SFB 823

Discussion Paper

Statistical process modelling for machining of inhomogeneous mineral subsoil

Claus Weihs, Nils Raabe, Manuel Ferreira, Christian Rautert

Nr. 47/2012

Statistical Process Modelling for Machining of Inhomogeneous Mineral Subsoil

Claus Weihs, Nils Raabe, Manuel Ferreira and Christian Rautert

Abstract Because in the machining process of concrete tool wear and production time are very cost sensitive factors the adaption of the tools to the particular machining processes is of major interest.
We show how statistical methods can be used to model the influences of the process parameters to the forces affecting the workpiece as well as the chip removal rate and the wear rate of the used diamond. Based on these models a geometrical simulation model can be derived which will help to predetermine optimal parameter settings for specific situations.
As the machined materials are in general abrasive, usual discretized simulation methods like Finite Elements Models can not be applied. Hence our approach is another type of discretization namely subdividing both material and diamond grain into their Delaunay tessellations and interpreting the resulting micropart connections as predetermined breaking points. Then the process is iteratively simulated and in each iteration the interesting entities are computed.

1 Introduction

Tool wear and machining time represent two dominant cost factors in cutting processes. To obtain durable tools with increased performance these factors have to

Claus Weihs, Nils Raabe
TU Dortmund University, Faculty of Statistics, Dortmund, Germany, e-mail: weihs, raabe@statistik.tu-dortmund.de

Manuel Ferreira
TU Dortmund University, Institute of Materials Engineering, Dortmund, Germany, e-mail: manuel.ferreira@tu-dortmund.de

Christian Rautert
TU Dortmund University, Institute of Machining Technology, Dortmund, Germany, e-mail: rautert@isf.maschinenbau.uni-dortmund.de

be optimized demanding for the investigation of the interactions between tool and workpiece. Unlike ductile materials such as steel, aluminum or plastics, material characteristics for mineral substrates like concrete are difficult to determine due to their strongly inhomogeneous components, the dispersion of the aggregates and porosities, the time dependency of the compression strength etc. (see Denkena et al (2008)). As a result of the brittleness of mineral materials and the corresponding discontinuous chip formation, there are varying engagement conditions of the tool which leads to alternating forces and spontaneous tool wear by diamond fracture.

Despite the manifold of concrete specifications, tools for concrete machining are still more or less standardized, not adapted to the particular machining application. In non-percussive cutting of mineral subsoil such as trepanning, diamond impregnated sintered tools dominate the field of machining of concrete because of the diamonds' mechanical properties. These composite materials are fabricated powder-metallurgically. Well-established techniques like cold pressing with a following vacuum sintering process or hot-pressing, being a very productive manufacturing route, are used for industrial mass production. The powder-metallurgical fabrication process implies a statistical dispersion of the the diamonds embedded in the metal matrix. Additionally, the composition and allocation of different hard phases, cement and natural stone grit in the machined concrete are randomly distributed. Because of these facts, the exact knowledge of the machining process is necessary to be able to investigate for appropriate tool design and development.

To obtain a better understanding of these highly complex grinding mechanisms of inhomogeneous materials, which can not be described solely by physical means, statistical methods are used to take into account the effect of diamond grain orientation, the disposition of diamonds in the metal matrix and the stochastic nature of the machining processes of brittle materials. The first step to gain more information about the machining process is the realization of single grain wear tests on different natural stone slabs and cement.

2 Experimental Setup

To gain information about the fundamental correlations between process parameters and workpiece specifications, single grain scratch tests have been accomplished. Within these, isolated diamond grains, brazed on steel pikes have been manufactured (see Fig. 1, left and middle) to prevent side effects from the binder phase or forerun diamond scratches as they occur in the grinding segments in real life application. To provide consistent workpiece properties high strength concrete specimens of specification DIN 1045-1, C80/90 containing basalt as the only aggregate had been produced. Besides these the two phases, cement binder and basalt were separately prepared as homogeneous specimens for an analysis of the material specific influence on the wear.

