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EXPERIMENTAL INVESTIGATION AND STATISTICAL ANALYSIS OF SURFACE ROUGHNESS PARAMETERS IN MILLING OF PA66-GF30 GLASS-FIBRE REINFORCED POLYAMIDE

N.M. VAXEVANIDIS[1], N.A. FOUNTAS[1], I. NTZIANTZIAS[2], A. KOUTSOMICHALIS[3], A. VENCL[4]

[1]School of Pedagogical and Technological Education, Department of Mechanical Engineering Educators, GR 14121 N. Heraklion Attikis, Greece. e-mail: vaxev@aspete.gr

[2]Maintenance Department, General Hospital of Amfissa, GR 33100 Amfissa, Fokida, Greece

[3]Hellenic Air-Force Academy, Faculty of Aerospace Studies, Dekelia Air Force Base, GR 19005, Greece, e-mail: a.koutsomichalis@gmail.com

[4]University of Belgrade, Faculty of Mechanical Engineering, Tribology Laboratory, Kraljice Marije 16, 11120 Beograd 35, Serbia, e-mail: avencl@mas.bg.ac.rs

In Memoriam **Prof. G.P. Petropoulos (1959-2010)**

Abstract: *A multi-parameter analysis of surface finish imparted to PA66-GF30 glass-fibre reinforced polyamide by milling is presented. The interrelationship between surface texture parameters is emphasized. Surface finish parameters studied include arithmetic mean deviation of the assessed profile* R_a*; maximum height of profile,* R_t*; ten point height* R_z*; mean width of the profile elements* R_{sm}*; skewness of the assessed profile,* R_{sk} *and kurtosis of the assessed profile,* R_{ku}*. The correlation of these parameters with the machining conditions was investigated. By applying analysis of variance and regression analysis to the experimental data close correlation was obtained among certain surface finish parameters and the machining conditions. To facilitate industrial operations full quadratic prediction models were developed for capturing trends for machining quality in advance.*

Key Words: *statistical analysis, surface finish, roughness parameters, milling, glass-fibre reinforced polyamide*

1. INTRODUCTION

Milling is one of the most often-used metal cutting processes in manufacturing industry and control of relevant process parameters always attract research interest for studying machinability characteristics of engineering materials. Prismatic; as well as other types of parts manufactured by milling operations involve a range of critical features that should be of high surface finish to meet requirements for functional behaviour. Thereby, any proposed description of a technological surface should take into account the features of the surface texture imparted by the machining process performed. This is a crucial point since the process can be controlled through surface texture recognition, and may be also used for generating suitable profiles for tribological functioning [1]. Surface texture characterization refers to all manufacturing processes and is an essential machinability attribute associated to reliability; functionality and part quality [2, 3]. Since machinability is based upon the context of selecting proper machining parameters, their scientific investigation in terms of the effects on quality objectives is a critical issue. Quality surface patterns can be typically achieved during milling, yet; significant variations owing to tool wear; chattering; chip discontinuity as well as low stability may influence the overall outcome. From the tribological perspective such phenomena yield a negative impact on friction and affect significantly the lubrication conditions of contact surfaces. Having such tribological aspects directly related to the profile shape and surface roughness, an extensive statistical analysis involving surface roughness indicators needs to be conducted [4, 5]. Surface roughness evaluation is very important for many fundamental phenomena such as friction and wear, contact deformation, heat and electric current conduction and positional accuracy [2, 6]. The real surface geometry is so complicated that a finite number of parameters cannot provide a full description. If the number of parameters used is increased, a more accurate description can be obtained. This is the main reason for introducing new parameters for surface evaluation [7]. Since the estimation of the roughness based on one parameter is ambiguous, the multi-parameter estimation of roughness is recommended [1, 2, 4, 7]. Surface roughness parameters are normally categorized into three groups according to its functionality. These groups are defined as amplitude parameters, spacing parameters, and hybrid parameters [8].

The work presented here emphasizes the statistical analysis of the aforementioned roughness indicators as key quality objectives in milling of PA66-GF30 reinforced polyamide. Crucial machining parameters such as cutting speed and cutting feed were treated as independent variables to examine their outcome on roughness indicators. Based on the analysis of variance and corresponding outputs, regression models were developed in order to examine the correlation of machining parameters with surface finish characteristics. The present work can be considered as a solid basis to understand how such crucial objectives are affected by process parameters, whilst providing a future perspective to look further ahead for optimization techniques implemented to machining processes.

2. EXPERIMENTAL

2.1. Design of milling experiments

For the present study which is part of a study on the machinability of PA66-GF30 composite material; see [9, 10], and for developing reliable stochastic models to predict various parameters of surface roughness during machining, a two parameter experiment was designed; two input cutting parameters were selected; namely cutting speed (*U*) and feed-rate (*S*). According to this design, cutting speed and feed rate were treated as the independent variables having three levels; whilst depth of cut was kept constant at α=1 mm. Table 1 summarizes the independent variables and their levels for the experimental design.

Table 1. Investigated machining conditions and levels

Parameter	*Units*	*Level 1*	*Level 2*	*Level 3*
Cutting speed, *U*	(m/min)	50	200	500
Feed rate, *S*	(mm/rev)	0.20	0.32	0.40

Common material removal operations deal with modern products that ought to meet several requirements depending upon their type and design scope. Contact deformation; tightness of contact joints; friction and heat/electric current conduction are some of the essential problems suggesting the assessment of several roughness parameters. To capture a broader spectrum of surface analysis; roughness indicators found in several categories should be selected for evaluation. To avoid the inherent ambiguity in terms of the surface characterization when studying a single roughness indicator; more than one roughness parameters need to be examined [2, 5, 8]. Hence, the surface roughness parameters under study were:

- the arithmetic mean surface roughness, R_a;
- the maximum height of the profile, R_t;;
- the ten point height surface roughness, R_z;
- the mean width of the profile elements, R_{sm};
- the skewness of the assessed profile, R_{sk};
- the kurtosis of the assessed profile, R_{ku}.

