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INFLUENCE OF COOLING LUBRICANTS ON THE INTERACTION BETWEEN INDENTER AND MATERIAL SURFACE DURING SCRATCH TESTS

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Abstract. Striving for the optimization and the increase of efficiency of various systems demands further developments of the classic manufacturing methods. Especially grinding processes, which are characterized by undefined cutting-edge geometries, reveal many fields where there still is a lack of understanding. In particular, the processes at and their effects on the individual abrasive grit are insufficiently researched and, therefore, do not allow sufficiently accurate behavior predictions.

In order to optimize grinding processes and, ultimately, the resulting quality of the workpiece surface, it is necessary to look at the entire process in a holistic way. Due to the large number of influences to which the grinding process is subject, it is initially advisable to break down the process as far as possible into individual scratch tests and then gradually return to the overall process. One approach is the development and expansion of an FEM-based physical force model, which allows for the simulation and prediction of a scratch tests and, subsequently, also the entire grinding process with all relevant influencing factors.

One of these influencing factors, which are essential but mostly unconsidered, are cooling lubricants, especially their tribologically favorable influence on the interaction between workpiece and indenter. Therefore, it is important to identify and investigate the different aspects, such as the friction phenomena of scratch tests that are influenced by the use of cooling lubricants. In addition to temperature and force characteristics, which have been found to differ with and without cooling lubricant, differences in the scratch geometry on the material surface have also been observed in recent tests. Based on these findings, this work examines the relationship between scratch geometry and cooling lubricant.

It turned out that scratch tests conducted with cooling lubricants have an influence on the topography of the scratch on the workpiece surface in addition to the influence on the tangential and normal forces. The ratio of scratch width to scratch depth is used for evaluation. A reduction of this ratio is observerd in the scratches with cooling lubricants and is, therefore, interpreted as a reduction of the scratch width as a result of the use of cooling lubricants.

1 INTRODUCTION

Interactions between particles significantly determine the behavior of many machines and systems. Particle to particle interactions are very important in the field of tribology. Tribology describes the material science that deals with friction, wear and lubrication between surfaces that move relative to each other [1]. Tribological phenomena can be found in almost any system. In addition to those systems in which tribological effects are essential for the functionality of processes, in other systems tribological effects can cause problems and high energy losses [2]. In addition to the negative impacts of tribological effects, they are a decisive aspect for the functionality of many industrial manufacturing processes. This includes all machining processes, and among these, in particular grinding and lapping [3,4]. Both manufacturing processes have similar process behavior within a small observation range [5]. Here, the removal mechanism by individual abrasive grains is noteworthy. In grinding, the abrasive grains are distributed in a fixed compound, whereas in lapping these are loose abrasive grains [1]. However, even with lapping, individual cutting grains can "jam" and create continuous scratch marks similar to the grinding process.

These two manufacturing processes have become indispensable in almost every branch of industrial production. As a result of constantly increasing demands on precision and surface quality, grinding and lapping are becoming more and more important. For example, many manufacturing tools such as drills or milling cutters are produced by grinding. In particular, grinding as a manufacturing process known since ancient times is subject to continuous optimization [6]. However, even with all the advancements, both the grinding and lapping process remain very complex. This is mainly due to the fact that during grinding, as well as lapping, several geometrically undefined abrasive grains are constantly interacting with the workpiece. As a consequence, both processes are difficult to describe and the mechanisms at individual abrasive grains are not yet fully understood. As an exemplary approach, the process forces can be recorded and statistically reduced to a single abrasive grain of a grinding wheel. However, this does not provide an understanding of the individual processes and the reaction forces occurring at the individual abrasive grain. [5]