To eliminate further side effects such as hydrodynamic lubrication, interaction of previously removed material and adhesion, the experiments have been carried

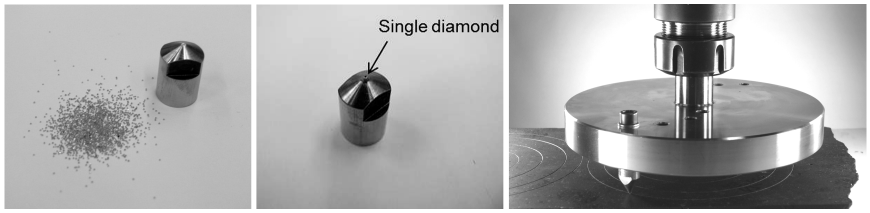

Fig. 1 Sample before and after brazing (left and middle) and scratch test device on basalt (right).

Table 1 Factor Levels of the CCD

Factor	Levels				
d_p	50	80	110	130	
a_p	3.75	5	7.5	10	11.25
v_p	346	525	900	1275	1454

out without any coolant. The brazed diamond pikes had been attached to a rotating disc which in turn had been mounted to the machine (see Fig. 1, right) to simulate the original process kinematic. Parameters for the experimental design were chosen according to common tools and trepanning processes. To guarantee constant depth of cut the rotatory motion of the diamond pike had been superimposed by a constant feed which generated a helical trajectory. To generate a measurable diamond wear, a certain distance had to be accomplished. Therefore a total depth of cut of 250 μm had been achieved in every test.

3 Design of Experiments and Regression Models

In order to investigate the influences of the process parameters to the responses tool wear and forces a series of 92 single grain scratch experiments had been carried out based one a statistical Design of Experiments (DoE). Table 4.1 shows the factor levels of this DoE. Note that because the outer hole diameter d_p (in mm) is not adjustable continuously a twice-replicated Central Composite Design (CCD) of the cutting speed v_p (in rpm) and the depth of cut a_p (in $\mu m/r$) with 7 center point runs had been repeated for each of the four diameter levels.

In a first attempt to provide a basis for the simulation models the results of these experiments had been analyzed by fitting regression models using stepwise forward-backward-selection based on the Akaike Information Criterion taking into account linear, quadratic and two-fold interaction effects. This procedure led to the following equations for average normal and radial forces $\bar{F}_n$ and $\bar{F}_r$ (in N) and for the tool wear measured by the height decrease Δh of the diamond grain:

$$\hat{\hat{F}}_n = 44.025 - 0.524 d_p - 0.351 a_p^2 + 0.062 d_p a_p,$$
$$\hat{\hat{F}}_r = -5.204 + 0.007 v_p + 2.425 a_p - 0.187 a_p^2 - 0.00009 v_p d_p + 0.007 d_p a_p,$$
$$log(\hat{\Delta} h) = -10.67 + 1.386 a_p - 0.069 a_p^2 + 0.00007 d_p^2.$$

The regressors of these models are all significant on a level of 5%, the R^2s are 0.181, 0.236, and 0.131. The low goodness of fit has to be seen in the context of the relatively high reproduction variance, due to which the R^2 values are limited by 0.652, 0.628, and 0.395.

4 Simulation Model

The regression formulas of the previous section had been used to fit the parameters of a geometrical physical simulation model of tool and workpiece. The main idea behind this model is to see the abrasive materials as bonds of microparts which are flattened and broken out during the process. Our approach is to determine these bonds by the Delaunay tessellations of sets of points which are stochastically distributed within the corresponding workpiece or diamond shape (see Fig. 2). Thereby the workpiece is reduced to a ring covering the scratch line to be produced and the diamond is idealized to the shape that is formed when the corners of a cube are flattened, where the amount of the reduction due to flattening is described by two parameters k_k and v_k (see Fig. 2).