Average surface roughness (R_a) gives very good overall description of height variations but does not give any information on waviness and it is not sensitive on small changes in profile. R_{sk} is sensitive on occasional deep valleys or high peaks. Zero skewness reflects in symmetrical height distribution, while positive and negative skewness describe surfaces with high peaks or filled valleys, and with deep scratches or loss of peaks, respectively. On the other hand, kurtosis (R_{ku}) describes the probability density sharpness of the profile. For surfaces with lower peaks and low valleys, R_{ku} is less than 3, and more than 3 for surfaces with higher peaks and low valleys [5, 8]. The load bearing ratio as well as maximum contact pressure in tribological applications increase with the increase of skewness and kurtosis [6].

2.2. *Experimental procedure and test material*

Specimens were made from PA66-GF30 polyamide; reinforced with 30% non-continuous; random-directional glass fibre. The material was supplied in the form of solid rods; Ø150 x 1000 mm. For the milling experiments specimens Ø150 x 40mm were prepared. Fig. 1a depicts the material as it was supplied. An OKUMA®MX45-VAE 3-axis CNC Machine Tool was used for the machining experiments. Work pieces were fixtured on the Machine Tool table using a three-jaw vise properly secured using a special base. The CNC Machine Tool is depicted in Fig. 1b. All milling experiments were conducted with on-pass cuts at the center of specimens; so as to observe results derived from both climb and conventional milling modes (Fig. 1c). An Ø50 mm Mitsubishi® LSE445-A050 face milling cutter was used for machining. The face mill had 4 square-type carbide inserts with 20 degrees positive angle (Fig. 1d).

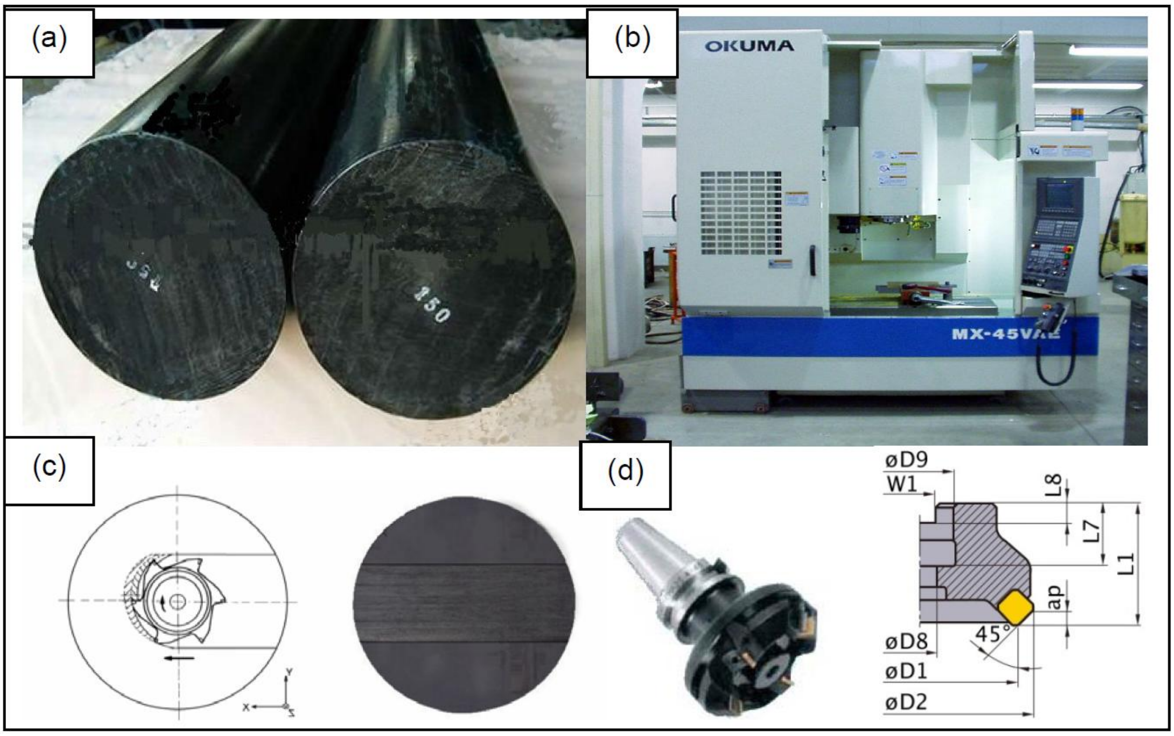

Fig. 1. Test material and machining equipment: (a) PA66-GF30 polyamide rods; (b) OKUMA® 3-axis CNC vertical machining center; (c) one-pass experimental cut on workpiece; (d) Mitsubishi® carbide-inserted face mill

The surface roughness measurements were performed using a Rank Taylor-Hobson® Surtronic 3 profilometer equipped with the Talyprof® software. A Gaussian-type cut-off filter was adopted whilst cut-off length was 0.8 mm as it is indicated for milling operations. Sample length was set to 4mm. For each cut three measurements were performed in order to ensure validity of experimental results in terms of all roughness parameters under study. Then, average values were calculated and transferred to StatEase MINITAB 17® for statistical processing.

