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Discussion Paper

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The influence of different diamond spacings in diamond impregnated tools on the wear behavior and material removal

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Abstract

The influence of the spacing of four diamonds on the breakout time and material removal is investigated for a diamond impregnated tool for machining concrete workpieces. A statistical analysis using the Cox-model shows a positive effect of larger spacings on the lifetime of the diamonds where no effect on the material removal can be found. Moreover, a relationship between the position of the diamond and its lifetime is observed.

Keywords: Diamond impregnated tools, deterministic diamond placement, concrete machining, lifetime analysis, Cox-model, material removal.

1 Introduction

Within the large area of the construction industry, as well as natural stone extraction and further post-processing applications, diamond impregnated grinding segments are firmly established as cutting and grinding tools. Due to the high abrasive mineral materials, the demands concerning the wear resistance and the cutting performance of such diamond-metal composite tools are very high. Therefore, the used composite materials consist of synthetic diamonds, which are embedded in a metallic matrix with a concentration between 5 and 10 vol-%. These corresponding diamond segments which are attached on drill bits, wire saws or blade saws by means of brazing or laser welding are fabricated near-net shaped in a powder metallurgical process route such as vacuum sintering and

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hot-pressing [1, 2, 3, 4, 5, 6, 7].
The main metallic powders which were used for the production of diamond tools mainly consist of cobalt, iron and combinations of iron, copper and tin [8, 9, 10, 11].

The conventional method of producing metal powder diamond mixtures consists of a purely random distribution of the diamonds, which is realised by means of a homogenisation process in a multi-axis mixer. This procedure also leads to a purely stochastical exposure of embedded diamond grains during the grinding process with diamond tools manufactured in this way. However, in order to ensure more uniform diamond exposure and consequently better control during the machining process, current developments in the production of diamond metal matrix composites aim to position the diamonds in a targeted and orderly manner across the entire volume of the segment [12, 13].

In previous publications, the lifetime of more than 14 randomly distributed diamond grains on a drilling tool was analyzed using statistical methods based on parametric maximum likelihood approaches by assuming independent and exponentially distributed lifetimes of the diamond grains [14, 15].

In the study presented in this paper, the number of diamond grains on a tool is reduced to four and the influence of a deterministic placement on the lifetime and material removal is investigated. The study shows that larger spacings between the diamonds provide longer lifetimes of the diamonds but do not influence the material removal. Moreover, a relationship between the position of a diamond and its lifetime was observed so that the assumption of [14, 15] concerning independent and identically distributed lifetimes of the diamonds on a tool may not be correct.

Section 2 provides the experimental setup and the statistical analysis is presented in Section 3. These results are summarized and discussed in Section 4.

2 Experimental setup

This chapter describes the technological methods used for the fabrication of specific diamond segment samples, the machining process on a concrete cylinder and the analyses of the diamond loss and wear characteristics.

2.1 Sintering of samples with precisely positioned diamonds

The specimens used for the machining tests and the wear analyses of the single diamonds are made of a standard DiaBaseV21 powder from Dr. Fritsch GmbH & Co. KG, which consists of 50-80 % Fe; max. 15 % Co; 10-25 % Cu; max. 5 % Sn; max. 2 % P. To obtain suitable powder greenbodies for the subsequent diamond positioning, this metal powder is compacted using a uniaxial cold press. The green compacts had a rectangular geometry with a cross-sectional area of 10 mm x 8 mm and a maximal height of 17-20 mm. Afterwards, four monocrystalline synthetic diamonds, each with a grain size of 20/30 us-mesh (600-850 µm), were positioned on the surfaces of the pressed greenbodies using a special perforated plate system and were pressed into the surface of the green compacts. In total, five different setting patterns (1, 2, 3, 4, 5 with different horizontal (value A) and vertical (value B) diamond spacings, see Figure 1) with the feed rate $f = 0.15$ mm and the cutting velocity v_c= 120 m/min were applied. The exact diamond spacings in mm are shown in Table 1.

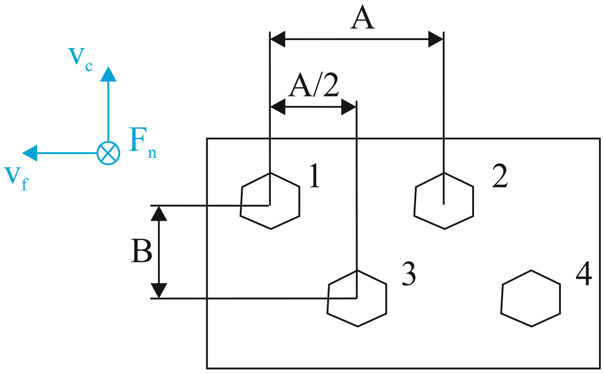

Figure 1: Diamond arrangement on the metal surface

perforated plate	A [mm]	B [mm]	AB [mm^2]	# exp.
P1	1	3	3	9
P2	1.5	3	4.5	8
P3	3.5	3	10.5	9
P4	1	1.5	1.5	8
P5	3.5	1.5	5.25	6

Table 1: Diamond spacings set by five different perforated plates and the number of experiments

Figure 2: Cold pressed powder greenbodies with positioned diamonds

The samples of the different perforated plates are referred to as P1 to P5, respectively. For the statistical analysis, the distances in A and B are defined as 'small' and 'large' distances. Note that P1 and P2 are expected to behave similarly since the horizontal and vertical distances between the diamonds are almost equal. The smallest distances, and thus the smallest area between the diamonds, can be observed with P4. P5 has a similar area to P1 and P2, but the horizontal distance is greater, instead of the vertical distance. P3 has larger distances for both directions and thus the largest area between the diamonds.

