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Portability study of surface roughness models in milling

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Abstract

In spite of the huge number of research studies around empirical surface roughness models, there is no methodology applied in industry to model and adapt accurately the surface roughness in machining operations. Any change of the process with respect to the initial conditions where the experiments were conducted implies an additional estimation error which difficulties the use of the model in the current process. This paper studies the portability of empirical models for surface roughness prediction in face milling operations. As portability problem, we refer to how a proper surface roughness model obtained from theoretical/experimental data under specific conditions decreases its performance when it is applied in a different environment. The work gives some guidance for future design of more robust surface roughness models.

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Keywords: Machining; Design of Experiments; Surface Roughness; Model Error; Model Portability.

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1. Introduction

In machining processes, the surface roughness of the machined parts is one of the most significant product quality characteristic. It is a key factor in evaluating the quality of a product and has a great importance on manufacturing costs and functional behavior of the machined parts in exploitation such as assemblability. The surface roughness also influences the tribological characteristics, the fatigue strength, the corrosion resistance and the aesthetic appearance of the machined parts. For instance, in aerospace industry high pressure hydraulic systems and fuel

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injections systems in particular require high quality surfaces and precisely defined features, such as o-ring grooves in order to maintain system integrity [1]. Therefore, the lack of good surface quality fails to satisfy one of the most important technical requirements for mechanical products, while extremely high level of surface quality causes higher production costs and lower overall productivity of cutting operations [2].

Surface quality is directly related to cutting conditions and thus, it is of great importance to quantify the relationship between surface roughness and cutting parameters such as cutting speed, feed rate and depth of cut. However, surface roughness is not only influenced by these cutting parameters but also by a large number of factors such as cutting-tool wear, material characteristics, tool geometry, stability and stiffness of the machine tool - cutting tool - workpiece system, built-up edge, cutting fluid, etc [3] .

Surface roughness is composed of two components: the first is the ideal or geometric finish, which is defined as the finish that would result from the geometry and kinematic motions of the tool and, the second is the natural (or inherent) finish, which results from tool wear, vibration and dynamics of the cutting process, work material effects such as residual stresses, inhomogeneity, built-up edge formation (BUE), and rupture at low cutting speeds. The ideal roughness can be calculated from the feed rate per tooth, the tool nose radius, and the tool lead angle and it is usually the predominant component of the finish in operations in which tool wear and cutting forces are low, for example, when machining aluminum alloys with diamond tools. Unlike the ideal finish, the natural component is difficult to predict in general and it is often the predominant component of the finish when machining steels and other hard materials with carbide tooling, or when machining inhomogeneous materials such as cast iron or powder metals [3]. Therefore, the ideal surface quality is not generally achieved even in the ideal cutting conditions and the prediction of surface roughness is usually not reliable in industrial practices.

A large number of research studies have tried to model surface roughness according to these factors in order to predict surface roughness and optimize cutting parameters. The effect of axial and radial runout and its modelisation was described in Franco et al. [4] and later they expanded their study to analyze the back cutting effect on surface roughness [5]. The effect of machine-tool rigidity on the surface roughness generation was also investigated in [6] where it was observed that a good surface roughness for slender tools can be achieved provided the tooth passing frequency used in the milling process (and its harmonics) does not produce high frequency response values.

Tool wear is probably the most common factor studied when surface roughness is critical. According to [7], higher roughness values are observed especially at the very early stage where the inserts are rather new. Afterwards due to the friction these inserts become wear and the radiuses of tool edges increases, therefore, the heights of feed marks decreases. However, in most operations when the tool wear value exceeds certain value, surface roughness tends to increase considerably [3].

The effect of coating layers and tool material on surface roughness was also studied in [8,9]. Nalbant et al. [8] analysed the effects of uncoated, PVD- and CVD-coated cemented carbide inserts and cutting parameters on surface roughness in CNC turning. In the experimentation it was observed that increasing the number of coating layers decreases the friction coefficient and parallely decreases the average surface roughness value of the workpiece. In [9] two types of inserts with the same geometry and substrate but different coating layers were used to evaluate the effects of two coating layers as well as the cutting parameters onto the surface roughness. In this research the authors found out that surface roughness values were significant lower when employing PVD coated (TiAlN) inserts instead of CVD coated (TiCN+Al2O3+TiN).

