Influence of the Sintering Process on Productivity and Energy Efficiency in the Production of Bronze-Bonded Grinding Wheels

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Abstract: Bronze bonded grinding wheels are characterized by their high wear resistance and thermal conductivity. Beside the bond composition the sintering process plays a major role regarding the resulting grinding wheel properties. This paper contributes to a better understanding of the relationship between the manufacturing process and the resulting properties of the grinding wheel. Therefore, the influence of the sintering temperature and the heating rate in interaction with the bronze composition are investigated. The hardness and the critical bond stress measured at grinding layer samples are used to evaluate the mechanical strength and the structural cohesion. It is also shown how the mentioned parameters affect the productivity and energy efficiency of the manufacturing process by calculating the total time and the energy demand of the sintering process.

Key words: Bronze-bond, diamond, grinding layer, pressure sintering.

1. Introduction

The properties of sintered metal-bonded diamond grinding wheels depend mainly on the components of the bonding system and the process parameters during their manufacturing process. Beside the process parameters, the grinding wheel properties have a significant impact on the grinding result and the process productivity. Grinding wheels are clearly described regarding their macroscopic geometry, the used bond and abrasive grain specification [1]. Other properties such as the hardness or the pore structure are not clearly defined and individually dependent on the grinding wheel manufacturing process [2].

Bronze is predominantly used as bonding material for sintered metal-bonded grinding wheels. The bronze bond shows comparatively high values in terms of mechanical stability, wear resistance, edge stability, thermal conductivity and grain retention forces compared to vitrified and resin bonds. For this reason, bronze-bonded diamond grinding wheels are used exemplarily for profile grinding of cemented carbides and for machining ceramics, glass and other mineral materials [3]. The hardness of the bond can be influenced via the tin content (10-40 m%) of the bronze. Examinations of the wear resistance of bronze-bonded diamond grinding wheels have shown that more ductile bonding alloys (10 m% copper) wear out more slowly than brittle alloys with higher tin contents when grinding cemented carbide [4], [5].

Sintered metal grinding wheels are manufactured by hot pressing, which creates virtually dense grinding surfaces [6]. A modification of this process is the Field Assisted Sintering Technology (FAST), in which the heating current is passed directly through the sintering mold and the sintering material instead of through an external heater [7]. This enables rapid heating rates that are desirable from a technological point of view in order to increase the productivity of the grinding wheel manufacturing process. In addition, the use of slow heating rates causes an increased time for heat dissipation through the cooling system and radiation from the sintered mold [8]. Therefore, it is less energy efficient and environmentally friendly.

Apart from the examination of ductile bronzes, there is no scientific knowledge regarding the effects of the sintering variables on the resulting grinding wheel properties. In order to characterize the grinding wheel properties as a function of the sintering parameters, the critical bond stress was introduced as a characteristic value for the mechanical strength of the grinding layer [9]. It is evaluated in a three-point bending test, in which the stress is calculated from the maximum force that leads to breakage and the dimensions of the sample. Investigations have shown that the critical bond stress influences the sharpening result and thereby the application behavior during grinding. It was also shown that the sintering temperature has the greatest effect on the resulting critical bond stress and thus the grinding behavior [9]. A linear relationship between grain concentration and critical bond stress can be observed. The reason for this behavior is explained by the fact that the proportion of the bond material decreases with increasing grain concentration. As a result, the cohesion of the grinding layer and thus its mechanical strength decreases [10]. The mechanism of sintering leading to cohesion is diffusion, which is based on atomic location changes. The effectiveness of this process depends on the sintering parameters as well as on the material and is described by the diffusion velocity, which depends on the diffusion coefficient DK. However, the diffusion coefficient is proportional to the sintering temperature TSint [11]. Lin showed that the main influencing factor from the manufacturing process on the grinding ratio of vitrified-bonded grinding wheels is the sintering temperature. The resulting density strongly depends on the viscosity, which decreases with increasing temperature [12]. Investigations by Kühl show that the influence of the sintering parameters in hot-pressed metal-bonded diamond grinding wheels is comparable to that of vitrified-bonded grinding wheels. The temperature has the greatest influence on the resulting grinding wheel wear [11]. According to these two sources, there is an optimal sintering temperature for all examined grinding tool specifications, which leads to the highest grinding layer density and the highest grain retention force [11], [12]. Previous studies on sintering have already shown that temperature has the greatest influence on density. However, the relationship between bond composition and the sintering parameters, especially the heating rate, was not directly scientifically investigated. The advantage of the sintering process using field assisted sintering technology in terms of energy efficiency depending on the sintering parameters and bond compostions has not yet been scientifically investigated.

