Design and validation of a kinematic numerical dressing model of conventional grinding wheels

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Abstract. Dressing is one of the most critical parameters that determine the efficiency of subsequent grinding processes. In this study, the analysis and validation of the proposal of a kinematic dressing model for the case of conventional corundum wheels is done. In this initial analysis, the accuracy of the model will be evaluated by predicting the abrasive surface after the dressing operation for the case of a single point dresser, observing the deviations made between simulations and experimental results. The results obtained show deviations of 19.2%, 7.57% and 19.69% for the roughness parameters S_q, S_{pd}, and S_{pk} respectively, which will be indicators of the cutting ability of the grinding wheel and will influence on the subsequent grinding process in terms of the surface finish obtained on the finished parts. These results will show the way of future research work, giving useful information for optimizing this numerical model and extending the analysis for different types of dressing tools.

1. Introduction

The grinding process is a manufacturing operation that is mainly used for applications that require high requirements on finished parts; being surface finish, being surface integrity or being dimensional or shape tolerances. In industrialized countries, grinding accounts for 20-30% of the total cost of manufacturing operations [1]. In grinding processes, the abrasive grains located randomly on the surface of the grinding wheel, are used for remaining certain amount of material [2].

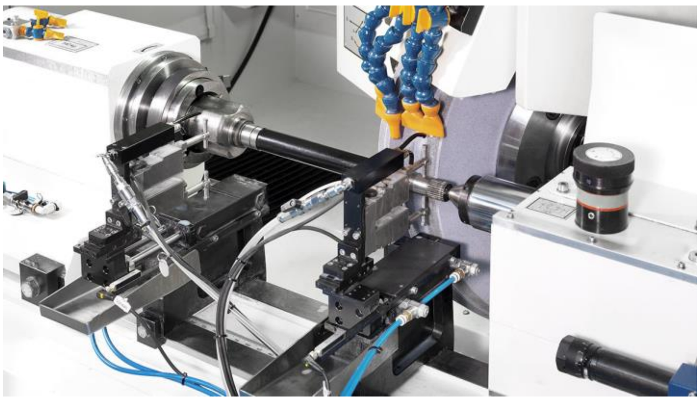

Fig. 1: Outer diameter (OD) cylindrical grinding process [www.danobatgroup.com].

Grinding will be conditioned by the cutting surface condition of the grinding wheel and the arrangement of the grains on the surface, which will affect directly to the cutting ability of the wheel. This fact will have influence on the cutting forces, temperatures and wear of the wheel that occurs during grinding. As a consequence of wheel wear, the topography of the grinding wheel will vary as the grinding process goes on. That is, the surface condition of the wheels is not constant due to wear or dullness of abrasive tools. In order to restore the optimum cutting ability of the grinding wheel, dressing operation is necessary. This operation is based on eliminating worn grains and dull material from the abrasive surface, generating new and sharper cutting edges on the grinding wheel surface. Although at the research level there are multiple dressing solutions, the most common and flexible solution in the industry is the mechanical dressing of abrasive wheels, which consists on transforming the surface of the grinding wheel with the help of a diamond cutting tool.

Knowing that the surface condition of the grinding wheel is one of the key parameters that determines the grinding operation and surface integrity of the ground parts, many authors have tried to characterize the wheel surface condition based on roughness measurements. Among others, Nguyen and Butler [3] related areal roughness parameters S_q, S_{ds} and S_{sc} with grinding behavior, based on the evaluation parameters marked by DIN ISO25178 standard. Their main contribution, was to relate the S_q with abrasive grains protrusion on grinding wheel external surface, S_{ds} with a potential number of active grains on the grinding process and S_{sc} with the abrasives sharpness.

Recently, Barth & Klocke [4] related the surface condition of grinding wheels, measuring its topography and evaluating the thermo-mechanical behavior of the wheel along the grinding process. For this analysis, wheel surface parameters related to Abbott-Firestone curve as S_{pk}, and V_{mp} where correlated with temperatures reached during grinding operation.

Brinksmeier and Cinar [5] defined that the active surface of the wheel depended directly on the number of collisions (i_d) of the cup roller dressing operation, where the parameter i_d defines the number of collisions. Linke [6] developed this concept to extend Brinksmeier’s work to stationary and roller dressers.

