Analysis of the influence of feed and lateral force on productivity and hand-arm vibration in interaction with drill bit wear and concrete strength

Michael Uhl, Marius Gauch, Jan-Heinrich Robens, Thomas Gwosch, Sven Matthiesen *

Karlsruhe Institute of Technology, Kaiserstr. 10, 76131, Karlsruhe, Germany

ARTICLE INFO

Keywords:
Rate of penetration
Hand arm vibration
Human factors
Ergonomic design
bit wear analysis
bit dullness
Concrete
User

ABSTRACT

The productivity and vibration are important aspects of the ergonomic evaluation of hammer drills and are influenced by drill bit wear and the feed force. In addition, the user applies a lateral force. The influence of the lateral forces in interaction with the drill bit wear on productivity and hand arm vibration (HAV) has not been investigated yet. In this study, first, the influence of the feed and lateral force on drill bit wear was investigated and subsequently how this wear interacts with the user forces to change hammer drill vibration and the rate of penetration. Furthermore, the concrete strength and the drill bit manufacturers were varied. The experiment was performed on a robot-based test rig with a total of 4800 boreholes. The rate of penetration, the hammer drill vibrations, and the wear of the drill bit were measured. It could be shown that the lateral force has a strong effect on the helix diameter wear ($p < .001$). Furthermore, the feed and lateral force each had an influence on the hammer drill vibration (each $p < .001$) and on the rate of penetration (each $p < .001$). The lateral force in interaction with the drill bit wear changed the vibration at the main handle. Further, it could be shown that the wear pattern varies depending on the concrete strength and drill bit manufacturer. These findings help manufacturers in developing reliable and ergonomic products and for class societies in designing standards for HAV.

1. Introduction

In Germany, approximately 870,000 skilled workers are employed in the construction industry (Fachkraftesituation im Bauhauptgewerbe), where the usage of a hammer drill constitutes a considerable part of all activities. When it comes to construction projects, dowels and concrete screws are standard materials at construction sites. For their successful installment, drilling of holes into the concrete is essential and make up a large part of the time required for the installation of fastening systems. The work on large projects may require over 100,000 boreholes. While operating the hammer drill, the user strongly interacts with the tool, which may lead to illness. According to user surveys and other research studies, most disorders are caused by the weight of the power tool (Eaves et al., 2016), especially when working overhead (Anwer et al., 2021), and by the vibrations that are produced by these tools (Anwer et al., 2021; Bovenzi, 1994; Poole et al., 2019). Therefore, it is of high importance and considered an ergonomic goal to optimize the productivity of the overall system while prioritizing the well-being of the operator (DIN EN ISO 9241-210, 2011).

For ergonomic products to be developed, there is a need for analysis methods (Coenen et al., 2014; Maeda et al., 2019), conducting studies to identify the influencing factors (Rempel et al., 2019; Silva et al., 2021), as well as deriving design solutions (Dong et al., 2020; Thota et al., 2022). The resulting takeaways, methods, and information can then be used by developers to optimize their product. In addition to the tool, the drill bit itself can be further developed. This must be done in such a way that the drill bit has the desired properties, such as geometry, material hardness, in order to achieve the ergonomic target values over its service life. Since productivity and Hand-arm vibration (HAV) are relevant variables from an ergonomic point of view, the challenge for the manufacturer is to understand which factors are responsible for the geometry of the drill bit changing over its service life as well as what effect these changes have on the productivity and HAV. Only by understanding this chain of dependence, the developer is in a position to adapt the properties of the drill bit in a targeted manner. Important parameters to evaluate the drilling process in this respect are the rate of penetration (ROP) (Botti et al., 2020; Gruner and Knoll, 2000; Kivade et al., 2015; Lindenmann et al., 2021; Uhl et al., 2019, 2021) and the user load due to housing vibrations (Frequency-weighted acceleration: a_{hv} value) (Cronjager and Jahn, 1985; Jahn, 1985; Rempel et al., 2019;

* Corresponding author.
E-mail address: sven.matthiesen@kit.edu (S. Matthiesen).

Uhl et al., 2019).

In its current state of research, there are already a handful of studies having focused on and examined the influencing factors on the ROP and in particular the a_{hv} value. Beside the technical system and the concrete, the user has a significant influence on the ROP and the a_{hv} value. It has been shown that the vibration characteristics of the user have an influence on the a_{hv} values (Aldien et al., 2005; Welcome et al., 2004). This influence can change by variation of the contact pressure, gripping force, and body posture (Matthiesen et al., 2018). Due to this, it is necessary to simulate the characteristics of the hand-arm system of the user on test rig correctly. This can be done by the use of a hand-arm model that corresponds to the relevant characteristics of the user (Jahn and Hesse, 1986; Marcotte et al., 2010; Rempel et al., 2017). Likewise, the contact or feed force changes the a_{hv} value (Botti et al., 2020; Matthiesen et al., 2018). An increase in the feed force also leads to an increase in ROP, and thus ensures an increase in productivity per borehole (Botti et al., 2020; Kivade et al., 2015; Uhl et al., 2019). However, Botti et al. (2020) were able to show that for their investigated hammer drill-drill bit setup the a_{hv} value increased more relative to the ROP. As a result, productivity calculated on an 8-h basis became lower, as the operator reached the maximum vibrational exposure earlier on. Another variable known at this current state of research to have an effect on the ROP and the a_{hv} value is the concrete strength. The higher the strength, the lower the ROP and the higher is the measured HAV (Cronjager and Jahn, 1985).

Since the developer can only influence the drill bit properties such as the geometry and drill bit material, these factors are of particular interest to the developer. However, the interaction with other factors should also be known, which in turn can also influence the service life of the products. Investigations by Antonucci et al. (2017), Botti et al. (2017) and Weinert et al. (1993) proved that the wear of the drill bit is related to the variables ROP and the a_{hv} value. It was shown for drill bits with two cutting edges that the ROP decreased with increasing wear (Antonucci et al., 2017; Botti et al., 2017; Carty et al., 2017) whereas the a_{hv} value increased with increasing wear. The investigations also revealed that the greatest influence occurs at the beginning of the cumulative drilling depth. Botti et al. (2017) and Momeni et al. (2017) also identified the most influential geometric parameters on drill bits regarding the change due to wear. The type of wear that occurs on the drill bit tip depends largely on the distance from the drill bit axis. The further out the wear on the drill bit cutting edge is observed, the more abrasive wear and less chipping occurs (Momeni et al., 2017; Saai et al., 2020; Tkalich et al., 2017). Botti et al. (2017) pointed out that drill bits with four cutting edges could wear out differently and therefore still need to be investigated.

Furthermore, in a study by Flegner et al. (2016), it was shown for core drills with water flushing that the pressure force applied by the machine has an influence on drill bit wear. Whether this effect can be transferred to hand-held electro-pneumatic hammer drills with helix shafts has not yet been proven. For further developments of the drill bit or to monitor its state of wear during operation, it is necessary not only to understand which variables influence wear, and thus reliability, but also to know how wear interacts with other variables as a function of vibrations and productivity.

Studies by Rimell et al. (2008) and Vergara et al. (2008) have shown that there are significant differences between the vibration results performed according to the standard (DIN EN ISO 28927-10, 2011) and field applications. Thus, there must still be relevant influencing variables which are not known, and therefore not constant or described by the standard. According to two investigations, the user applies a lateral force in addition to the feed force (Uhl et al., 2019, 2021). The authors determined the median over each borehole. In Uhl et al. (2021), professional users applied a median lateral force of 16.7 N, 37.7 N in the 95th percentile, and extreme outliers up to 73.1 N under laboratory conditions. In a manual experiment, Momeni et al. (2017) also detected a lateral motion of the hammer drill, respectively the drill bit, caused by the user. Findings as to whether the lateral force influences the hammer drill process have not yet been documented at the present state of research. However, Cronjager et al. (1984) mentioned that a hammer drill poorly aligned to the concrete block can have strong influences on the vibrations. Furthermore, the state of research lacks proof as to whether the forces exerted by the user influence the wear of the drill bits, as well as whether there is an influence of the interaction between the forces exerted by the user and the wear on the a_{hv} value and rate of penetration. Intending to close this research gap and to support manufacturers in the development of ergonomically optimized drill bits, the following research question was addressed:

What influence do the feed and lateral force in interaction with the drill bit wear have on productivity and hammer drill vibrations?

In order to show the developers not only the influence of the lateral forces on ROP and a_{hv} value, but also which properties or changes in the drill bit are responsible for this, the influence of the users applied forces on the drill bit wear is investigated in a preceding step. For this purpose, the research question is to be answered:

Do the feed and lateral force in interaction with the concrete and drill bit manufacturer have an influence on the drill bit wear?

To answer the above questions, an experiment with 4800 runs was carried out on a robot test bench with a hammer drill adapter (Cronjager et al., 1984; Jahn and Hesse, 1986), having the same vibration characteristics as the human arm. With this test bench, it was possible to control forces in all three-dimensional directions in order to be able to reproduce the influence of humans on the hammer drill process. The current state of research has shown that both the drill bit shape and the concrete strength have an influence on the ROP, as well as the vibrations of the hammer drill. For this reason, these two parameters were included in addition to the feed and lateral force, in order to be able to make a more general statement. The knowledge about the influence of the users' applied forces can be applied in both scientific and industrial fields. The knowledge helps to evaluate whether the forces should be investigated further. In the industrial environment, this knowledge can be used in testing, but also in the specification of the standards and development of hammer drills and drill bits. An overview of all notifications of this paper can be found in Table 1.

2. Materials and methods

2.1. Experimental setup

In this study, a GBH 3–28 DFR professional hammer drill (see point 5 in Fig. 2) with a weight of 3.6 kg an SDS-plus chuck (model GBH 3–28 DFR, Robert Bosch Power Tools GmbH, Leinfelden-Echterdingen, Germany) was used. The frequency-weighted acceleration value was

Table 1
Description of notations used.

Notation	Description
a_{hv}	Frequency-weighted acceleration
AC	Cutting edge angle of the drill bit
AN	Notch angle of the drill bit
C	Concrete
CDM	Cumulative drilling meters
D05	Drill bit tip diameter at 0.5 mm
D35	Drill bit tip diameter at 3.5 mm
D47	Drill bit tip diameter at 4.7 mm
FF	Feed force
H	Height of the drill bit tip
HAV	Hand-arm vibration
IQR	Interquartile range
LF	Lateral force
M	Mean value
Mdn	Median
ROP	Rate of penetration
SD	Standard deviation
DBM	Drill bit manufacturer

specified as 13 m/s^2 with an uncertainty of 2 m/s^2 by the manufacturer. The drill bits used in the study are a BOSCH SDS plus-7X drill bit (Ø10 – 150 mm working length, weight: 91 g, SDS plus-7X, Robert Bosch Power Tools GmbH, Leinfelden-Echterdingen, Germany) and a Hilti TE-CX drill bit (Ø10 – 150 mm, weight: 81 g, type TE-CX (SDS plus), Hilti AG, Schaan, Liechtenstein), which is shown including nomenclature in Fig. 1. Both drill bits had four cutting edges and a full-head carbide tip. The concrete blocks (point 4) had the dimensions 800 × 800 × 300 mm (C50/60 - Rau-Betonfertigteile, Ebhausen, Germany) and 2400 × 2000 × 200 mm (C20/25 - Rau-Betonfertigteile, Ebhausen, Germany). Thus, both met the minimum requirements of DIN EN ISO 28927-10 (2011). The minimum compressive strength of the cubes after 28 days of curing is 25 N/mm^2 for C20/25 and 60 N/mm^2 for C50/60. This is specified based on DIN EN 206 (2017). All concrete blocks came from the same batch.