Prior to the statistical processing of results, measured values obtained for all roughness parameters were, first, examined and discussed below. Note also that the order of milling experiments was kept as it was suggested by the software, without randomization, since preliminary work indicated no significant variations owing to observation order. Average measured values for all surface roughness parameters under study are tabulated in Table 2 along with the corresponding machining parameter values.

Table 2. Measured values for surface roughness parameters

No. Exp.	*U* (m/min)	*S* (mm/rev)	R_a (μm)	R_t (μm)	R_z (μm)	R_{sm} (mm)	R_{sk}	R_{ku}
1	50	0.20	0.89	7.33	6.02	0.081	-0.09	3.23
2	200	0.20	0.81	7.20	5.67	0.085	-0.20	3.63
3	500	0.20	0.76	6.79	5.34	0.070	0.30	4.49
4	50	0.32	0.99	8.25	6.21	0.085	-0.61	3.74
5	200	0.32	0.90	7.59	6.06	0.091	-0.56	3.19
6	500	0.32	0.82	7.01	5.47	0.076	-0.11	3.23
7	50	0.40	1.09	9.60	7.37	0.108	-0.04	3.47
8	200	0.40	0.96	8.50	7.28	0.118	-0.38	3.69
9	500	0.40	0.88	7.51	6.81	0.090	0.16	4.57

Worth mentioning that for studies concerning the influence of machining parameters on the machinability (surface roughness, cutting forces and tool wear) of glass fibre reinforced composites besides statistical methods, soft computing techniques have been already applied see e.g. Refs [9-14].

3. RESULTS AND DISCUSSION

3.1. Experimental observations

Experimental results for all roughness parameters investigated are presented in Fig. 2. As far as amplitude parameters (R_a, R_z, R_t) is concerned; expected variation trends are observed. Note that the envelopes may change if experimental runs are presented under a randomized order; however, basic observations are still valid and meaningful. It can be seen that R_a takes its highest values for experiments using low cutting speed (experimental runs 1; 4 and 7). Thus, the assumption that mean surface roughness increases under low cutting speeds can be supported in advance. The same trend is also evident for the rest of amplitude parameters; i.e., R_z and R_t. On the contrary amplitude is facilitated when determining high applicable values for cutting speed given the constraints. These two observations regarding high and low amplitude are more profound in the case of maximum profile height, R_t as it is expected.

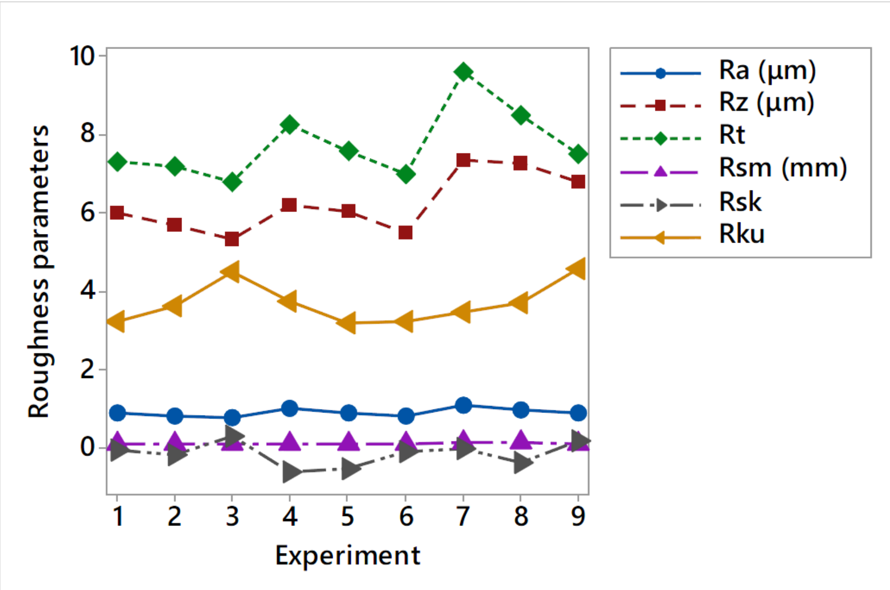

Fig. 2. Experimental variation for amplitude, spacing and statistical roughness parameters

An important evidence drawn from experimental results is that surface roughness average R_a does not seem to yield significant variation at least to some extent. Note that R_a ranges from 0.76μm to 1.09 μm according to Table 2. Spacing parameters presented in the form of the width of the roughness profile elements, R_{sm} varies from 0.070 to 0.118 and practically may be considered of insignificant variation when referring to the levels of cutting conditions. Shape (statistical) parameters represented by skewness and kurtosis yield significant variations in the case of high cutting speed and; either the lowest or the highest value for feed rate given an applicable parameter selection range. This phenomenon is profound in experimental runs 3 and 9 for kurtosis, with U = 500 (m/min) / S = 0.20 (mm/rev) and U = 500 (m/min) / S = 0.40 (mm/rev), respectively. A more extensive study considering the experimental results is presented in the diagrams depicted in Fig. 3.