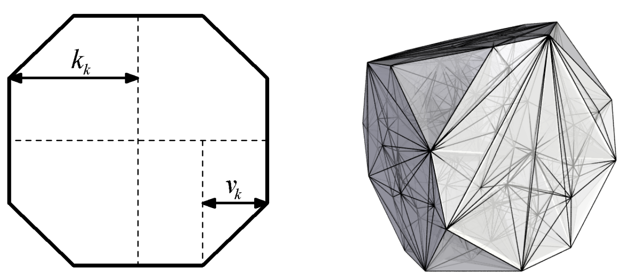

Fig. 2 Edge length reductions and Delaunay tessellations of randomly distributed points.

For the simulation of the process diamond grain and workpiece are adjusted according to the settings of the corresponding machining process leading to initial coordinates of workpiece and diamond vertices S_w and S_k. Then for each iteration i of length t_d (= reciprocal sampling rate) the process is simulated by computing the actual vertex coordinates (by rotating the diamond around the center of the scratch circle and shifting) and the forces which depend on the intersection volumes of a workpiece simplex j with grain vertices and which are distributed to normal and radial forces $F_{n;ij}$ and $F_{r;ij}$. The simplices of the workpiece always break out when hit

Fig. 3 Simulated machined workpiece and Diamond grain.

by a diamond and the continuous wear of the diamond is modeled by decreasing all simplices in action by a specific factor η_k. However, when the mass $w_{w;j}$ of the active workpiece simplex exceeds a threshold defined by the inequality $w_{w;j}\rho_w > \mu_k m_{k;j}$ with a specific constant μ_k, the density ρ_w of workpiece material and mass $m_{k;j}$ of active diamond simplex, the diamond simplex also breaks out. See Raabe et al (2011) for details of the proposed simulation model. Figure 3 shows an exemplary view of a machined workpiece and a diamond grain, for better visualization in unrealistic proportions.

4.1 Model Fitting

For the optimal determination of the unknown simulation model parameters μ_k and η_k and of the reciprocal sample rate t_d a two step procedure is applied (with the other model parameters fixed). In the first step parameters are chosen by minimizing the deviation of simulated and real response data in a statistical design and in the second step the model is calibrated by introducing some process parameter dependent scale terms adjusting for the remaining discrepancy of the equations in section 3 and the corresponding regressions applied to the simulated data.

In the first step, based on a combined design with $8 * 27 = 216$ experiments consisting of the process parameter settings of the cube of the CCD for the two middle diameter levels (see Table 4.1) replicated for each setting of a full factorial 3^3-Design (with levels in Table 2) for the model parameters a quadratic model of the squared deviations of simulated and measured forces is fitted in dependence of the model parameters. By minimizing the squared Euclidian distance between the simulated and realized two-dimensional force vectors the model parameters are estimated by $\mu_k = 10.638, \eta_k = 0.036,$ and $t_d = 39.8$.

In the second step, the model calibration, process parameter dependent scale terms $s_r(v_p, a_p, d_p)$ and $s_n(v_p, a_p, d_p)$ for the simulated forces are introduced to adjust for the remaining systematic model deviations. These scale terms are obtained by fitting the models $F_{r;M}/F_{r;S} = (v_p \quad a_p \quad d_p)\beta_r + \varepsilon_r$ and $F_{n;M}/F_{n;S} = (v_p \quad a_p \quad d_p)\beta_n + \varepsilon_n$. The estimated ratios are taken as the scale terms and are stored as multiplicative factors for the simulated forces.