The automated test bench included a robot (point 1) with a position repeat accuracy of ±0.08 mm (robot: KR500MT, control: KRC4, KUKA, Augsburg, Germany). A hand-arm model (point 7) based on Cronjager et al. (1984) and Jahn and Hesse (1986) formed the link between the hammer drill and the robot. The rear and front connections of the hand-arm model to the hammer drill are equally designed and have an equivalent spring stiffness in the feed direction of 49.29 N/mm and in both transverse directions (y- and z-direction) of 23.7 N/mm. A force-torque sensor (point 2) (model NET FT OMEGA 160-IP65, ATI, Apex, NC, USA) was used to control the feed and lateral force. The hammer drill path was measured using the robot control output. At a constant feed force and over the total borehole, the hammer drill depth corresponded to the robots motion.

Two tri-axial accelerators (point 9) (model 356A02, PCB Piezotronics, Depew, NY, USA) were used to measure the vibrations at the housing and at the handle of the hammer drill. The position of the accelerator on the hammer drill main handle corresponded to the prescribed position of the standard DIN EN ISO 28927-10 (2011). Because of the hand-arm model, it was not possible to use the position of the second accelerator of the standard. To monitor the hammer drill temperature, a sensor (point 8) (TJC100-ICSS-M050U-150, OMEGA Engineering GmbH, Deckenpfronn, Germany) was placed at the hammer drill housing. The same sensor type (point 6) was used additionally to control the drill bit temperature between the boreholes. A real-time system (ADwin-Pro II, Jager Computergesteuerte Messtechnik GmbH, Lorsch, Germany) was used to acquire the data. The sampling frequency was 12500 Hz.

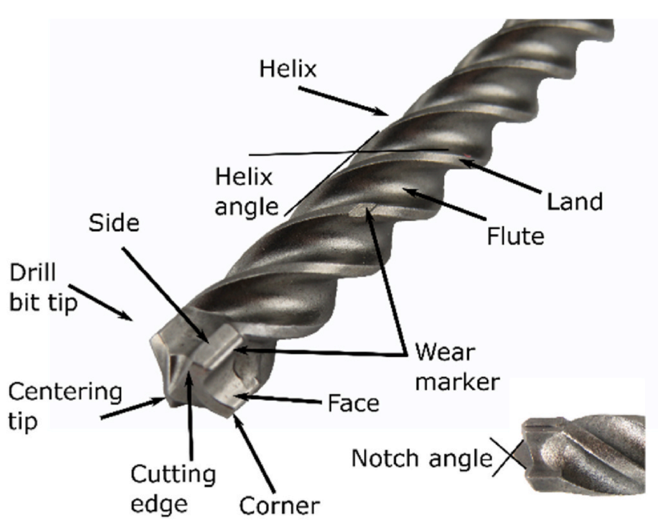


Fig. 1. Drill bit nomenclature.

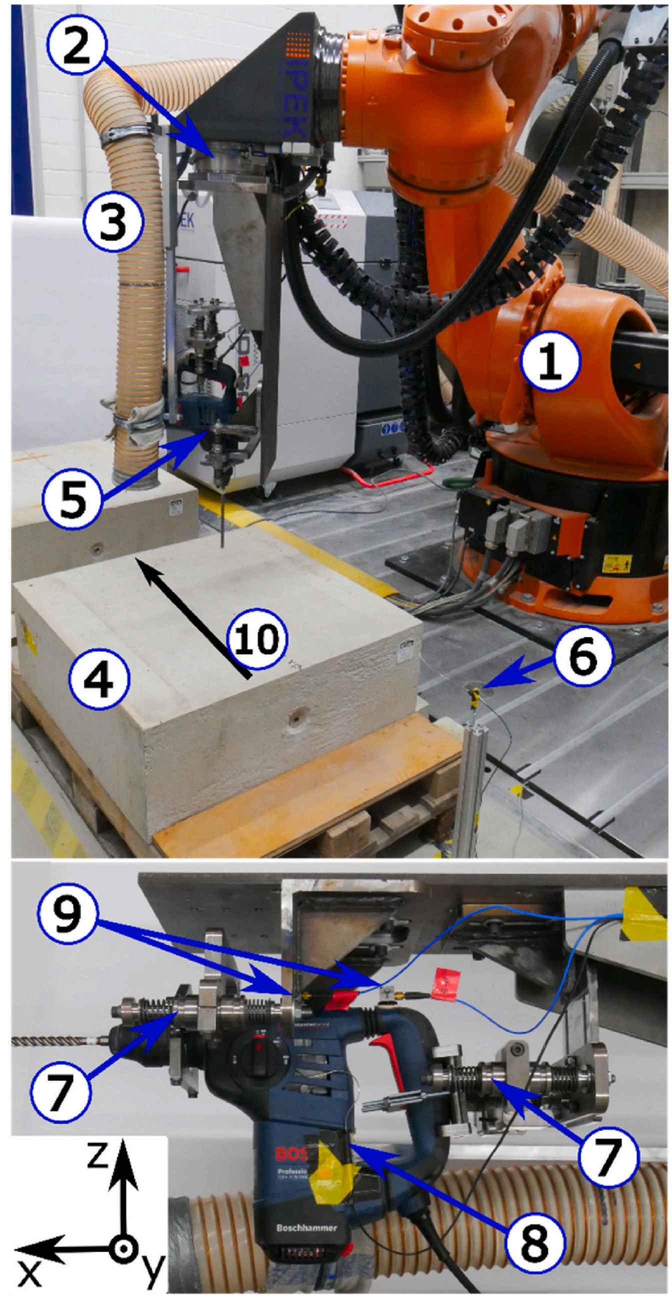


Fig. 2. Robot-based test bench with robot (1), force-torque sensor (2), dust extraction (3), concrete block (4), hammer drill (5), temperature sensor (6 and 8), hand-arm model (7), accelerators (9) and direction of pouring (10).

2.2. Experimental design and procedures

Each hole was drilled with a depth of 140 mm. The compression of the springs caused a relative motion between robot and hammer drill. Therefore, depending on the feed force, the measured robot motion must be increased by approx. 9–12 mm (see Fig. 5). The actual drilling depth was checked again for each new drill bit and at every 50th run. The drilling was done with a drill retraction at 50% of the total drilling depth. When concrete is poured, the aggregate sinks downwards and thus depends on the direction of pouring (point 10). Therefore, a randomized distribution of the borehole position on the concrete block was used for each concrete block to minimize the effects of the irregularities in the concrete. In this study, the *drill bit*, the *feed force*, the *lateral force* in y-direction, and the *type of concrete* were investigated (see Table 2). For

Table 2
Investigated factors with adjusted levels.

Factor	*Level*
Lateral force (LF)	0 N/60 N
Feed force	110 N/170 N
Drill bit manufacturer	0: Hilti/1: Bosch
Concrete strength	C20/25/C50/60
Number of repetitions of each setup	2
Number of runs for each setup	150

the individual runs, the target *feed force* was applied over the entire drilling path, the target *lateral force* only after 30 mm of drilling. This was to prevent the drill bit from deviating to the side or breaking out. In the second spatial direction, the lateral force (z-direction) was controlled to 0 N after 30 mm. A full factorial randomized experimental design with one replicate for each setup was performed. A setup describes a combination of each factor (eg. LF 0, FF …). Within each setup, a test run series of 150 boreholes was performed with one drill bit (4800 runs in total). In each setup, the factor values remained constant.

In order to minimize the influence of the temperature of the hammer drill and drill bit on the drilling process, both were monitored and controlled with a waiting time between each run. The chosen range of the hammer drill temperature was 80–90 °C. This was the range where the temperature was nearly constant during one run. With regard to the drill bit temperature, a waiting time was observed until the tip of the drill bit reached a temperature below 60 °C.

2.3. Wear analysis

In order to better discuss the ROP and a_{hv}-value results with regard to further influences on the wear, the drill bit weight was measured before and after 21 drill meters. For this purpose, the drill bits were cleaned in an ultrasonic bath and then the weight was measured with a precision balance (model I2000 D, Sartorius AG, Goettingen, Germany) with an accuracy of 0.001 g.

The wear measurements of the drill bit tips loss of volume were performed with a digital microscope (model VHX-6000, KEYENCE DEUTSCHLAND GmbH, Neu-Isenburg, Germany). With the lenses VH-Z20R/VH-Z20W/VH-Z20T 20x to 200x and VH-Z100UR/VH-Z100UW/VH-Z100UT 100x to 1000x, it was possible to measure the geometry of the tip. The wear of the drill bits were analyzed under three different conditions, i.e. with a digital microscope at the initial state, after 50% of the drilled boreholes were completed, and at the end of each series with a 2-D image. The diameter of the helix was measured

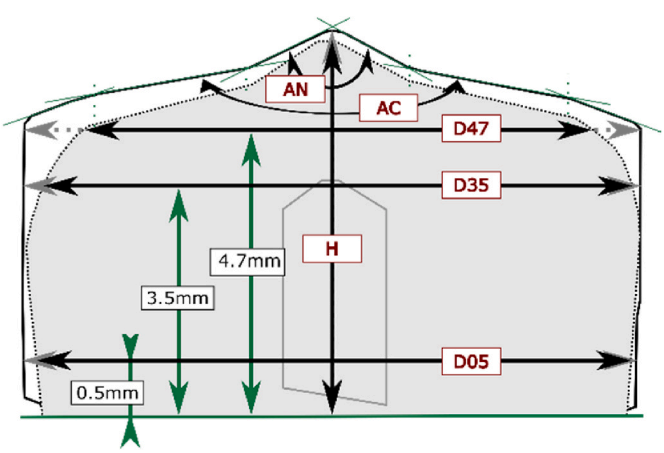


Fig. 3. Evaluated parameters at the tip with original dimension (dotted gray), dimension after drilling (black), and auxiliary lines/dimensions (green). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

with a caliper at a distance of 10, 60, and 100 mm behind the beginning of the drill bit tip. The parameters are shown in Fig. 3 and Fig. 4 and are explained in Table 1.