In order to address this gap of knowledge and to get a better understanding of these both processes, Sridhar et al. [7] has created a physical force model that is especially designed to map the grinding process completely. Therefore, this force model should be capable of depicting the precise processes between the abrasive grain and the workpiece. Among other things, this includes the representation of the plastic deformation of the workpiece, such as the pile-up of the edge areas of a scratch, as well as the prediction of the process forces for a single or multiple abrasive grains. Previous approaches to the description of grinding processes and their effects on the grinding forces are partially related to specific material pairings and exclusively to the recording of the total forces [8]. Qiang et. al [9] uses an empirical approach to describe the grinding process, but also uses only the total force of the process for validation. Demir et al. [10] investigated the influence of the abrasive grain size on the total force by using different grinding wheels. Nie et al. [11] have used mathematical statistics to derive a cutting grain and used it to show the influence of cutting speed and cutting depth on the process forces. However, the inclusion of cooling lubricants in the simulation approaches is not provided [11,12]. In the same way, the physical force model of Sridhar et al. [7] also does not include the integration of cooling lubricants and only considers the dry interaction between the cutting grain and the workpiece. But since cooling lubricants are almost always present at an industrial standard, they must be included in such a physical force model. Therefore, it is necessary to extend the developed force model by considering the cooling lubricant as well as investigating the influence of cooling lubricants on the grinding process experimentally. Preceding investigations already showed that scratch tests with cooling lubricants produce higher tangential and normal forces than dry scratch tests [13,14]. In order to provide an explanation for this effect, a macroscopic observation of this effect using optical measuring methods will be used. The aim is to uncover if the effects in the force progression also show specifically optical indications on the surface of the workpiece. In order to be able to make a general conclusion regarding the influence of cooling lubricants on the surface finish or the scratch geometry and to be able to include this knowledge in the physical force model, real experiments with various cooling lubricants have been carried out.

2 MATERIALS AND METHODS

In order to investigate the influence of cooling lubricants on the workpiece surface during scratch tests, first of all scratch tests are carried out with and without cooling lubricants. For this purpose, the test rig shown in Figure 1 is used, which allows to vary the scratching speed, scratching depth and grain geometry in addition to dry and lubricated scratching tests. In addition, during the scratch test, the resulting forces, which are divided into tangential forces and normal forces, can be detected by a force sensor and the workpiece surface by a distance laser. A dynamometer (type 9109AA from Kistler) is used to record the forces. Measuring the distance and setting the scratch depth is realized by a confocal displacement sensor (model series CL-3000 from Keyence). To perform the scratch test itself, a standard procedure of several steps is carried out first. An important step is, that the workpiece is cleaned with acetone in

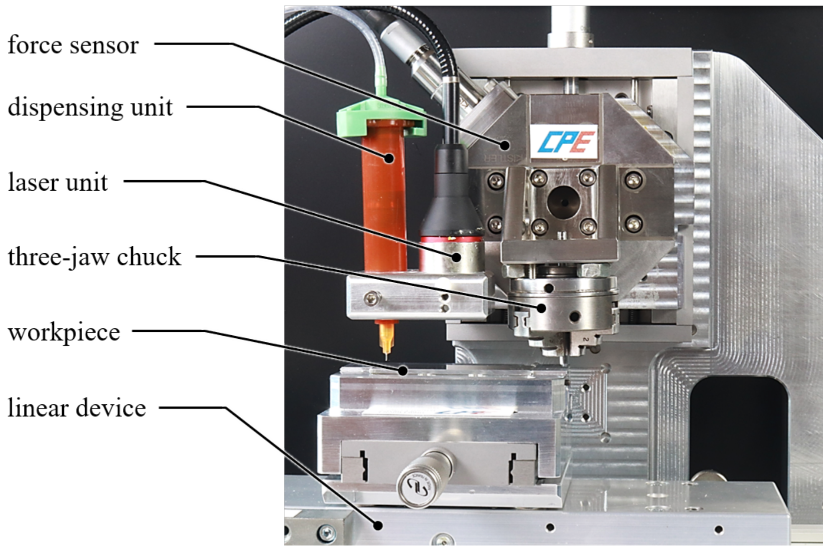

Figure 1: Test rig used for the preparation of unlubricated and lubricated scratches

an ultrasonic bath. This step is necessary to ensure that there are no remains of production-related cooling lubricants or other contaminants, such as those caused by skin contact. The cleaned workpiece, made of aluminum (EN AW-2024) in these tests, is then placed in the rig's clamping device. By using the confocal displacement sensor, the workpiece and the indenter, as the scratching tool, can be adjusted to the reqierd scratch depth. First for this purpose those both parts are placed in such a relation, that the indenter is barely touching the workpiece surface. From this initial contact point the scratch depth can be set afterwards the indenter has been moved away from the workpiece surface. To carry out the scratch test itself, the linear unit, which contains the fixing device with workpiece, is moved to its starting position. Before a test starts, the required scratching speed has to be set. Following this, the test can be carried out. During the test, the linear unit moves from left to right and passes with the workpiece surface through the tip of the indenter.