Noticed that dressing operation affects significantly the topography of the wheel, some researchers have tried to predict the resulting topography on a grinding wheel after dressing operation, in order to get useful information about grinding wheel surface condition.

With the intention of characterizing the surface of the wheel after dressing operation, Chen et al. [7] made the first 2D dressing model where they assumed the grain fracture depends on the interaction area between the abrasive grain and the trajectory of the single-point dresser. Later, taking this model as a reference, Darafon [8] optimized the previous model by extrapolating it to a 3D modelling.

Other authors such as Baseri [9] or Chowdhury [10] have tried to characterize the topography of the abrasive surfaces for the case of a rotary dresser. Main contribution of Chowdhury [10] was that his model allowed estimating the trajectories of the diamonds of the brazed rotary dresser after several dressing passes based on the kinematics of the process. He concluded that contact length of the dressing process is larger in up-dressing operations and less number of dressing passes are needed at same speed ratio for dressing effectively if up-dressing strategy is adopted. However, they did not characterize the abrasive grains of an abrasive surface, assuming a totally flat grinding wheel surface.

Generally, the resulting topographies of the dressing models, serve as "input" of another grinding numerical model, so the “outputs” of these models are helpful to predict variables of the grinding process (forces, temperatures, surface finish…). However, all these numerical models have very specific and case-limited applicability due to the multiple and stochastic variables that dressing and grinding processes have.

Therefore, in this document, it is presented a dressing model that aims to reproduce the active topography of the grinding wheel, adding the possibility of introducing different type of dressers and a wide range of kinematical dressing parameters.

2. Numerical model description

2.1. Contextualization, limitations and goals of the dressing model. This article describes a proposal for a numerical dressing model that aims to predict to the surface condition of a conventional vitrified grinding wheel. The model consists of two main steps: characterization of the grinding wheel topography based on wheel characteristics (section 2.2), and estimation of the path followed by the dresser taking into account the geometry of the diamond and technological dressing parameters (section 2.3). As a result of the model, the dressed surface of the modelled wheel is obtained considering the dressing process as interaction of rigid bodies where the diamond removes all the abrasive material that is in its trajectory.

Being able to predict accurately the topography of a certain wheel according to dressing parameters, will give to the user lots of information, allowing to estimate behavior of grinding operation by visualizing the effects generated by dressing process, helping to select the best wheel or dresser specifications and reducing considerably manufacturing set-up times and the number of tests in part validation phase.

In section 3, a quantitative method to compare the numerical model with surfaces real dressed wheels will be detailed.

2.2. Main Assumptions. The stochastic nature of abrasive tools and the enormous variety of grinding wheels and dresser configurations adds complexity generate a predictive tool which will be able to predict dressed wheel topography for all the cases. That´s why this paper focuses on the case of single-point dressing of vitrified corundum grinding wheels. Also, some simplifying assumptions where adopted to afford the chaotic nature of abrasive surfaces:

- Spherical grain shape was assumed. So, the model responds better for reduced aspect ratio grain geometry.
- Bonding material and pores of abrasive tool are not considered on simulations.

2.3. Grinding wheel characterization. The first step of this model consists on the characterization the grinding wheel surface based its specifications. Taking Hou and Komanduri's [11] as reference, the size and special distribution of the abrasive grains experimentally through statistical approximations. They related the average size of the abrasive grains of the surface with the number of the grain size that appears in the specifications (M) of the corundum and silicon carbide wheels (Eq. 1):

$$dg_{mean} = 28.9 * M^{-1.18}. \qquad \{1\}$$

They also estimated the density of grains on grinding wheel surface, and related it to the structure number and the average grain size of the grains:

$$N_a = (\frac{10}{dg_{mean}} * V_g^{\frac{1}{3}})^2. \qquad \{2\}$$

where, $V_g = 0.02(32 - S)$ and S is the structure number of conventional wheels.

Malkin [4] assumed that the grain sizes of a grinding wheel followed a normal distribution according to its specifications, where the standard deviation of the distribution would satisfy Eq. 3:

$$\sigma = \frac{d_{g\_max} - d_{g\_min}}{6} \,. \qquad \{3\}$$

where,

d_{g_max}: next sieve (larger) than the indicated on the wheel specifications.

d_{g_min}: next sieve (lower) than indicated on the wheel specifications.

