Annals of DAAAM for 2010 & Proceedings of the 21st International DAAAM Symposium, Volume 21, No. 1, ISSN 1726-9679
ISBN 978-3-901509-73-5, Editor B. Katalinic, Published by DAAAM International, Vienna, Austria, EU, 2010
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Annals of DAAAM International

PORTABILITY PROBLEM OF EMPIRICAL SURFACE ROUGHNESS MODELS

ABELLAN NEBOT, J[ose] V[cte]; SERRANO MIRA, J[ulio]; BRUSCAS BELLIDO, G[racia] M & VILA PASTOR, C[arlos]

Abstract: *Machining empirical models for surface roughness based on statistical or artificial intelligence (AI) approaches have been intensively studied during last decades. However, continuous changes in the cutting process such as cutting-tool replacements or changes in material workpieces make the application of empirical models unfeasible. This paper presents the problem of empirical model portability for surface roughness prediction in face milling operations, and shows the influence of factors such as material, cutting-tool and machining system on surface roughness generation.*
Key words: *machining process, surface roughness, design of experiments*

1. INTRODUCTION

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 production (cutting-tools, workpiece material, etc.). Westkamper *et al.* (1998) and Van Luttervelt & Peng (1999) exposed the adaptation problem, but they did not deal with any physical example. Risbood *et al.* (2003) modelled surface roughness and dimensional quality in turning using an artificial neural network (ANN) and tested the use of the model in different machining conditions which were not modelled. They showed that it was necessary to apply two different ANN models for modelling the cutting process depending on the presence of coolant, as the cutting process changes considerably. In order to adapt the surface roughness model when a cutting-tool change occurred, Risbood proposed a proportional compensation. More recently, Abellan-Nebot *et al.* (2008) presented a methodology to develop empirical surface roughness models based on few experimental data and to adapt them when some machining conditions change. However, any of the previous works clearly quantifies which are the variables that difficulties the most the use of empirical surface roughness models on different environments.

This paper presents the problem of empirical model portability for surface roughness prediction in face milling operations. As portability problem, we refer to how a proper surface roughness model obtained from experimental data in a specific environment decreases its performance when it is applied in a different environment. Obviously, a quantification of the portability problem is important in order to study later the adaptability process required in changing environments.

2. EXPERIMENTAL SETUPS

In order to analyse which process variables significantly influence the surface roughness generation and which of them may represent a problem for empirical model portability, a design of experiments (DoE) with different setups were analysed. Table 1 shows the different process variables and their possible values to be considered in the experimentation. Two levels (+, -) are considered per factor: machine-tool factor considers a vertical machining center (VMC) of high precision and a milling machine (Milling); cutting-tool factor considers a cutting-tool with 50 mm diameter and 5 round cutting inserts coated with TiAlN (Tool A) and a cutting-tool with 20 mm diameter and 2 round cutting inserts uncoated (Tool B); workpiece material factor considers a hard steel material for moulds (D3) and a carbon steel material (F113); lubrication factor considers possible (Yes) and non-possible (No) lubrication; the levels of the rest of factors refer to cutting parameters, and they are shown in Table 1.

	+	-		-	+	units
Machine-tool (MT)	VMC	Milling	Vc	57	107	m/min
Cutting-tool (CT)	Tool A	Tool B	fz	0.045	0.105	mm
Workp. Material (WM)	F113	D3	ap	0.5	1	mm
Lubrication (Lb)	Yes	No	ae	40	80	%

Tab. 1. Process variables considered at each experimental setup

3. DESIGN OF EXPERIMENTS

Taguchi's orthogonal arrays (OAs) is a fractional factorial DoE which is applied to get the most information conducting the fewest experiments (Roy, 2001). In order to analyse the significance of each of the eight factors considered in the experimental setup, only OAs for two-level factors can be applied. For our experimentation, in addition to the eight factors shown in Table 1, five interactions are considered as potential significant effects: Vc x fz, Vc x WM, MT x Lb, fz x CT and fz x MT. Thus, the OA L16 was applied in the DoE. For each setup/cutting-parameter combination, three experimental replicates were conducted, measuring at each experimental run the surface roughness with a Mitutoyo Surftest 301 profilometer at three equidistant surface points in the workpiece zone. Thus, a total of 144 experimental data was obtained.

4. EXPERIMENTAL RESULTS

Figure 1 shows the Pareto diagram to sort the factors according to their influence on the mean of surface roughness values. The results of this graph indicate the high importance of WM on surface roughness generation, which explains almost the 63% of surface roughness variability. This is mainly due to the built-up edge (BUE) generation when cutting the workpiece material F113. Unlike D3 workpiece material, F113 workpiece material is a sticky material which requires high cutting speeds during machining to avoid BUE. Therefore, the WM is the most important factor for surface roughness portability, and it must be assured that the cutting parameters for different workpiece materials are within the cutting parameters ranges where BUE effects are minimised.