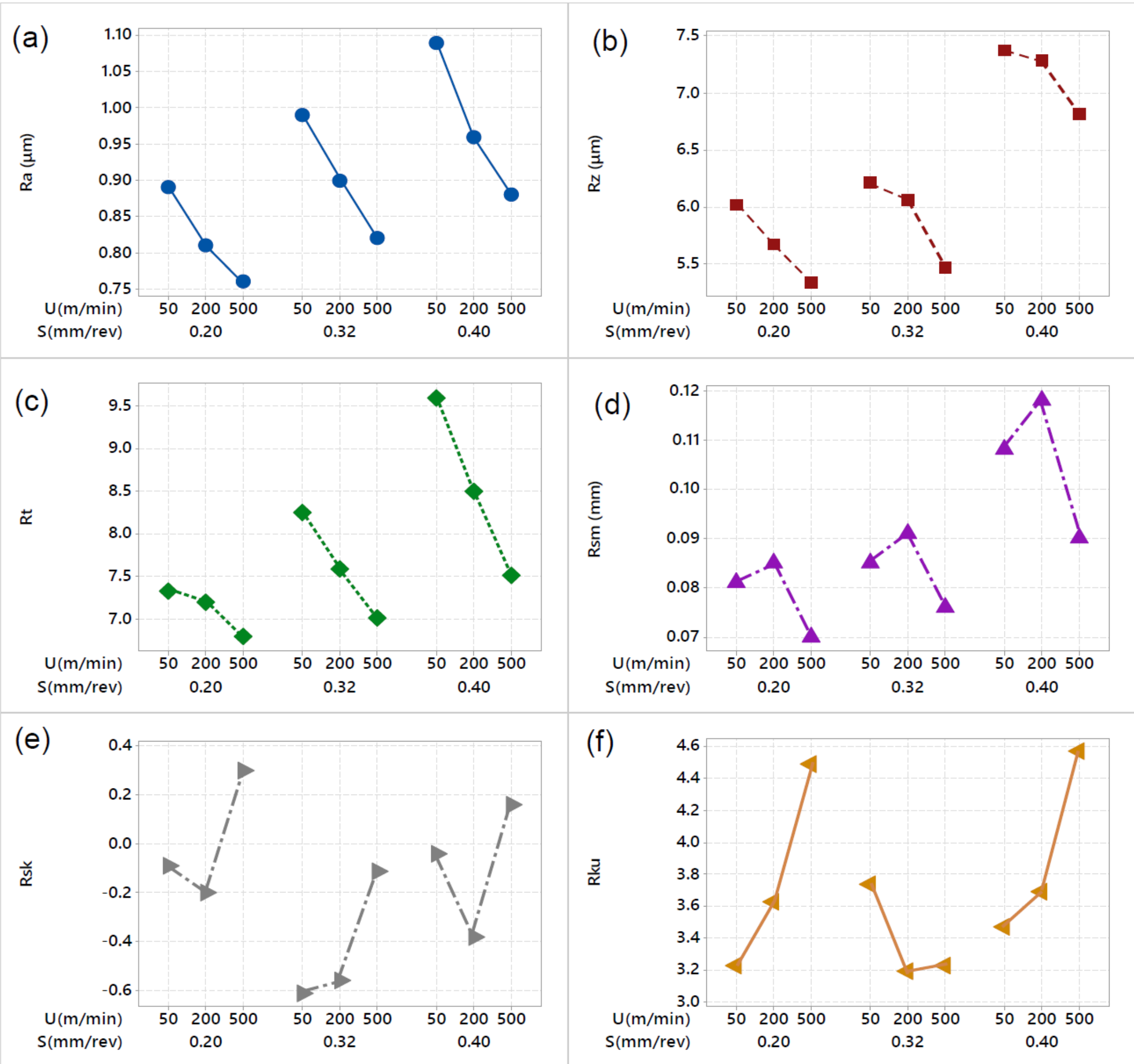

Fig. 3. Variation of surface roughness parameters in relation to cutting conditions: (a) R_a; (b) R_z; (c) R_t; (d) R_{sm}; (e) R_{sk} and (f) R_{ku}

According to the diagrams presented in Fig. 3, high levels for feed rate, affect negatively (increase) all roughness indicators except skewness parameter which has its highest value in the case of S = 0.20 (mm/rev) for all three cutting speed levels. Experimental variation trends suggest outputs at it were expected and are in agreement with the relevant literature. Indeed, amplitude parameters tend to increase their levels when low cutting speed and low feed rate are set. For R_a, a linear pattern is observed concerning its resulting values when varying cutting speed whilst keeping the feed rate constant. This linear attitude is more profound when setting a middle-leveled value for feed rate and varying cutting speed form lower to upper values. Ten-point height roughness R_z, starts to be affected when dealing with feed rate values other than the one set for being the lowest range; whilst in the case of the highest feed rate level, an exponential increase is indicated. This is strong evidence that interactions among the levels of the two cutting conditions are found and should to be taken into consideration. The opposite phenomenon occurs when studying maximum height of the profile R_t, yet; in terms of the linearity of obtained results. Indications for R_t have their lowest values when setting the lowest value for feed rate whereas roughness is greatly reduced when employing the highest value for cutting speed. The pattern is non-linear for that range of conditions and when dealing with higher feed rate values experimental trend-lines suggest a non-linear behaviour which is also non-beneficial since values are increased when setting higher feed rate levels under different cutting speeds. Width of the roughness profile elements represented by R_{sm}, follows the same pattern for all machining parameter combinations suggesting that its highest value is experienced when setting middle-leveled cutting speeds for a given feed rate value. The indicator's values are greatly reduced when setting high levels for cutting speed whereas no interactions are expected despite its unusual trend. Shape representation via skewness and kurtosis share a common feature; that of attaining their lowest value when setting relatively low to middle-leveled cutting speeds whilst maintaining a middle-leveled feed rate. For skewness the lowest value is measured for U=50 (m/min) and S=0.32 (mm/rev) whereas kurtosis obtains its lowest experimental result for U=200(m/min) and S=0.32 (mm/rev). However, great difference is indicated in terms of their trends. The former indicator (skewness) exhibits a non-linear behaviour when altering the levels of machining parameters whilst the latter (kurtosis) maintains a slightly linear change when it comes to lower and upper feed rate levels for all cutting speeds. What is observed in the case of S=0.32 (mm/rev) is that the measured value is the worst for U=50 (m/min); the best for U=200 (m/min) and close to the best for U=500 (m/min).

