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Manufacturing of graded grinding wheels for flute grinding

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Abstract. In this paper, two different methods for manufacturing of graded grinding wheels for two different metal bonds are presented. One method is based on the use of a mask and manual moulding and the other on a height-adjustable holder for moulding. For this purpose, a brittle and a ductile bronze bond are compared. The graded grinding wheels are fabricated through sintering with Field Assisted Sintering Technology (FAST). An analysis of the grain distribution is used to demonstrate the reproducibility of the manufacturing methodology. For analysis, light microscope images of cross-sections of the abrasive layers are taken. The grain distribution is determined using image processing software and a greyscale method. Finally, the advantages of each method are compared. As a result, both manufacturing methods are evaluated in terms of precision, feasibility and efficiency. From this, a recommendation on the implementation and further development of the methods is derived. This method enables the manufacturing of graded grinding wheels for an effective reduction of wear differences for grinding cemented carbide end mill cutters.

Introduction

Cemented carbide end mill cutters are used in a wide range of applications. These include, for example, the aerospace industry, medical technology or electrical engineering [1]. High demands are therefore placed on the quality of the workpieces that are machined with these end mill cutters. In particular, this requires a high level of precision and surface quality. To ensure this, the end mill cutters used must also meet the highest standards. The quality of the flutes of the end mill cutters has a major influence on their performance [2,3]. However, the deep grinding process of the flutes is characterised by high and varying thermomechanical loads. The high thermomechanical loads result from the high depth of cut associated with the process kinematics and the properties of the cemented carbide [4-6]. Cemented carbide possesses a high degree of hardness and wear resistance [4,5]. In addition, the engagement conditions vary significantly along the width of the grinding tool [6,7]. This is a consequence of the flute geometry. These factors result in a high and at the same time uneven radial wear.

This causes an increasing number of defects in the flute bottom and the cutting edges as well. A defect-free flute, however, is decisive for the operational behaviour of the end mill cutters [2]. To counteract this effect, the dressing intervals must be shortened. This ensures the contour accuracy of the grinding wheel. That is decisive for the necessary manufacturing accuracy. However, the frequent dressing intervals reduce the efficiency of the grinding process. This is due to higher downtimes caused by the more frequent dressing on the one hand and the resulting increased dressing wear on the other. The lifetime of the grinding tools is thus shortened.

Another method of ensuring contour accuracy is to adapt the abrasive layer properties to the local wear conditions. By levelling the radial wear occurring, this allows the dressing intervals to be increased. Economic efficiency will be increased as a result, too. The radial wear can be reduced, for example, by increasing the grain retention forces [8]. Likewise, an adjustment of the bond properties can be made. By using a more ductile bronze bond, the wear can be reduced compared to a brittle bronze [9]. Both methodologies are not applicable in the present case due to quantification limitations. The reason for this is that in the state of the art there is no sufficient accurate model of the influence of the bond properties as well as the grain retention forces on the resulting wear. Another approach is to adjust the number of abrasive grains. An increasing number of abrasive grains reduces the thermomechanical load per individual grain. As a result, this decreases the radial wear occurring [7,10,11]. Depending on the bond properties, the maximum number of abrasive grains is limited. The grains act as defects in the bond. If the number of abrasive grains is too high, the forces acting on the abrasive layer will cause the bond to fail. Wear then increases in turn. These so-called percolation limits depend on the toughness of the bond and the load occurring during the process [12]. Influencing the number of abrasive grains can therefore be used to affect the radial wear.

First approaches have already shown that the adjustment of the grain concentration in the abrasive layer in two steps can level the resulting radial wear [13]. The authors of the present paper have introduced a model in previous work enabling the radial wear differences to be reduced by up to 50 % compared to conventional grinding wheels on the basis of adapting the number of grains to the occurring loads. The model is based on a simulation-supported analysis of the locally occurring load on the grinding wheel. The resulting abrasive grain numbers for a defined application are shown in Fig. 1 [14].