2.4. Data analysis

The post-processing of the raw data was performed using MATLAB (R2017b, MathWorks, Natick (Massachusetts), USA). Constant conditions must be available for the comparison of the influences of the feed and lateral force. For this reason, only the range of the drilling process could be evaluated, where both the feed and lateral force corresponded to the target force. Only in the second drilling step (after drill bit retraction), the lateral force was thoroughly and reliably achieved in all test runs. For this reason, only the second drilling step was evaluated with regard to the ROP and a_{hv} value for all runs, as soon as the feed and lateral force had reached the target value in this range. The data were first filtered with a low-pass filter (6 Hz) to detect the point in time when the target force was reached for the first time. Fig. 5 shows the total path, feed, and lateral force as well as the evaluation range marked in gray.

For the actual evaluation, the vibration and displacement data (for ROP) were filtered with a fourth-order Butterworth bandpass filter, and the cut-off frequencies of 10 and 2000 Hz. To calculate the ROP, the total displacement was divided by the total time of the evaluation range. The a_{hv} values were calculated according to DIN EN ISO 5349-1 (2001).

The subsequent statistical analysis was done using the software SPSS (IBM SPSS Statistics 25, IBM, Armonk (New York), USA). Afterwards, the data were tested for normal distribution using the Shapiro–Wilk test, and an additional check was made using histograms. Depending on the result, a parametric or non-parametric test was chosen. For the analysis of the drill bit wear, only non-parametric tests were applied. A Friedman's two-factorial analysis of variance by margin for paired samples was used to determine whether the weight of the drill bits changed significantly over the cumulative drilling meters. The extent to which the factors influence the helix diameter was determined using the Mann-Whitney U test, and the influence on the geometry of the drill bit tip was determined using the Friedman test, as well as the Mann-Whitney U test. The correlation of the independent variables on the ROP and a_{hv} value were determined using a multi-factorial ANOVA. Mean values (M), standard deviation (SD), median (Mdn), and interquartile range (IQR) were given. P values $< .05$ were considered significant.

3. Results

3.1. Do the feed and lateral force in interaction with the concrete and drill bit manufacturer have an influence on the drill bit wear?

3.1.1. Weight changes of drill bit

Using the Friedman test, it can be shown that the changes in drill bit weight are statistically significant for both the Hilti drill bit (Chi-Square (2) 32, $p < .001$, n 16) and the Bosch drill bit (Chi-Square(2) 30, $p < .001$, n 15). Hilti's unused drill bits had a median weight of Mdn 80.8 g, IQR 0.2 g. After 10.5 cumulative drilling meters (CDM), it had

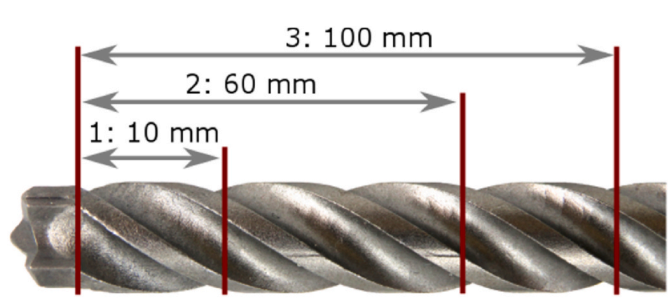


Fig. 4. Evaluated measuring points (1: 10 mm, 2: 60 mm, and 3: 100 mm) at the helix.

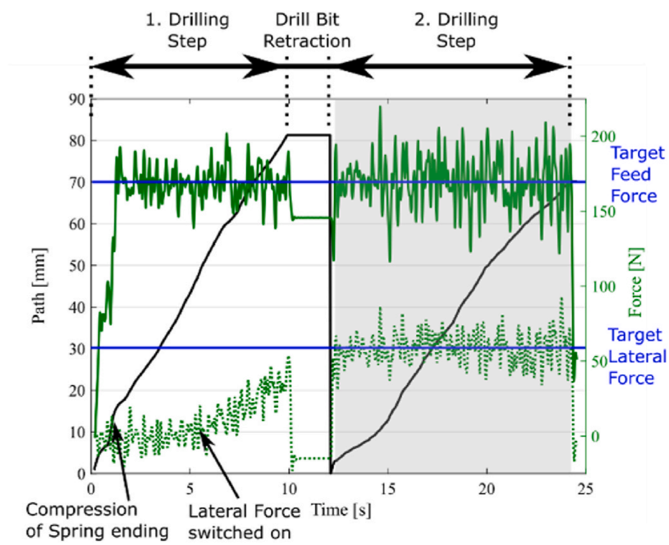


Fig. 5. Path signal (black), feed (green solid line), and lateral force (green dotted line) signal, target forces (blue), and the evaluation range (gray) of the drilling process. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

already dropped to 80.1 g, IQR 0.5 g, and after 21 CDM, it dropped once more to 79.1g, IQR 1.0 g. In terms of their initial weight, the Bosch drill bits had a median weight of Mdn 91.3g, IQR 0.6. After 10.5 CDM it already decreased to 90.6, IQR 0.7 g, and after 21 m, it dropped further to 89.4, IQR 0.9 g. Thus, the two types of drill bits lost a total of 1.9 and 1.7 g of material, respectively, and slightly more on the second 10.5 CDM than on the first (difference: 0.5 and 0.1 g).

3.1.2. *Wear of the helix*

Since no normal distribution can be assumed for the data, a Mann-Whitney *U* test was performed for each factor to demonstrate whether the *feed force*, *lateral force*, *concrete,* or *drill bit manufacturer* have an influence on the wear of the helix. In addition, it was checked whether the drill bit wears out differently at the different measuring points. Since the two types of drill bits had different starting diameters (type 0 at 1: 9.54 mm, 2: 9.54 mm, 3: 9.53 mm and type 1 at 1: 9.4 mm, 2: 9.39 mm, 3: 9.39 mm), the relative changes in diameter were analyzed to determine whether one of the above-mentioned factors has an influence.

At **measuring point 1** (see Fig. 4), a *lateral force* of 60 N (Mdn 8.65 mm) leads to a higher helical wear than 0 N (Mdn 8.86 mm), asymptotic Mann-Whitney *U* test: *z* 2.3000, *p* .021. The effect strength according to Cohen (1992) is *r* 0.41 and corresponds to a strong effect. For the factor *feed force*, no significant effect could be proven (170 N: Mdn 8.68 mm, 110 N: Mdn 8.84 mm) asymptotic Mann-Whitney *U* test: *z* 1.395, *p* .163. Also, no significance could be detected for the factor *drill bit manufacturer* (asymptotic Mann-Whitney *U* test: *z* 1.885, *p* .059) whereas for the *concrete*, there was a clear difference between C20/25 (Mdn 8.88 mm) and C50/60 (Mdn 8.60 mm), asymptotic Mann-Whitney *U* test: *z* 4.053, *p* <.001, *r* 0.72 and corresponds to a strong effect. In general, the coil diameter is significantly smaller after 21 *cumulative meters of drilling* (0 m: Mdn 9.47 mm, 21 m: Mdn 8.75 mm), asymptotic Wilcoxon test: *z* 4.937, $p < .001$, N 32). The effect strength according to Cohen (1992) is *r* 0.87, which corresponds to a strong effect.

At **measuring point 2** (see Fig. 4), and thus 60 mm away from the drill bit tip, the higher *lateral force* (60 N: Mdn 8.78 mm) also produces higher wear (0 N: Mdn 9.13 mm), asymptotic Mann-Whitney *U* test: *z* 4.451, $p < .001$. The effect strength according to Cohen (1992) is *r* 0.79, which also corresponds to a strong effect. In contrast to the lateral force, no significant effect could be demonstrated for the other factors *feed force* (asymptotic Mann-Whitney *U* test: *z* 1,169, *p* .242), *drill bit manufacturer* (asymptotic Mann-Whitney *U* test: *z* 1.924, *p* .34), and *concrete strength* (asymptotic Mann-Whitney *U* test: *z* 1.528, *p* .127). Also at measurement point 2, the spiral diameter was shown to be significantly smaller (0 m: Mdn 9.47 mm, 21 m: Mdn 8.95 mm) after 21 *cumulative drilling meters*, asymptotic Wilcoxon test: *z* 4.938, $p <$ .001, n 32), *r* 0.87 which corresponds to a strong effect.

At **measurement point 3** (see Fig. 4), as at measurement point 2, a significant difference could be detected for the *lateral force* (60 N: Mdn 9.12 mm, 0 N: Mdn 9.26 mm), asymptotic Mann-Whitney *U* test: *z* 3.513, $p < .001$, *r* 0.62, which corresponds to a strong effect. For the factor *feed force*: asymptotic Mann-Whitney *U* test: *z* 0.302, *p* .78, no effect could be detected.

Whereas for the *drill bit manufacturer,* asymptotic Mann-Whitney *U* test: *z* 2.682, *p* .007, a significant difference could be shown (0: Mdn 9.13 mm, 1: Mdn 9.20 mm). The effect strength according to Cohen (1992) is *r* 0.47 and corresponds to a medium effect. For the *concrete*, there was a clear difference between C20/25 (Mdn 9.26 mm) and C50/60 (Mdn 9.16 mm), asymptotic Mann-Whitney *U* test: *z* 2.096, *p* .036, *r* 0.37, which corresponds to a medium effect. However, the spiral diameter is significantly smaller after 21 *cumulative drilling meters* (0 m: Mdn 9.46 mm, 21 m: Mdn 9.19 mm), asymptotic Wilcoxon test: *z* 4.941, $p < .001$, N 32). The effect strength according to Cohen (1992) is *r* 0.87, which corresponds to a strong effect.

When it comes to statistical analyses, it could be shown that the lateral force has the greatest influence at all three measuring points. As a result, the wear of the helix at the individual measuring points as a function of the lateral force is shown in Fig. 6.

The lateral force increases the median wear of the helix at all measuring points over all setups compared to the same feed force, concrete, and manufacturer. The difference in the median is highest at measuring point 2.

3.1.3. *Wear of the drill bit tip*

The Friedman test was used to demonstrate the changes of the wear of the six dependent parameters over the cumulative drilling meters. The change of the measured variables was examined. The results are shown in Table 4.

When looking at the outside diameters, it becomes clear that for drill bit manufacturer 1, all outside diameters change significantly and there

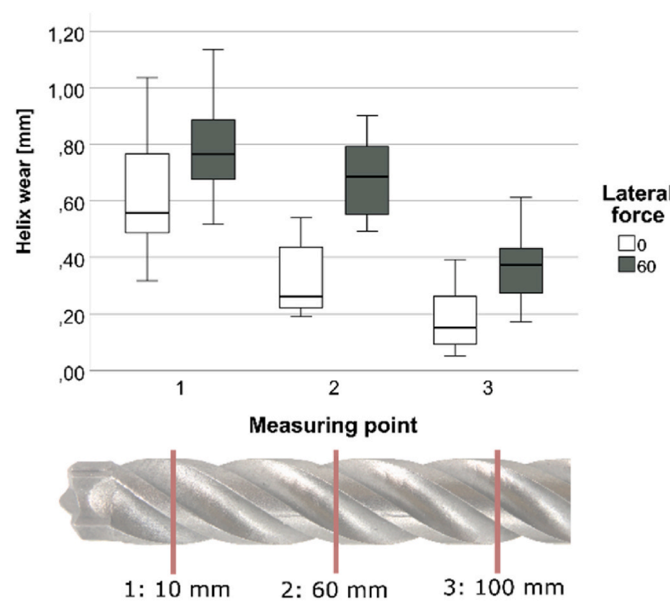


Fig. 6. Delta of the origin and the used helix with 32 drill bits. The data includes measurements with both feed force and concrete strength levels.