In the final manufacturing step, the cold-pressed green compacts (Figure 2) were placed in a suitable electrically heatable graphite die and were sintered in a hot press at 840°C and a holding time of 3 minutes. The uniaxial mechanical pressure on the graphite punches was 51 bar with a sintering area of 12.8 cm^2.

2.2 Setup

For the lifetime analysis of the diamond impregnated segments with arranged diamonds, a force controlled experimental setup was used. The experimental setup was installed on a conventional lathe from Boehringer. For the experiments it was necessary to establish the tool holder with an electric magnet, a carriage guide and a 3-component force measurement. The electric magnet is subjected to a constant voltage and constant current. Hence, the tool is pressed onto the surface of the workpiece with a constant passive force of $F_p = 20\,\mathrm{N}$.

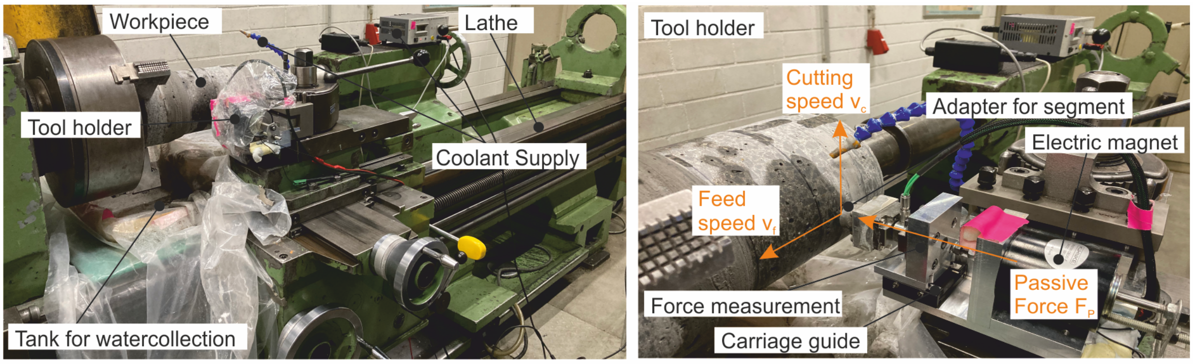

Figure 3: a) Experimental setup and b) force measurement

Two concrete cylindrical workpieces with a diameter of $d_c = 220$ - $185\,\mathrm{mm}$ and a length of $l_c = 300\,\mathrm{mm}$ are used. The concrete has a compressive strength of C100/115, $100\,\mathrm{N/mm^2}$ for cylindrical workpieces and $115\,\mathrm{N/mm^2}$ for cubes. For this high-strength concrete only Basalt stones are used as aggregate. Furthermore, water is used as coolant supply. To avoid damaging the machine, a tank to collect the water is installed. The experimental setup is shown in Figure 3.

The concrete workpiece with cylindrical shape is prepared with a special grinding tool before use. To achieve the constant passive force $F_p = 20\,\mathrm{N}$ and speed velocity $v_c = 120\,\mathrm{m/min}$, the numbers of revolutions per minute (rpm) were adjusted continuously. A constant feed of $f = 0.15$ mm was set for the feed movement. The diamond impregnated segments are used until a distance of $d = 3000$ m is reached or until all diamonds are broken out. During the experiments, problems occurred when all diamonds on the surface were broken out. Hence, the experiments were already finished with only one diamond left.

2.3 Measurement methods of wear behavior and material removal of concrete

Different measurement methods were used to investigate the influence of the five different deterministic diamond distances on the wear behavior and the material removal of concrete.

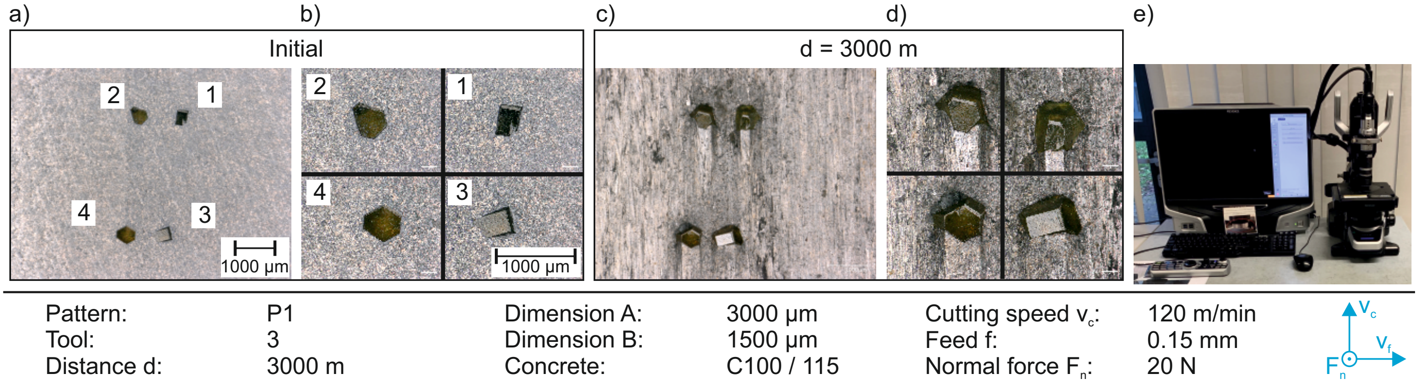

Figure 4: Wear behavior a) diamond impregnated tool before the experiment, b) high resolution of the four diamonds before the experiment, c) diamond impregnated tool after distance d = 3000 m, d) high resolution of the four diamonds after distance d = 3000 m and e) digital microscope Keyence VHX5000