In turn, another variable to consider for the characterization of the wheel surface condition is the grain spacing. In this case, based on grain density data, a shaking-process proposed by Koshy [12] is performed. In case of assuming a spherical geometry of the abrasives, it consists of randomly distributing the abrasive grains on the surface of the grinding wheel to meet the non-overlapping condition (Eq. 4):

$$(\frac{x_i - x_{i+1}}{2})^2 + (\frac{y_i - y_{i+1}}{2})^2 + (\frac{z_i - z_{i+1}}{2})^2 \geq (\frac{d_{g\_i} - d_{g\_i+1}}{2})^2 \,. \qquad \{4\}$$

Based on this bibliographic analysis, the active surface of conventional wheels has been characterized for subsequent dressing process analysis (Fig. 2):

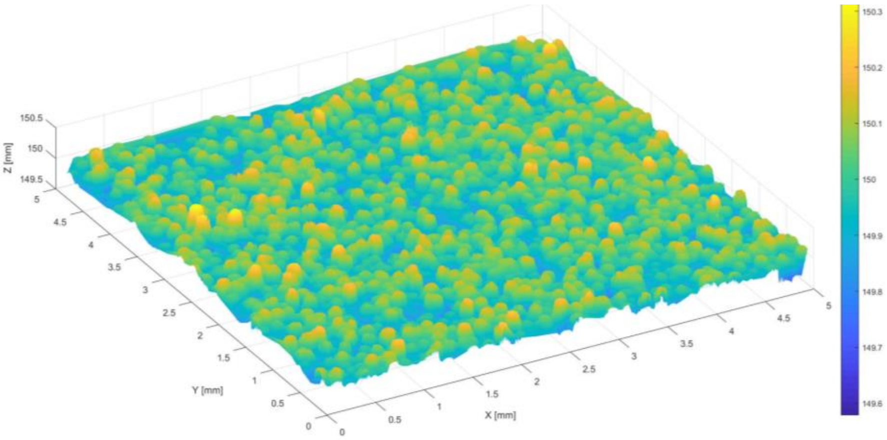

Fig. 2: Ø300mm, grit size 100 and structure number 8 wheel surface characterization.

2.4. Dressing trajectories estimation. In accordance with the Darafon [6] dressing model, the geometrical profile of the diamond will be incorporated as input parameter, which will be measured using a Sensofar PluNeox 3x confocal microscope, approximating the measured profile to a 6th order polynomial.

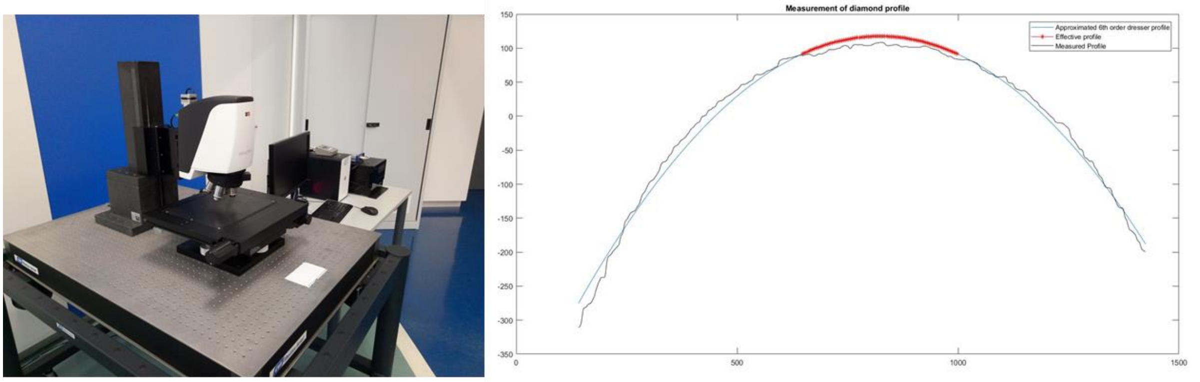

Fig. 3: Single-point dresser profile measurement and its characterization.