Table 3
Result of the multi-factorial ANOVA for the analysis of influencing factors (C = concrete, DBM = drill bit manufacturer, FF = feed force, LF = lateral force, CDM = cumulative drilling meters) on the ROP.

Source	*df*	*F*	η^2
DBM	1	44,974***	,009
C	1	7442,946***	,591
FF	1	20,783***	,004
LF	1	80,830***	,015
CDM	2	1156,546***	,310
C * CDM	2	138,000***	,051
DBM * C	1	74,475***	,014
C * LF	1	38,514***	,007
C * FF	1	,379	,000
DBM * CDM	2	8579***	,003
LF * CDM	2	1940	,001
FF * CDM	2	15,517***	,006
DBM * LF	1	4677*	,001
DBM * FF	1	52,231***	,010
FF * LF	1	38,036***	,007
Error	5141		
Total	5162		

Basis: N = 4800; df = degrees of freedom.

is a strong effect. For manufacturer 0 however, the effect strength decreases from the drill tips closest measured diameter (D47) to diameter D05. Significant changes could also be demonstrated for the angle AN. It is interesting to note that the angle change is positive for manufacturer 0 (medium effect strength) and negative for manufacturer 1 (medium effect strength). The changes in the AC angle are also significant for both drill bit types. For manufacturer 0, only a medium effect strength (0 vs. 21 CDM) and a decrease in effect strength from the first (medium effect) 10.5 to the second (small effect) CDM could be shown. For manufacturer 1, a high effect on AC could be demonstrated over the entire CDM. It could be shown for both drill bit manufacturers that the height of the drill bit tip also changes significantly. According to Cohen (1992), only a small effect strength from 0 to 21 CDM could be detected for manufacturer 0. For manufacturer 1 however, a medium effect could be detected from 0 to 21 CDM and a small effect from 10.5 to 21 CDM. In general, the data does not show a difference between the effects from 0 to 10.5 CDM compared to 10.5 to 21 CDM.

The Mann-Whitney *U* test was used to investigate which factor has an influence on the relative change of the wear parameters. In the following, only those test results are presented which included a significant effect ($p < .05$). Since the drill tips of the two drill bit manufacturers have different geometries, it was first examined whether the **drill bit manufacturer** has an influence on the wear of the drill tip (N 32). It was found that the drill bit manufacturer has a large effect on wear at the outer diameter D05 (z 4.185, $p < .001$, r 0.74). The difference in outside diameter for manufacturer 0 is Mdn 0.12 mm, whereas for manufacturer 1, the difference is Mdn 0.17 mm. A large effect on the variable D47 (z 3.430, $p < .001$, r 0.61; 0: Mdn 1.82 mm 1: Mdn 2.48 mm) could also be demonstrated. Also for the two investigated angles AN (z 4.824, $p < .001$, r 0.85 median 0: 3.24 mm 1: 4.69 mm) and AC (z 4.824, $p < .001$, r 0.85 median 0: 8.12 mm 1: 18.23 mm), a large effect could be shown. Although the height of the drill tip changed only minimally with both drill bits (0: Mdn 0.04 mm vs 1: Mdn 0.07 mm), a strong effect (z 2.846, p .003, r 0.5) could be demonstrated.

Since the drill bit manufacturer has an influence, further investigations were carried out separately for the two types (N 16 each). For manufacturer 0, it could be shown that the **concrete strength** has a strong effect on the two outside diameters D35 (U 64,000, $p < .001$, r 0.84 Median C20/25: 0.24 mm, C50/60: 0.81 mm) and D47 (U 64,000, $p < .001$, r 0.84, C20/25: Mdn 1.5 mm C50/60: Mdn 2.19 mm). Otherwise, only an influence of the concrete strength on the variable AC (U 60,000, p .002, r 0.74, C20/25: Mdn 6.08 mm C50/60: Mdn 9.44 mm) could be demonstrated for this drill bit manufacturer. The Mann-Whitney *U* test was subsequently also applied to manufacturer 1. It was shown that the concrete strength had a strong effect on all three outside diameters D05 (U 61,500, p .001, r 0.78 median 0: 0.12 mm 1: 0.25 mm), D35 (U 64,000, $p < .001$, r 0.84 median 0: 0.45 mm 1: 0.74 mm), and D47 (U 57,000, p .007, r 0.66 median 0: 2.15 mm 1: 3.08 mm). For this drill bit manufacturer, a strong effect was also observed on both measured angles AN (U 2.000, p .001, r 0.79 median 0: 3.4° 1: 7.41°) and AC (U 62.000, p .001, r 0.79 median 0: 16.73° 1: 19.24°). The influence of the concrete strength in interaction with the drill bit manufacturer on the diameter D47 is illustrated in Fig. 7. It is shown that the scatter of manufacturer 1

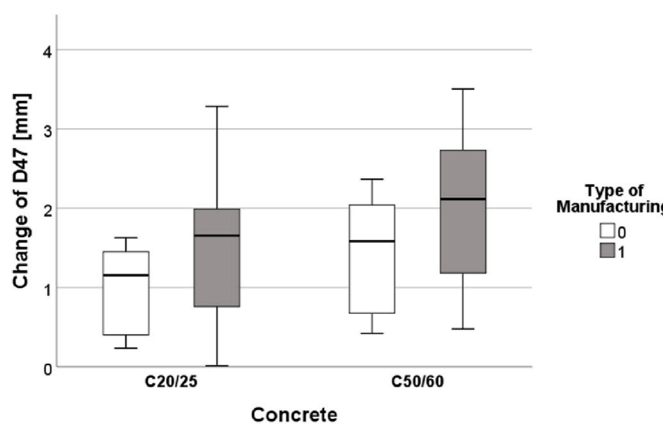


Fig. 7. Change of D47 as a function of concrete strength and drill bit manufacturer. Boxplot scatters include IQR * 1.5 of the data.

Table 4
Result of the Friedman test for the analysis of influencing factors on the wear of the drill bit tip. N = 32.

			Friedman test		0 vs. 21 m	0 vs. 10.5 m			10.5 vs. 21 m		
independent variable		df	χ^2	*p*	*r*	*z*	*p*	*r*	*z*	*p*	*r*
manufacturer 0	D05	2	12.794	.002	0.29	1.000	.014	0.25	0.156	1.000	0.04
	D35	2	30.125	<.001	0.48	0.875	.040	0.22	1.062	.008	0.27
	D47	2	15.125	.001	0.5	1.000	.014	0.25	1.000	.014	0.25
	AN	2	15.125	.001	0.34	0.688	.155	0.17	0.688	.155	0.17
	AC	2	26.000	<.001	0.44	1.250	.001	0.31	0.500	.472	0.13
	H	2	6.500	.039	0.22	0.625	.231	0.16	0.250	1.000	0.06
manufacturer 1	D05	2	32.000	<.001	0.5	1.000	.014	0.25	1.000	.014	0.25
	D35	2	32.000	<.001	0.5	1.000	.014	0.25	1.000	.014	0.25
	D47	2	32.000	<.001	0.5	1.000	.014	0.25	1.000	.014	0.25
	AN	2	28.500	<.001	0.47	- 1.125	.004	0.28	- 0.750	.102	0.19
	AC	2	32.000	<.001	0.5	1.000	.014	0.25	1.000	.014	0.25
	H	2	15.500	<.001	0.34	0.500	.472	0.13	0.875	.04	0.22

N = 32.

is clearly higher.

With regard to the factors **feed force** and **lateral force**, no significant effect on a dependent variable could be proven for either drill bit manufacturer.

For a visual illustration of the results, Table 5, four example margins are shown in Table 5. In the images a), b), and d), scoring occurs and runs from top right to bottom left. This wear occurred with almost all drills. Nearly all drill bits of manufacturer 0, which were used for drilling in the higher-strength concrete, had horizontal scoring just above the control wear edge. When comparing the two drill bit manufacturers, it is noticeable that type 1 showed significantly more crater wear, which is reinforced by the harder concrete.

3.2. *What influence do the feed and lateral force in interaction with the drill bit wear have on productivity?*

A multi-factorial ANOVA was performed to analyze whether the factors feed force, lateral force, concrete, and manufacturer and their interactions have an influence on the ROP. Table 3 summarizes the result of the ANOVA. The model has an adjusted R^2 of 0.668. The results show that each of the factors are significant *($p < .001$)*. In the previous chapter, it could be shown that the wear depends strongly on the drilling meters. Thus, in this chapter, the factor drilling meters can be understood as a synonym for drill bit wear. However, since this factor has not been set, we will continue to use the term drilling meters. Among the factor combinations, only the combinations *concrete* feed force* and *lateral force*drilling meters* are not significant. However, when looking at the strength of the effect over time, the factors *concrete* (*f* 1.2, C20/25: M 8.3 mm/s, C50/60: M 6.7 mm/s) and *cumulative drilling meters* (*f* 0.67, 0 m: M 8.1 mm/s, 10.5 m: M 7.5 mm/s, 21 m: M 6.9 mm/s) have a large influence. Whereas the *lateral force* (*f* 0.12, 0 N: M 7.6 mm/s, 60 N: M 7.4 mm/s), as well as the factor combinations *concrete*cumulative drilling meters* (*f* 0.23), *drill bit manufacturer*concrete* (*f* 0.12) and *drill bit manufacturer*feed force* (*f* 0.1), have a small influence. With regard to the factors *drill bit manufacturer* and *feed force*, both have nearly no effect.