To analyze the wear behavior in these experiments two-dimensional data based on microscopic pictures were collected at several inspection times. For the analysis of the wear behavior, inspection times are set after a distance of $d = 250$ m$, 500$ m$, \ldots, 3000$ m. After each inspection time a digital microscope from company dnt Innovation GmbH is used to check whether the diamonds are still active. After $d = 500$ m, 1000 m$, \ldots,$ 3000 mm two-dimensional pictures with a digital microscope VHX5000 from Keyence Deutschland GmbH were taken. This microscope allows higher resolution data. Figure 4 shows exemplary tool number 3 for pattern P1 and the wear behavior over the distance of $d = 3000$ m. Note that the removed concrete leads to wear of the bond and the diamonds. Furthermore, a polliwog tail forms behind the active diamond due to the wear of the metallic matrix. The diamond breaks out if it can no longer be held in the bond. High mechanical forces can also cause wear of the diamonds in form of cracks or chipping.

The removal of the material was detected after $d = 500$ m$, 1000$ m$, \ldots, 3000$ m. In order to analyze the material removal, it was favorable to measure replicas of an area of the concrete workpiece because of the workpiece's shape, see Figure 5 a). These replicas can be digitalized and profiles of the material removal can be created, see Figure 5 c). The software μsoft analysis from NanoFocus AG enables the evaluation of the profile. This method provides quantitative and qualitative data of the with different diamond impregnated segments generated hollows on the workpiece surface. For the replicas, Reprint 1000 from Cloeren Technology GmbH was used. The measurements were conducted using Alicona InfiniteFocus G5, see Figure 5 b).

The tool holder prepared with an electric magnet, a carriage guide and a 3-component force measurement led to challenges during the experiments. Despite a cover on the

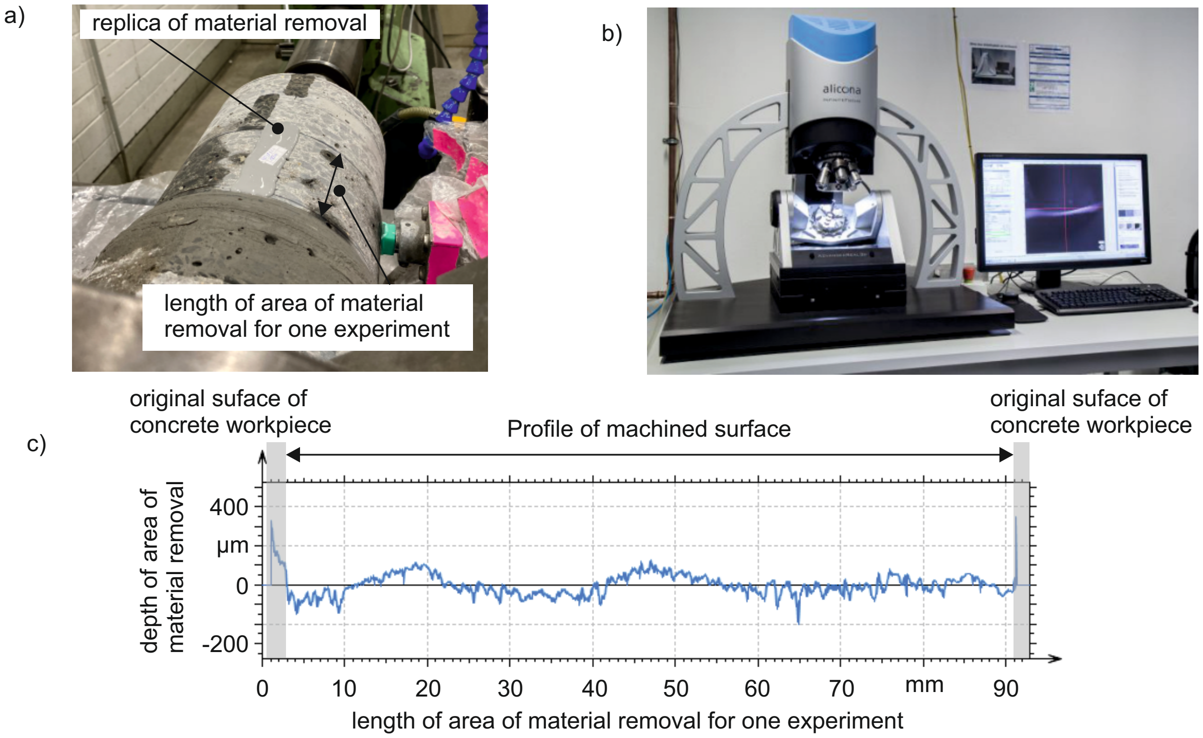

Figure 5: a) Creation of replicas of the machined surface, b) Alicona InfiniteFocus G5 and c) Profile of machined surface for analysis of material removal

device, the carriage guide does not slide freely. The ball cages were damaged so that the carriage guide had to be replaced during the tests. The guide play had to be adjusted on the new carriage guide over a considerable period of time. In addition, there are pores in the concrete that can affect the material separation. Larger pores were filled in, while smaller pores continued to exist.