2. Experimental Setup

In the case of sintered metal-bonded grinding wheels, the grinding layer is sintered onto a base body. In order to examine the mechanical properties of the grinding layer itself, the grinding layer has to be removed from the base body. However, this layer then has an unsuitable geometry for the three-point bending test due to the small layer thickness of 6 mm and the outer grinding wheel radius. Therefore, special samples with a diameter of 22 mm and a height of 5 mm were produced in a graphite mold. This is analogous to the production of the grinding layer of a grinding wheel and is used to evaluate the resulting properties depending on the manufacturing process. These smaller-sized grinding layer samples can then be examined using a three-point bending test at five samples. Based on these investigations, the mechanical strength can be described via the critical bond stress σ_c [9] as shown in Fig. 1. Furthermore, the hardness of the samples is determined via Vickers hardness tests in HV0.3 which corresponds to a test force of 2.942 N. The hardness is measured five times on the three different samples per test point.

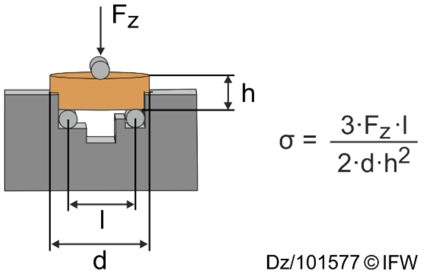

Fig. 1. Measurement of the critical bond stress.

The hydraulic pressure applied by the sintering machine DSP 510 from the company Dr. Fritsch has to be adapted for different sintering molds and the associated sintering surfaces. The hydraulic pressure $p_{hydraulic}$ is calculated as a function of the sintering surface A_{mold} of the sintering mold, the effective surface of the hydraulic cylinder A_{zyl} and the desired sintering pressure p_{sint} as follows:

$$p_{\text{hydraulik}} = p_{\text{sint}} \cdot A_{\text{mold}}/A_{\text{zyl}} \tag{1}$$

The process parameters temperature and pressure are monitored during the experimental tests. The temperature is measured using three thermocouples that are 120° apart in the mold in order to evaluate the temperature distribution in the mold and to prevent temperatures above the desired sintering temperature. Furthermore, the electric power of the machine is recorded and can be used to calculate the total energy demand of a sintering process as shown in Fig. 2. At high heating rates there is a fluctuation in the electrical power, but the energy flow is almost constant, as can be seen from the calculated energy demand.

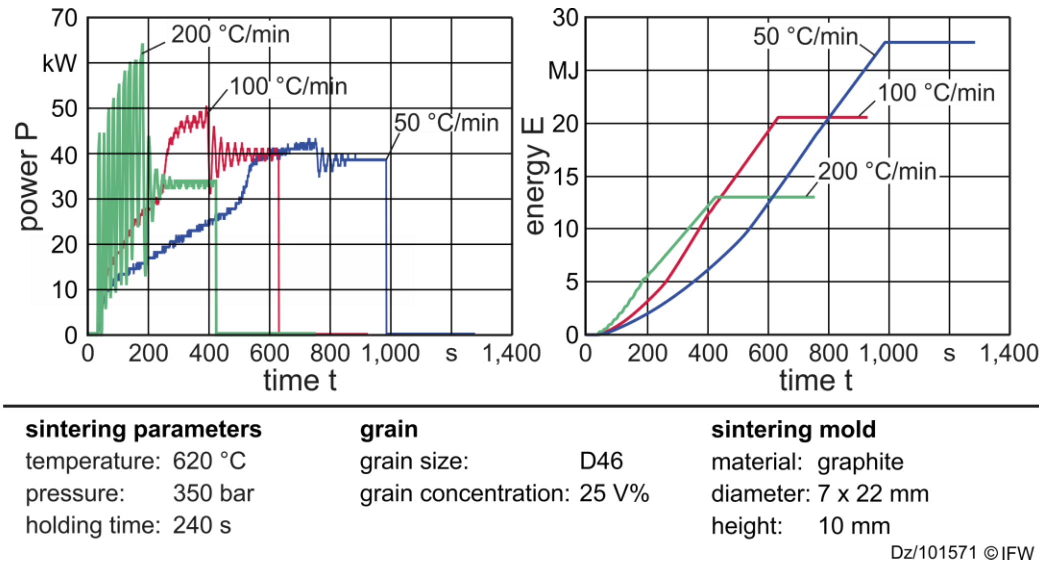

Fig. 2. Power and energy demand in the sintering process as a function of the heating rate.

In the investigations regularly shaped FMD-60 diamond grains from the company Van Moppes were used. They have an average size of 46 µm and their shape corresponds to an octahedral stump. The grain concentration per volume was chosen to be 25 V% in analogy to a usual grain concentration C100 for grinding wheels. The bond composition was varied with regard to the mass proportions of copper and tin, see Fig. 3. This results in copper/tin mass ratios of 60/40; 70/30; 80/20 and 90/10 in pre-mixed condition.