Fig. 8 shows the ROP curves over the cumulative drilling meters. Since no distinction was made between the different manufacturers, each curve contains the average of four test run series (4 × 150 holes). The diagram shows that in test runs with C50/60 the ROP at a feed force of 170 N was initially higher. With increasing cumulative drilling meters and drill bit wear, the ROP becomes similar to the ROP of test runs with a feed force of 110 N and, at least with a higher-strength concrete, the curves even cross (LF 0 N: after 14 CDM, LF 60 N: after 7 CDM). In

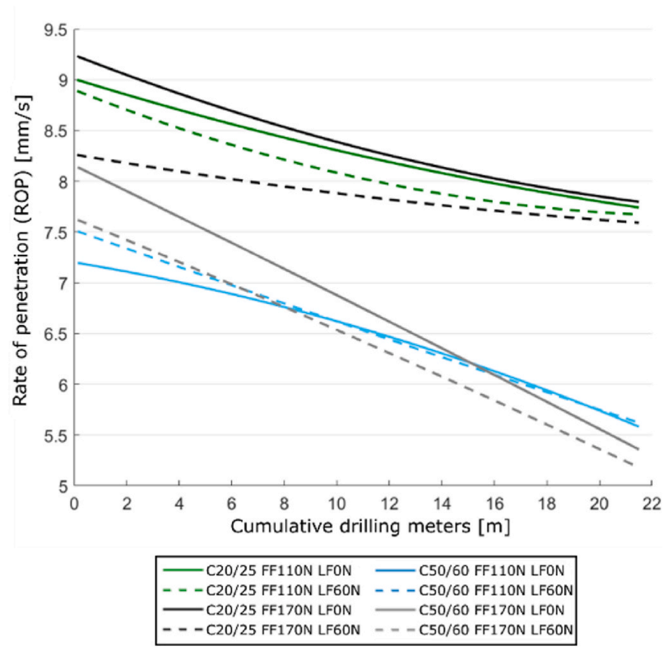
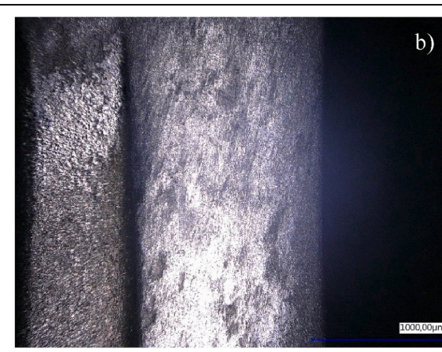
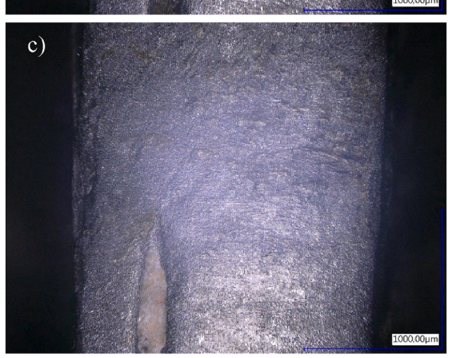


Fig. 8. Course of rate of penetration (ROP) over cumulative drilling meters for each concrete (C), feed force (FF), and lateral force (LF). Each curve includes 600 test runs. In total, 4800 test runs are shown.

Table 5
Exemplary wear on the side of the drill bit tip.

		Drill bit manufacturer 0	Drill bit manufacturer 1
Concrete strength	C20/25		
	C50/60		

C20/25, the curves in the examined area come closer and closer together, but do not cross.

3.3. *What influence do the feed and lateral force in interaction with the drill bit wear have on hammer drill vibrations?*

In order to analyze which of the factors influence the hammer drill vibration, a multifactorial ANOVA with main effects and first-order interactions was performed for both the a_{hv} value on the housing and the main handle. The model generated for the main handle has an adjusted R^2 of 0.728 (see Table 6). It is shown that all factors and factor combinations are statistically significant. Except for the combination *drill bit manufacturer*cumulative drilling meters* ($p < .05$), all have a p-value of less than 0.001. If Cohens *f* is calculated from the partial η^2(described in Table 6), it can be shown that a strong effect can be demonstrated for the *lateral force* (*f* 0.93, 0 N: M 12.9 m/s^2, 60 N: M 15.7 m/s^2), the *concrete* (*f* 0.62, C20/25: M 15.2 m/s^2, C50/60: M 13.4 m/s^2), and the *drill bit manufacturer* (*f* 0,49, 0: M 15 m/s^2, 1: M 13.6 m/s^2). For the factors *feed force* (*f* 0.34, 110 N: M 14.8 m/s^2, 170 N: M 13.8) and *cumulative drilling meters* (*f* 0.32, 0 m: M 14.9 m/s^2, 10.5 m: M 14.3 m/s^2, 21 m: M 13.7 m/s^2), as well as the combinations *concrete*cumulative drilling meters* (*f* 0.28), concrete**lateral force* (*f* 0.36), and *drill bit manufacturer*lateral force* (*f* 0.3), a medium effect strength can be shown. For all other combinations, no, or only a lower effect strength can be proven. Fig. 9 and Fig. 10 show the a_{hv} values at the main housings over the cumulative drilling meters. The manufacturers were not particularly distinguishable here either.

The model for the a_{hv} values at the housing has an adjusted R^2 of 0.844 (see Table 6). Except for the combination *drill bit manufacturer*concrete*, all factors and factor combinations are statistically significant. Regarding the effective strength, it can also be shown that the *lateral force* with an η^2 0.531 (*f* 1.06, 0 N: M 18.1 m/s^2, 60 N: M 15 m/s^2) has the greatest effect. In contrast to the main handle, the *feed force* now has the second largest effect (*f* 0.68, 110 N: M 17.6 m/s^2, 170 N: M 15.6 m/s^2), followed by *concrete* (*f* 0.59, C20/25: M 17.4 m/s^2, C50/60: M 15.7 m/s^2) and *drill bit manufacturer* (*f* 0.5, 0: M 17.3 m/s^2, 1: M 15.8 m/s^2), which also have a strong effect. The *cumulative drilling meters* (*f* 0.33, 0 m: M 17.2 m/s^2, 10.5 m: M 16.4 m/s^2, 21 m: M 16.1 m/s^2) and the factor combinations *concrete*cumulative drilling meters* (*f* 0.32) and *feed force* lateral force* (*f* 0.4) have a medium effect.

Table 6
Result of the multi-factorial ANOVA for the analysis of influencing factors (cumulative drilling meters (CDM), drill bit manufacturer (DBM), concrete strength (C), feed force (FF), and lateral force (LF)) on the a_{hv} of the main handle and the housing. N = 4800.

		a_{hv} main handle[a]		a_{hv} housing[b]	
Source	*df*	*F*	η^2	*F*	η^2
DBM	1	1215.648***	.191	1311.307***	.203
C	1	1962.429***	.276	1800.538***	.259
FF	1	603.253***	.105	2372.088***	.315
LF	1	4427.110***	.462	5827.077***	.531
CDM	2	267.784***	.094	284.629***	.100
C * CDM	2	205.103***	.074	268.828***	.095
DBM * C	1	36.258***	.007	,138	.000
C * LF	1	668.238***	.115	90.634***	.017
C * FF	1	310.685***	.057	8.374**	.002
DBM * CDM	2	3.159*	.001	4.416*	.002
LF * CDM	2	9.223***	.004	134.564***	.050
FF * CDM	2	4.777**	.002	7.150**	.003
DBM * LF	1	460.367***	.082	11.120**	.002
DBM * FF	1	17.056***	.003	54.256***	.010
FF * LF	1	221.775***	.041	801.957***	.135
Error	5150				
Total	5171				

[a] R^2 = .763 (adjusted R^2 = .728); b. R^2 = .864 (adjusted R^2 = .844).
[b] (C = concrete, DBM = drill bit manufacturer, FF = feed force, LF = lateral force, CDM = cumulative drilling meters, df = degrees of freedom).

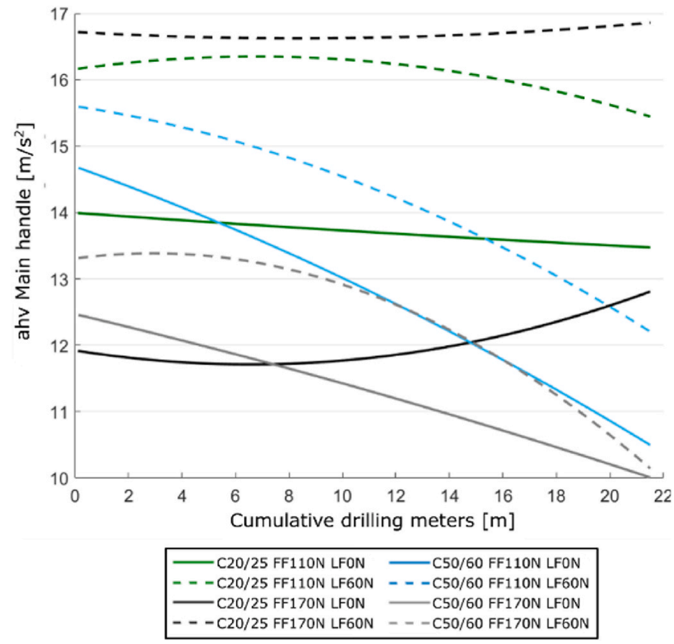


Fig. 9. Course of a_{hv} of the main handle over cumulative drilling meters for each concrete (C), feed force (FF), and lateral force (LF). Each curve includes 600 test runs and 4800 in total.

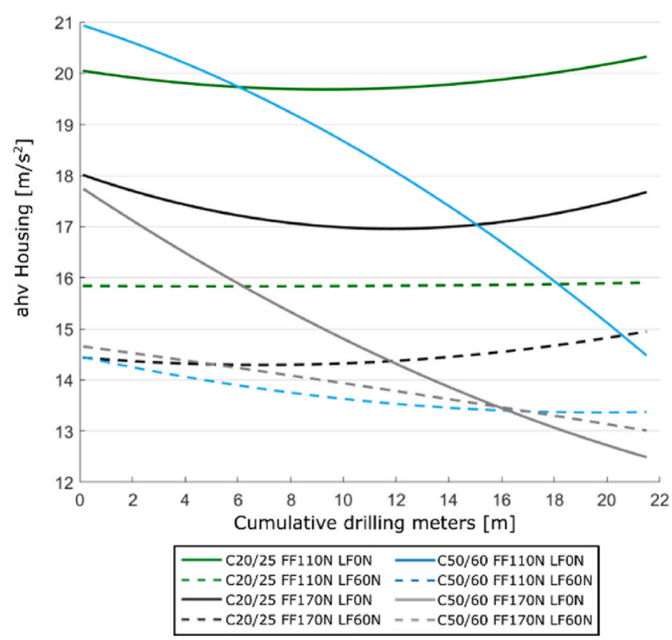


Fig. 10. Course of a_{hv} of the housing over cumulative drilling meters for each concrete (C), feed force (FF), and lateral force (LF). Each curve includes 600 test runs and 4800 in total.

4. Discussion

In this study, an experiment was carried out on a robot-based test rig with 4800 test runs. At first, influencing factors on the drill bit wear were examined. In a further step, the influence of the user forces in interaction with the drill bit wear, the concrete strength and the drill bit manufacturer on the ROP and a_{hv} value was analyzed. These two analysis steps were necessary so that the developer can connect possible influences with the design properties of the product and can optimize them from an ergonomic point of view.

4.1. Do the feed and lateral force in interaction with the concrete and drill bit manufacturer have an influence on the drill bit wear?