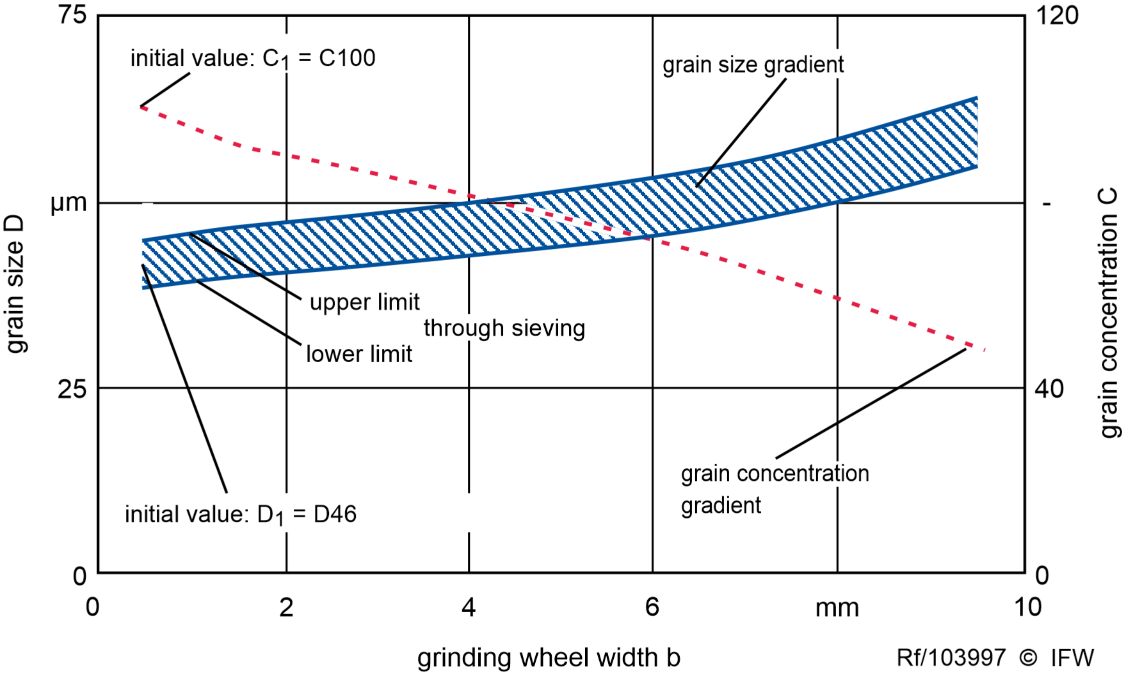

Fig. 1. Comparison of different types of grain number gradients, based on [14].

Two adaptation options are shown. One is via the grain size and the other via the grain concentration. The adjustment via the grain size turned out to be too inaccurate due to the differences in grain sizes after sieving them. This can be seen in the scatter band marked in blue. The grain concentration, on the other hand, can be applied individually in the necessary increments. This is shown in the red line. It has been shown that the implementation of a continuous gradient of the grain concentration is not possible. There are sharp transitions between the concentration ranges [15]. The present work follows on from the preceding research work. So far, only the production of test specimens has been investigated. Therefore, a methodology for the efficient and process-safe production of graded grinding wheels is presented in the following. At the same time, the moulding method is optimised in order to accurately adjust the heights of the grain concentration ranges. This has led to fluctuations in grain concentration differences in the previously used method based on bulk density.

Materials and Methods

First, grinding layer specimens were sintered. These were used to adjust the moulding accuracy through powder dosing. Specimens are cylindrical with a diameter of 22 mm and a height of 6 mm. The process is comparable to the production of grinding wheels and therefore offers good transferability. The manufacturing of the specimens and the later grinding wheels is shown in Fig. 2.