It is also well-known that the cutting-tool geometry such as lead angle, relief angle, rake angle, nose radius, tool facet or wiper geometry are well-known parameters that may influence on surface roughness generation as it is shown in several technical data [10,11]. Some of these parameters have been also considered by researchers in order to analyze and model surface roughness under different cutting conditions. For instance, Grzesik [12] studied the effect of different shaped ceramic tools on surface roughness in hard turning, and Ozel et al. [13] also analysed the cutting edge geometry (honed edges) effect on surface roughness.

The cutting parameters and their effect on surface roughness is also well-known and it is reported in machining handbooks and technical data from vendors [10,11]. In [9] it is shown how increasing cutting speed improves surface quality since it reduces cutting forces together with the effect on natural frequency and vibration. Furthermore, too low cutting speeds may produce material adhesion at the inserts (built up edge) increasing surface quality [14]. A critical aspect in cutting parameters is the feed rate and its relation on the minimum undeformed chip thickness. Surface profile presents more fluctuations as feed decreases, which can be explained by the influence of the undeformed chip thickness. As feed decreases, smaller values of undeformed chip thickness are obtained and chip removal becomes more difficult. In such circumstances, there is a higher tendency towards elastic and plastic deformation of the workpiece surface, which involves more fluctuations at the surface profile.

Depth of cut is another cutting parameter that may have an impact on surface roughness. In [15], it was reported that surface roughness increases rapidly with the increase in feed rate and decreases with an increase in cutting speed, but the effect of depth of cut was not regular. Cakir [9] also reported that the depth of cut has an insignificant effect on surface roughness, however, Darwish [16] reported that this effect was important, and the greater is the depth of cut the lower is the surface roughness.

The effect of workpiece material on surface roughness was also analysed in [17,18]. Desale et al. [17] found out that the influence of workpiece material hardness on surface finish is significant. Routara et al. [18] found in their experimentation that cutting parameters (spindle speed, depth of cut and feed rate) have a significant effect on roughness parameters but their influence vary with the nature of workpiece material (steel, aluminium and brass). Thus, the surface roughness model based on response surface had to be specific to the workpiece material.

The coolant effect is another cutting parameter that has been studied in detail in different researches. In [19] it is reported the effect of different lubricant environments (flooded lubricant, minimum quantity lubricant, and dry conditions) when 6061 aluminium alloy is machined with diamond-coated carbide tools. In the experimentation it was observed that the surface roughness could be improved according to the application of coolant. The improvement in surface finish was attributed to the reduction in the material transfer onto the machined surface. Yalcin et al. [20] reported similar results when machining soft materials with different coolant strategies. They found out that dry cutting for soft materials milling operation cannot be used for HSS tool due to adhesion tendency for soft materials. Coolant strategies are also related to the formation of built up edge and surface quality. In [20] it was reported that air cooling process can minimize build-up-edge occurred during soft material milling in comparison with other strategies.

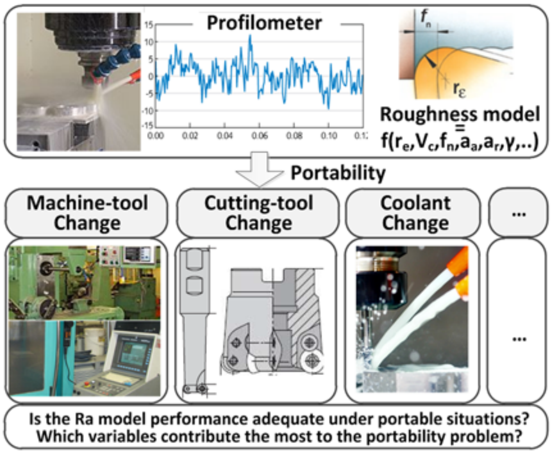


Fig. 1. Description of the portability problem.

