C. \quad (2)$$

The values for optimum (minimum) R_t are as follows: A = 500 rpm, B = 0.29 mm, and C = 50 mm/min. It is noticed that only the feed rate value is common between minimum R_a and minimum R_t.

4.3. Multiobjective Optimization for R_a and Metal Removal Rate (Q). Though reducing the feed rate and depth of cut improves the surface roughness, it also reduces the metal removal rate (Q) which is a measure of productivity during the machining process. Maximizing (Q) should be a goal from the economic point of view. In this analysis, multiobjective optimization was conducted to minimize R_a and maximize (Q) simultaneously. Metal removal rate was calculated according to

$$Q = a_p * a_e * V_f, \quad (3)$$

where a_e is working engagement being 35 mm in all test experiments.

A target was set to minimize R_a and to maximize (Q) keeping R_a between 0.15 and 0.2 μm (from industrial

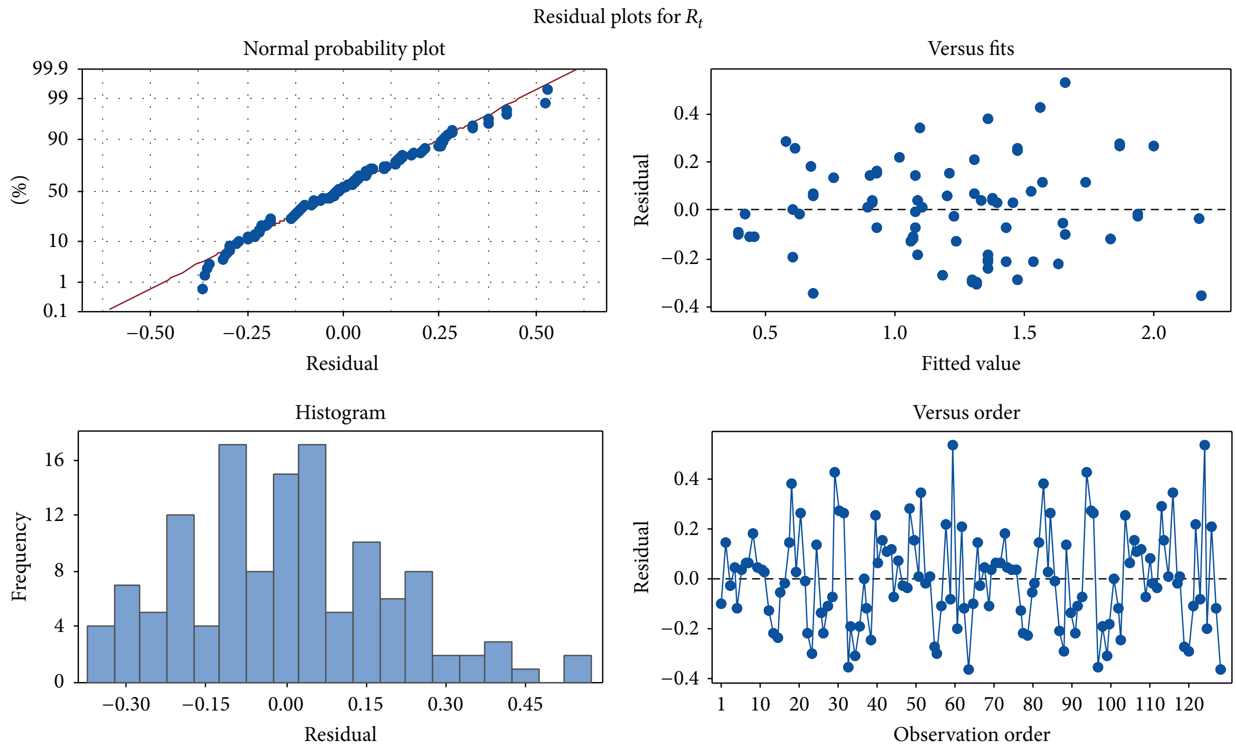

Figure 11: Residual plots for the response R_t.