Depending on the selected scratch speed, scratch depth, and grain geometry of the indenter, a representative scratch formation results on the workpiece surface. In order to carry out the tests in a lubricated environment, a cooling lubricant is applied in front of the indenter with the use of a dosing unit (type C1000 from Vieweg), see Figure 1. To simplify the investigation and focus on the main interaction between workpiece, cooling lubricant and indenter, the cooling lubricant is represented by reference oils (FVA2 and FVA3 differ in terms of their viscosity from Weber Reference Oils) because they do not contain any additives which could cause additional effects on the force signal. For further evaluation, the workpieces are cleaned again to eliminate remaining cooling lubricant and aluminum chips, which can lead to misinterpretations during the evaluation. A digital microscope (VHX-7000 series from Keyence) is used for the optical analysis of the workpiece surface. With the use of this digital microscope, the surface topography of the workpiece can be measured contact-free and additionally displayed as a three-dimensional relief.

3 RESULTS

All data measured here refer to a scratch depth of 80 µm and a scratch speed of 500 mm/s. The varying parameters considered are the grain geometry of the indenter and the scratching

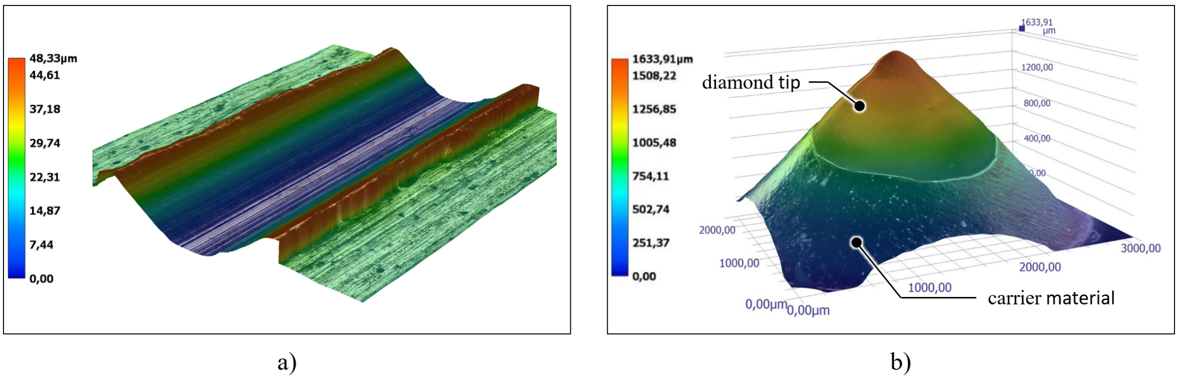

Figure 2: a) Magnification of a scratch relief caused by a cone indenter with an angle of 90° b) Magnification of a cone indenter with an angle of 90°

environment, which is either dry or lubricated. The cooling lubricants used are represented by the two reference oils FVA2 and FVA3. The reference oil FVA2 with $\nu = 85\ \mathrm{mm}^2/\mathrm{s}$ at 20°C has a significantly lower viscosity than the reference oil FVA3 with $\nu = 300\ \mathrm{mm}^2/\mathrm{s}$ at 20°C. The variation of the indenter geometry is limited to the size of the grain angle. We used exclusively indenters with a diamond tip and cone shapes with the angles 90°, 105° and 120°. Figure 2a shows the magnification of a scratch relief preformed by a cone indenter with an angle of 90° wich is shown in Figure 2b. For the evaluation, a plane cut is made through the previously mentioned relief of a scratch. Figure 3 shows the scratch as a profile generated by this cross section. It is noticeable that the preset 80 µm is not reached due to elastic material effects and possible elasticities of the mounting of the indenter. Therefore, we do not evaluate the absolute depth of the scratch, but the ratio of width d to depth t, which should not change for a cone depending on the depth. Based on these values, the ratio d/t between