In spite of the huge number of research studies around empirical surface roughness models, there is no methodology applied in industry to model and adapt accurately the surface roughness in machining operations. Any change of the process with respect to the initial where the experiments were conducted implies an additional prediction error which difficulties the use of the model in the current process. Few works have presented methods for adapting empirical models due to changes in the process. This paper studies the portability of theoretical/empirical models for surface roughness prediction in face milling operations. As portability problem, illustrated in Fig. 1, we refer to how a proper surface roughness model obtained from theoretical/experimental data in a specific environment decreases its performance when it is applied in a different environment.

This paper is organized as follows. First, the methodology and experimental procedure to derive a surface roughness model is presented in Section 2. Then, the results of the experimentation and the surface response models derived are shown in Section 3. In order to evaluate the capability of the model to be applied in different environments, two sets of experiments are conducted in Section 4: one with the same conditions than those during the modeling process, and another one with different cutting conditions such as use of different coolant strategy, different machine-tool, workpiece or cutting-tools. Finally, Section 5 briefly reviews the conclusions of the paper.

2. Methodology and experimental procedure

In order to derive a surface roughness model for face milling operations, a design of experiments (DoE) is defined. The experiment is based on 3 main factors: cutting speed (Vc), feed per tooth (fz), and depth of cut (ap). As presented previously, there are many factors that may influence the final surface roughness profile. In this experimentation, only one tooth is used in the face milling cutter to remove the axial and radial run-out effect, and a new cutting-tool edge is used every six cutting passes of 250 mm length in order to avoid the tool wear effect. Thus, the surface roughness model is only studied for new or nearly new cutting-tools. Furthermore, the experimentation is conducted under dry conditions and the same cutting-tool and machine-tool is used, a CNC machining center DMC70V and a Kennametal face milling cutter of 52 mm diameter (code KDM200RD12S075C) and round cutting inserts (code RDHX12T3M0SGN KC715M) of 12 mm diameter. The workpiece material is a DIN S275JR steel grade (non-alloy steel, Brinell hardness HB 150) with dimensions 250 x 250 x 55 mm and it is clamped to the machine-tool table using a single vise. The cutting conditions are fixed for each cutting pass of 250 mm length, and the radial depth of cut is fixed to 37.5 mm. The experimental setup is shown in Fig. 2.

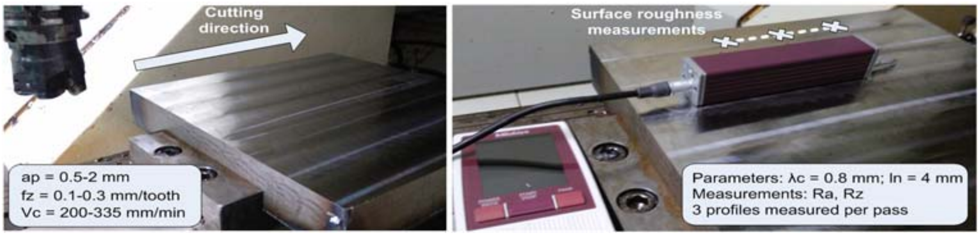
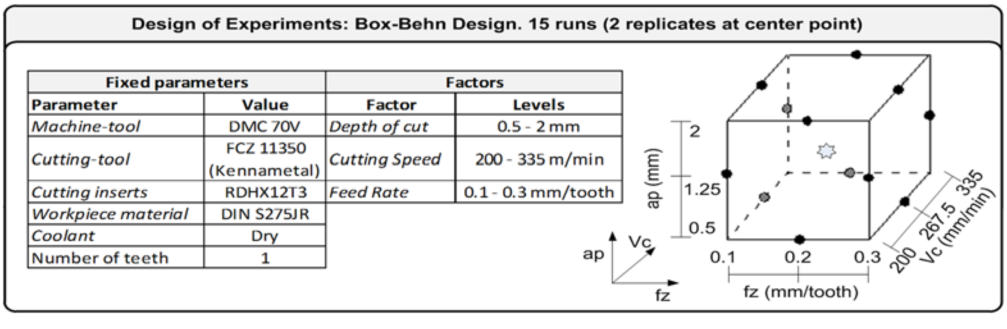


Fig. 2. Experimental setup.