3.2. Statistical analysis

Statistical analysis was conducted to further investigate the variation of cutting conditions on roughness parameters. Main effects and interactions were examined to estimate the influence of each of cutting conditions as well as their combined effect, respectively. Fig. 4 illustrates the effects of cutting conditions on roughness parameters. According to Fig. 4 cutting speed slightly dominates against feed rate for average surface roughness (Fig. 4a); feed rate dominates against cutting speed in the case of the ten-point height roughness R_z (Fig. 4b); both cutting conditions yield important effects in case of the maximum height of the profile R_t (Fig. 4c); as well as for the mean width of the profile R_{sm} (Fig. 4d). Skewness and kurtosis are affected by both machining parameters with the upper feed rate level and lower cutting speed level to closer approach the means for skewness. Kurtosis mean is best approached by lower feed rate level along with the middle-leveled cutting speed; see Fig. 4e and Fig. 4f, respectively.

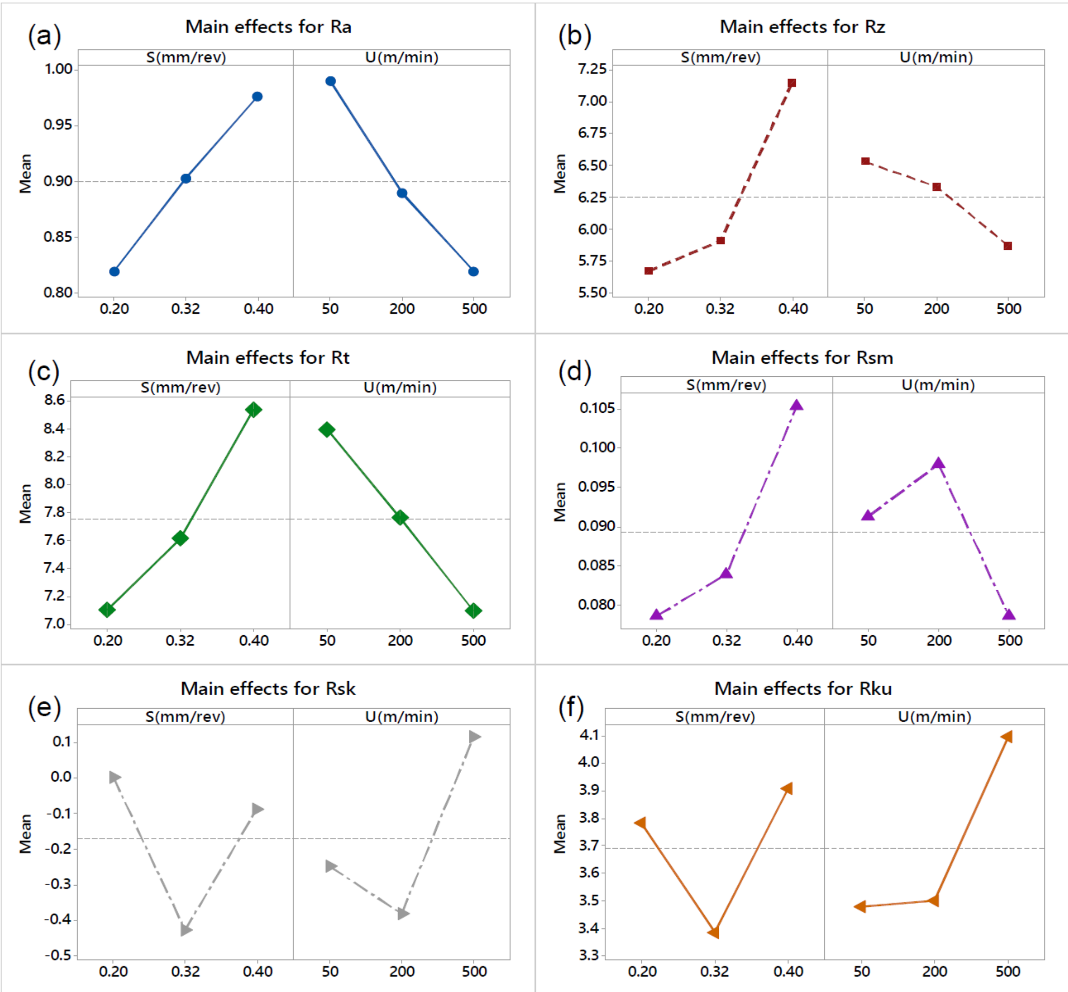

Fig. 4. Main effects plots for: (a) R_a; (b) R_z; (c) R_t; (d) R_{sm}; (e) R_{sk} and (f) R_{ku}

Similar analysis was followed to interpret the effect of interactions exerted among machining parameter levels. Note that an early estimation can be made given the trend that experimental results follow. Surface roughness average Ra has no significant interactions in terms of the machining parameter levels. The same also was indicated by looking at the experimental results in Fig. 3. This result is maintained the same for the rest of roughness indicators representing amplitude (R_z and R_t). However trends illustrated in Fig. 5a; 5b and 5c, suggest that interactions may occur if altering cutting conditions using levels beyond the experimental investigation domain. Even though spacing indicator (R_{sm}) exhibits a non-proportional relation among cutting conditions' levels and its experimental results; no significant interactions are observed at least for the studied range. Yet; strong evidence is existed; suggesting the interaction among the highest level of cutting speed and the highest level of feed rate (Fig. 5d). Shape parameters for roughness exhibit the strongest interactions among cutting conditions. For skewness (R_{sk}) lower and upper feed rate levels interact to each other if cutting speed is set to its lowest level. The best result is given if determining low cutting speed for all feed rate levels with emphasis to the middle level (Fig. 5e). For kurtosis (R_{ku}) the best result is obtained when selecting the middle feed rate level, yet; under a middle-leveled setting for cutting speed.