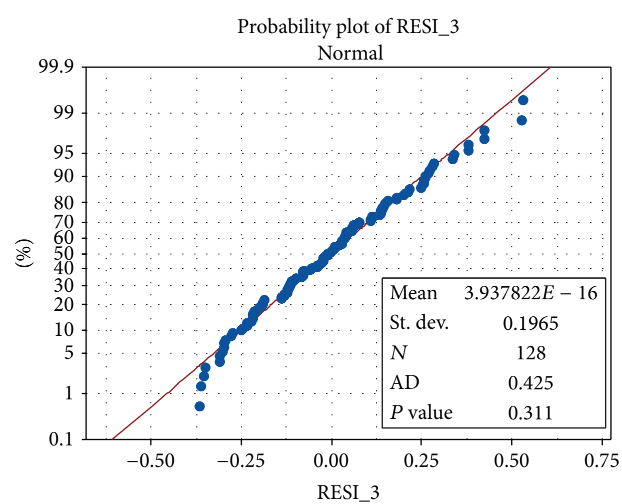

Figure 12: Anderson-Darling normality test results for R_a residuals.

experience for fine milling) with higher priority to optimizing (Q). The optimization resulted in spindle speed = 1250 rpm, depth of cut = 1.0 mm, and table feed rate = 67 mm/min with composite desirability of 0.83. Composite desirability measures the goodness of optimization and ranges between zero and one, where one is the ideal case and zero means that at least one of the terms is out of limits. The expected R_a and (Q) were calculated to be 0.15 μm and 2333 mm^3/min, respectively. Figure 13 shows the multiobjective optimization plot.

High strength steel has relatively high hardness that correlates well with good surface quality. This is due to the harder material possessing low plastic flow capability which results in better surface finish. This is attributed to the brittle nature of the interaction between the cutting tool and the workpiece surface, for the hard materials, that leads to material separation rather than plastic flow that would result in surface irregularities. Surface roughness was found to increase with increasing feed rate and depth of cut which both result in bigger cut areas that are consequently