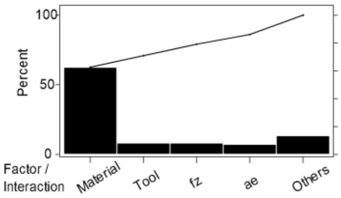

Fig. 1. Pareto diagram for the mean of surface roughness

Other important factors are the CT, fz and ae which explain the 8.4%, 8.1% and 7.2% of the variability of the mean surface roughness respectively. The importance of the CT in the experimentation is explained by the cutting tool runout errors. This is because of the fact that cutting tools with higher diameters and number of inserts tend to produce worst surface roughness due to spindle and cutting-tool runout errors. The fz effects are obviously explained by the geometrical influence of the tooth marks on workpiece surface, and it is usually the most common parameter modified by the machinist to improve surface roughness. The ae influences the surface roughness considerably. This fact may be due to two possible effects: 1) smaller radial depth of cuts produce a smaller average chip thickness, so less forces and vibrations occur; 2) smaller radial depth of cuts tend to reduce the built-up edge effects.

On the other hand, Figure 2 represents the Pareto diagram to quantify which factors explain the variability of surface roughness. Referring to this graph, two main factors explain the surface roughness variability: the WM and the MT which explain the 49.7% and the 27.7% of the variability respectively. The WM influences greatly in the surface roughness variability due to the BUE effects. The BUE effects not only increase the mean surface roughness value as it was seen previously but also the surface roughness variability due to its randomness nature. The MT factor also explains a great part of surface roughness variability. The VMC machine (high precision machine) keeps the variability in a low value whereas the milling machine increases it considerably. This effect is due to the milling machine structure, which has less robustness and higher spindle runout than the VMC machine, so the vibrations during milling are higher. Less important are other factors such as the ae, which explains the 7.4%, or the factor interaction of fz x MT, which represents the 4.5%. The ae may be explained in the same manner that for the mean surface roughness: higher radial depth of cuts increases BUE effects and vibrations, so surface roughness variability is also increased. The fz x MT also influences surface roughness variability since the milling machine-tool has a lower robustness. In the experimentation, the VMC tool increases surface roughness variability when increasing fz, as forces and vibrations increases. However, the milling machine-tool keeps almost constant the surface roughness variability when fz increases since the vibrations in this machine are higher even if a low fz is applied.

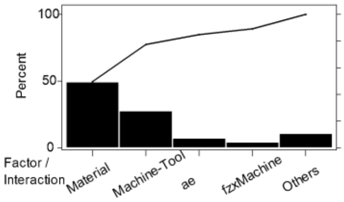

Fig. 2. Pareto diagram for the variability of surface roughness

5. PORTABILITY PROBLEM

Three main groups of factors can be defined in the portability problem: controllable factors which are related to cutting parameters (Vc, fz, ap, ae, Lb), the uncontrollable factors which are fixed by the part specifications (WM) and other factors not considered in the experimentation (unmodelled factors), and product/process factors which are factors that may be controllable or uncontrollable depending on production (MT, CT, and interactions such as Vc x WM, MT x Lb and MT x fz, etc.). Figure 3a shows the influence of the three groups of variables in the mean surface roughness and Figure 3b shows the same influence discarding the WM factor. Figure 3c and 3d shows the same influence but on surface roughness variability. These figures outline the portability problem which is not commonly studied in the literature.

When a surface roughness model is obtained for a specific purpose, the model deals with controllable factors and also with product/process factors. This is due to the fact that the model is only built for a specific application where there is no change on CT, WM, MT, etc. Therefore, if we would apply a specific model for our experimental data, the model could easily achieve a prediction accuracy of average roughness around 81% using simple linear regressions (note that for a specific application, there is no change on WM, and thus, only the uncontrollable factors in Figure 3b produces a model inaccuracy of 19%). In the same way, the variability could be predicted around 93%. However, when manufacturing is conducted in changing environments where the MT, WM or CT can change according to resources availability or product specifications, the product/process planning factors can negatively impact on surface roughness model reliability. According to our experimentation and considering that WM is not changed, a specific surface roughness model could decrease its accuracy from 81% to 46% in mean surface roughness predictions, and from 93% to 20% in variability predictions. These percentages show the importance of model adaptation when a specific surface roughness model requires to be applied in other systems where product/process factors change.

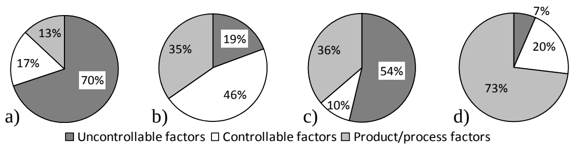

Fig. 3. Factor influence on surface roughness

6. CONCLUSION

This paper has described and quantified experimentally the portability problem of empirical surface roughness models in machining operations. The study remarks that the adaptation of surface roughness models is mandatory in environments where machining changes occur due to machine-tools or cutting-tools availability, or changes on raw material properties.

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