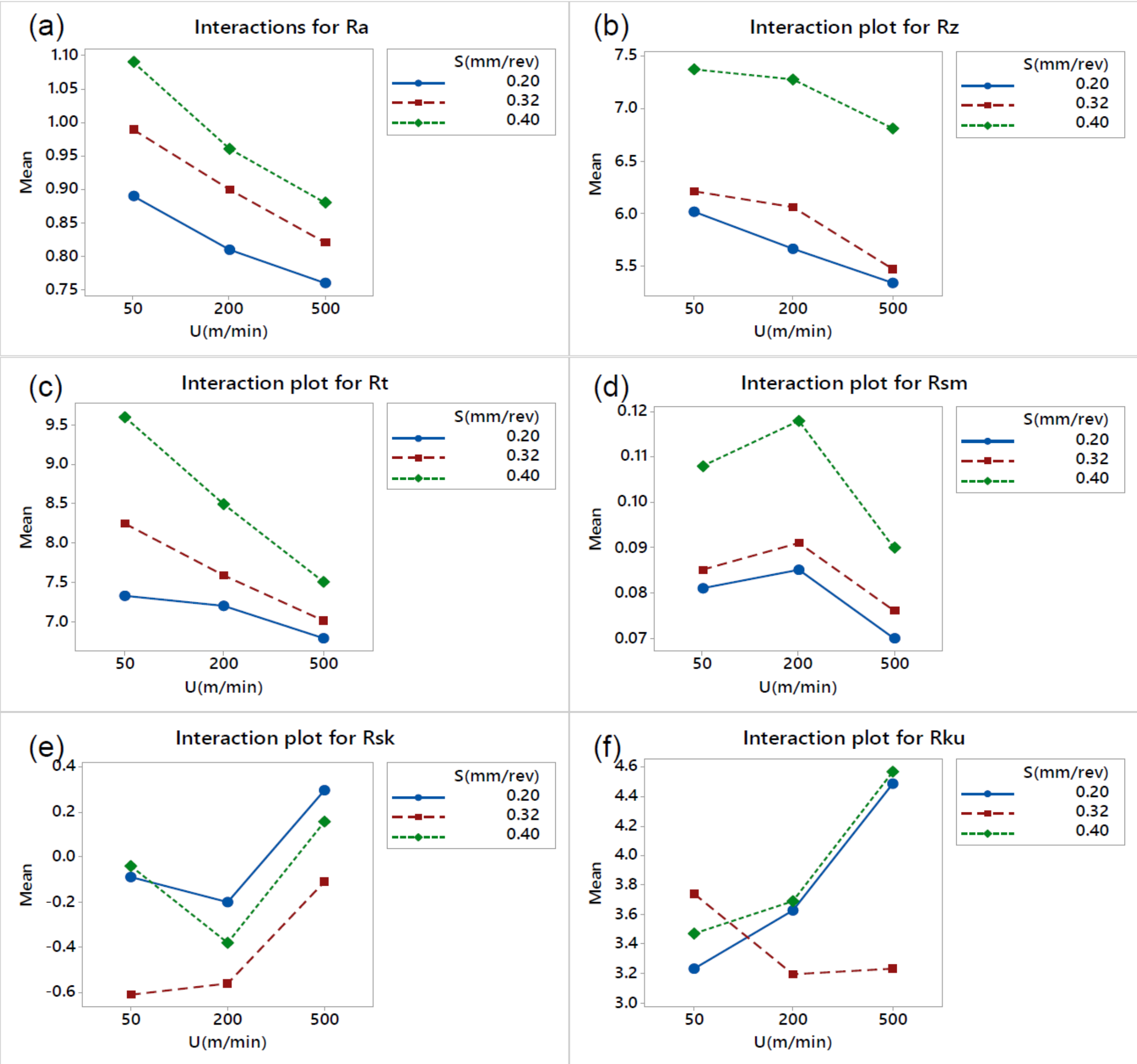

Fig. 5. Interaction plots for: (a) R_a; (b) R_z; (c) R_t; (d) R_{sm}; (e) R_{sk} and (f) R_{ku}

More accurate results concerning the effects of machining parameters on the responses of amplitude; spacing and stochastic parameters can be obtained by conducting ANOVA analysis. Through the outputs of *ANOVA* analysis significance of the prediction models to be created is obtained and regression according the original outputs is facilitated [9, 15-17]. Table 3 summarizes the ANOVA attributes for all roughness parameters investigated. Analysis of variance shows the contribution of each machining parameter on the responses of roughness. Important results are derived from F-value; P-value; and perc.(%) indicators. R-Sq and R-Sq(adj) terms show the correlation adequacy provided by the model to be generated for predicting the responses. The larger percentage these terms hold; the better the correlation among experimental and predicted results is. The general outcome concerning the correlation capability suggests that all models can be adequate enough to predict the responses studied earlier; however models corresponded to shape parameters and mainly Rku are not adequate enough to provide acceptable correlation.

For each of the roughness parameters investigated, influential conditions are those with p-value less that 0.05 whilst perc. (%) indicator reveals the exact percentage of the contribution of cutting conditions on the responses. It is evident that all observations previously discussed are validated according to ANOVA results in Table 3.