In a first series of tests, the sintering temperatures were varied in stages 520, 620 and 720 °C with a constant holding time of 300 s and a constant pressure of 350 bar. The heating rate was set at a constant value of $\dot{T}$ = 50 °C/min in order to consider the interaction between sintering temperature and bond composition without the influence of the heating rate. If the copper content is reduced, the lower melting temperature of the binary system also reduces the maximum temperature that can be used for sintering, as too high liquid phase sintering proportion should be avoided. The test points with a mass fraction of 40 m% tin were therefore only sintered with a sintering temperature of 520 °C and the test points with a mass fraction of 30 m% tin with 520 and 620 °C. In a second series of experiments, the heating rate was varied in steps of 50, 100 and 200 °C/min as well as the bond composition. The sintering temperatures (720 °C for 90/10; 620 °C for 80/20 and 520 °C for 70/30 as well as 60/40) and holding time (240 s) were selected in accordance with the bond manufacturer's recommendations. A schematic sintering process with the typical process parameters is shown in Fig. 4.

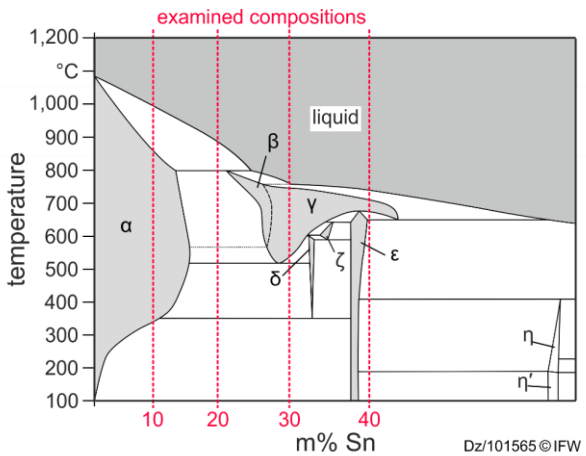

Fig. 3. Phase diagram of bronze.

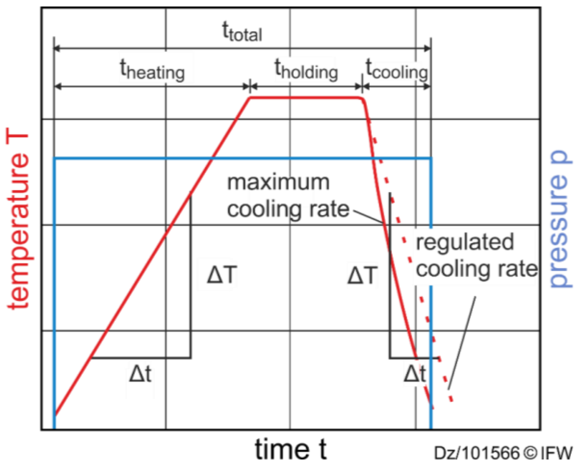

Fig. 4. Sintering process.

3. Results and Analysis

Fig. 5 shows the critical bond stresses of the first series of tests. It can be seen that the critical bond stress decreases with increasing tin content. With a composition of Cu/Sn 60/40, the ε-bronze phase predominates. The crystal structure ε phase is a superstructure based on a hexagonally close packing. This leads to a higher hardness and brittleness of the bond [13].

The resulting low fracture toughness leads to an earlier failure in the three-point bending test and thus to lower critical bond stresses. The composition Cu/Sn 90/10 consists of the copper-rich α-phase. This has a significantly higher ductility and lower hardness due to a cubic closed packed crystal structure. With the Cu/Sn 80/20 composition, the δ-phase is formed in addition to the α-phase. Due to the complicated crystal structure of the δ unit cell, the sliding of the atomic layers is much more difficult. The δ-phase is therefore less ductile and harder than the α-phase [4]. The different phases are shown in the cross-sections in Fig. 6. The processes that take place at hot pressing are essentially the same as those that occur in pressureless sintering, except that when pressure is applied in a first compression stage, a purely mechanically forced rearrangement of the particles is achieved. In the further stages diffusion occurs, which is strongly dependent on temperature. Therefore, the diffusion is accelerated at higher temperatures, so that individual grains can grow together faster and improve the resulting structural cohesion. If the diffusion process is not entirely completed, some of the powder grains are still unalloyed in the bond. The missing connection of the particles in the grinding layer leads to a faster crack propagation under stress and thus to an earlier failure. With the ductile compositions 80/20 and 90/10 in particular, it becomes clear that the diffusion process has not yet been entirely completed at lower temperatures, Fig. 5. The temperature difference of 200 °C leads to a doubling of the critical bond stress in both compositions, which results from an increased bond cohesion at higher temperatures. Due to the higher proportion of tin in the bond composition 70/30 and the resulting higher proportion of liquid phase sintering, less time and lower temperatures are necessary. As a result, the diffusion process for this bond composition is almost complete at 520 °C despite the identical holding time. The critical bond stress remains almost constant when the sintering temperature is increased to 620 °C.