Under these setup conditions, a Box-Behnken DoE is defined in order to fit a surface response with quadratic and interaction terms. The levels for each factor are defined considering vendor’s cutting data and the face milling application studied for this steel grade. The levels defined are: Vc = 200-335 m/min; fz = 0.1 – 0.3 mm/tooth; ap = 0.5 – 2 mm. The DoE design is shown in Fig. 3. For each cutting parameter combination the surface roughness parameters Ra and Rz are measured with a Mitutoyo Surftest profilometer SJ-210. The measurements are conducted at three different points along the cutting pass with a separation of 25 mm approximately.



Design of Experiments: Box-Behn Design. 15 runs (2 replicates at center point)

Fixed parameters		Factors	
Parameter	**Value**	**Factor**	**Levels**
Machine-tool	DMC 70V	*Depth of cut*	0.5 - 2 mm
Cutting-tool	FCZ 11350 (Kennametal)	*Cutting Speed*	200 - 335 m/min
Cutting inserts	RDHX12T3	*Feed Rate*	0.1 - 0.3 mm/tooth
Workpiece material	DIN S275JR		
Coolant	Dry		
Number of teeth	1		

Fig. 3. Design of experiments for modeling surface roughness.

A second experimentation will be carried out to analyse the performance of the model under the same conditions and under portability conditions, that means, under changes on cutting-tool, machine-tool, workpiece hardness and coolant. This second experimentation will study the capability of the model to be used under environmental changes and will quantify which of these changes are more critical for model performance.

3. Surface roughness model

After conducting the experimentation defined by the Box-Behnken DoE, a surface response is fitted for both Ra and Rz parameters. Tables I and II show the model coefficients for both parameters and the analysis of variance obtained from the software Minitab 16 to show the significant terms of the model. It can be shown that both parameters can be well-fitted with a quadratic and linear effect (the R^2 adjusted is 93.7% and 87.9% for Ra and Rz, respectively) and a lack of fit is discarded according to the p-value obtained in the analysis (lack-of-fit of 0.069 and 0.555 for Ra model and Rz model, respectively).

Table 1. Results of DoE. Analysis of variance and model coefficients. Surface roughness parameter Ra.

Source	D.o.f	F-value	p-value	Source	D.o.f	F-value	p-value
Regression	5	43.14	0.000	Square	2	11.71	0.003
Linear	3	64.09	0.000	Vc x Vc	1	19.62	0.002
Vc	1	0.09	0.771	ap x ap	1	5.11	0.050
fz	1	190.85	0.000	Residual error	9		
ap	1	1.33	0.279	Lack of fit	7	13.88	0.069
				Pure error	2		

Regression: $Ra = 0.434 + 0.25fz + 0.117Vc^2 + 0.06ap^2$; $R^2 = 95.99\%; R^2_{adj} = 93.77\%$

Table 2. Results of DoE. Analysis of variance and model coefficients. Surface roughness parameter Rz.

Source	D.o.f	F-value	p-value	Source	D.o.f	F-value	p-value
Regression	6	18.09	0.000	Square	3	13.74	0.002
Linear	3	22.44	0.000	Vc x Vc	1	31.32	0.001
Vc	1	0.08	0.790	fz x fz	1	7.33	0.027
fz	1	58.81	0.000	ap x ap	1	7.55	0.025
ap	1	8.42	0.020	Residual error	8		
Pure error	2			Lack of fit	6	1.07	0.555

Regression: $Rz = 2.12 + 0.963fz - 0.365ap + 1.035Vc^2 + 0.508ap^2 + 0.500fz^2$; $R^2 = 93.1\%; R^2_{adj} = 87.9\%$

As it is observed, the feed rate is the most critical factor for both Ra and Rz models. The Ra model seems to be almost completely defined by the feed rate parameter, and only the cutting speed and the depth of cut, both in quadratic terms, have an additional influence. In both cases, an increase of cutting speed or depth of cut has a slight negative impact on surface roughness. On the other hand, the Rz model seems to be influenced by more terms. The feed rate is again the most important factor but the cutting speed in quadratic term is also a critical factor. The rest of factors in quadratic terms are significant but in a minor extent.