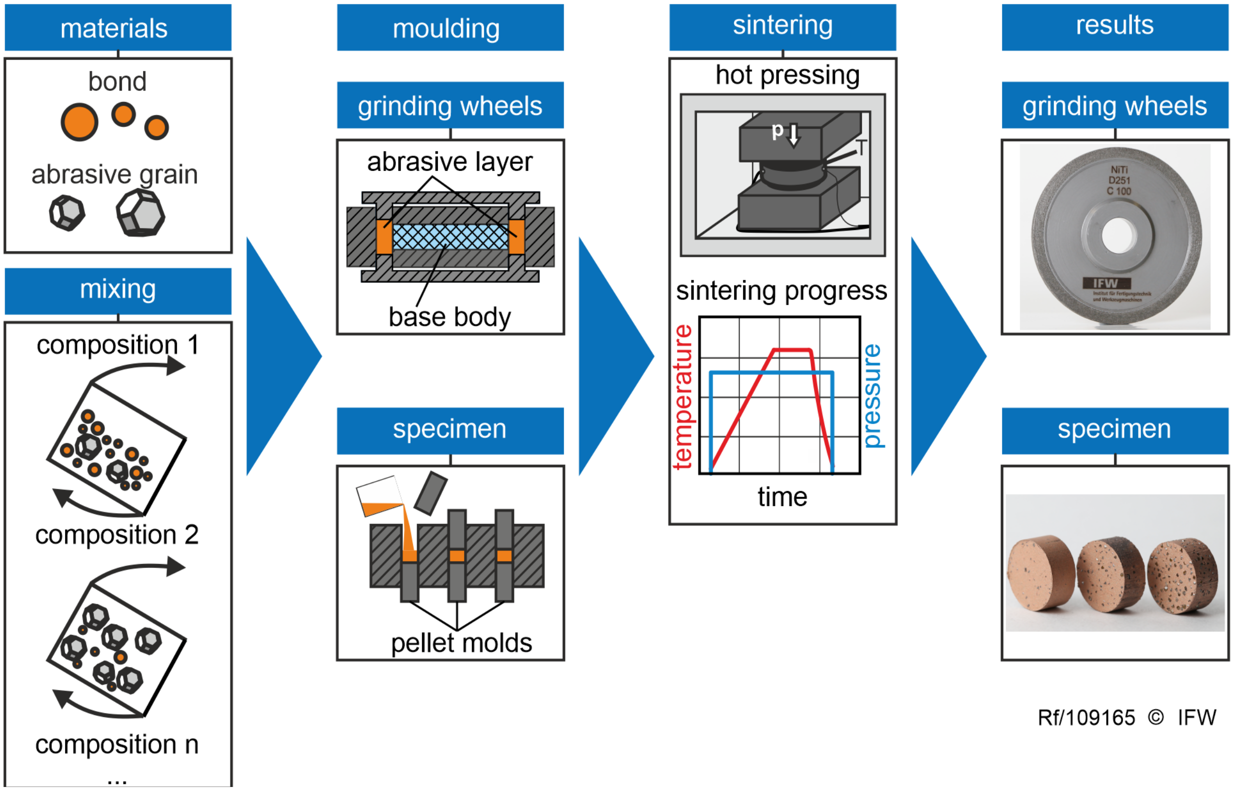

Fig. 2. Grinding wheel and specimen manufacturing.

From this, Fig. 2, also follows the comparability of the two methods. For their production, the components of the abrasive layer must first be mixed and pre-compacted to form a green body.
A Turbula mixer is used for mixing. The mixing time was 30 minutes. The components consist of a bronze bond and diamond grains. Two different pre-alloyed powders were used to evaluate influences on the manufacturing accuracy depending on the components. The composition was 60 wt.% copper and 40 wt.% tin (60/40 bronze), respectively 80 wt.% copper and 20 wt.% tin (80/20 bronze) with an irregular particle shape and an average diameter of 40 µm. Alloys similar to those used are also used in the industrial environment. The sintering temperature used was 420°C for the 60/40 bronze and 620°C for the 80/20 bronze. The holding time was 240 seconds in each case at a pressure of 35 MPa. The diamond grain chosen was an irregular shape grain of size D54 according to the FEPA standard. For each bond type, test specimens with the concentration C0, C25, C50, C75, C100 and C125 were produced. The C specification also complies with the FEPA standard. C100, for example, corresponds to a volume fraction of 25 % of the used grain. Weighting was carried out according to the following equation:

$$m_{bond} = V_{Specimen} \cdot \left(100 - V_{grain}\right) \cdot \rho_{bond} \cdot 0.98 \quad (1)$$