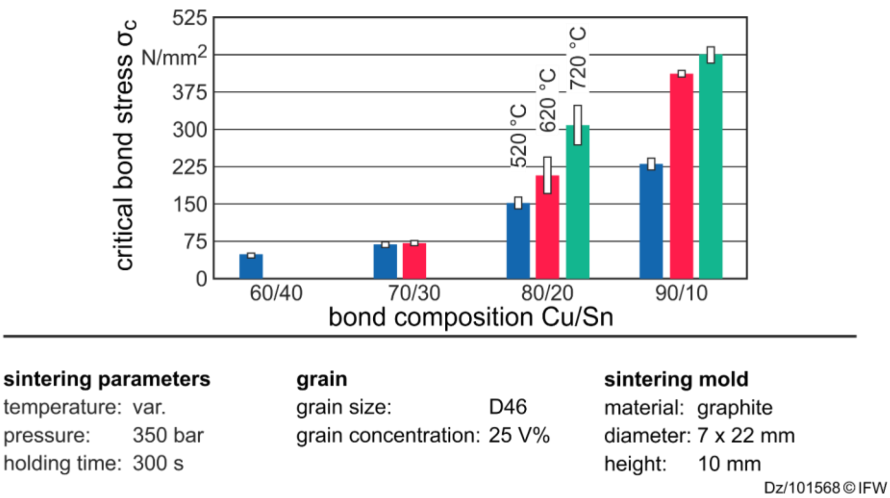

Fig. 5. Critical bond stress depending on temperature and bond composition.

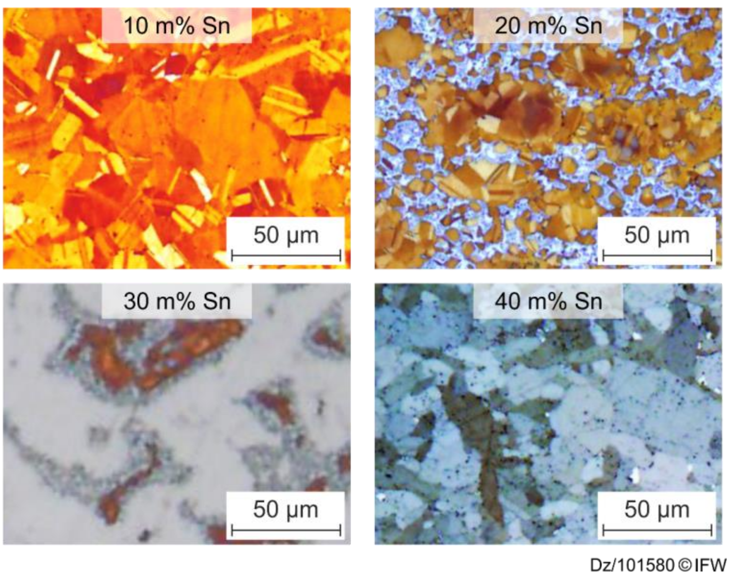

Fig. 6. Cross-sections of the different bond compositions.

Fig. 7 shows the calculated critical bond stresses depending on the heating rate and bond composition. As before, the results show a strong dependence of the critical bond stress on the bond composition. The heating rate, on the other side, has no observable influence on the resulting critical bond stresses, as it remains approximately constant. This is due to the fact that the diffusion process depends to a large extent on the sintering temperature and not on the heating rate. The process can thereby be completed with fast heating rates.

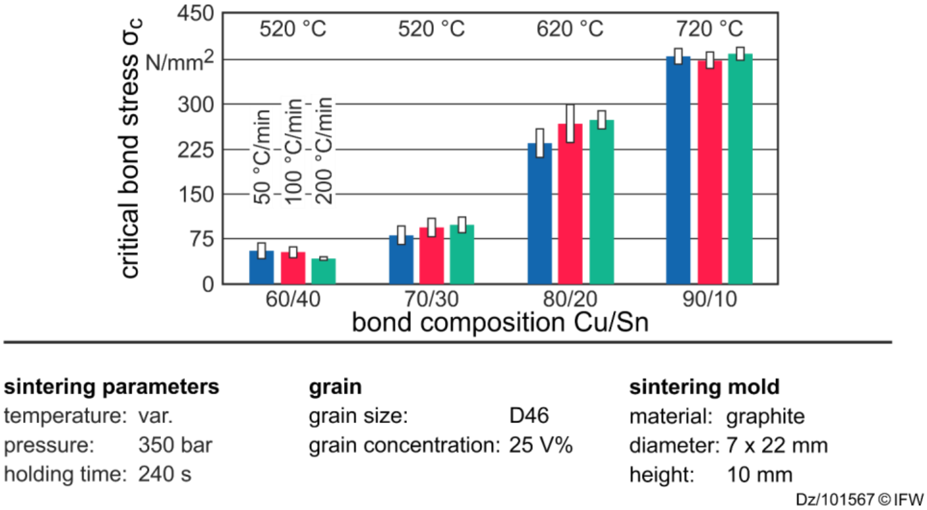

Fig. 7. Critical bond stress depending on heating rate and bond composition.