Fig. 4 shows the actual values and the fitted values for the set of experiments conducted for both Ra and Rz parameters. The figure shows a reasonable valid model for both Ra and Rz parameters, and it will be used for the analysis of the portability problem in the next section.

4. Model performance under environmental changes

The Ra and Rz model previously defined are now tested under different situations to analyze the robustness of the model and its portability capability. As a first step, the Ra and Rz models are tested under the same cutting conditions as the previous one in order to identify the model error. For this purpose, six face milling operations with different cutting parameter combinations were analysed. Table III shows the experimental results and the error deviation of the model. It can be seen that the model error under the same conditions used for building the model is 11.2% and 9.8% for Ra and Rz, respectively. Fig. 5 shows the results of the model prediction, the confidence interval of the prediction which is set to 95%, and the experimental result. It is seen that all experimental results are within the confidence interval except number 4 for Ra and 6 for Rz, which are slightly out of the confidence region.

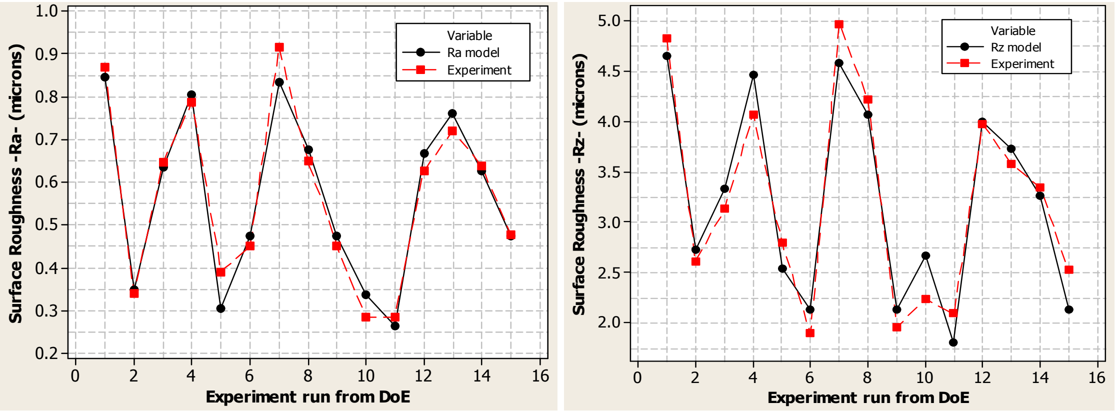


Fig. 4. Model adjusted for Ra (left) and Rz (right) parameters and comparison with the experimental data from the Box-Behnken DoE.

Table 3. Model performance comparison under similar cutting conditions.

Run	Vc	fz	ap	M-T	Coolant	Material	Tool	Ra	Ra-pred	%Error	Rz	Rz-pred	%Error
1	335	0.10	2.00	MT1	Dry	M1	T1	0.36	0.39	6.8	2.46	2.87	14.5
2	200	0.10	2.00	MT1	Dry	M1	T1	0.35	0.38	5.9	2.79	2.80	0.5
3	200	0.20	2.00	MT1	Dry	M1	T1	0.72	0.62	-14.7	3.59	3.27	-9.8
4	268	0.1	0.5	MT1	Dry	M1	T1	0.37	0.31	-20.2	2.25	2.53	11.1
5	335	0.2	2	MT1	Dry	M1	T1	0.70	0.64	-10.6	3.51	3.34	-5.2
6	335	0.3	1.3	MT1	Dry	M1	T1	0.77	0.85	9.0	3.82	4.66	17.9
								Mean Error (Ra)		**11.2**	**Mean Error (Rz)**		**9.8**

MT1: DMC 70V; T1 is Ø52 mm cutter and Ø12 mm round inserts; M1: DIN S275JR.