The results of the wear investigation of the **drill bit helix** showed that only the *lateral force* had a significant influence on the helix wear at all measuring points. In the test runs with a *lateral force*, the robot applied a horizontal motion. Since the hammer drill was connected to the robot via elastomers and the hammer drill had a type of pivot joint due to the drill bit in the borehole, the hammer drill tilted, in addition to the lateral motion. This resulted in a sickle-shaped contact between the drill bit helix and the borehole. Since this contact area was constantly shifting along the helix shaft, the absolute diameter change due to the *lateral force* was approximately the same at all measuring points. This wear reduced the depth of the helix flutes, which means that less drilling dust could be removed. This can lead to clogging of the drill bit, making the drill bit less reliable (Hecker, 1983). A sufficiently large volume of the helix is particularly important for small drill bit diameters, as these tend to clog. This in turn has a negative influence on the ROP and can also lead to deflagration, which causes a larger amount of drilling dust blown out into the surrounding air in an impulsive manner. For these drill bit diameters, the helix should be developed in such a way that it wears more slowly. This could be realized by geometrical adjustments, such as a wider helix land, or by a more wear-resistant material of the helix. The wear patterns of the helix showed that abrasive wear occurred due to the rotation of the drill bit. This was further reinforced by lateral forces that occurred. Thus, the example images confirmed the results of the statistical analysis.

At measuring points 1 and 3, the *concrete strength* had a significant effect on the wear of the helix. The drilling dust produced during drilling was identified by the helix flutes. It may be assumed that drilling dust was also located between the helix land and the borehole wall. Due to the friction at the helix in interaction with the higher-strength concrete and with its drilling dust, the wear increased. This effect could be proven at the middle measuring point and at measuring point 1. Thus, this effect was significantly stronger close to the drill bit tip than at point 3. Probably, this is due to the fact that the shafts at these measuring points were not in contact with the borehole for a long time due to the increasing drilling depth. This hypothesis fits the results from Fig. 6. For the drill bit manufacturer, a significant difference could only be shown at measurement point 3, but the p-value at the other measurement points was below 0.06. It can therefore be assumed that with more test repetitions, an influence could have been demonstrated here as well. The influence of the factor could be related to the drill bit material or the land width. As already noted by Vergara et al. (2008), optimization potential can be uncovered by comparing different manufacturers to optimize the helix by a suitable choice of design parameters. In this way, the reliability, and thus the changes in terms of productivity can be kept constant for as long as possible.

The main wear on the **drill bit tip** was caused by pitting at the top of the tip and abrasive wear, resulting from the combination of impact and rotation at the side of the drill bit. This behavior is consistent with the study by Momeni et al. (2017) and Tkalich et al. (2017). This hypothesis is supported by the diagonal scoring, respectively by the abrasive wear on the rounded side of the drill bit. The horizontal scoring, which occurred only on the very heavily worn drill bits (C50/60), probably occurred when the affected surface no longer had the current largest drill bit diameter, but was at the same time nearly perpendicular to the direction of impact. As a result, presumably hardly any energy was transferred into the concrete at this point, which meant that no crushing process occurs. However, since the drill bit had to expand the borehole to the largest diameter at this point, this can only be done by reaming it due to rotation. Regarding the observed influencing variables, the study has shown that no influence of the factors *feed and lateral force* on the drill bit tip wear could be proven. Comparing these results with those of the helix wear, it can be assumed that this was due to the considerably harder material of the tip. From this finding, it can be concluded that manufacturers of drill bits do not need to consider user forces in the development of the drill bit tip. At the current state of research, there are no studies investigating the influence of *concrete strength* on the wear of drill bits for hammer drills. In terms of the study carried out here, it could be shown that through harder *concrete*, the diameter of the drill bit tip decreased faster. However, studies by Botti et al. (2017), Carty et al. (2017), and Momeni et al. (2017) have shown that it is basically the drill bit corner that wears out fastest, which is confirmed by our study. The largest wear at this point was due to the fact that the combination of impact and frictional stress generates the greatest load on the drill bit. This hypothesis is supported by studies by Antonov et al. (2015) and Saai et al. (2020), which investigated the wear behavior of WC–Co cemented carbides with and without impacts. Due to a higher *concrete strength*, this load at the drill bit tip increased further, which is why different concrete strength should always be considered in simulations and in the testing of drill bits. A comparison with the factor *drill bit manufacturer* showed that the result can be transferred in principle, but that the drill bit tip of *manufacturer* 1 worn out faster. Nevertheless, the drill bits of both manufacturers were still within the target range according to ETAG 001-1 (1997) after 21 cumulative drilling meters for C20/25. In contrast to type 0 of the manufacturer, type 1 is just at the limit or slightly below in the test runs with C50/60, and would therefore be considered worn out for this application. This shows that the range of drill bit service life considered is also suitable for insights regarding changes in productivity and vibration over time.

4.2. What influence do the feed and lateral force in interaction with the drill bit wear have on productivity?

The *concrete strength* and the *cumulative drilling meters,* respectively the drill bit wear, had the greatest influence on the ROP. These findings are in line with the results by Cronjager and Jahn (1985) and Kivade et al. (2015), which showed that the ROP decreases with increasing concrete strength or subsoil strength, respectively. Furthermore, investigations by Antonucci et al. (2017), Botti et al. (2017), and Weinert et al. (1993) have proven that the ROP depends significantly on the *cumulative drilling meters* and the resulting drill bit wear. When looking at the worn drill bits, several phenomena are noticeable. The edges wore out along the cutting edge. On the one hand, this resulted in a larger contact area between the drill bit and the concrete while the impact energy remained constant and, on the other hand, the notch angle became flatter. This led to a worsening of crack formation in the concrete. Therefore, these two effects should have a negative influence on the ROP. It is interesting to see that the centering tip of the drill bit manufacturer 0 became blunt, whereas the drill bit of type 1 became sharper. However, it cannot be assessed whether this had a positive or negative influence on the ROP.

Botti et al. (2017) found that the ROP decreases the most on the first drilling meters. This behavior is consistent with the behavior from our study at C20/25. The influence of the factor combination *concrete*cumulative drilling meters* indicates that the ROP decreased more over the cumulative drilling meters with higher-strength concrete. This decrease was almost linear over the total drilling distance. This can be attributed to the fact that the drill bit side wore out more quickly with a higher concrete strength. A wedge shape was formed on the drill bit side. This was more pronounced in C50/60 after 10.5 CDM than in C20/25 after 21 CDM. It is assumed that this wedge shape caused the impact energy to be transferred into the concrete in a less directed way. The course of the curves at C20/25, which is increasingly approaching a horizontal line, can also be explained by the fact that at the beginning (Botti et al., 2017), the wear was more pronounced at the corner and this did not changed so strongly at C20/25. With C50/60, on the other hand, the wedge shape was formed more and more. This could explain the is clearly higher.

With regard to the factors **feed force** and **lateral force**, no significant effect on a dependent variable could be proven for either drill bit manufacturer.

For a visual illustration of the results, Table 5, four example margins are shown in Table 5. In the images a), b), and d), scoring occurs and runs from top right to bottom left. This wear occurred with almost all drills. Nearly all drill bits of manufacturer 0, which were used for drilling in the higher-strength concrete, had horizontal scoring just above the control wear edge. When comparing the two drill bit manufacturers, it is noticeable that type 1 showed significantly more crater wear, which is reinforced by the harder concrete.

3.2. What influence do the feed and lateral force in interaction with the drill bit wear have on productivity?

A multi-factorial ANOVA was performed to analyze whether the factors feed force, lateral force, concrete, and manufacturer and their interactions have an influence on the ROP. Table 3 summarizes the result of the ANOVA. The model has an adjusted R^2 of 0.668. The results show that each of the factors are significant *($p < .001$)*. In the previous chapter, it could be shown that the wear depends strongly on the drilling meters. Thus, in this chapter, the factor drilling meters can be understood as a synonym for drill bit wear. However, since this factor has not been set, we will continue to use the term drilling meters. Among the factor combinations, only the combinations *concrete* feed force* and *lateral force*drilling meters* are not significant. However, when looking at the strength of the effect over time, the factors *concrete* (*f* 1.2, C20/25: M 8.3 mm/s, C50/60: M 6.7 mm/s) and *cumulative drilling meters* (*f* 0.67, 0 m: M 8.1 mm/s, 10.5 m: M 7.5 mm/s, 21 m: M 6.9 mm/s) have a large influence. Whereas the *lateral force* (*f* 0.12, 0 N: M 7.6 mm/s, 60 N: M 7.4 mm/s), as well as the factor combinations *concrete*cumulative drilling meters* (*f* 0.23), *drill bit manufacturer*concrete* (*f* 0.12) and *drill bit manufacturer*feed force* (*f* 0.1), have a small influence. With regard to the factors *drill bit manufacturer* and *feed force*, both have nearly no effect.

Fig. 8 shows the ROP curves over the cumulative drilling meters. Since no distinction was made between the different manufacturers, each curve contains the average of four test run series (4 × 150 holes). The diagram shows that in test runs with C50/60 the ROP at a feed force of 170 N was initially higher. With increasing cumulative drilling meters and drill bit wear, the ROP becomes similar to the ROP of test runs with a feed force of 110 N and, at least with a higher-strength concrete, the curves even cross (LF 0 N: after 14 CDM, LF 60 N: after 7 CDM). In

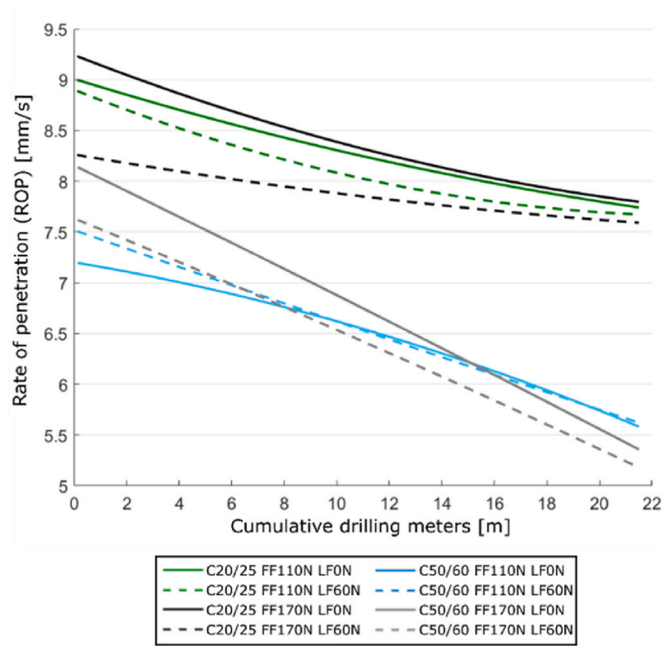
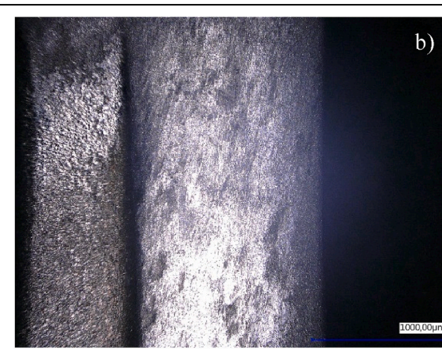
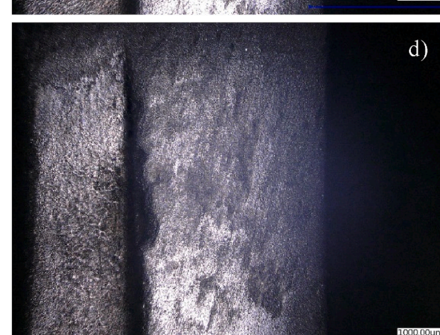


Fig. 8. Course of rate of penetration (ROP) over cumulative drilling meters for each concrete (C), feed force (FF), and lateral force (LF). Each curve includes 600 test runs. In total, 4800 test runs are shown.