The target parameter is the mass of the bond m_{bond}. $V_{specimen}$ describes the target volume of the grinding layer specimen, respective the grinding wheel abrasive layer. The volume of the bond is calculated by the difference to the volume of the grains, corresponding to the grain concentration, V_{grain}. The density of the used bond material is given by ρ_{bond}. Based on the available knowledge, porosities smaller than 2 % occur during FAST sintering of metallic bonds. Therefore, the correction factor 0.98 was chosen for the metal content to compensate for its larger volume due to porosity. The test specimens were then measured to ensure the accuracy of the process. The method was verified by sintering graded specimens of composition C100/C0/C50 (gradient 1) and the composition C0/C50/C100 (gradient 2). Each layer was 2 mm thick. Accuracy was evaluated using light microscope images.

Based on the results, the graded grinding wheels were manufactured. Both bonding systems were used for this. The variation of the grain concentrations is shown in Table 1:

Table 1. Composition of the graded grinding wheels for the 60/40 bond.

Layer number and position	Grain concentration	Bronze powder mass	Diamond grain mass	Total mass
1 (0 – 1 mm)	C125	11.974 g	1.949 g	13.923 g
2 (1 – 2 mm)	C121	12.149 g	1.887 g	14.035 g
3 (2 – 3 mm)	C114	12.453 g	1.778 g	14.231 g
4 (3 – 4 mm)	C102	12.976 g	1.590 g	14.566 g
5 (4 – 5 mm)	C83	13.803 g	1.294 g	15.097 g
6 (5 – 10 mm)	C47	76.854 g	3.664 g	80.518 g

The gradients were chosen for future application tests so that they would match the corresponding application. There, they should lead to uniform radial wear when grinding a cemented carbide rod with a diameter of 16.8 mm at an engagement width and depth of 6 mm. The calculation was carried out according to the results from [14]. For comparison, a non-graded reference wheel was manufactured for each bond system. The concentration of the reference wheels was set at C125 over the total grinding wheel with. The composition of the graded grinding wheel with the 80/20 bond corresponds to the same concentration steps. The mass of the bond and diamonds were adjusted concerning this.

Moulding Methods

Two different moulding methods were investigated. For both, the sinter die was placed on a turntable to avoid unsteady rotation. This is to prevent segregation of the abrasive layer components. In the first moulding method, the powder for each abrasive layer was weighed out in i (i = 6; 12; 24) portions. These were filled into the mould along a taped-on mask in the corresponding portioning. The smoothing of the powder layers was done by manual drawing using a metallic plate. The number of steps i is used to evaluate how high the effort must be for reproducible filling. A too high number reduces the economic efficiency. The mould was filled using an aluminium hopper. This counteracted the adhesion of powder.

A height-adjustable holder was used for the second moulding method. The powder for a segment was filled in evenly by turning the sintering mould as required by eye. Subsequently, the powder was smoothed by means of the holder and an appropriate metal plate. In the first step, the height of the holder was adjusted in such a way that a pile of powder was first pushed in front of the plate when the powder was being smoothed out. By raising the height of the plate, an even surface was gradually generated. This was repeated for all layers. Both methods were first carried out using an analogue sintering mould made of acrylic glass. This allowed a visual evaluation of the moulding process for adhesions on the mould edge or the grinding wheel base body. Concept 2 with the analogue mould can be seen in Fig. 3.