3 Statistical analysis

The wear of the regarded tools mainly depends on the time points when the four diamonds break out. Therefore, the statistical analysis of the wear behavior is based on these failure times (lifetimes) of the four diamonds in Section 3.2. The used statistical methods of lifetime analysis follow [16]. Moreover, the relationship of the position of the diamonds and their lifetime is of interest so that a χ^2-test is applied for testing the independence of the diamond position and the lifetime in Section 3.3. In Section 3.4 the influence of the different perforated plates on the material removal is discussed. The applied `R`-functions [17] for the statistical analysis will always be given.

3.1 Overview of the data

Five types of perforated plates with different configurations of diamonds are used as given in Table 1. Since the horizontal distance A and the vertical distance B between the

perforated plate	1^{st}	2^{nd}	3^{rd}	4^{th}
P1	0	3	5	6
P2	1	2	3	4
P3	1	2	3	3
P4	0	1	1	7
P5	1	2	2	3

Table 2: Overview of the number of experiments with right-censored data for the event of the first, second, third and fourth diamond breakout

diamonds can be varied, data with all four different combinations, i.e., small and large distances for horizontal and vertical direction, should be collected. This variation is also necessary for computing models with both explanatory variables and their interaction. In particular, P4 has small distances in both directions, P3 has two high distances and the other plates have one small and one high distance, as shown in Table 1. In sum, 40 experiments were carried out. In these experiments, the time points with first, second, third and fourth breakouts of the four diamonds were studied separately. In some experiments even the first breakout has never been observed. However, more frequently the second, third or fourth breakout were not observed. All these not observed breakout times lead to so-called censored lifetimes. These censored lifetimes occur if an experiment has already taken too long or due to technical problems. Table 2 gives an overview of the number of censored lifetimes. For five experiments (P1, P2, P5 once and P3 twice), the microscopic pictures were not taken so that the lifetime of the diamonds could not be analyzed for them. Hence, only 35 experiments are used for the analysis of the wear behavior.

3.2 Analysis of the lifetimes of diamond breakouts

The following two questions will be investigated:

1. Do the lifetimes behave differently under different configurations of diamonds?
2. Can a suitable model for the lifetimes be derived with the distances and area between the diamonds as explanatory variables?

At first, the reliability functions (given the probability that the lifetime of an object is larger than a given time point) are estimated seperately for the different configurations of diamonds by the Kaplan-Meier estimator with `survfit()` from the package `survival` in `R` [18]. Figure 6 presents the Kaplan-Meier estimations of the reliability functions for the first, second, third and fourth diamond breakout.

The figure shows that the estimated reliability functions of P1, P3 and P5 are similar and the lifetimes are the highest for the event of the first, second and third diamond breakout for these plates. The reliability function of P4 decreases more quickly than that of the other plates, especially for the third diamond breakout. P1 and P2 behave similarly for the second and third diamond breakout, which is plausible since the distances between the diamonds are almost equal. The lifetimes of P1 and P2 are further nearly as good