Once characterized the geometry of the dresser, based on the profile of the dresser and selected dressing parameters, eq. 5 will determine the path of the diamond over the grinding wheel, where parameter i is related to time step and parameter j is related to measured diamond profile discretization. Thus, dresser profile location for each time step should be determined by following equation system, where PHI, Z and RHO are the arrays that define the location of dresser profile in cylindrical coordinates.

$$\begin{aligned} PHI(i,j) &= n_s * t(i)[rad] \\ Z(i,j) &= v_d * t(i) + x_{dress}(j)[mm]. \\ RHO(i,j) &= z(i) - y_{dress}(j)[mm] \end{aligned} \quad \{5\}$$

where, x_{dres} and y_{dress} are profile coordinates of measured diamond in axial and radial directions (Fig. 3), n_s is the turning speed of wheel and v_d the transversal feed of the dresser.

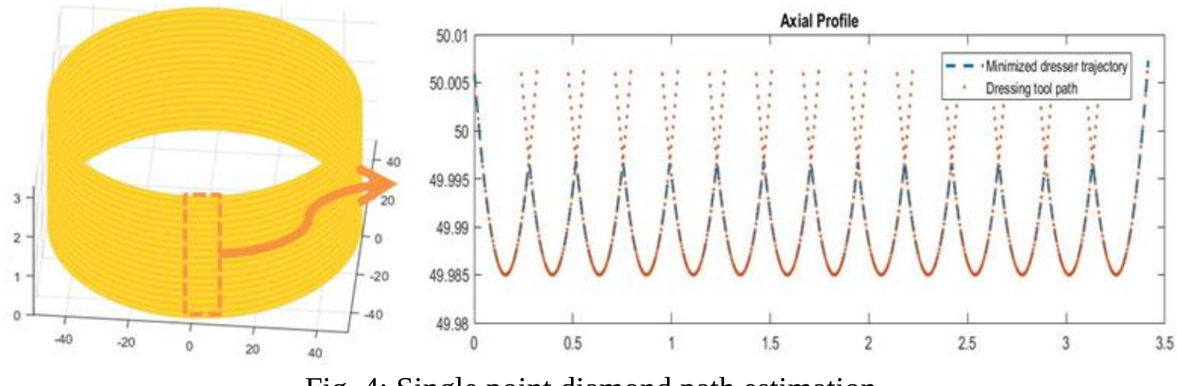

Fig. 4: Single point diamond path estimation.

3. Experimental and measurement tests methodology.

3.1 Selecting parameters for surface analysis. Areal roughness parameters such as R_q and R_{pk} will be evaluated, which in turn are related to the heights of the active grains in the wheel. In addition, another parameter such as the S_{pd}, which is an indicator of the density of active grains, will also be evaluated. In addition, volume parameters described by BAC curve will be evaluated in order to prove the efficiency of the numerical model.

For comparing simulated surfaces with the real ones, a set of dressing experiments was planned (section 3.2).

3.2 Dressing experiments. For experimental tests was used a grinding conventional corundum wheel with specifications MA100IJ8V489 and dimensions Ø250x50xØ127mm manufactured by Abrasives Unesa S.L.

A key parameter that will determine the topography of the wheel after the dressing process is the area of intersection between diamond and abrasive grains [4]. This will be strongly influenced by the feed of dresser tool and the tool geometry. Therefore, dressing tests were planned varying the transversal feed speed of a single-point dresser along the grinding wheel width (Fig. 5). The dressing parameters of the tests are shown in Table 1:

Table 1: Dressing parameters of experimental tests.

Zone	Width [mm]	ns (rpm)	Vs (m/s)	Vd (mm/min)	fd (mm/rev)	bef (mm)	Ud(-)
A	0-12.5	2000	25,88	2000	1	0,6	0,6
B	12.5-25	2000	25,88	1200	0,6	0,6	1
C	25-37.5	2000	25,88	300	0,150	0,6	4
D	37.5-50	2000	25,88	150	0,075	0,6	8

Note that large variety of the overlapping ratio (U_d) was utilized in the tests. This parameter depends on dresser tool profile shape and on the axial feed of the dresser. Its value is the ratio between effective width of the diamond divided by axial feed per revolution of the grinding wheel (eq. 6).

$$U_d = \frac{b_{ef}}{f_d} \quad \{6\}$$

where b_{ef} is the effective width of the diamond tool at established dressing depth and f_d is the axial feed of dresser per revolution of the wheel.