Table 5
Exemplary wear on the side of the drill bit tip.

		Drill bit manufacturer 0	Drill bit manufacturer 1
Concrete strength	C20/25		
	C50/60		

more oval borehole was created in softer material due to the helix, which means that the drill bit has more backlash in the hole. The interaction of the *lateral force* with the *manufacturer* could be presumed by the fact that the helix, e.g. sharpness of the helix flutes, differs. The two manufacturers choose a different manufacturing process in addition to the geometry. A sharper edge could lead to the fact that the helix glides less well in the borehole, but that a cutting process takes place in some cases. An alternative explanation could be the difference in bending stiffness of the drill bits.

When looking at the a_{hv} values on the housing, they were slightly above those of the main handle. Furthermore, the effect strengths were mostly comparable. Although the *lateral force* had a similarly strong effect as at the main handle, the a_{hv} value decreased at this measuring point. Thus, the a_{hv} value behaved contrary to the effects at the main handle when the lateral force was increased. A possible explanation is the stiffening of the total system, especially the hand-arm system and the percussion mechanism. It can be assumed that the vibrations on the side handle will also decrease since it is rigidly attached. This therefore would have a positive effect on the user's load. The fact that the *feed force* had the second largest main effect at the side handle and a medium effect in interaction with the *lateral force* is attributed to the vibration decoupling of the main handle. The correlation that with higher feed force, the vibrations at the main handle decreased to a lesser extent than those at the side handle rigidly mounted at the housing or on the housing has already been demonstrated by Lindenmann et al. (2021). In their study, the same hammer drill type was used.

The findings obtained in this study were developed on a test bench. Furthermore, the results of our study have shown that the lateral force had an influence on the wear of the helix, but also on the a_{hv} value and ROP. Uhl et al. (2021) showed that without an intentionally applied lateral force, the median was lower than the 60 N applied here. Based on this, further investigations should be carried out in which more factor levels of the lateral force are set. In this way, it can be shown whether a linear relationship exists. The investigation of the influence of the feed force on the a_{hv} value in this study, as well as in the current state of research, has shown that it can cause different effects. Therefore, it should be investigated how far the findings are transferable to other types of drill bits and hammer drills. This could also help to describe these relationships by physical equations. Thus, the knowledge would be directly useable for the development of technical systems. However, the knowledge gained here can already be used by developing power tools that provide feedback to the user. For example, the user could be warned in the case of too much drill bit wear or too high a_{hv} values due to an excessive lateral force. Furthermore, by adjusting the design of the drill bits and the wear behavior the reliability could be improved. Botti et al. (2017) pointed out that drill bit wear leads to lower ROP and productivity. As a result, the user is exposed to vibrations for a longer period of time. Since in this study, the vibrations did not decrease over the cumulative drilling meters, this would lead to a higher stress for the user. However, with a higher concrete strength, the a_{hv} value dropped more relative to the ROP value. As a result, the user would be less stressed by the vibrations, whereby wear would even have a positive effect. The influence of the lateral force is also critical in this consideration. By applying a lateral force, the ROP dropped, and in all cases, the vibrations increased. These findings could also be incorporated into the development of hammer drills or at least be taught to craftsmen in training courses. The creation of boreholes is almost exclusively carried out in order to subsequently attach fastening systems such as concrete anchors or dowels. Therefore, it would be interesting to find out what influence the lateral force and the drill bit wear have on the borehole geometry, and thus, ultimately on the setting and holding behavior of the fastening systems.

5. Limitations

In this study, 4800 individual runs were performed. Changes in the hammer drill, such as wear of the impact components, can change the single impact energy over time. The influence of these changes has been reduced due to the randomization of the drilling sequence but cannot be completely excluded. However, the changes should mainly lead to an increase in the scattering of the dependent variables. Because of the above mentioned reasons, effects with small effect strength should be verified again in a separate study.

Furthermore, the hand-arm model used in this study was developed by Cronjager (Cronjager et al., 1984; Jahn and Hesse, 1986) to simulate the human vibration characteristics in the direction of impact. It is therefore not clear how well the vibration characteristics of the hand-arm model transverse to the direction of the drilling direction correspond to those of the human. The vibration properties of the human being should tend to stiffen by an additionally applied force in lateral direction. This effect also occurs with the hand-arm model. However, whether both systems stiffen to the same extent has not yet been investigated. For this reason, the results should be verified by experiments with humans at the extremes of the experimental plan. If the results differ, a hand-arm model should be developed that better models these vibration characteristics.

The transferability of the results to other hammer drills and drill bits is also unclear. Although the basic design of the various hammer drills is quite similar, there are differences, for example, in the mass ratios and the types of gears. Especially since manufacturers develop their own product combinations in such a way that they are adjusted to each other. Even with hollow drill bits that do not have a helix, the results can vary considerably. Although the basic design of the hammer drills is quite similar, there are differences, for example, in the mass ratios and the types of gear. For hammer drills of the same or of very similar design, the results should therefore be transferable. For other types of construction, it has to be analyzed whether the physical relationship is transferable.

6. Conclusion

The objective of this study was to understand the influence of user forces in interaction with drill bit wear on HAV and productivity. To enable the developer to further improve the design of the drill bit, its wear was also analyzed. It was investigated which factor influences the wear at the drill bit tip as well as at the drill bit helix. Therefore, a study with 4800 runs was carried out on a test bench.

The results of this study show that there is a large influence of the lateral force on the vibrations, which caused an opposite influence at the two measuring points of the housing of the hammer drill. Furthermore, a minor negative influence of the lateral force on the productivity could be proven. Based on the findings, it can be concluded that in the development of hammer drills and drill bits, but also in standards to evaluate the HAV, lateral forces should be considered. In the tests, according to the standard DIN EN ISO 28927-10 (2011), an idealized drilling situation is defined, which is why the lateral force in real applications should be significantly higher, and thus, the vibrations generated are higher. In order to be able to quantify the influence in real applications, field studies should be carried out to measure the lateral force. It can be assumed that these are at least higher on average than those determined by Uhl et al. (2021) under laboratory conditions. As soon as the range of lateral force in the field is known, investigations can be carried out in which more factor levels of the feed and lateral force are set, in order to analyze the relationship to a_{hv} value and ROP. The knowledge gained in this study can also be used by hammer drill manufacturers to develop more ergonomic tools. Up to now, hammer drills have been designed to reduce vibrations in the direction of the impact through vibration decoupling concepts. However, in the future, they should also be designed to absorb lateral forces without bypassing vibration decoupling. Similar to the research for decoupling concepts in the direction of the impact from Gillmeister (1998), research work could also take place in science with the aim of developing different concepts. Another development approach for hammer drill manufacturers could be a feedback by the tool to the user to reduce vibrations or increase productivity. For this purpose, the lateral forces could be measured and, above a certain level, the user could be warned by a visual feedback. Furthermore, users should also be trained to gain knowledge about the influence of the lateral forces.

Regarding the investigations of the drill bit wear, it can be stated that the lateral force has a negative influence on the wear of the helix. However, no evidence could be provided concerning the drill bit tip. With an increase in the lateral force, the wear along the helix geometry increases. The smaller the drill bit diameter, the more important is the volume of the helix for transporting the drilling dust. Drill bits with small diameters should be developed in such a way that the helix wears out more slowly. This could be realized by geometrical adjustments or by surface hardening. An exciting finding in the analysis of wear at the drill bit tip is revealed by the variation in concrete strength. When drilling in higher strength concrete, the drill bit wears significantly more on the sides. This leads to a sharp decrease in productivity and vibration. From a manufacturer's point of view, a hammer drill-drill bit combination could be developed on the basis of this knowledge to prevent the sharp drop in productivity. Possible solutions could be to reduce the rotational speed of the hammer drill, to adapt a geometry on the drill bit side or corner, or to increase the hardness locally on the drill bit side, without the tip itself becoming too brittle.

Funding

This research was supported in part by Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) through the financing of the test environment within the context of the proposal GZ: INST 121384/81-1 FUGG. The research results are solely the responsibility of the authors and do not necessarily represent the official views of DFG.

CRediT authorship contribution statement

Michael Uhl: Conceptualization, Methodology, Data acquisition, Data processing, Writing – original draft, preparation, Visualization, Investigation, Project administration, Formal analysis, Validation. **Marius Gauch:** Data acquisition, Data processing. **Jan-Heinrich Robens:** Data acquisition, Writing – review & editing. **Thomas Gwosch:** Conceptualization, Supervision, Writing – review & editing. **Sven Matthiesen:** Conceptualization, Supervision, Writing – review & editing, Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Aldien, Y., Marcotte, P., Rakheja, S., Boileau, P.-E., 2005. Mechanical impedance and absorbed power of hand-arm under x(h)-axis vibration and role of hand forces and posture. Ind. Health 43, 495–508. https://doi.org/10.2486/indhealth.43.495.

Antonov, M., Veinthal, R., Yung, D.-L., Katušin, D., Hussainova, I., 2015. Mapping of impact-abrasive wear performance of WC–Co cemented carbides. Wear 332–333, 971–978. https://doi.org/10.1016/j.wear.2015.02.031.

Antonucci, A., Barr, A., Martin, B., Rempel, D., 2017. Effect of bit wear on hammer drill handle vibration and productivity. J. Occup. Environ. Hyg. 14, 642–651. https://doi.org/10.1080/15459624.2017.1316385.

Anwer, S., Li, H., Antwi-Afari, M.F., Wong, A.Y.L., 2021. Associations between physical or psychosocial risk factors and work-related musculoskeletal disorders in construction workers based on literature in the last 20 years: a systematic review. Int. J. Ind. Ergon. 83, 103113 https://doi.org/10.1016/j.ergon.2021.103113.

Botti, L., Mora, C., Antonucci, A., Carty, P., Barr, A., Rempel, D., 2017. Carbide-tipped bit wear patterns and productivity with concrete drilling. Wear 386–387, 58–62. https://doi.org/10.1016/j.wear.2017.05.017.

Botti, L., Martin, B., Barr, A., Kapellusch, J., Mora, C., Rempel, D., 2020. R2: drilling into concrete: effect of feed force on handle vibration and productivity. Int. J. Ind. Ergon. 80, 103049 https://doi.org/10.1016/j.ergon.2020.103049.