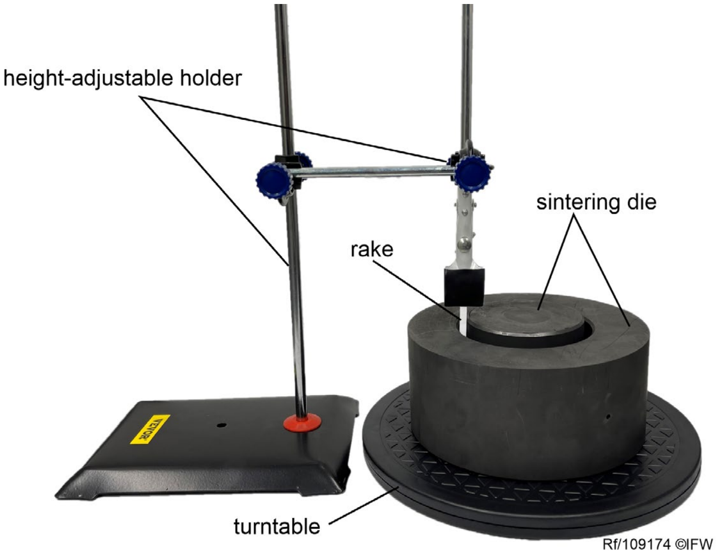

Fig. 3. Manufacturing method using a height-adjustable holder.

All grinding wheels were sintered with the parameters of the test specimens. The evaluation was carried out on the basis of cross-sections of the abrasive layers. Images of these were taken using an optical microscope and a scanning electron microscope. The evaluation of the grain concentration curves was carried out using the evaluation software ImageJ. The method is shown in Fig. 4.

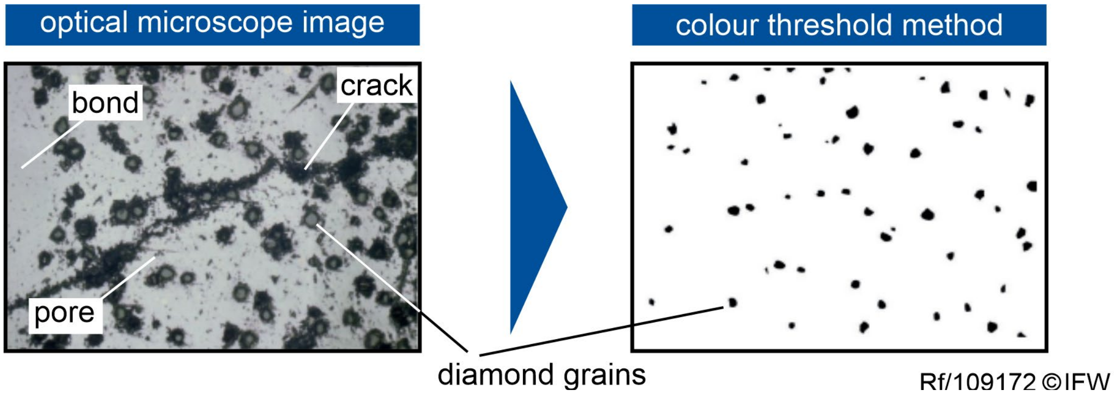

Fig. 4. Evaluation method for the grain concentration.

Analysis of the Specimen Height

As a first step, an assessment of the achieved heights of the abrasive layer specimen was carried out in order to evaluate Eq. 1. This is necessary in order to be able to accurately reproduce the gradients of the grinding wheels. The results of the evaluation are shown in Fig. 5.

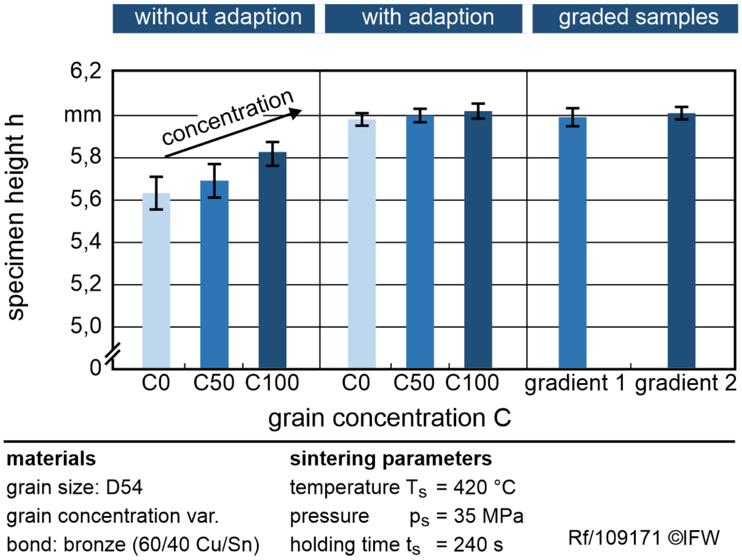

Fig. 5. Evaluation of the sample height adjustment.