To test the capability of the model to be used in different environments, an additional set of experiments is conducted under the following situations: a) a change in the coolant strategy; b) a change in the hardness of the workpiece material; c) a change in the cutting-tool; and d) a change in the machine-tool. Each experiment is repeated 2 times and average values are used. The results of this experimentation are shown in Table IV and Fig. 6. In the first 3 experiments (runs 1-3), the face milling operation is conducted under a flood coolant strategy unlike the dry strategy that it was used during the model building stage. It can be seen that the prediction error is low and the experimental results are within the confidence interval defined by the model (see Fig. 6). Then, the coolant strategy is not significant in this process and the same models could be used for predicting Ra and Rz despite differences in the coolant strategy.

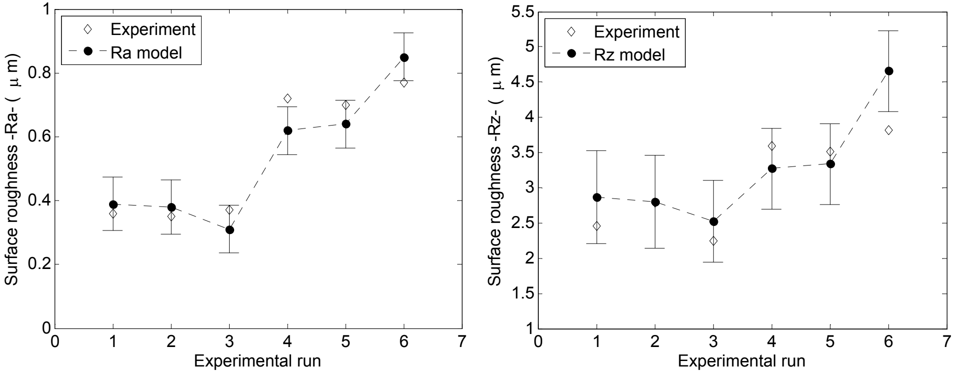


Fig. 5. Model performance for new data under similar cutting conditions (dry cutting, same machine-tool, cutting-tool and workpiece material).

The experiment run 4 and 5 are conducted under similar cutting parameters but a workpiece with a higher hardness is used. The workpiece material used previously was DIN S275JR, which is a non-alloyed steel with 0.2% carbon content and a Brinell hardness of 150. For runs 4 and 5, the workpiece used is a DIN C35, which is a non-alloyed steel with 0.35% carbon content and Brinell hardness of 175. Under these conditions, the results show that the model prediction is deficient and the prediction error is around 30%. At run number 4 the actual roughness is higher that the predicted one (Ra 0.82 μm instead of 0.62 μm) and at number 5 the opposite occurs, the actual roughness is lower that the predicted one (Ra 0.50 μm instead 0.68 μm). It clearly shows a different behavior of Ra and Rz parameter due to the hardness variation of the workpiece. Experiment run 6 shows the most critical parameter in the portability problem, the cutting-tool. The change of the cutting-tool is from a face cutter of Ø52 mm and round inserts of 12 mm to a face cutter of Ø25 mm and round inserts of 10 mm. Note that even with a slight change in the cutting-tool insert, the prediction error is increased to 50% (see Table IV and Fig. 6), which reveals the critical effect of cutting-tool geometry on surface roughness generation. Finally, run number 7 also shows the influence of the machine-tool on the surface roughness models. At this experiment run, the machine-tool used is a manual milling machine-tool (Milko 35R) instead of the CNC machining center DMC 70V. As it is shown in Table IV and Fig. 6, the prediction error is again around 50%, and the Ra and Rz model are unreliable to be applied under this environmental change.

Therefore, although a change in coolant strategy seems to be non-significant in the surface roughness generation, the effect of workpiece hardness, cutting-tool and machine-tool are significant, especially the last two factors, and any change in these factors will prevent the use of the Ra and Rz model with the consequent portability problem.

Table 4. Model performance comparison under portability conditions.