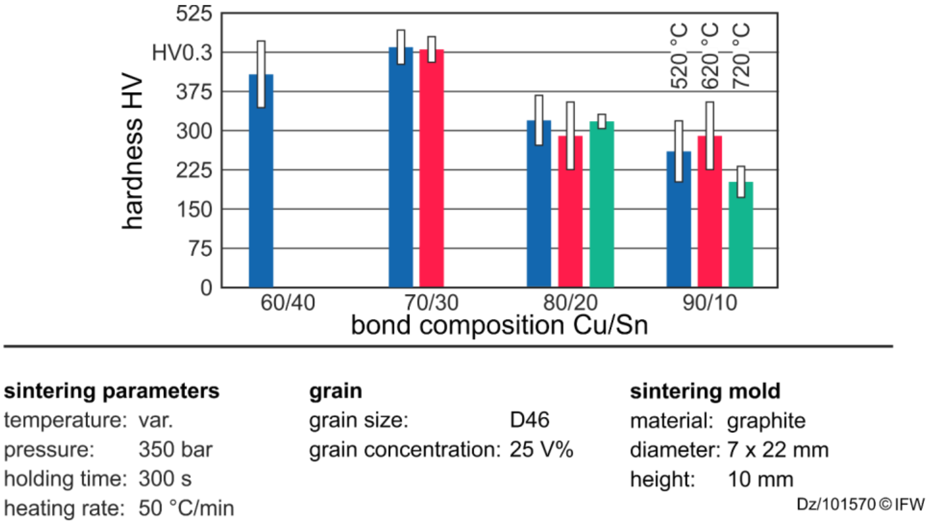

Fig. 8. Bond hardness depending on temperature and bond composition.

Fig. 8 shows the hardness depending on the temperature and bond composition. It should be noted that the measurements overall have a high standard deviation. This is due to the heterogeneous nature of the grinding layer composition that consists of the different bronze phases and diamond grains. Even though the hardness measurements were conducted on areas, which did not show any diamonds on the surface, diamonds may be hidden underneath the bronze bond. This results in a higher measured hardness compared to the pure bond material and limits possible statements about the maximum achievable hardness. From the literature [14] it is known that the hardness of bronze decreases with increasing copper content. This correlation was observed in this study as well, except the composition 60/40, which does not show the highest hardness for the reasons mentioned above. However, statements about global cohesion are not possible. The measured hardness values of the bronze 80/20 for the different temperatures are almost on the same level considering the standard deviation. The varied temperatures in case of the composition 90/10 also show no clear influence on the hardness. This does not reflect the results of the critical bond stress since the hardness is only measured locally. Thus, phases of equal hardness are already forming, but the structural cohesion is not yet fully developed.

However, the measured hardness shows a different dependence on the bond composition and the heating rate, Fig. 9. Although the standard deviation is very high, the hardness decreases as expected with increasing copper content. Just as in the case of the critical bond stress, the heating rate has no influence on hardness. The measured hardness values for the respective bond composition are at one level considering the standard deviation. Since the heating rate does not affect the hardness or the critical bond stress, high heating rates can be used. This can increase productivity through a faster sintering process and decrease the consumed total energy.

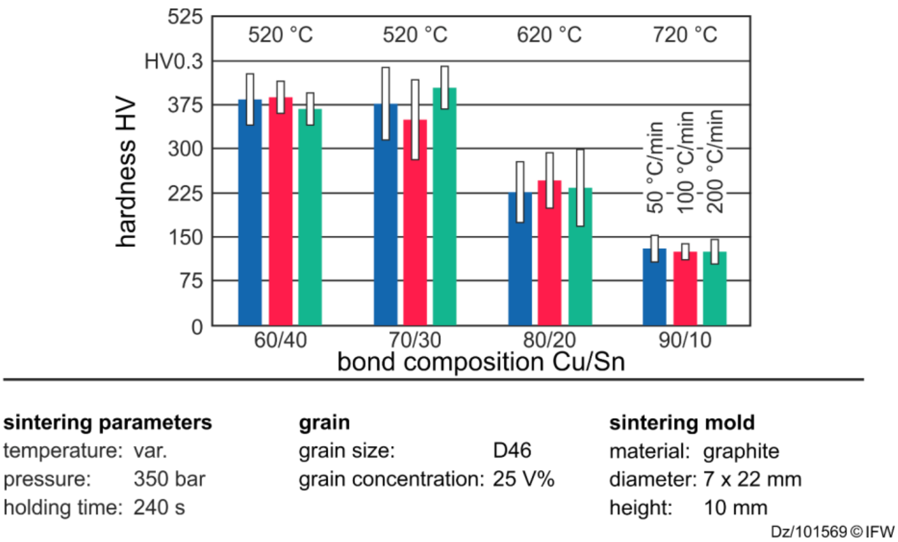

Fig. 9. Bond hardness depending on heating rate and bond composition.