Table 3. Analysis of variance (ANOVA) for experimental results

Parameter	*Source*	*DF*	*Seq SS*	*Adj SS*	*Seq MS*	*F*	*P*	*Perc.%*
R_a	S	1	0.035849	0.02223	0.035849	285.54	0	44.83%
	U	1	0.038553	0.00276	0.038553	307.07	0	48.21%
	U*U	1	0.003584	0.003584	0.003584	28.55	0.006	4.48%
	S*U	1	0.001983	0.001983	0.001983	15.8	0.016	2.48%
	Error	4	0.000502	0.000502	0.000126			
	Total	8	0.080472					
	S	0.0112	R-Sq	99.38%	R-Sq(adj)	98.75%		
R_z	S	1	2.9327	0.5551	2.9327	495.61	0	66.03%
	U	1	0.6879	0.6879	0.6879	116.25	0	15.49%
	S*S	1	0.8208	0.8208	0.8208	138.71	0	18.48%
	Error	5	0.0296	0.0296	0.0059			
	Total	8	4.4710					
	S	0.0769	R-Sq	99.34%	R-Sq(adj)	98.94%		
R_t	S	1	2.9053	0.0575	2.9053	72.12	0.001	47.69%
	U	1	2.4185	0.0898	2.4185	60.04	0.001	39.70%
	S*S	1	0.2392	0.2392	0.2392	5.94	0.071	3.93%
	S*U	1	0.5286	0.5286	0.5286	13.12	0.022	8.68%
	Error	4	0.1611	0.1611	0.0403			
	Total	8	6.2527					
	S	0.2007	R-Sq	97.42%	R-Sq(adj)	94.85%		
R_{sm}	S	1	0.0009538	0.0001451	0.0009538	58.05	0.002	54.61%
	U	1	0.0003439	0.0001254	0.0003439	20.93	0.01	19.69%
	S*S	1	0.0002233	0.0002233	0.0002233	13.59	0.021	12.78%
	U*U	1	0.0002256	0.0002256	0.0002256	13.73	0.021	12.92%
	Error	4	0.0000657	0.0000657	0.0000164			
	Total	8	0.0018124					
	S	0.0040	R-Sq	96.37%	R-Sq(adj)	92.75%		
R_{sk}	S	1	0.02967	0.29446	0.02967	2.78	0.171	4.20%
	U	1	0.27343	0.06054	0.27343	25.6	0.007	38.65%
	S*S	1	0.27991	0.27991	0.27991	26.21	0.007	39.57%
	U*U	1	0.12431	0.12431	0.12431	11.64	0.027	17.58%
	Error	4	0.04272	0.04272	0.01068			
	Total	8	0.75006					
	S	0.1033	R-Sq	94.30%	R-Sq(adj)	88.61%		

R_{ku}	S	1	0.0069	0.3963	0.0069	0.02	0.89	0.51%
	U	1	0.6664	0.0007	0.6664	2.16	0.238	54.96%
	S*S	1	0.4436	0.4436	0.4436	1.44	0.317	36.64%
	U*U	1	0.0638	0.0638	0.0638	0.21	0.68	5.34%
	S*U	1	0.0305	0.0305	0.0305	0.1	0.774	2.54%
	Error	3	0.9261	0.9261	0.3087			
	Total	8	21,373					
	S	0.5556	R-Sq	56.67%	R-Sq(adj)	0.00%		

3.3. Regression

By default, analysis of variance (ANOVA) leads to the generation of regression equations capable of predicting results for dependent variables in advance. Independent variables are adopted under the role of regressors to correlate their predicted outputs to those of experimental results. In general, up to first-order models are preferred as well as general exponential ones [5]. In this work, full quadratic models have been developed for all roughness parameters concerning machinability when milling PA66-GF30 polyamide.

Correlation for all models has been verified by examining R-sq term in ANOVA table as well as manually through the implementation of the models to predict the responses. Thereby, experimental results were compared to predictions using a commercially available statistical package (StatEase® MINITAB 17). Full quadratic models involve the individual terms of cutting conditions; their quadratic expressions as well as their products. Should a number of such entities is not influential on the response studied; then is omitted to come up with a more robust model expression. The mathematical expressions representing the prediction models along with their R-sq (R^2) term are summarized in Table 4. Fig. 6 depicts a graphical representation for the correlation result for all models, using both experimental and predicted data.

Table 4. Full quadratic prediction models for all surface roughness parameters

a/a	*Roughness parameter*	*Regression model*	R^2
1	R_a	$= 72.048\ 10^{-2} + 1.009\ S - 6.01\ 10^{-4}\ U + 0.1\ 10^{-5}\ U^2 - 9.65\ 10^{-4}\ S\ U$	99.38%
2	R_z	$= 9.945 - 32.936\ S - 1.478\ 10^{-3}\ U + 67.176\ S^2$	99.34%
3	R_t	$= 8.064 - 10.675\ S + 2.062\ 10^{-3}\ U + 36.26\ S^2 - 1.576\ 10^{-2}\ S\ U$	97.42%
4	R_{sm}	$= 0.138 - 53.25\ 10^{-2}\ S + 1.04\ 10^{-4}\ U + 1.108\ S^2 - 2.4\ 10^{-7}\ U^2$	96.37%
5	R_{sk}	$= 3.254 - 23.988\ S - 2.292\ 10^{-3}\ U + 39.229\ S^2 + 0.6\ 10^{-5}\ U^2$	94.30%
6	R_{ku}	$= 7.131 - 28.04\ S + 3.06\ 10^{-4}\ U + 49.39\ S^2 + 0.4\ 10^{-5}\ U^2 - 3.78\ 10^{-3}\ S\ U$	56.67%