The figure shows the inaccuracy in the height of the abrasive layer, as demonstrated in a previous study [15]. Moulding based on bulk density, or a high final porosity, shows that the specimen height decreases correspondingly with an increasing proportion of bond compared to the diamond grain. This is due to the increasing influence of the bond on the specimen height after sintering. The deviations from the target width of the segments can be considered uncritical if the grain concentration differences between them are small. This is the case due to the continuous load progression during deep grinding of the flutes. With larger grain concentration differences, the deviations from the target width can lead to increased radial wear. If, for example, the segment with a lower grain concentration is in the area of a higher load due to the higher shrinkage, the radial wear will increase there. This then counteracts the load design. The deviations should therefore not be greater than a few grain layers. The adjustment of the filling quantities according to Eq. 1, or based on a remaining porosity of 2 %, allows the abrasive layer specimens to be produced at the required target height. This can also be repeated for graded specimens, gradient 1 and gradient 2. Nevertheless, small deviations occur due to inaccuracies caused by the manual manufacturing process and the process chain. Since the deviations correspond to only a few grain layers, it can be assumed that these have only a minor influence on the operational behaviour.

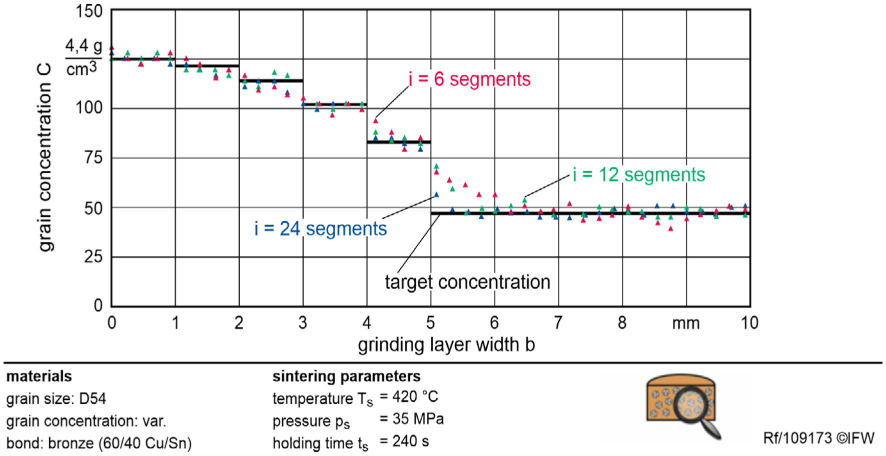

Fig. 6. Concentration gradients of the manufacturing

Fig. 6 shows the process as a microscope image for the evaluation of the single layer heights within the specimen of gradient 1 and 2. From this it is visible that the presented moulding methodology allows an accurate adjustment of the gradients as well. Within the specimen, the deviations from the target concentration are quite small. The presented methodology is therefore suitable for the dimensioning of the moulding-in amounts for graded grinding wheels.

Comparison of the moulding methods

Using the previously presented moulding quantity calculation, the two moulding methods from the previous chapter were compared. Fig. 7 shows the grain concentration curves for the moulding method using the taped mask and manual smoothing for the different divisions of the masks in i segments (i = 6; 12; 24).

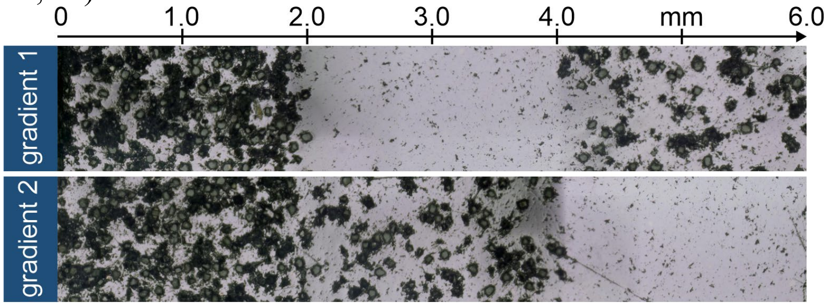

Fig. 7. Evaluation of the gradient course within the samples.