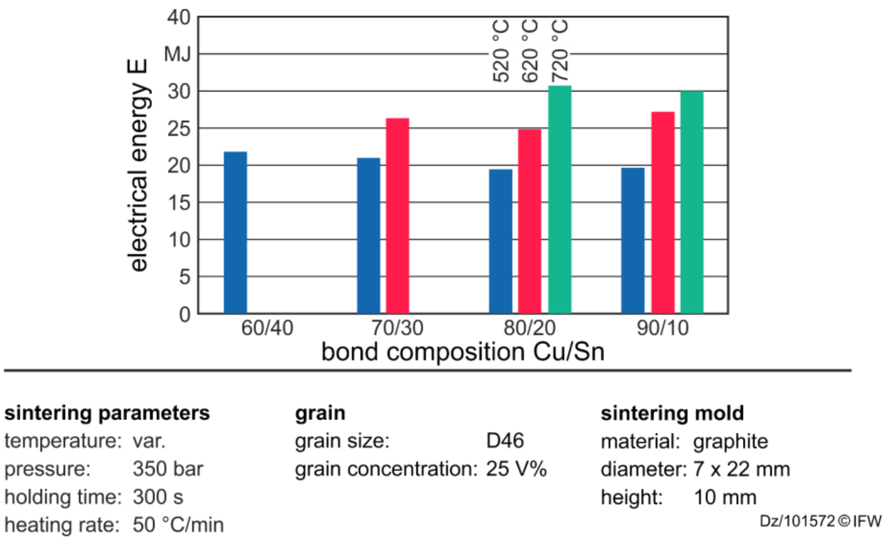

Fig. 10. Energy demand depending on temperature and bond composition.

In addition to the resulting grinding layer properties and the productivity, the cost-efficiency of manufacturing of grinding wheels is also of particular importance. To assess the economic efficiency, the energy demand of the machine was considered. This is shown in Fig. 10 depending on the temperature and the bond composition. From the results it can be seen, that higher sintering temperatures result in a higher energy demand.

The increase in energy demand with increasing temperature can be explained not just by an increased maximum temperature but also by the heat dissipation along the process. This, however, is highly time dependent. The total time of the sintering process is longer, when maintaining the heating rate and increasing the maximum temperature. The cooling also requires more time even though no additional energy is consumed. With the heating rate of 50 °C/min selected here, the sintering process takes 4 min longer to reach the maximum temperature of 720 °C compared to 520 °C. This results in a 35 % lower energy demand when increasing the sintering temperature from 520 °C to 720 °C in case of the composition 90/10. With the composition 80/20, this change in temperature equals a reduction in energy demand of 37 %. The influence of the bond composition is not clearly evident. Although the energy demand tends to decrease with increasing copper content, the energy demand of the 90/10 at 520 °C and 620 °C does not show this tendency. A higher proportion of tin goes hand in hand with a higher proportion of liquid phase sintering. The change in aggregate state that occurs is associated with a higher energy demand, so that more energy is required to maintain the temperature in the sintered material. Overall, the energy demand for all bond compositions is close to one another. The maximum deviation is 12 % for the 60/40 and 80/20 at 520 °C.

The energy demand is influenced largely by the heating rate, Fig. 11. This is due to the different total times of the sintering processes. To reach the sintering temperature of 720 °C, which is recommended for a tin content of 10 m%, takes about 14 minutes with a heating rate of 50 °C/min starting from room temperature. The total time including the cooling time is calculated as 24 minutes. If the heating rate is increased to 200 °C/min, the total time can be significantly reduced to 14 min. This results in a reduction of process time by 42 %. In average, the total energy demand was reduced in this way by 46 % when increasing the heating rate from 50 to 200 °C/min for the compositions 90/10, 80/20 and 70/30. For the composition 60/40, this corresponds to a reduction of 43 % in energy demand. This is due the fact that faster heating rates lessen the heat loss caused by heat conduction in the on lying electrodes and the heat radiation in the furnace chamber, since these heat flows occur over a significantly shorter time.