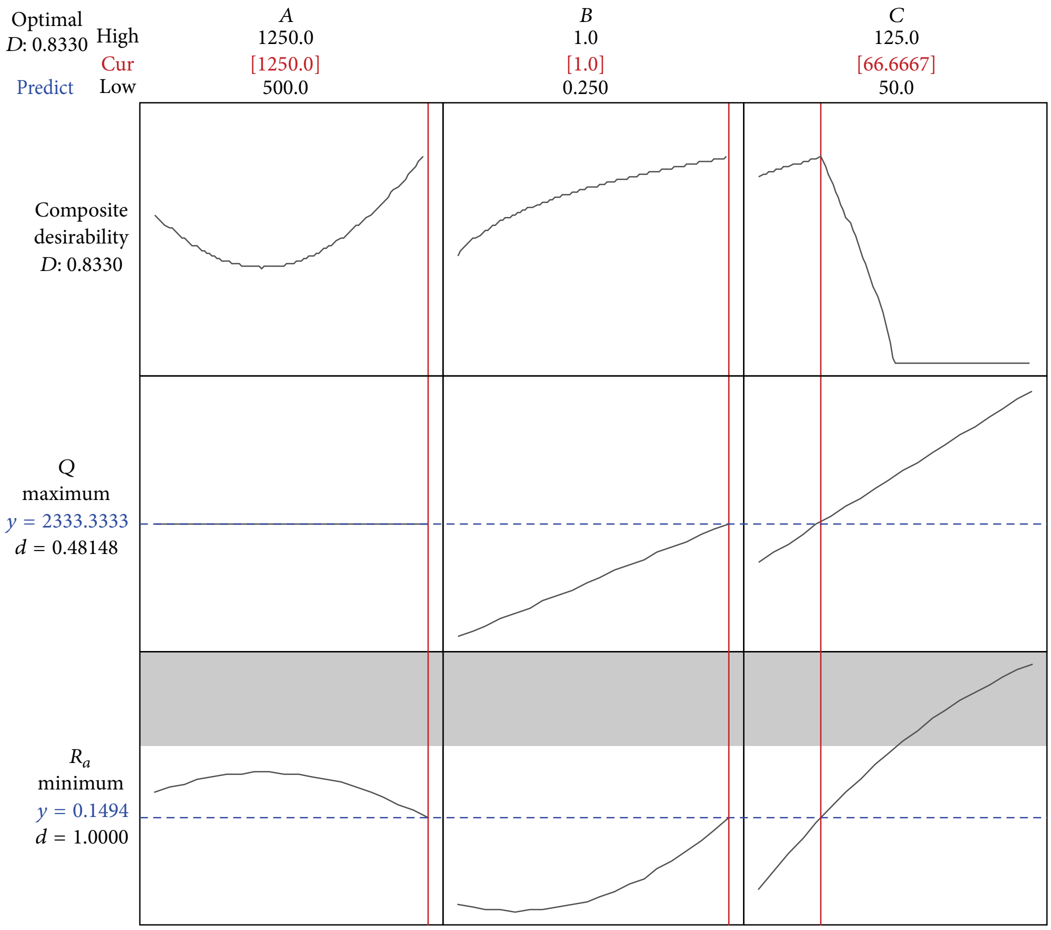

Figure 13: Multiobjective optimization plot for R_a and metal removal rate (Q).

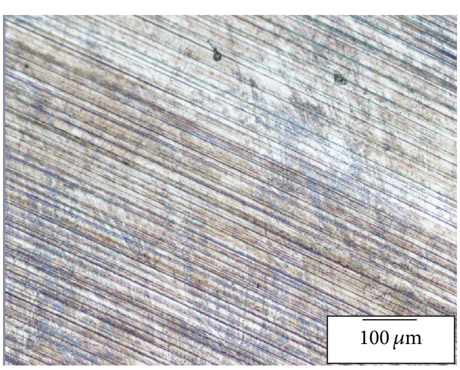

Figure 14: Optical microscopy of the machined surface under spindle speed = 1250 rpm, depth of cut = 0.5 mm, and table feed rate = 50 mm/min.

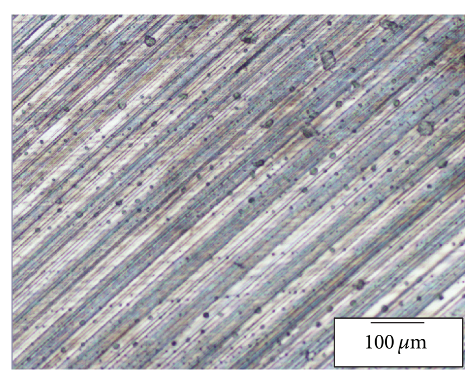

Figure 15: Optical microscopy of the machined surface under spindle speed = 1250 rpm, depth of cut = 0.5 mm, and table feed rate = 125 mm/min.

associated with higher cutting forces and higher friction which lead to poor surface finish. It was noticed from the surface roughness profile that high feed rates were associated with larger roughness markings horizontal spacing. Also, with higher depth of cuts, the vertical spacing between peaks and troughs of the surface irregularities was larger. Thus, higher feed rates and depth of cuts led to higher surface roughness.

Figure 14 represents an optical microscopy of the machined surface under spindle speed of 1250 rpm, depth of cut of 0.5 mm, and table feed rate of 50 mm/min, while Figure 15 represents an optical microscopy for the following

Table 6: Cutting conditions for group A.