Table 2 Factor Levels of model parameters

Factor	Levels		
μ_k	5	15	25
η_k	0.01	0.025	0.04
t_d	10	55	100

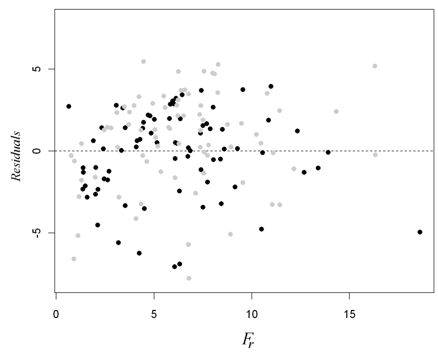

Fig. 4 Comparison of cross residuals for F_r based on measured (grey) and simulated (black) data.

With the simulation model calibrated this way the whole statistical design had been repeated and by comparing the results of this simulation series with the real experiments it can be shown that simulated and real data are very close. This impression is exemplarily emphasized by a comparison of the cross residuals, i.e. the residuals from applying the models for simulated forces to measured forces and vice versa (Fig. 4). Moreover, in order to decide, whether the differences between the models are significant, joint models for simulated and measured forces are fitted. In these models, an indicator variable I_F showing if a specific data point had been measured ($I_F = -1$) or simulated ($I_F = +1$) is introduced both as main effect as well as in interactions with all contained regressors. Since for both forces I_F had no significant influence in the models, neither as main effect nor in any interaction, the results confirm that the same models hold for both simulated and measured forces.

4.2 Extensions

As shown in the previous section the simulation model is able to reflect the process behavior quite well. However, it still neglects some important components namely the adjustment of the diamond and the heterogeneity of the material which causes highly non-stationary processes.

Table 3 Regression models of forces and tool wear

Target	Model	R^2_{loo}
$\bar{F}_n$	$= 44.025 - 0.524d_p - 0.351a_p^2 + 0.062d_pa_p + \varepsilon,\ \varepsilon \sim N(0, 9.458)$	0.118
	$= 16.697 + 0.025v_p - 0.321d_p - 0.003v_pa_p + 0.037a_pd_p + 9.968x + Du + \varepsilon,$ $u \sim N(0, 8.604), \quad \varepsilon \sim N(0, 6.66)$	0.474
$\bar{F}_r$	$= -5.204 + 0.007v_p + 2.425a_p - 0.187a_p^2 - 0.00009v_pd_p + 0.007d_pa_p + \varepsilon$ $\varepsilon \sim N(0, 2.976)$	0.114
	$= 1.408 + 0.009v_p - 0.039a_p^2 - 0.0001v_pd_p + 0.008a_pd_p + 2.35x + Du + \varepsilon,$ $u \sim N(0, 2.36), \quad \varepsilon \sim N(0, 2.35)$	0.300
$log(\Delta h)$	$= -10.67 + 1.386a_p - 0.069a_p^2 + 0.00007d_p^2 + \varepsilon,\ \varepsilon \sim N(0, 1.644)$	0.128
	$= -12.88 + 1.85a_p + 0.000001v_p^2 - 0.057a_p^2 + 0.0003d_p^2 - 0.007a_pd_p$ $-1.02y + Du + \varepsilon, \quad u \sim N(0, 0.914), \quad \varepsilon \sim N(0, 1.329)$	0.24

For the investigation of the first component the influence of the diamonds had been studied by including them into the regression analysis. There, the multi-used diamonds are directly taken into account as random effects D. Additionally the orientation of the diamonds is analyzed (see Tillmann et al (2011)) leading to a pair of coordinates x and y, which are also included in the regression analysis.

By these additions the low Leave-One-Out cross validated multiple correlation coefficients R^2_{loo} of 0.118 ($\bar{F}_n$), 0.114 ($\bar{F}_r$) and 0.128 (Δh) for the three regressions could be improved significantly. By repeating the stepwise model selection with the orientation and diamond data the R^2_{loo} values increase to the values shown in table 3, which also summarizes the corresponding models for each of the target variables.