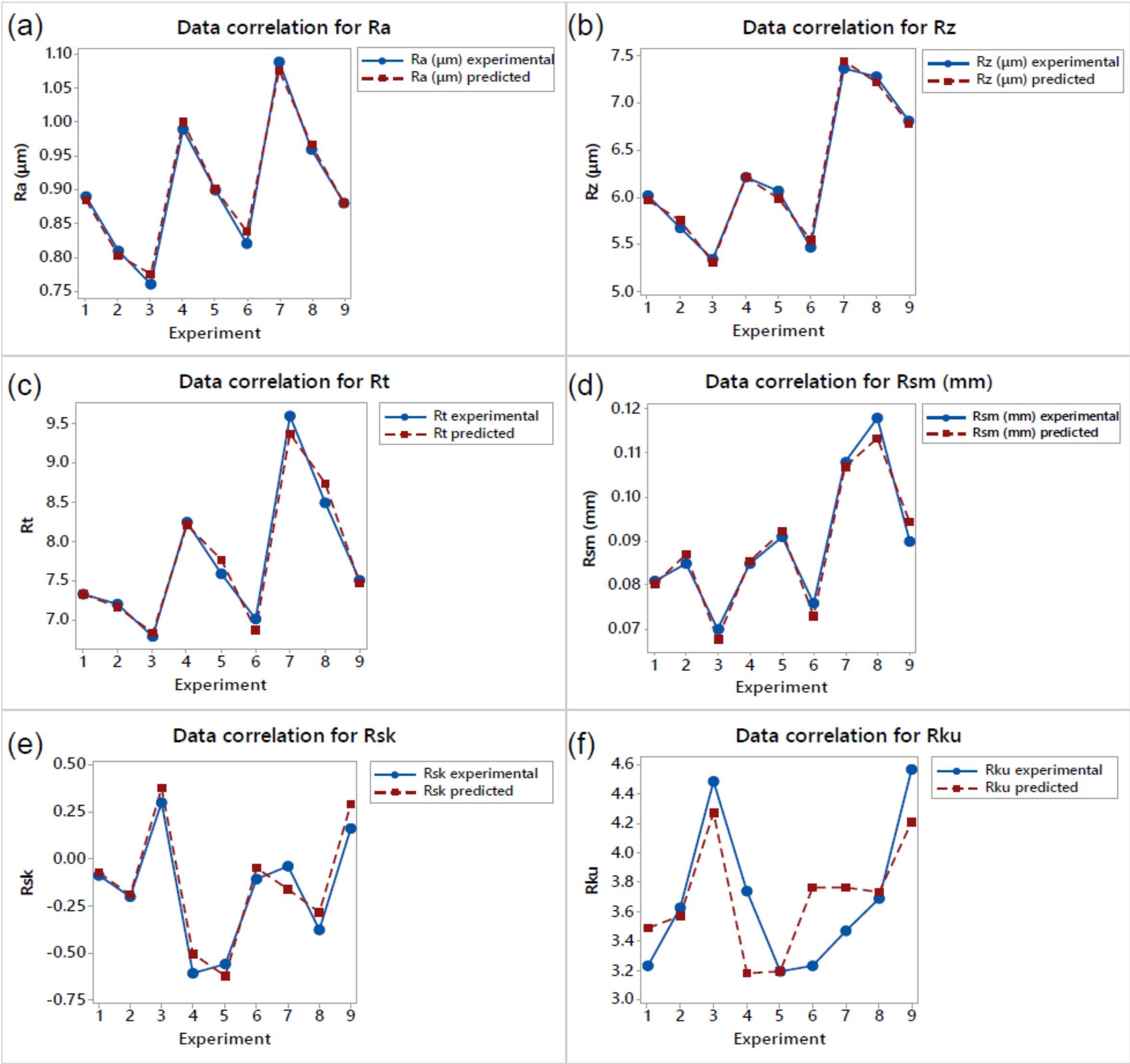

Fig. 6. Data correlation (both experimental and predicted) for: (a) R_a; (b) R_z; (c) R_t; (d) R_{sm}; (e) R_{sk} and (f) R_{ku}

4. CONCLUSIONS

A multi-parameter analysis of surface finish imparted to PA66-GF30 glass-fibre reinforced polyamide by milling was presented. The surface finish parameters under study included amplitude (R_a, R_t, R_z) spacing (R_{sm}) and shape/stochastic (R_{sk}, R_{ku}) roughness indicators. The correlation of these parameters with the machining conditions was investigated and the interrelationship between surface texture parameters was emphasized. It was found that both amplitude and spacing surface roughness parameters are minimized when machining with the highest cutting speed (U=500 m/min) and the lowest feed-rate (S=0.20 mm/rev).

Then by applying analysis of variance and regression analysis to the experimental data close correlation was obtained among certain surface finish parameters and the machining conditions. To facilitate industrial operations full quadratic prediction models were developed for capturing trends for machining quality in advance.

It was found that experimental results for amplitude parameters may be correlated to independent variables' predictions with excellent estimations. For spacing parameter correlation is not that adequate, yet; the model can be used for predicting actual data. For shape parameters correlation is marginal with the one for R_{sk} to be totally inadequate to predict shape responses. This leads to the conclusion that those roughness indicators cannot be efficiently correlated to independent variables' predictions thus; regression models are not deemed useful for estimating actual data prior to physical machining. The latter conclusion is in agreement with the relevant literature, distinguishing these parameters to the category of non-correlated ones.

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CORRESPONDENCE

Nikolaos VAXEVANIDIS:
Professor, School of Pedagogical and Technological Education (ASPETE), Department of Mechanical Engineering Educators, ASPETE Campus, GR 14121, N. Heraklion Attikis, Greece.
e-mail: vaxev@aspete.gr