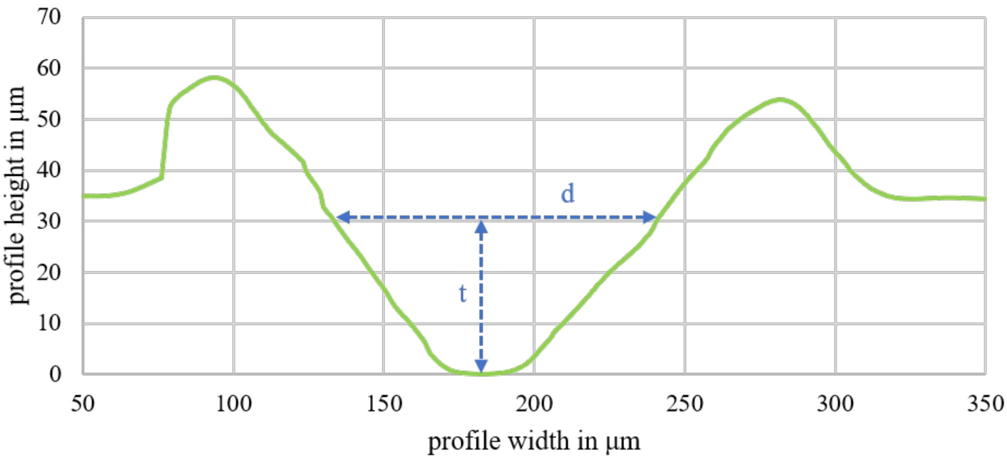

Figure 3: Profile of a scratch caused by a cone indenter with an angle of 90°

scratch width and scratch depth is then used for further interpretation. Considering the ratio has the advantage that the values can be recorded at any point of the scratch. In contrast, when recording workpiece surface to absolute scratch depth, the scratch width cannot always be determined without uncertainty. In addition, the consideration of the ratio offers better comparability than the pure parameters scratch width and scratch depth. Figure 4 shows the mean values of the ratios of scratch width and scratch depth for the different conditions. It can be seen that the use of the reference oils FVA2 and FVA3 shows a different ratio of scratch width to scratch depth than in dry scratch tests. The ratio decreases when the reference oils are used, which in turn means that the scratch width decreases when the reference oils are used. Therefore in particular the reference oils FVA2 and FVA3, causes not only an increase in force [13,14] but also a recognizable influence on the surface structure or the appearance of a scratch. The increase in the ratio of scratch width to scratch depth in the lubricated tests indicates a decrease in the scratch width. Consequently, scratches under the influence of cooling lubricants are less wide than the corresponding unlubricated scratches. As an explanatory approach, two possible effects should be considered, which in combination can explain the findings. Firstly, the use of cooling

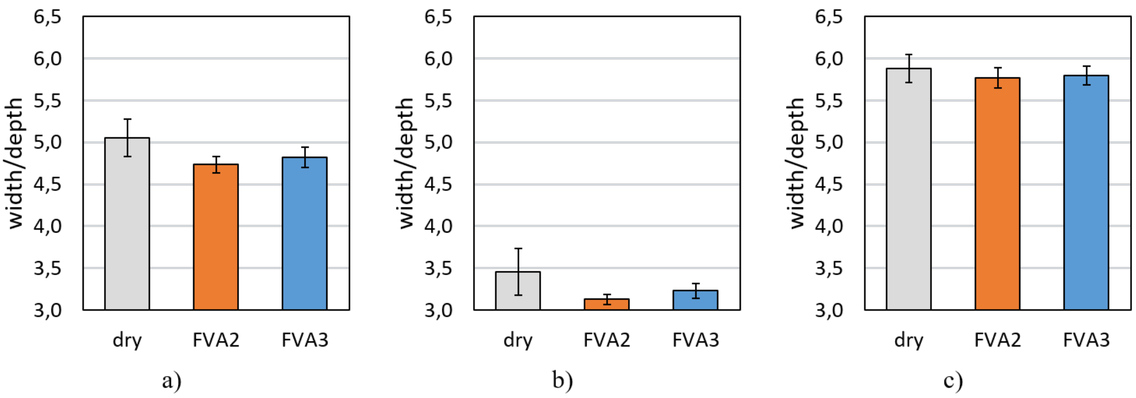

Figure 4: Mean values d/t for different cone angles in unlubricated and lubricated tests, a) cone angle of 90°, b) cone angle of 105°, c) cone angle of 120°