The second important component that is stated above to be neglected in the actual simulation model is the heterogeneity of the material. This topic will become even more severe when more heterogeneous materials like armored concrete will be studied. The consideration of the heterogeneity demands for the investigation of the force time series. A closer look to these reveals the high non-stationarity of the process. As the scratch lines are concentric circles with fixed radius and the rotational frequency of the tool is also fixed it is possible to reconstruct images of the forces corresponding to the positions of the drilled wall for each process. These images are typically very noisy due to the high variability in measuring the forces and therefore have to be smoothed spatially by an appropriate procedure. Figure 5 shows a typical process signal and corresponding force images where the lower image had been smoothed using local polynomial regression in the x- and y-coordinates.

We plan to include the distributions and equations derived from the investigations of diamond orientation and material heterogeneity into the simulation model to make it more realistic and to be able to test optimization strategies for the machining process in a more reliable way.

Acknowledgement: We thank the German Science Foundation (DFG) for its support in the Collaborative Research Center (SFB) 823.

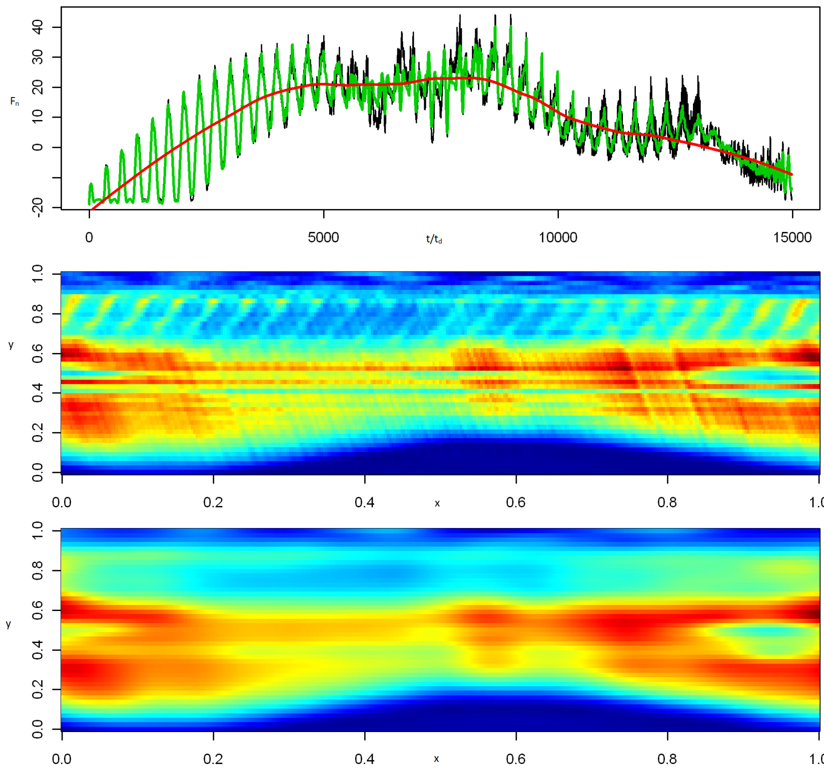

Fig. 5 Top: Exemplary process with time smoothed (red) and spatially smoothed (green) paths. Middle: Force image of drilling wall. Bottom: Spatially smoothed force image of drilling wall.

References

Denkena B, Boehnke D, Konopatzki B, Buhl JC, Rahman S, Robben L (2008) Sonic analysis in cut-off grinding of concrete. Production Engineering 2(2):209–218

Raabe N, Rautert C, Ferreira M, Weihs C (2011) Geometrical Process Modeling of Concrete Machining Based on Delaunay Tessellations. In: World Congress on Engineering and Computer Sciences 2011, vol 2, pp 991–996

Tillmann W, Biermann D, Ferreira M, Rautert C, Raabe N, Trautmann H (2011) Crystal orientation determination of monocrystalline diamond grains for tool application with electron backscatter diffraction (EBSD). In: Euro PM2011 Proceedings, vol 1, pp 265–270

Index