Once the diamond passes are completed, the grinding wheel was dismantled and 3 samples of the grinding wheel surface were collected for its topography analysis. Each sample contains 4 zones dressed by different feed. Therefore, 12 measurements were made at all by confocal microscopy.

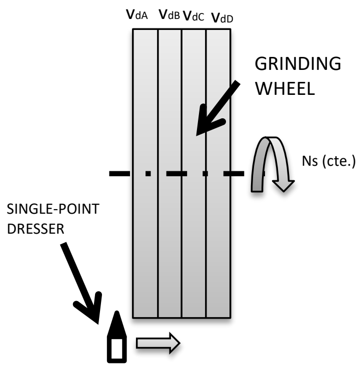

Fig. 5: Dressing test disposal.

3.3 Surface Measurement methodology. Abbott-Firestone curve of surfaces could be used for filtering the abrasive surfaces in 3 different areas to stay with the desired area of interest: peak zone, core-zone and valley-zone. Considering that simulation returns the topography of a dressed wheel at the peak zone and in order to compare correctly the simulated surfaces and measured ones, in case of measured dressed surfaces it was necessary to eliminate the influence of pores and bonding material of measured surfaces.

Thus, it has been decided to filter measured surfaces by heights, subtracting all the measured points below 63µm (Fig. 6). Note that 63µm is the half of the 100-grit grain size of conventional grinding wheels according to eq. 1.

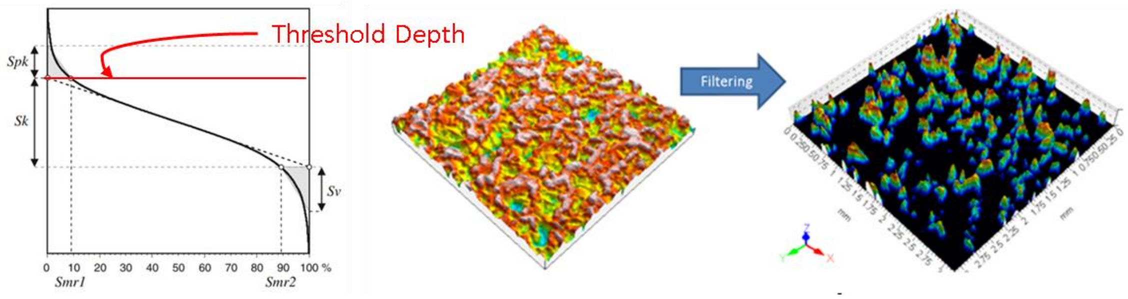

Fig. 6: Example of BAC curve and filtering measurement of abrasive surface.

4. Results

This section, compares measurements obtained by simulated and measured surfaces. In Fig. 8 the results of S_q parameter are shown. These results show that in speed values of $U_d<2$ value of simulated S_q is lower than measured value, while for values $U_d>2$ simulated S_q is higher. The reason that S_q value increases with a reduction of transversal feed is that active wheel surface is assumed to be 63µm in depth. Following this criterion, at low U_d values effective area of dresser increases and more material is removed from abrasive surface, generating less peaks on the active surface of the wheel (Fig. 11).