Test number	Group #	Spindle speed (rpm)	Depth of cut (mm)	Table feed (mm/min)	Surface finish (μm) R_a	R_t
A1	A1	500	0.25	50	0.042	0.295
A2				75	0.120	1.039
A3				100	0.151	1.198
A4				125	0.202	1.419
A5	A2	500	0.5	50	0.055	0.336
A6				75	0.129	0.945
A7				100	0.171	1.256
A8				125	0.210	1.366
A9	A3	500	0.75	50	0.073	0.855
A10				75	0.165	1.132
A11				100	0.194	1.369
A12				125	0.233	1.426
A13	A4	500	1.00	50	0.087	0.928
A14				75	0.206	1.216
A15				100	0.241	1.400
A16				125	0.253	1.596
A17	A5	750	0.25	50	0.083	0.607
A18				75	0.184	1.220
A19				100	0.208	1.736
A20				125	0.239	1.478
A21	A6	750	0.5	50	0.085	0.871
A22				75	0.104	1.069
A23				100	0.115	1.149
A24				125	0.143	1.177
A25	A7	750	0.75	50	0.094	0.901
A26				75	0.118	1.103
A27				100	0.136	1.316
A28				125	0.167	1.547
A29	A8	750	1.00	50	0.109	1.002
A30				75	0.201	1.991
A31				100	0.294	2.140
A32				125	0.354	2.263
A33	A9	1000	0.25	50	0.046	0.334
A34				75	0.104	0.899
A35				100	0.120	1.005
A36				125	0.140	1.174
A37	A10	1000	0.5	50	0.094	0.601
A38				75	0.116	0.950
A39				100	0.134	1.109
A40				125	0.236	1.719
A41	A11	1000	0.75	50	0.109	0.743
A42				75	0.220	1.364
A43				100	0.239	1.675
A44				125	0.259	1.855
A45	A12	1000	1.00	50	0.115	0.853
A46				75	0.243	1.598
A47				100	0.265	1.914
A48				125	0.278	2.140

Table 6: Continued.

Test number	Group #	Spindle speed (rpm)	Depth of cut (mm)	Table feed (mm/min)	Surface finish (μm) R_a	R_t
A49	A13	1250	0.25	50	0.060	0.859
A50				75	0.110	1.082
A51				100	0.144	1.112
A52				125	0.165	1.435
A53	A14	1250	0.5	50	0.064	0.404
A54				75	0.121	0.896
A55				100	0.137	0.907
A56				125	0.165	0.996
A57	A15	1250	0.75	50	0.068	0.321
A58				75	0.128	1.233
A59				100	0.174	1.348
A60				125	0.203	2.186
A61	A16	1250	1.00	50	0.072	0.409
A62				75	0.163	1.514
A63				100	0.190	1.713
A64				125	0.223	1.820

cutting conditions: spindle speed of 1250 rpm, depth of cut of 0.5 mm, and table feed rate of 125 mm/min. The effect of feed rate is obvious, in a sense that low feed rate produced relatively thin surface roughness markings that are closely spaced, whereas high feed rate produced relatively thick roughness markings that are distantly spaced.

5. Conclusion

ANOVA and regression analysis, through a DOE full factorial design (4^3), were conducted to relate the surface roughness of face milled high strength steel to the most common machining parameters, namely, table feed rate, depth of cut, and spindle speed. Two surface roughness indicators, namely, R_a and R_t, were experimentally measured through a set of 64 experiments and their replicates. The recorded roughness values are the average of four readings on each surface. For R_a, the results show that speed, depth of cut, and table feed rate have a significant effect on the surface roughness in both linear and quadratic terms. There is also an interaction between depth of cut and feed rate. It also appears that feed rate has the greatest effect on the data variation followed by depth of cut. The minimum R_a was achieved at the following machining conditions: spindle speed = 1250 rpm, depth of cut = 0.447 mm, and table feed rate = 50 mm/min. For R_t, the results show that the feed rate is the most effective factor followed by the depth of cut, while the speed had a significant small effect only in its quadratic term. Also, the interaction between the feed rate and depth of cut does exist as in the case of R_a. The minimum R_t was achieved at the following conditions: spindle speed = 500 rpm, depth of cut = 0.29 mm, and table feed rate = 50 mm/min. It is noticed that only the feed rate value is common between minimum R_a and minimum R_t. Moreover, multiobjective optimization was conducted with the target of minimizing R_a and maximizing metal removal rate (Q). The optimization resulted in spindle speed of 1250 rpm, depth of cut of 1.0 mm, and table feed rate of 67 mm/min with a composite desirability of 0.83, to give R_a and (Q) values of 0.15 and 2333 mm^3/min, respectively.