The figure shows that the method with filling based on 6 up to 24 portions of the respective abrasive layer amount enables the production of graded grinding wheels. A smaller quantity of subdivisions (i = 6) results in less accurate production compared to 12 or 24 subdivisions. This can be seen in the more pronounced transitions between the concentration zones. The deviation from the target concentration is particularly noticeable in the transition between C83 and C47. However, the gradient is still within the range of the target gradient. Especially the transition areas between the concentration levels are not to be regarded as disadvantageous. Softer transitions between them are to be aimed for, as the load in the application case is also continuous and not discrete (see Fig. 1). However, a continuous course cannot be implemented in production with current methods. But the inaccuracy, as in the case of production by means of 6 subdivisions, enables an approximation to a continuous course. In addition, the method with fewer subdivisions is advantageous because the moulding time is reduced. If high manufacturing accuracy is required, this can be reached by using 24 subdivisions. The transitions between the concentration zones are strongly pronounced. The fluctuations occurring are in the range of concentration differences >C5. These also appear in non-graded abrasive layers. The outlier in the transition area from C83 to C47 is explained by the smoothing of the layers. Since this was done manually, there are slight variations in their heights. When evaluating the grain concentration in image sections, it is therefore possible that both layers are measured partially in the corresponding section. Nevertheless, the overall small number of outliers also shows that the width of the concentration ranges was fulfilled for all grinding wheels.

Equally, the method based on a height-adjustable holder without individual single weighted amounts was investigated. The results of these investigations are shown in Fig. 8.

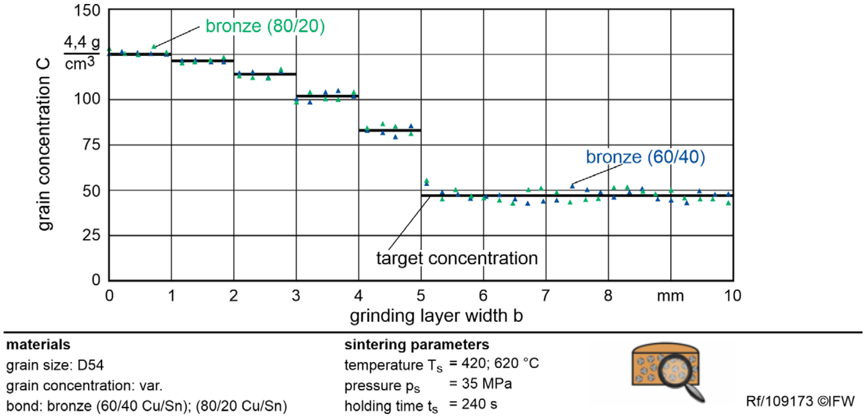

Fig. 8. Concentration gradients of the manufacturing method with the height-adjustable holder.

Two main observations can be drawn from this. First, it shows, as was expected, that the bond has no effect on manufacturing accuracy. Both the (60/40) bronze and the (80/20) bronze can be moulded and sintered into a graded abrasive layer. The differences exist only in local and small variations of the grain concentration. Secondly, the method with the height-adjustable holder shows that the transitions between the grain concentration ranges are even more accurate than the method with the mask. The higher accuracy is due to the fact that the layer heights can be set to the appropriate height without manual influence. A small inaccuracy is again only seen in the transition from C82 to C47. However, this is very slight for both bonds. The grain concentration steps, that can be quantitatively evaluated, are visually indistinguishable. This can be seen in the section of a microscope image of the grinding wheel with the (60/40) bronze. Regardless of the manufacturing method, the more brittle bronze (60/40) has been found to have a tendency to crack. This can be seen in Fig. 9.