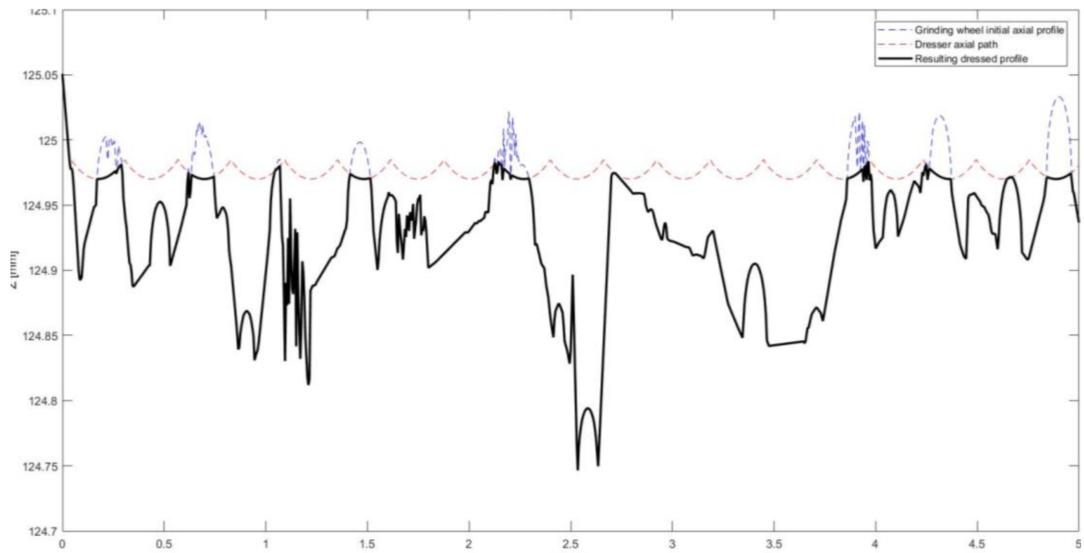

Fig. 7: Dresser path in axial direction and wheel active surface interaction (Ud=1.5).

Another assumption of the model consists of all material crossed by dressed is removed from wheel surface. However, at real surfaces fragile fracture of grains and grit subtraction of abrasives occurs and this effect is increased at high transversal speed or low values of U_d. That could be one of the reasons which explain the lower variability of real surface referring to S_q parameter.

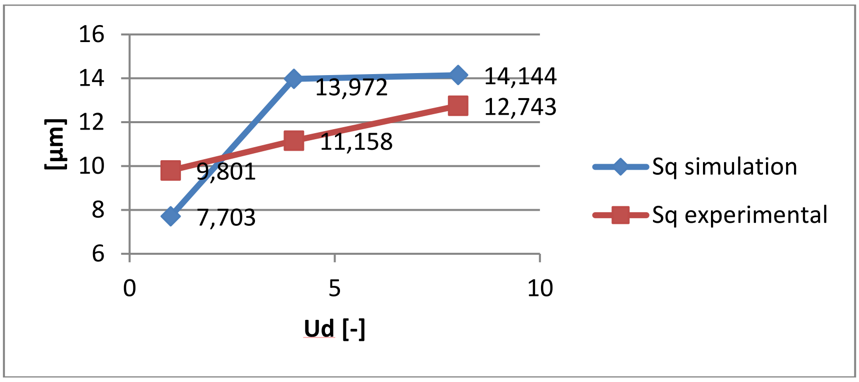

Fig. 8: Comparison of simulated and measured S_q parameter.

Fig. 9 shows the comparison of the number of active grains (S_{pd}) on the peak zone of the grinding wheel. Looking to that figure, it´s possible to conclude that the simulation estimates accurately the number of peaks in all range of feeds analyzed ($1<U_d<8$), where the mean deviation of S_{pd} between both curves is 7.57%. Also, in case of S_{pd} parameter, measured experimental surfaces show lower variability than simulated surfaces. This aspect could be related to fragile fracture which attenuates the resultant surfaces removing the sharper edges form the abrasive surface.

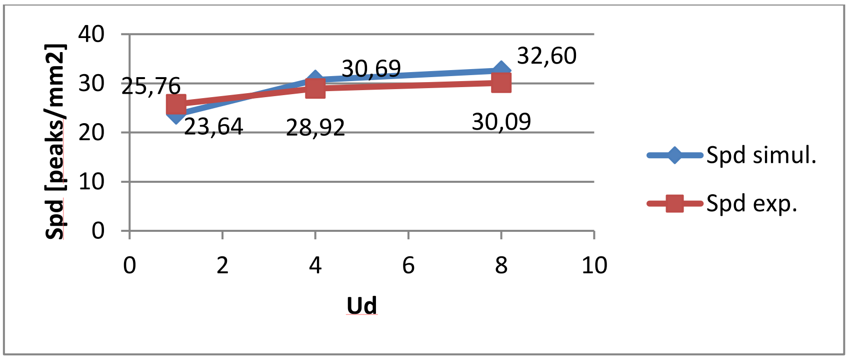

Fig. 9: Comparison of simulated and measured S_{pd} parameter.