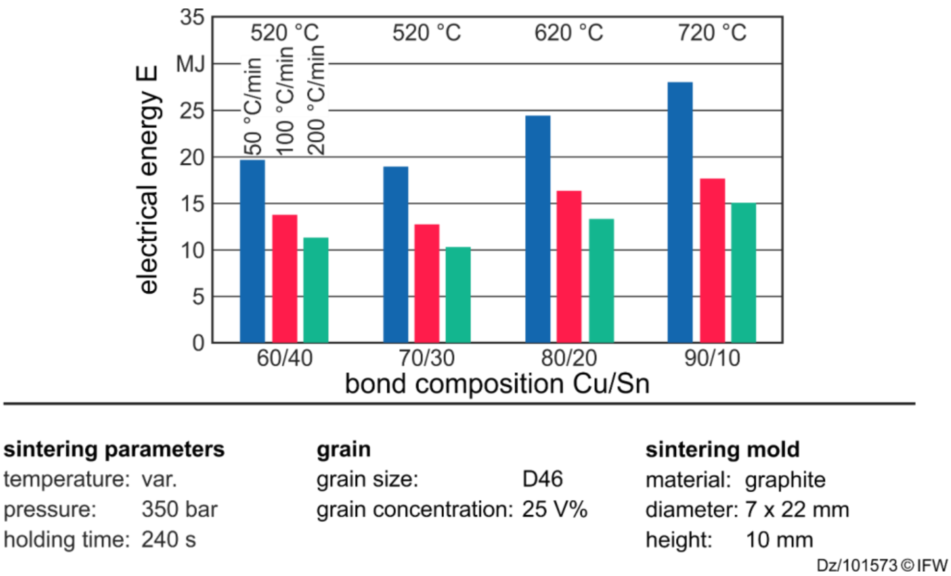

Fig. 11. Energy demand depending on heating rate and bond composition.

The influence of the bond composition on the energy demand cannot be compared directly, as only the 60/40 and the 70/30 were sintered at the same temperature of 520 °C. In these cases, however, the same effect can be seen as in the first series of tests. The energy demand decreases with an increase in the copper content, which is also explained by the higher proportion of liquid phase sintering.

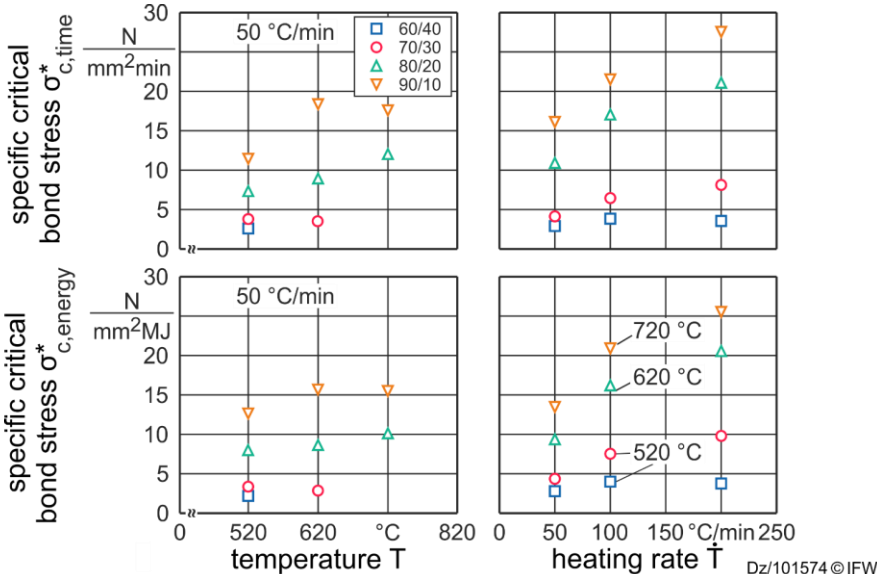

Fig. 12. Specific critical bond stress depending on temperature and heating rate.

In order to relate the resulting critical bond stress to the energy or time demand, the specific critical bond stress is introduced. For this purpose, the mean value of the critical bond stress measurement of the two test series is divided by the energy demand respectively the total time. The resulting specific critical bond stresses are plotted in Fig. 12 over the temperatures and heating rates used. With the connection between the critical bond stress and the energy demand and the total time it would be possible to target productivity to the application case.

The diagrams show that the temperature has nearly the same effect on the total time and the energy demand, recognizable by the similar courses of the time and energy specific critical bond stresses of the respective bond composition. Higher sintering temperatures lead to longer total times and a higher energy demand. This is due to the described heat transfer, which occurs over a longer time depending on the total time and consequently more energy is required to maintain the temperatures in the sintered material and the sintering mold. Furthermore, the critical bond stress and energy demand do not behave proportionally, since the energy demand increases linearly and the critical bond stress strives against a material-related limit. As in the case of the 70/30 bronze, the sintering process is almost complete at low temperatures and there is almost no increase in the critical bond stress.