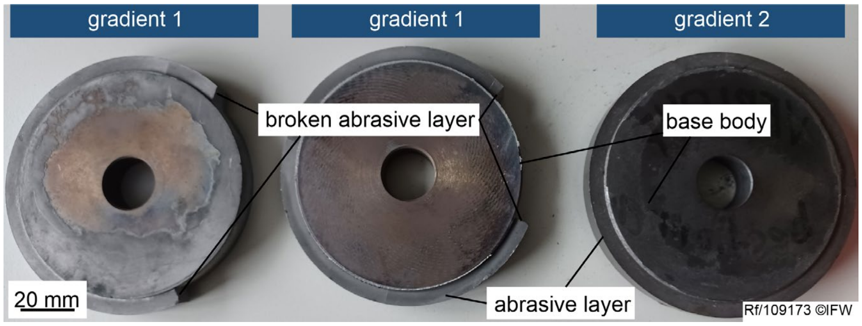

Fig. 9. Graded grinding wheels manufactured on the basis of (60/40) bronze.

The cracks only occurred in the brittle (60/40) bronze. Due to the different diamond concentrations, it can be assumed that the shrinkage of the segments varies with different grain concentrations. Segments with high concentrations are expected to shrink less. This is the case because diamond has a very low coefficient of thermal expansion compared to bronze. As a result, residual stresses in the abrasive layer are to be expected. Unfortunately, these cannot be determined analytically. The reason for this is the geometry of the abrasive layer, the large diamond grains and the fact that some of the residual stresses are already removed after fracture. It was also observed that the non-graded grinding wheels of the (60/40) bronze with C125 also break more frequently than those with C100. The reason for this could be the additionally reduced abrasive layer strength due to the increased number of grains, as discussed in the introduction [12]. As a solution, an additional gradient was manufactured, starting at C100 (Fig. 9 gradient 2). The structure of the segments is analogous to the gradients from the methods chapter with the steps (C100/C96/C91/C82/C66/C47). As can be seen in Fig. 9, graded grinding wheels with the (60/40) bronze can be manufactured with these gradations. The last segment with C47 was deliberately not chosen lower in order to keep the shrinkage differences small and because concentrations significantly below C50 would lead to increased bond friction when using the grinding wheels.

Summary

In the present work, two methods for moulding and one method for weighing graded grinding wheels were investigated. In the investigation of the weighing-in method, it was demonstrated that the presented Eq. 1 enables an exact implementation of the gradients. This is the case regardless of the bond chosen. With regard to the methods for moulding in, it was shown that the method based on the height-adjustable holder produces the highest precision for moulding in. In addition, this method significantly reduces the time required compared to the method of filling in portions and manual smoothing. The latter method also achieves a high degree of accuracy when using 12 or 24 filling portions per segment. The reduction to 6 portions reduces the time required, but also the interface sharpness. This can be considered favourable with regard to the operational behaviour, as the loads also proceed in non-discrete steps. With regard to the moulding-in method, the use of the height-adjustable holder is therefore nonetheless considered appropriate for the highest reproducibility and productivity. The adjustment of smooth transitions can be achieved, for example, by using a notched metal plate or a rake for smoothing. Future investigations can take this as a starting point.

The layer cracking occurring with brittle bronze could be countered by reducing the grain concentration. Due to the brittleness, the bronze bond (60/40) is more challenging in the manufacturing process than the more ductile bond (80/20). Nevertheless, the more brittle bond results in better operational behaviour due to the improved operational preparation, the self-sharpening during the process and the higher contour accuracy due to the lower ductility. In order to reduce the rejects during the production of graded grinding wheels based on brittle bronzes, two approaches are conceivable for future investigations: First, the use of coated abrasive grains to increase bond strength. Second, the use of specific annealing steps during sintering or quenching to optimise the residual stress states.

In conclusion, it can be stated that the present work represents a functional approach to the production of metal-bonded graded grinding wheels. Furthermore, attempts were presented that will be followed up by subsequent investigations in order to optimise the manufacturing. In addition, the profiling and sharpening of the graded grinding wheels will be the subject of future research.

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