Appendix

See Tables 6 and 7.

Nomenclature

a_p: Depth of cut, mm
a_e: Working engagement, mm
N: Spindle speed, rpm
V_c: Cutting speed, m/min
V_f: Table feed rate, mm/min
Z_n: Total number of teeth in cutter
Q: Metal removal rate, mm^3/min.

Competing Interests

The authors declare that they have no competing interests.

Acknowledgments

This project was supported by King Saud University, Deanship of Scientific Research, College of Engineering Research Center.

Table 7: Cutting conditions for group B.

Test number	Group #	Spindle speed (rpm)	Depth of cut (mm)	Table feed (mm/min)	Surface finish (μm) R_a	R_t
B1	B1	500	0.25	50	0.044	0.298
B2				75	0.122	1.042
B3				100	0.153	1.200
B4				125	0.204	1.417
B5	B2	500	0.5	50	0.056	0.338
B6				75	0.130	0.948
B7				100	0.173	1.257
B8				125	0.211	1.368
B9	B3	500	0.75	50	0.075	0.854
B10				75	0.166	1.133
B11				100	0.196	1.371
B12				125	0.235	1.428
B13	B4	500	1.00	50	0.087	0.928
B14				75	0.208	1.216
B15				100	0.242	1.401
B16				125	0.256	1.598
B17	B5	750	0.25	50	0.085	0.605
B18				75	0.186	1.223
B19				100	0.209	1.738
B20				125	0.240	1.479
B21	B6	750	0.5	50	0.088	0.872
B22				75	0.106	1.067
B23				100	0.117	1.150
B24				125	0.146	1.179
B25	B7	750	0.75	50	0.098	0.900
B26				75	0.121	1.102
B27				100	0.138	1.318
B28				125	0.169	1.549
B29	B8	750	1.00	50	0.110	1.002
B30				75	0.200	1.990
B31				100	0.296	2.143
B32				125	0.356	2.261
B33	B9	1000	0.25	50	0.049	0.338
B34				75	0.100	0.896
B35				100	0.120	1.007
B36				125	0.140	1.176
B37	B10	1000	0.5	50	0.096	0.605
B38				75	0.118	0.952
B39				100	0.136	1.112
B40				125	0.239	1.722
B41	B11	1000	0.75	50	0.110	0.746
B42				75	0.221	1.362
B43				100	0.240	1.677
B44				125	0.262	1.857
B45	B12	1000	1.00	50	0.118	0.856
B46				75	0.242	1.600
B47				100	0.268	1.917
B48				125	0.279	2.142

Table 7: Continued.

Test number	Group #	Spindle speed (rpm)	Depth of cut (mm)	Table feed (mm/min)	Surface finish (μm) R_a	R_t
B49	B13	1250	0.25	50	0.060	0.861
B50				75	0.110	1.084
B51				100	0.145	1.113
B52				125	0.165	1.437
B53	B14	1250	0.5	50	0.065	0.406
B54				75	0.122	0.899
B55				100	0.138	0.908
B56				125	0.166	1.000
B57	B15	1250	0.75	50	0.068	0.323
B58				75	0.129	1.235
B59				100	0.175	1.346
B60				125	0.201	2.189
B61	B16	1250	1.00	50	0.075	0.412
B62				75	0.165	1.516
B63				100	0.192	1.715
B64				125	0.225	1.822