Furthermore, an important S_{pk} parameter was analyzed on Fig. 10. This parameter represents the average height value of active grains on the active part of the wheel. Analyzing deeply the figure, the correlation between simulated and measured values is good, having the main error around 20%. For simulation, S_{pk} values are lower in all cases, and deviation is reduced for high values of U_d parameter. That means the peaks are more protruded in measured surface, especially for low overlapping ratios. The deviation of S_{pk} parameter is mainly related to errors produced at grinding wheel characterization. A solution for getting a better approach of grain heights can be to change the shape of abrasive grains increasing its aspect ratio a certain value.

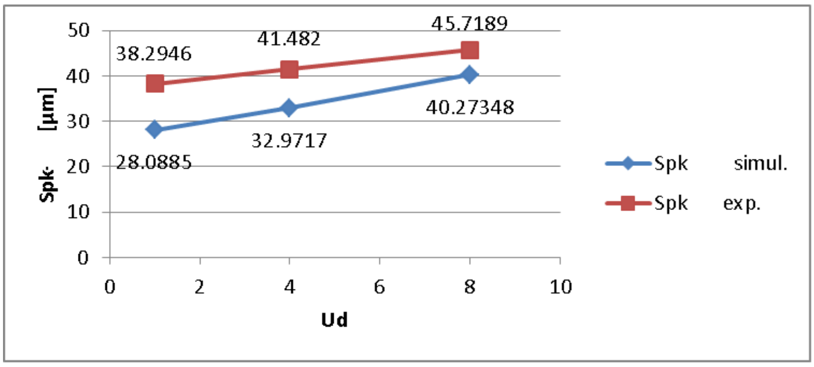

Fig. 10: Comparison of simulated and measured S_{pk} parameter.

The BAC curves comparisons of Fig. 11 show the volumetric deviations of active part of the wheel, at different overlapping ratios. Based on the shape of the analyzed curves, it is possible to conclude that real surfaces show lower cumulated material at filtered depth (63µm). Also, it could be seen that for U_d=1 the material volume in the external zone of the curve is higher for real surface. This aspect is closely related to S_q parameter, where its value is higher for measured real surface. For U_d=4 and U_d=8 simulated curves are situated mainly on the right compared to curves of real surfaces, where the percentage of the cumulated material is more at the same height. These results are consistent with the previous ones, where S_q results are higher for simulated topographies at U_d>2.