lubricants improves the penetration or sliding of the indenter through the material. Secondly, cooling lubricants are known to support the transport of chips and material accumulations [15]. These two effects cause less material to be agglomerated when cooling lubricants are used and, at the same time, excess material is removed more efficiently. In reverse, more material can accumulate in front of and around the indenter in unlubricated scratch tests. Material accumulations formed in this way can be the reason for the fact that these themselves have an additional contribution to the material removal in addition to the indenter. This material removal therefore results in a marginally larger scratch gap in unlubricated scratch tests. It can be seen that there is also a difference in the ratios between the two reference oils FAV2 and FVA3. It is important to mention that the reference oils differ significantly in their viscosity. The assumed effect between the reference oils can be explained by their different viscosities. As in industrial manufacturing processes, cooling lubricants with different viscosities are used for different requirements. For the elimination of heat, mainly low-viscosity oils are used, whereas high-viscosity oils are used for producing high surface qualities. [15]. However, it should be underlined that the standard deviations are in general quite high. The results presented here are based on 19 measured values with no lubrication, FVA2 and FVA3. As these results are preliminary, further series of experiments must be carried out to obtain more conclusive results and to confirm this trend.

Another effect that can be observed in Figure 4 is the considerably lower values for the indenter angle geometry with an angle of 105°. Despite the low values, the trend with relation to the cooling lubricants remains the same. Since measured values from different samples were used, a measurement error can be excluded in this aspect. For a possible explanation of this phenomenon, a close look at the indenter tip and scratch topography, as shown in Figure 2, is useful. It can be seen that both indenter tip and the deepest point in the scratch topography are not ideally pointed. In the case of the topography of the scratch, this simply represents the negative image of the indenter and is therefore always also dependent on its basic shape. However, the indenter is subject to manufacturing and physical limitations, which means that there can be no indenter with a perfect tip. This circumstance of course applies to all the indenter geometries we used. It is possible that production-related restrictions already exist between the indenter angles themselves. It is therefore obvious that the ratio of the indenter with a cone angle of 90°, especially in the area of the tip, already has greater deviations than this with a cone angle of 105°. Which can respectively mean that with 90° indenters mainly a more rounded tip, due to the manufacturing process, generates the scratch. Another possible cause could also be the increased wear with pointier indenters. In this case, it is possible that the indenter tip already wears out during the very first contact with the workpiece in such a way that an effective scratch test with a 90° indenters is not possible at all. However, in order to explain this effect better, special investigations are required with regard to the indenter geometries and their wear. At the current state of research and with the explanatory approaches already mentioned, it can only be concluded that a possible threshold exists between the indenter angles of 90° and 105°.

4 CONCLUSIONS

In summary, it can be observed that scratch tests with cooling lubricants have an influence on the topography of the scratch on the workpiece surface in addition to the influence on the tangential and normal forces. It can therefore be argued that differences between dry and lubricated scratch tests can be seen when considering the ratios of scratch width to scratch depth. A scratch on the workpiece surface always represents the negative image of the indenter which is used. The ratio of scratch width to scratch depth is the same at every point along the indenter and its depth can be assumed to be fixed. Therefore, a reduction of this ratio in the scratch is also interpretable as a reduction of the scratch width. In addition, the viscosity of the cooling lubricants also seems to have an effect on this ratio. Due to the high deviation in the mean values of the ratio d/t, however, no valid statement can be made about the influence of the viscosity at the present state.