An increase in the heating rate and the associated decrease in time leads directly to an increase in the specific critical bond stress due to the fact that the heating rate has no influence on the resulting critical bond stress but decreases energy demand. The optimum for the choice of temperature and heat rate can be seen from the maximum of the curves for the respective bond composition.

4. Conclusion

The properties of bronze-bonded diamond grinding wheels are largely dependent on the selected bond composition. The series of investigations show how the structural integrity of the grinding layer and the efficiency of the manufacturing process can be controlled via the sintering variables sintering temperature and heating rate. The bond composition specifies which phases can be formed during sintering and which maximum sintering temperature is possible. The maximum achievable hardness is specified via the hardness of the phases formed, but this does not yet provide any information about the structural cohesion. To evaluate the structural cohesion, the critical bond stress was determined. The critical bond stress has an indirect effect on the application behavior of the grinding wheel via the ability to be sharpened and the grain protrusion. An increase in the sintering temperature generally leads to an improvement in the structural cohesion with a simultaneous increase in energy demand. The heating rate does not affect structural cohesion, but has the greatest impact on productivity. Fast heating rates should be selected for each sintering process in order to reduce the energy demand of the sintering process by reducing heat loss and to shorten the production time. Due to the almost identical energy demand of the different bond compositions, the specific critical bond stress obtained decreases with increasing copper content, analogous to the measured critical bond stresses..

Conflict of Interest

The authors declare that they have no conflict of interest.

Author contributions

Berend Denkena is the director of the institute and is in charge of the successful research and the strategy orientation of the institute. Alexander Krödel, head of the Manufacturing Processes department, is responsible for the successful execution of the research project. He led the critical discussion of the results and the strategic direction of the paper. Patrick Dzierzawa concerted the research, analyzed the data, and wrote the paper. All authors had approved the final version.

References

[1] Webster, J., & Tricard, M. (2004). Innovations in abrasive products for precision grinding. *CIRP Annals - Manufacturing Technology*, *32(2)*, 597-617.

[2] Klocke, F. (2019). *Fertigungsverfahren 2* (5th ed.). Springer-Verlag, ch. 3.

[3] Holz, R., & Sauren, J. (2016). *Schleifen mit Diamant und CBN*, 2nd ed. Essen: Vulkan-Verlag, 1988, ch. 2.

[4] Denkena, B., Grove, T., Bremer, I., Behrens, L. Missing Link. *dihw Magazin*, *3*, 10-16.

[5] Tillmann, W., Kronholz, C., Ferreira, M., *et al*. (2010). Comparison of different metal matrix systems for diamond tools fabricated by new current induced short-time sintering processes. Proceedings of *Conference Proceedings PM 2010* (pp. 531-538).

[6] Linke, B. (2016). Manufacturing and sustainability of bonding systems for grinding tools. *Production Engineering, 10*, 265-276.

[7] Kessel, H. U., *et al.* (2016). Feldaktives Sintern "FAST" - ein neues Verfahren zur Herstellung metallischer und keramischer Sinterwerkstoffe. *Pulvermetallurgie in Wissenschaft und Praxis - Pulvermetallurgie - Kompetenz und Perspektive*, *22*, 201-237.

[8] Grasso, S., Hu, C., Maizza, G., Kim, B.-N., & Sakka, Y. (2011). Effects of pressure application method on transparency of spark plasma sintered alumina. *Journal of the American Ceramic Society*, *94(5)*, 1405-1409.

[9] Denkena, B., Grove, T., Bremer, I., & Behrens, L. (2016). Design of bronze-bonded grinding wheel properties. *CIRP Annals - Manufacturing Technology*, *65*, 333-336.

[10] Kempf, F. L., Bouabid, A., Dzierzawa, P., Grove, T., & Denkena, B. (2017). Methods for the analysis of grinding wheel properties. *WGP Jahreskongress*, *7,* 87-96.

[11] Kühl, C. (2010). Freies Sintern - Admix FS 0100 eine preiswerte Alternative zum konventionellen Heißpressen. *dihw Magazin*, *4*, 54-58.

[12] Lin, K.-H., Peng, S.-F., & Lin S.-T. (2007). Sintering parameters and wear performances of vitrified bond diamond grinding wheels. *International Journal of Refractory Metals & Hard Materials*, *25*, 25-31.

[13] Jang, G.-Y., Lee, J.-W., & Duh, J.-G. (2004). The nanoindentation characteristics of Cu6Sn5, Cu3Sn, and Ni3Sn4 intermetallic compounds in the solder bump. *Journal of Electronic Materials, 10*, 1103-1110.
[14] Deutsches, K. (2004). *Kupfer-Zinn- und Kupfer-Zinn-Zink-Gusslegierungen (Zinnbronzen)*, Bonn, *2*.

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