Bovenzi, M., 1994. Hand-arm vibration syndrome and dose-response relation for vibration induced white finger among quarry drillers and stonecarvers. Italian Study Group on Physical Hazards in the Stone Industry. Occup. Environ. Med. 51, 603–611. https://doi.org/10.1136/oem.51.9.603.

Carty, P., Cooper, M.R., Barr, A., Neitzel, R.L., Balmes, J., Rempel, D., 2017. The effects of bit wear on respirable silica dust, noise and productivity: a hammer drill bench study. Ann. Work Expo. Health 61, 700–710. https://doi.org/10.1093/annweh/wxx041.

Coenen, P., Formanoy, M., Douwes, M., Bosch, T., Kraker, H. de, 2014. Validity and inter-observer reliability of subjective hand-arm vibration assessments. Appl. Ergon. 45, 1257–1262. https://doi.org/10.1016/j.apergo.2014.03.003.

Cohen, J., 1992. A power primer. Psychol. Bull. 112, 155–159. https://doi.org/10.1037//0033-2909.112.1.155.

Cronjager, L., Jahn, R., 1985. Schwingungsbelastungen bei handgefuehrten Bohrwerkzeugen Techn. Prüfverfahren - Erarbeitung von technischen Prüfverfahren zur Bestimmung der Schwingungsbelastung beim Arbeiten mit handgeführten Bohrhammern und Schlagbohrmaschinen. Wirtschaftsverlag NW. Verlag für neue Wissenschaft GmbH, Bremerhaven, p. 80.

Cronjager, L., Jahn, R., Riederer, H., 1984. Entwicklung eines Versuchsstandes zur reproduzierbaren Messung der Vibration schlagender handgeführter Maschinen. VS Verlag für Sozialwissenschaften, Wiesbaden, p. 91.

DIN EN 206, 2017. Beton – Festlegung, Eigenschaften, Herstellung und Konformitat. Beuth Verlag GmbH, Berlin, p. 98.

DIN EN ISO 28927-10, 2011. DIN EN ISO 28927 Handgehaltene motorbetriebene Maschinen – Messverfahren zur Ermittlung der Schwingungsemission - Teil 10: Bohrhammer, Schlaghammer und Aufbruchhammer. Beuth Verlag GmbH, Berlin, p. 33.

DIN EN ISO 5349-1, 2001. DIN EN ISO 5349 Messung und Bewertung der Einwirkung von Schwingungen auf das Hand-Arm-System des Menschen - Teil 1: Allgemeine Anforderungen, first ed. Beuth Verlag GmbH, Berlin.

DIN EN ISO 9241-210, 2011. Ergonomie der Mensch-System-Interaktion – Teil 210: Prozess zur Gestaltung gebrauchstauglicher interaktiver Systeme, vol. 13. Beuth Verlag GmbH, Berlin, 180; 35.180. https://www.beuth.de/de/norm/din-en-iso-9241-210/135399380.

Dong, R.G., Welcome, D.E., Xu, X.S., Mcdowell, T.W., 2020. Identification of effective engineering methods for controlling handheld workpiece vibration in grinding processes. Int. J. Ind. Ergon. 77 https://doi.org/10.1016/j.ergon.2020.102946.

Eaves, S., Gyi, D.E., Gibb, A.G.F., 2016. Building healthy construction workers: their views on health, wellbeing and better workplace design. Appl. Ergon. 54, 10–18. https://doi.org/10.1016/j.apergo.2015.11.004.

ETAG 001-1, 1997. Bekanntmachung der Leitlinie für die europaische technische Zulassung für Metalldübel zur Verankerung im Beton - Teil 1: Dübel - Allgemeines, third ed. Beuth Verlag GmbH, Berlin, p. 19.

Flegner, P., Kačur, J., Durdán, M., Laciak, M., Stehlíková, B., Pástor, M., 2016. Significant damages of core diamond bits in the process of rocks drilling. Eng. Fail. Anal. 59, 354–365. https://doi.org/10.1016/j.engfailanal.2015.10.016.

Gillmeister, F., 1998. Passive und aktive sekundare Maßnahmen zur Reduzierung der Hand-Arm-Schwingungsbelastung. Dissertation, Dortmund.

Gruner, G., Knoll, P., 2000. Optimierung motorisch betriebener Handmaschinen (Schlagbohrmaschinen, Bohrhaemmer) und Werkzeuge hinsichtlich der Emissionsminderung des Feinstaubes. In: Wirtschaftsverlag NW, 893rd ed. Verlag für neue Wissenschaft GmbH, Bremerhaven, p. 122.

Hecker, R., 1983. Stoss- und Schallprobleme beim schlagenden Bohren. VDI-Verlag GmbH, Düsseldorf, p. 196.

Fachkraftesituation im Bauhauptgewerbe. https://www.bauindustrie.de/themen/auf-den-punkt-gebracht/fachkraftesituation-im-bauhauptgewerbe/. (Accessed 8 December 2020).

Jahn, R., 1985. Einflußgroßen auf die Beschleunigungen elektropneumatischer Bohrhammer. Dissertation, Dortmund, p. 58.

Jahn, R., Hesse, M., 1986. Applications of hand-arm models in the investigation of the interaction between man and machine. Scand. J. Work. Environ. Health 12, 343–346. https://doi.org/10.5271/sjweh.2132.

Kivade, S.B., Murthy, C.S.N., Vardhan, H., 2015. Experimental investigations on penetration rate of percussive drill. Proc. Earth Planet. Sci. 11, 89–99. https://doi.org/10.1016/j.proeps.2015.06.012.

Lindenmann, A., Uhl, M., Gwosch, T., Matthiesen, S., 2021. The influence of human interaction on the vibration of hand-held human-machine systems – the effect of body posture, feed force, and gripping forces on the vibration of hammer drills. Appl. Ergon. 95, 103430 https://doi.org/10.1016/j.apergo.2021.103430.

Maeda, S., Taylor, M.D., Anderson, L.C., McLaughlin, J., 2019. Determination of hand-transmitted vibration risk on the human. Int. J. Ind. Ergon. 70, 28–37. https://doi.org/10.1016/j.ergon.2019.01.002.

Marcotte, P., Boutin, J., Jasinski, J., 2010. Development of a hand–arm mechanical analogue for evaluating chipping hammer vibration emission values. J. Sound Vib. 329, 1968–1980. https://doi.org/10.1016/j.jsv.2009.10.042.

Matthiesen, S., Mangold, S., Bruchmueller, T., 2018. The influence of variating passive user interactions on power tools in the context of product development. Forsch. Im. Ingenieurwes. 329 https://doi.org/10.1007/s10010-018-0269-x.

Momeni, S., Moseley, S., Ante, M., Allaart, J., 2017. The wear of WC-Co drill bits during rotary-percussive drilling of reinforced concrete. Int. J. Refract. Metals Hard Mater. 62, 202–209. https://doi.org/10.1016/j.ijrmhm.2016.08.006.

Poole, C.J.M., Bovenzi, M., Nilsson, T., Lawson, I.J., House, R., Thompson, A., Youakim, S., 2019. International consensus criteria for diagnosing and staging hand-

arm vibration syndrome. Int. Arch. Occup. Environ. Health 92, 117–127. https://doi.org/10.1007/s00420-018-1359-7.
Rempel, D., Barr, A., Antonucci, A., 2017. A new test bench system for hammer drills: validation for handle vibration. Int. J. Ind. Ergon. 62, 17–20. https://doi.org/10.1016/j.ergon.2016.08.001.
Rempel, D., Antonucci, A., Barr, A., Cooper, M.R., Martin, B., Neitzel, R.L., 2019. Pneumatic rock drill vs. electric rotary hammer drill: productivity, vibration, dust, and noise when drilling into concrete. Appl. Ergon. 74, 31–36. https://doi.org/10.1016/j.apergo.2018.08.005.
Riederer, H., 1985. Untersuchungen zur Dynamik elektropneumatischer Bohrhammer. Dissertation, Dortmund.
Rimell, A.N., Notini, L., Mansfield, N.J., Edwards, D.J., 2008. Variation between manufacturers' declared vibration emission values and those measured under simulated workplace conditions for a range of hand-held power tools typically found in the construction industry. Int. J. Ind. Ergon. 38, 661–675. https://doi.org/10.1016/j.ergon.2007.10.023.
Saai, A., Bjørge, R., Dahl, F., Antonov, M., Kane, A., Diop, J.-B., Ojala, N., 2020. Adaptation of Laboratory tests for the assessment of wear resistance of drill-bit inserts for rotary-percussive drilling of hard rocks. Wear 456–457, 203366. https://doi.org/10.1016/j.wear.2020.203366.
Silva, G.H.M., de, J.S., Wijewardana, T.R.S.T., 2021. Preliminary results of hand arm vibration (HAV) exposures of chipping hammer operators in tropical weather: analysis of exposures and protective gloves. Int. J. Ind. Ergon. 86, 103197 https://doi.org/10.1016/j.ergon.2021.103197.
Thota, J., Kim, E., Freivalds, A., Kim, K., 2022. Development and evaluation of attachable anti-vibration handle. Appl. Ergon. 98, 103571 https://doi.org/10.1016/j.apergo.2021.103571.
Tkalich, D., Kane, A., Saai, A., Yastrebov, V.A., Hokka, M., Kuokkala, V.-T., Bengtsson, M., From, A., Oelgardt, C., Li, C.C., 2017. Wear of cemented tungsten carbide percussive drill–bit inserts: laboratory and field study. Wear 386–387, 106–117. https://doi.org/10.1016/j.wear.2017.05.010.
Uhl, M., Bruchmüller, T., Matthiesen, S., 2019. Experimental analysis of user forces by test bench and manual hammer drill experiments with regard to vibrations and productivity. Int. J. Ind. Ergon. 72, 398–407. https://doi.org/10.1016/j.ergon.2019.06.016.
Uhl, M., Lindenmann, A., Matthiesen, S., 2021. Analysis of factors influencing the productivity of hammer drilling – user forces, human fatigue, drilling direction, and drill bit. Appl. Ergon. 92, 103338 https://doi.org/10.1016/j.apergo.2020.103338.
Vergara, M., Sancho, J.-L., Rodríguez, P., Pérez-González, A., 2008. Hand-transmitted vibration in power tools: accomplishment of standards and users' perception. Int. J. Ind. Ergon. 38, 652–660. https://doi.org/10.1016/j.ergon.2007.10.014.
Weinert, K., Michel, O., Gillmeister, F., 1993. A Contribution to Optimize the Cutting Edge Angle of Hammer Drill. Carl-Hanser Verlag, München.
Welcome, D., Rakheja, S., Dong, R., Wu, J.Z., Schopper, A.W., 2004. An investigation on the relationship between grip, push and contact forces applied to a tool handle. Int. J. Ind. Ergon. 34, 507–518. https://doi.org/10.1016/j.ergon.2004.06.005.