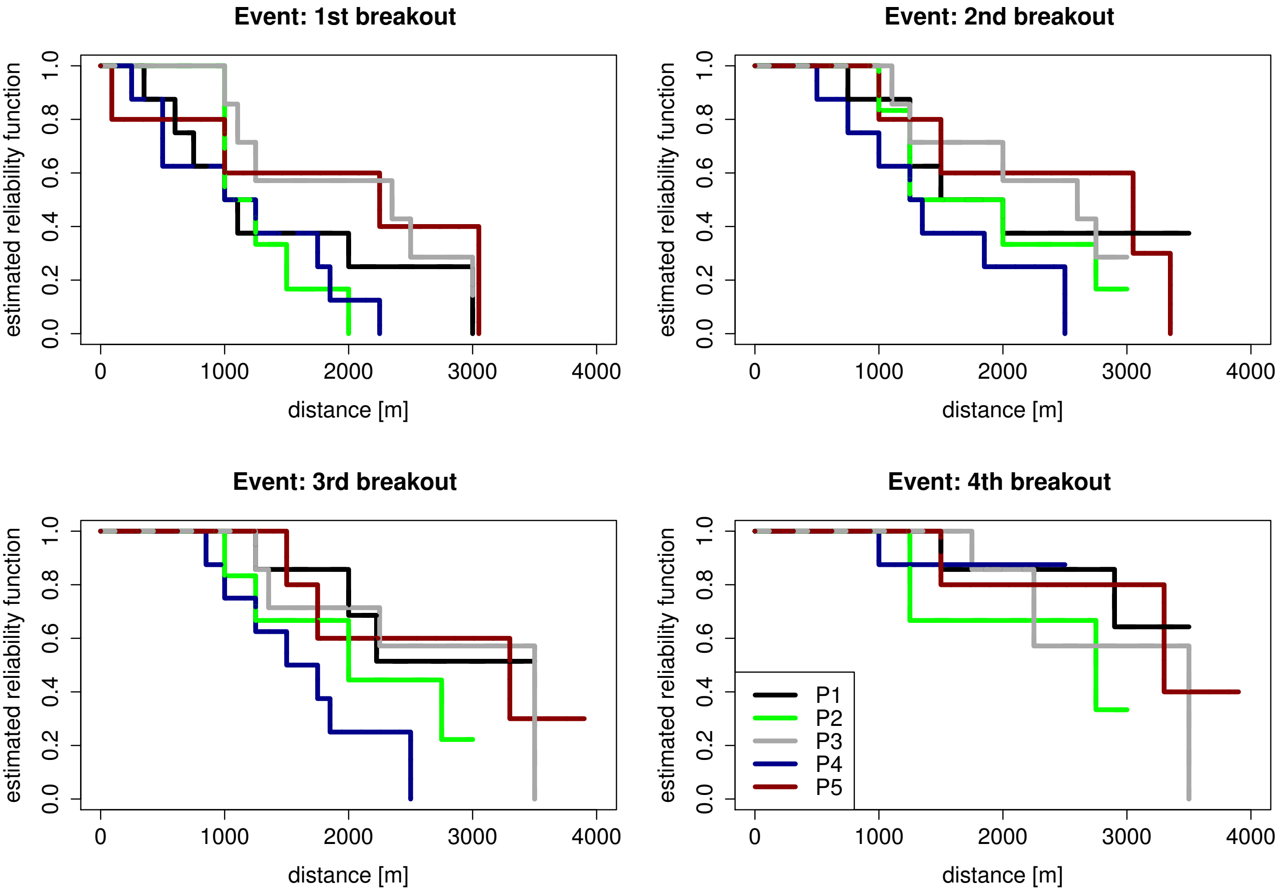

Figure 6: Estimated reliability functions based on the Kaplan-Meier estimator for different events and perforated plates

as plate P3 and P5 for the second and third diamond breakout. For the first diamond breakout, the reliability functions of P1, P3 and P5 all amount to zero after 3000 m. In contrast, the reliability functions of P2 and P4 decrease to zero earlier, at ca. 2000 m. For some experiments, P1 and P2 perform as badly as P4, but more experiments from P1 have a long lifetime. It can also be observed that the reliability functions cross each other for the first diamond breakout. However, for the second and third diamond breakout, the differences between P4 and the other plates, especially P1 and P2, are noticeably visible.

The fourth breakout is not ideal as an event for the lifetime analysis due to the high number of censored data for this event, see Table 2. Note that the lines of reliability functions in Figure 6 vanish if only censored experiments remain. Especially, almost all experiments of P4 are censored for this event. The experimenter stopped these experiments on purpose since the device got stuck multiple times after all diamonds had broken out. In this scenario, the experimental setup was disturbed and needed to be reorganized. Since this caused time delays, the last sequence of experiments (containing mostly P4) was stopped after the third breakout. Therefore, the event *fourth diamond breakout* is omitted for the following lifetime analysis.

For the events of the first, second, third diamond breakout, the Cox-model is given by

$$h(t \mid A, B, AB) = h_0(t) \exp\left(\beta_1 A + \beta_2 B + \beta_3 AB\right)$$

where h is the modeled hazard rate (momentary rate of diamond breakout at time t), A and B are the vertical or horizontal distances, respectively, $\beta_1, \beta_2, \beta_3$ are the parameters for A, B and AB the area between the diamonds (interaction) and h_0 is the unspecified baseline-hazard. In order to interpret the Cox-model, it should be noted that any reliability function $S(t)$ can be represented in dependence of the hazard function by

$$S(t) = \exp\left(-\int_0^t h(s)ds\right).$$

Thus, the larger a positive coefficient β_i is, the larger the hazard rate will be and the lower the reliability function is. The reversed interpretation holds for negative coefficients. The model is computed by `coxph()` from the package `survival`.

First diamond breakout

	$\widehat{\beta}_i$	p-value
horizontal distance A	-0.84	0.20
vertical distance B	-0.37	0.41
area AB	0.18	0.45

Second diamond breakout

	$\widehat{\beta}_i$	p-value
horizontal distance A	-0.88	0.11
vertical distance B	-0.84	0.11
area AB	0.29	0.20

Third diamond breakout

	$\widehat{\beta}_i$	p-value
horizontal distance A	-1.05	0.07
vertical distance B	-1.09	0.04
area AB	0.34	0.14

Table 3: The estimated parameters $\hat{\beta}_1, \hat{\beta}_2$ and $\hat{\beta}_3$ of the Cox-models for the first, second and third diamond breakout ($i = 1, 2, 3$ for A, B and AB, respectively)

Table 3 contains the estimations of $\beta_1, \beta_2, \beta_3$ and the p-values of the Wald-tests for the null hypothesis that the horizontal or vertical distances or their interaction have no significant influence, respectively. In all scenarios, the distances between the diamonds have negative coefficients and the area between the diamonds has a positive coefficient. Thus, increasing the distances between the diamonds decreases the hazard rate, which implies that diamond breakouts are less likely. Note that the area is interpreted as an interaction effect between the vertical and horizontal distances. The behavior of P1, P2 and P5 is similar to the behavior of P3 although the vertical or horizontal distances are smaller than for P3. Thus, the interaction effect of this model compensates this equality of the plates by a reversed sign of the coefficient for the interaction so that P1 and P5 perform similarly to P3. Thus, increasing one distance is sufficient to increase the lifetime noticeably and the drilling tool can be applied longer for the practice.