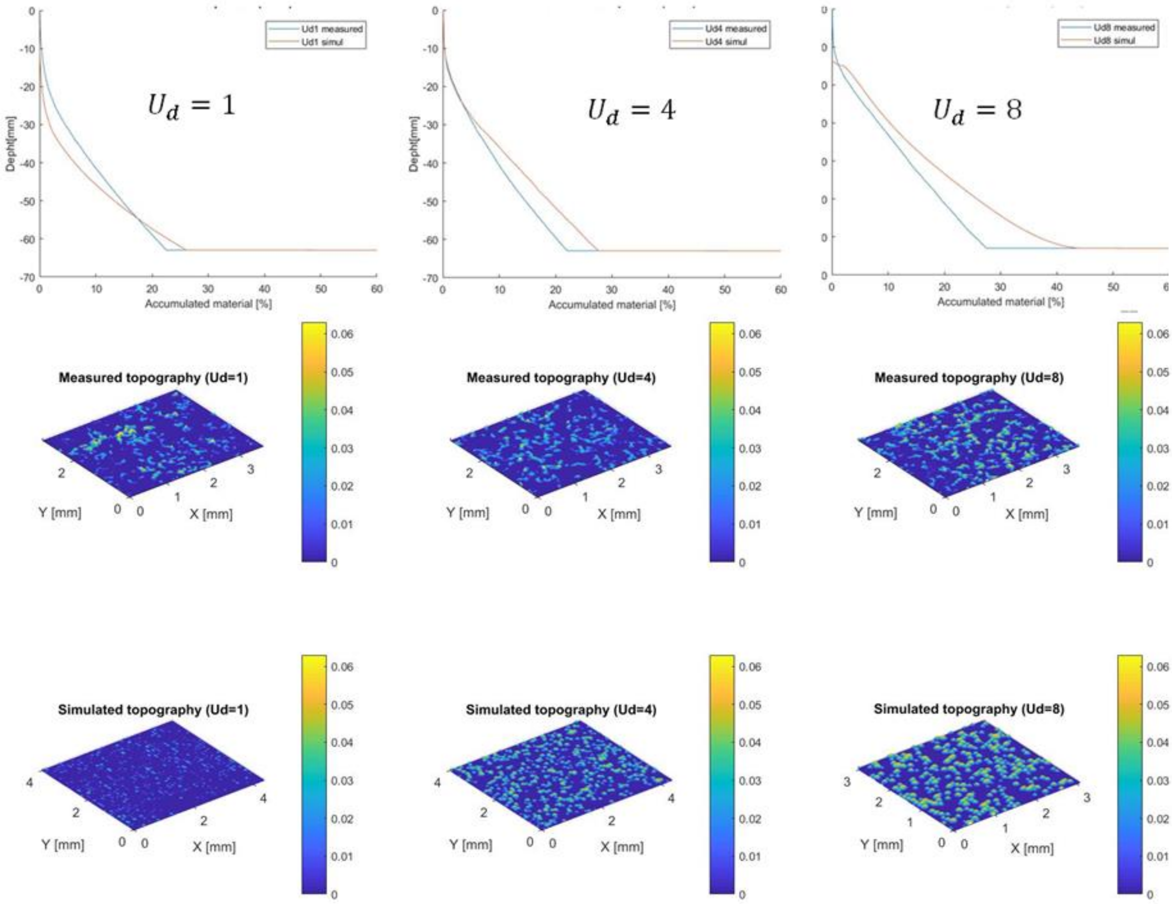

Figure 11: Comparison of measured and simulated BAC curves and 3D topographies.

Viewing the BAC curves, consider that the value of parameter M_{r1} and S_{pk} is higher for simulated surfaces in all cases. That means simulated and real abrasives shapes is not equal, even if the error made by S_q and S_{pk} parameter is less that 20% in relative values.

Also simulated and measured 3D topographies are shown in the same figure. It´s visually noticed that simulated grit density is slightly higher compared to real surfaces and show more homogeneity in their size. As it was mentioned when S_{pk} parameter was analyzed, a proper way to reduce deviations produced could be to change the geometry of the abrasive grits increasing its aspect ratio.

5. Conclusions and future work

In this study a relatively simple first approach of dressing mechanism was developed and evaluated its validity for the case of single-point dressing of conventional corundum grinding wheels. This tool will permit predicting the topography of dressed grinding wheel, which will be helpful to predict the behavior of the subsequent grinding process and approximating the final surface condition of ground part after grinding operation.

For resume the results shown in the document, it´s possible to conclude the following:

- The model represents the trends of real dressed grinding wheel in terms of number of active grains (S_{pd}) with 7.57% deviations between simulated and measured data. The increasing value of S_{pd} indicates more active grains are generated at high U_d values.
- Also, the relative deviations produced between model and simulation for S_q and S_{pk} are below 20%.
- The BAC curves comparatives show an increasing value of curmulated material when U_d value increases. Also the M_{r1} values for simulations are higher for all cases. The relative positions of curves between simulated and real surfaces is directly related to the difference of S_q parameter.
- According to the analysis of Fig. 11, changing the shape of abrasives from spherical to another shape with a more elevated aspect ratio could reduce deviations produced related to grain protrusion.

Even if aformentioned adjustements can be done to increase the accuracy of the model, the trends and effects produced by dressing feed are reproduced by the model. This work has been a first stage in validating a proposal of a numeric model of dressing process based on a simple kinematical approach.

Analyzing the results, it may be concluded that in single point dressing, transversal feed has a great influence on wheel topography. Intersecting area between diamond and abrasive grains of the wheel surface has a vital role at dressing operations, and this affects on abrasive grains wear mode. Accuracy of the developed dressing model increases at low transversal feed rates where less fragile fracture and grain breakout is expected. A proper way to reinforce these assumptions could be to register dressing forces or collecting and measuring the size of the abrasive material removed at dressing operations. Based on obtained results, the intention is to increase the model accuracy by two criteria:

- Removing sharp edges from the simulated surface.
- Increasing aspect ratio of abrasives.

Once the accuracy of model is optimized by these adjustments, the applicability of the numerical model should be extended for the case of different types of dressing tools, such as the case of an infiltrated rotary dresser, where another dressing parameter, q_d, will affect markedly the generated active surface of the grinding wheel, in order to develop an attractive product to manufacturing industry.

6. References

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