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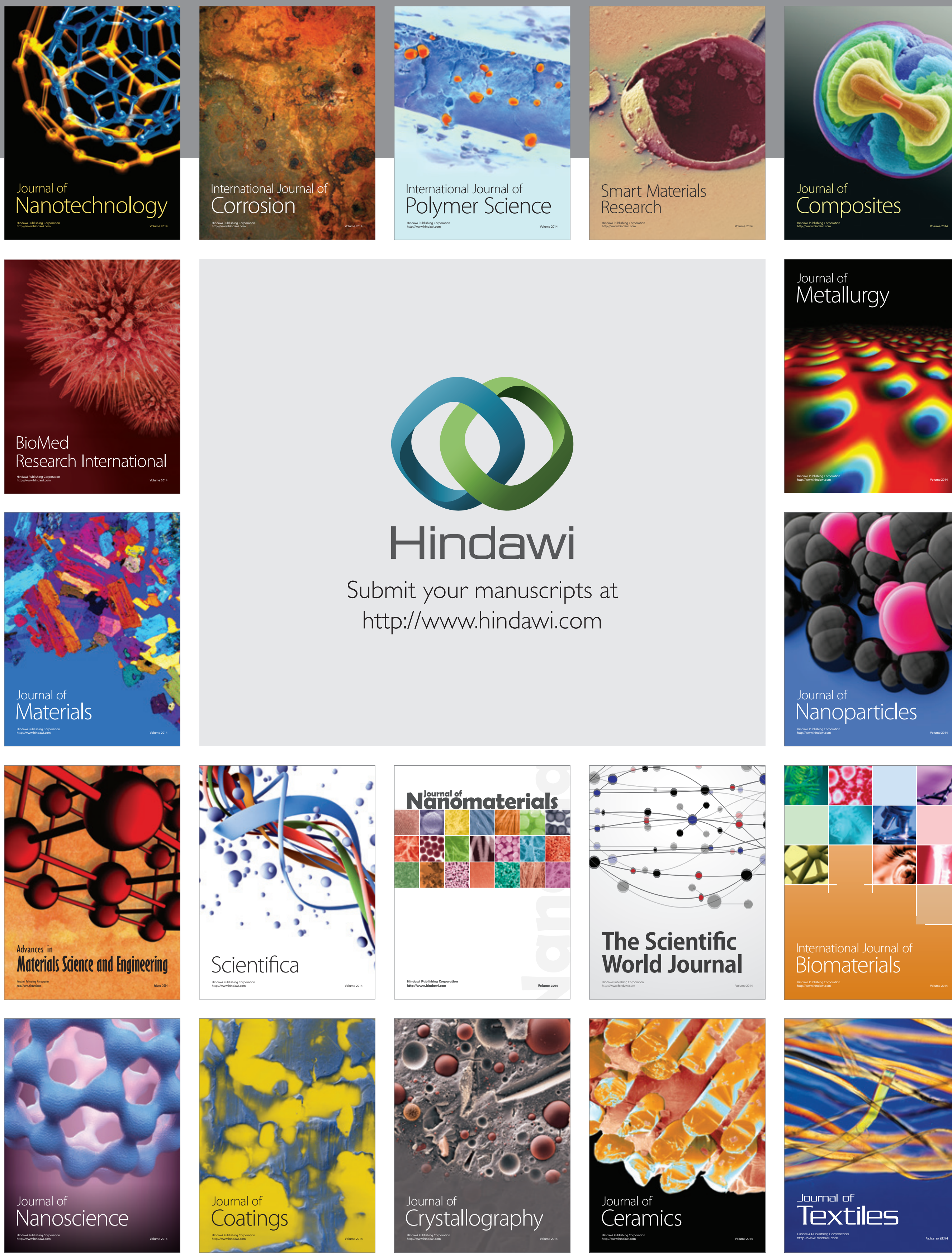
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