Run	Vc	fz	ap	M-T	Coolant	Material	Tool	Ra	Ra-pred	%Error	Rz	Rz-pred	%Error
1	335	0.2	0.5	MT1	Flood	M1	T1	0.73	0.68	-7.8	3.62	4.06	10.8
2	200	0.2	0.5	MT1	Flood	M1	T1	0.71	0.67	-6.0	4.07	4.00	-1.8
3	268	0.1	0.5	MT1	Flood	M1	T1	0.36	0.31	-16.9	1.99	2.53	21.3
4	200	0.2	2	MT1	Dry	M2	T1	0.82	0.62	-30.4	5.06	3.27	-54.8
5	335	0.2	0.5	MT1	Dry	M2	T1	0.50	0.68	26.4	2.63	4.06	35.3
6	200	0.20	0.50	MT1	Dry	M1	T2	0.33	0.67	51.0	1.95	4.00	51.2
7	267	0.20	2.00	MT2	Dry	M1	T1	0.72	0.51	-40.0	3.72	2.27	-64.1
							Mean Error (Ra)			**25.1**	**Mean Error (Rz)**		**34.2**

MT1: DMC70V; MT”: Milko 35R; T1: Ø52 mm & Ø12 mm round inserts; T2: Ø25 mm & Ø10 mm round inserts; M1: DIN S275JR; M2: DIN C35.

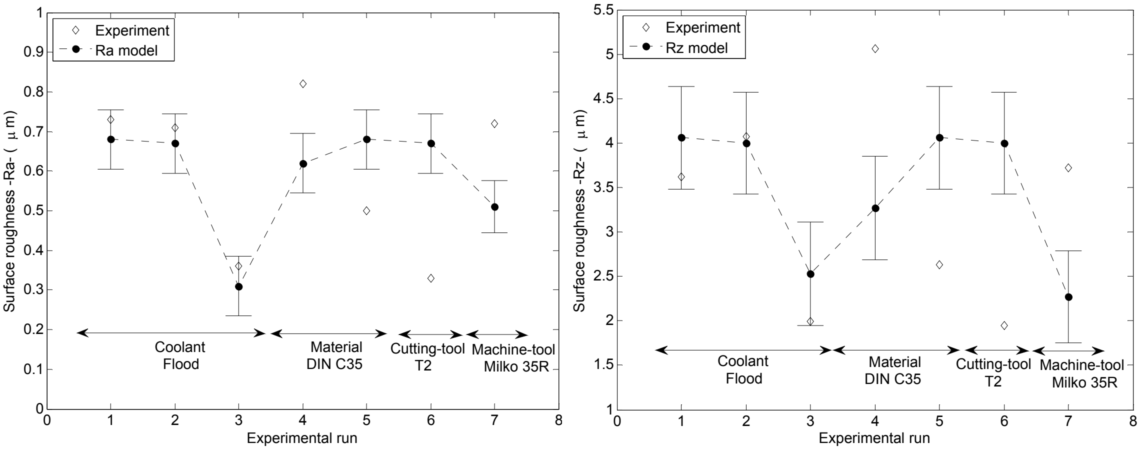


Fig. 6. Model performance for new data under portability cutting conditions.

5. Conclusions

This paper describes and quantifies experimentally the portability problem of theoretical/empirical surface roughness models in face milling operations. In a first set of experiments the model error for Ra and Rz estimation was around 10%. However, when the cutting conditions applied are different from the ones used during the model building stage, the average model error increased to 30%. In this set of experiments, the change from dry cutting to flood coolant was observed to be non-significant and the performance of the models was adequate. Nevertheless, the change of workpiece material (a slight increase of hardness from 150 HB to 175 HB) makes the model to decrease its performance notably, making the model non-reliable. The situation gets worse when cutting-tool changes (slight change of cutting insert geometry, from 12 mm diameter to 10 mm diameter) or the machine-tool changes (from a CNC machine-tool center to a manual milling machine-tool). In both cases, the surface roughness models from previous cutting conditions are not valid and new surface roughness models would be required. This experimentation shows the critical effect of other factors besides cutting parameters on surface roughness which demonstrates the challenge of developing surface roughness models that can be applied in different scenarios. The research in generating robust models that can be adapted to different cutting conditions with a minimum experimental data should be studied in detail as future work.

Acknowledgements

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