Beside the influence of the cooling lubricants, two further phenomena were observed. Firstly, the ratio of scratch width to scratch depth of the indenter with the cone angle of 105° deviates strongly from the other two angles. However, this can also be attributed to issues of the indenter with the cone angle of 90°. On the other hand, the set value of 80 µm for the scratch depth deviates considerably from the actual scratch depths obtained on the workpiece surfaces. This effect can be explained by the flexibility of the test rig and the material parameters of the workpiece.

The most important finding for the implementation of cooling lubricants in the existing physical force model is the reduction of the scratch width when using cooling lubricants. For this purpose, an appropriate modeling approach has to be created, which can reflect this effect and can be integrated into the existing one.

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REFERENCES

[1] Stachowiak, G.W. *Engineering Tribology.* Oxford: Elsevier, Vol. 4, (2014). ISBN 978-0-12-397047-3

[2] Bender, B. and Göhlich, D. *Dubbel Taschenbuch für den Maschinenbau 1: Grundlagen und Tabellen.* Berlin: Springer-Verlag GmbH, Vol. 26, (2020). ISBN 978-3-662-59710-1

[3] Klocke, F. *Fertigungsverfahren 2: Zerspanung mit geometrisch unbestimmter Schneide.* Berlin: Springer-Verlag GmbH, Vol. 6, (2018). ISBN 978-3-662-58091-2

[4] Marinescu, I.D., Uhlmann, E. and Doi, T. *Handbook of Lapping and Polishing.* Boca Raton: CRC Press, (2017). ISBN 9781574446708

[5] Macerol, N., Franca, L., Attia, H. and Krajnik, P. *A lapping-based test method to investigate wear behaviour of bonded abrasive tools.* CIRP Annals, (2022).

[6] Inasaki, I., Tönshoff H.K. and Howes, T.D. *Abrasive Machining in the Future.* CIRP Annals, Vol. 42, Issue 2, Pages 723-732, (1993).

[7] Sridhar, P., Mannherz, D., Bilz, R., de Payrebrune, K.M., Prasad, M.R.G. and Prieto, J.M.R. *Physical Modeling of Process Forces in Grinding.* iPMVM, Vol. 89, Pages 16:1-16:20, (2020).

[8] Huang, S. and Yu, X. *A study of grinding forces of SiCp/Al composites.* London: Springer-Verlag Inc., Int J Adv Manuf Technol, Vol. 94, Pages 3633–3639, (2018).

[9] Liu, Q., Chen, X., Wang, Y. and Gindy, N. *Empirical modelling of grinding force based on multivariate analysis.* Journal of Materials Processing Technology, Vol. 203, Issues 1–3, Pages 420-430, (2008).

[10] Demir, H., Gullu, A., Ciftci, I. and Seker, U. *An Investigation into the Influences of Grain Size and Grinding Parameters on Surface Roughness and Grinding Forces when Grinding.* Strojniški vestnik - Journal of Mechanical Engineering, Vol. 56, Issue 7-8, Pages 447-454, (2010).

[11] Nie, Zg., Wang, G., Jiang, F., LIN, Yl. and RONG, Ym. *Investigation of modeling on single grit grinding for martensitic stainless steel.* Springer-Verlag GmbH, Journal of Central South University, Vol. 25, Pages 1862–1869, (2018).

[12] Eder, S.J., Leroch, S., Grützmacher, P.G., Spenger, T. and Heckes, H. *A multiscale simulation approach to grinding ferrous surfaces for process optimization.* International Journal of Mechanical Sciences, Vol. 194, (2021).

[13] Opoz, T.T. *Investigation of Material Removal Mechanism in Grinding: A Single Grit Approach.* Doctoral thesis, University of Huddersfield. (2012).

[14] Kästner, F. and de Payrebrune, K.M. *Experimental Analyses of the Effects of Cooling Lubricants to Expand an FEM-Based Physical Grinding Force Model.* Wiley, PAMM, Vol. 21, Issue 1, (2021).

[15] Nadolny, K., Kieraś, S. and Sutowski, P. *Modern Approach to Delivery Coolants, Lubricants and Antiadhesives in the Environmentally Friendly Grinding Processes.* Springer-Verlag GmbH, Int. J. of Precis. Eng. and Manuf.-Green Tech, Vol. 8, Pages 639–663, (2020).