Since there are all together nine tests in total on the same data set, the p-values must be smaller than 0.05/9 or 0.1/9 to obtain a significant influence of the spacings A, B, or AB. This is never the case, which is caused by the small sample size. Hence, the p-values indicate some tendencies but more experiments are necessary to get statistically significant results.

To sum up, the concentration of diamonds is smaller for P3 due to higher distances, which leads to lower prices for the production with the same performance. Under this result and the lifetime as a criterion of quality, P3 is recommended to use in practice. It should also be noted that for the event of the first diamond breakout, the vertical distance has a lower impact on increasing the lifetime (or decreasing the hazard rate) than the horizontal distance. This is also noticeable in the estimated reliability functions since P1 and P2 perform worse than P5 in this particular scenario. On the other hand, the situation for P4 performs generally the worst, which can be explained well physically. The smaller the area between the diamonds is, the higher is the pressure during the drilling process and damage on each diamond. Note that the null hypotheses of the proportionality assumption cannot be rejected by the χ^2-tests from `cox.zph()` [19]. However, this might also be caused by the small sample size.

3.3 Spatial dependencies between the positions and lifetimes

Several methods of statistical analysis assume independent lifetimes. This is usually achieved by independent experiments as shown above by considering the first to fourth breakout separately. However, several independent experiments are often not possible as in [14, 15] where the breakout times of several diamonds on the same tool are studied and are assumed to appear independently of each other. Violations of this assumption can cause biased results and badly performing models. Therefore, the independence of the diamond breakouts based on their positions is discussed in the following.

Figure 7 shows the proportions of the first and later breakouts for the diamonds 1-4 using `mosaicplot` in `R`. This figure leads to the interpretation that diamond 1 and 3 are more likely to break out earlier than the other diamonds.

The χ^2-test for dependencies (`chisq.test()` in `R`, [20]) leads to a p-value of 0.26 (with χ^2-statistic 4.06 and three degrees of freedom), i.e., the null hypothesis of the independence cannot be rejected. However, the sample size may be too small to find statistical significances.

Other approaches, like also considering the second and third diamond breakout, have been analyzed with less noticeable results. Considering the second and third breakout is especially problematic due to two reasons: First, the data are interval censored and thus, many second and third breakouts cannot be distinguished. Second, the force system may change drastically after one breakout. A breakout of the diamond 1 might lead to a higher likelihood that diamond 2 would break out, too. For higher sample sizes and smaller inspection intervals, further research may be interesting.

This section leads to the conclusion that the position of the diamonds may have an influence on the likelihood for a first breakout, but no statistical significant results are found. However, the system of forces may be too complex or noisy for clearer results. In addition, more than four diamonds are impregnated in practice, which would lead to an even more complex situation. Previous research propose to differentiate active

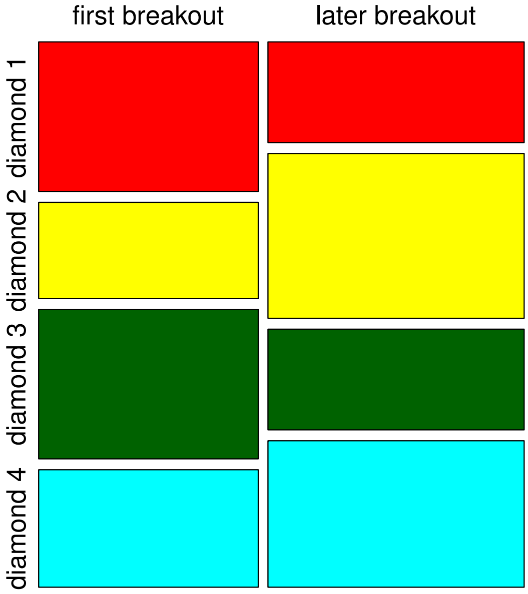

Figure 7: Mosaicplot for the distribution of the first and later diamond breakout under the different diamonds

and inactive diamonds, which can be a better approach to understand the dependency structures [15]. Overall, the typical assumption of independent and identically distributed lifetimes should be made with caution.

3.4 Material removal

Another variable from this experiment is the removed material from the workpiece. The material removal rate, per unit of time, at which material is removed from a workpiece during a grinding operation can be translated as the profit of the drilling process. The removed material was only measured on some distances where the experiment paused due to the high costs of measuring this variable. For some experiments, this variable has not been measured either. Table 4 gives an overview of the number of collected samples. The trend of the measured removed material can approximately be assumed to be linear, as Figure 8 shows (computed by `lm()` in `R`). Since the removed material is highly correlated with the area of the hollow, the area is used in the following.

For each experiment a regression line with origin in zero is computed since no removed material is removed at the beginning of an experiment. The slopes of the regression lines are collected and used to find differences between the plates, see Figure 9. The t-tests with null hypothesis $H_0 : \alpha_i = 0$ for $i = 1, 2, 3$ of the linear model

$$slope = \mu + \alpha_1 A + \alpha_2 B + \alpha_3 AB$$

plate	# experiments with measured removed material
P1	7
P2	7
P3	7
P4	8
P5	6

Table 4: Number of data with measured removed material

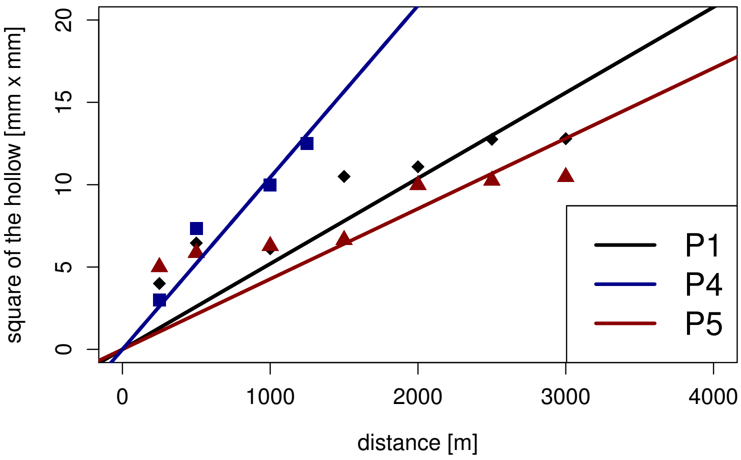

Figure 8: Some trends of the area of the hollows (representing the removed material) as an example

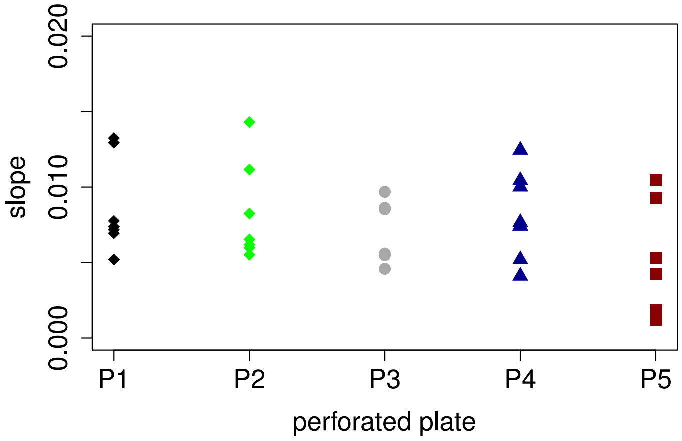

Figure 9: Comparison of the slopes of the regression lines

with intercept μ do not lead to any significant results, i.e., no differences between the plates on the value of the slopes can be found. The figure does not show noticeable patterns either. Two regression lines with smaller slopes from P5 were sampled under another experimenter and another workpiece has been drilled compared to the other experiments which could explain this outlying behavior. Since this variable is very expensive to collect and the data do not show any separation between the plates, the material removal cannot be recommended for data collection.

4 Summary and discussion

The influence of the spacing of four diamonds on the breakout time and material removal was investigated for a diamond impregnated tool for machining concrete workpieces. Five types of plates with different positions of the four diamonds were used in 40 experiments.

The breakout times of the diamonds were statistically analyzed with the Cox-model. This showed that larger spacings led to longer breakout times and leads to the recommendation to use a tool with the largest area between the diamonds. These tools not only have a longer lifetime but also a lower concentration of diamonds (and thus less costs). Moreover, a relationship of the position of a diamond and its lifetime was found so that the assumption of independent and identically distributed lifetimes of diamonds on the same tool as done in [14, 15] is questionable. However, an influence of the spacing on the worn material could not be observed.

Overall, the data does not lead to statistically significant results, which can be caused by the small sample sizes (6-9 samples for each of the five types of plates). The corn forms (triangular, rectangular, pentagonal) of the diamonds have also been considered, but no conclusion has been found. Moreover, as in [21], different workpieces and different experimenters showed a high influence on the results. In particular, the plate P4 with the smallest area between the diamonds was used only on one type of workpiece so that the bad behavior of this type of plate can also be caused by the workpiece. Hence, further research is necessary to validate the findings. For this, it is advisable that each experimenter uses the four extreme plates P1, P3, P4, P5 in a randomized order for each workpiece to avoid workpiece and experimenter effects.

Moreover, future research may lead to answers whether the distances between the diamonds can be increased further without changes of the lifetimes and material removal and how these results are visible for tools with more than four set diamonds.

The waiting times between diamond breakouts can also be used in lifetime analysis of diamonds as it was done in [14, 15]. If waiting times should be more focused in further research, it is recommended to note the two following advices. First, smaller distances between the inspection times are needed to reduce the number of interval censored experiments. Second, after diamond breakouts, the inspection times may be reduced since the probability for a diamond breakout will be higher. On the other hand, the detection of diamond breakouts by another criterion than stopping the drilling process and considering photos would improve the research. Previous research considered this question but did not find convenient criteria for an online algorithm that can detect a diamond breakout during the drilling process [21].

Acknowledgments

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References

[1] Denkena, B.; Tönshoff, H. K.; Friemuth, T.; Gierse, A.; Glatzel, T.; Hillmann-Apmann, H.: Innovative Trennschleifprozesse in der Natursteinbearbeitung, Werkstatttechnik online, Jahrgang 92, H. 6, 2002, 290-296

[2] Denkena, B.; Becker, J.C.; Gierse, A.: Examination of Basic Separation Mechanisms for Machining Concrete and Stone, Annals of the German Academic Society for Production Engineering (WGP), Production engineering, Vol. 2, 2004, 23-28

[3] Brook, B.: Principles of Diamond tool technology for sawing rock, Int. J. of Rock Mechanics I& Mining Sciences, 2002, vol.39, 41-58 DOI: 10.1016/S1365-1609(02)00007-2

[4] Tillmann, W.; Gathen, M.; Vogli, E.; Kronholz, C.: Diamond Tool Production - Materials and Processing, PM Asia 2007 Conference I& Exhibition, 2-4 April 2007, Shanghai, China

[5] Dwan, J.D.: Production of diamond impregnated cutting tools, Powder metallurgy, 1998, vol. 41, no. 2, 84-86 DOI: 10.1179/pom.1998.41.2.84

[6] Konstanty, J.; Bunsch, A.: Hot pressing of cobalt powders, Powder Metallurgy, Vol. 34, No. 3, 1991, 195-198 DOI: 10.1179/pom.1991.34.3.195

[7] Tillmann, W.; Kronholz, C.; Ferreira, M.; Theisen, W.; Knote, A.; Schütte, P.; Schmidt, J.: Comparison of Different Metal Matrix Systems for Diamond Tools Fabricated by New Current Induced Short-Time Sintering Processes. Conference Proceedings Powder Metallurgy World Congress PM 2010, Vol. 3, 531 - 538, 10. - 14. 10. 2010, Florenz/Italy

[8] Del Villar, M.; Echeberria, J.; Iturriza, I.; Castro, F.: Sintering/HIPing of Cobalt Powders for Diamond Tools, PM World Congress Superhard/Refractory Metals, 1998, 475-480

[9] Romanski, A.: Phase transformation in hot pressed cobalt and cobalt-diamond materials, Powder Metall., vol. 50, 2, 2007, 115-119 DOI: 10.1179/174329007X153260

[10] Molinari, A.; Marchetti, F.; Gialanella, S.; Scardi, P.; Tiziani, A.: Study of the Diamond-Matrix Interface in Hot-pressed Cobalt-based Tools, Mater. Sci. Eng. A, 130 (2) 1990, 257-262 DOI: 10.1016/0921-5093(90)90066-C

[11] Kamphuis, B.J.; Serneels, A.: Cobalt and nickel free bond powder for diamond tools: Cobalite CNF, Ind. Diamond Rev., Vol. 1, No. 4, 26-32

[12] Weber, G.: Gesetzte Diamanten - jetzt auch vollautomatisch, dihw Magazin - DIAMANT HOCHLEISTUNGSWERKZEUGE, 2 I/2010, 24-26

[13] Denkena, B.; Köhler, J.: Stahlbetonbearbeitung mit gesetzten Trennschleifwerkzeugen. Ritzuntersuchungen zu Materialtrennmechanismen von Stahl-Beton-Verbunden, Werkstatttechnik online, 101 H. 6, 2011, 398-406

[14] Malevich, N.; Müller, C. H.; Dreier, J.; Kansteiner, M.; Biermann, D.; Pinho Ferreira, M. de; Tillmann, W.: Experimental and statistical analysis of the wear of diamond impregnated tools. Wear [Online] 2021, 468-469, 203574. `https://www.sciencedirect.com/science/article/pii/S0043164820310334`

[15] Malevich, N., Müller, C.H., Kansteiner, M., Biermann, D., Ferreira, M. and Tillmann, W.: Statistical analysis of the lifetime of diamond impregnated tools for core drilling of concrete. In: Applications in Statistical Computing - From Music Data Analysis to Industrial Quality Improvement. Eds. K. Ickstadt, H. Trautmann, G. Szepannek, N. Bauer, K. Lbke, M. Vichi, 2019, Springer, 233-249,.

[16] Rezaul Karim, Md. and Ataharul Islam, M.: *Reliability and Survival Analysis*. Springer, Rajshahi and Dhaka, 2019.

[17] R Core Team, `R`: A Language and Environment for Statistical Computing. `R` Foundation for Statistical Computing, Vienna, Austria, `https://www.R-project.org/`, 2021.

[18] Therneau, T. A Package for Survival Analysis in `R`. `R` package version 3.2-10, `https://CRAN.R-project.org/package=survival`, 2021.

[19] Grambsch, P. and Therneau, T. Proportional hazards tests and diagnostics based on weighted residuals. *Biometrika*, 81, 515-26, 1994.

[20] Corder, G. W. and Foreman, D. I. Nonparametric Statistics: A Step-by-Step Approach, New York: Wiley, 2014.

[21] Müller, C.H., Dohme, H., Malcherczyk, D., Biermann, D. and Tillmann, W.: Statistical analysis of force measurements of diamond impregnated tools for coredrilling of concrete. To appear in: Data Science, Big Data and Artificial Intelligence in Statistics for Environmental Science, Natural Sciences and Technology. Eds. A. Steland, K.-L. Tsui, Springer, 2021.