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## **ELID dressing behaviour of fine grained bronze bonded diamond grinding wheels**

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**Abstract:** The application of metal bonded grinding wheels generally results in high wear resistance and profile constancies of the grinding wheels. Especially bronze bonded grinding wheels can efficiently be used for the grinding tasks, as it is easier to modify their chemical composition – and therefore their bond hardness – to suit a specific grinding task. The combination of very small grained diamonds and a metal bond causes great difficulties for conventional dressing. In this paper, an assessment on the capabilities of ELID for dressing of bronze bonded diamond grinding wheels is presented. Distinct types of bronze-bonds with different chemical composition are investigated regarding their electrochemical dissolution and oxidation behaviour during ELID. Iron-based (Fe-Bz) and cobalt-based (Co-Bz) bronze-bond types showed good performance regarding oxide layer formation during the pre-dressing. An extensive oxide layer growth prevents the metal bond from a too fast anodic dissolution. In contrast, pure bronze type (Cu-Bz) showed no closed oxide layer formation resulting in an extensive anodic dissolution of the grinding wheel bond.

**Keywords:** electrolytic in-process dressing; ELID; dressing; grinding; grinding wheel; diamond grinding wheel; metal bond; bronze bond; electrochemical dressing; oxidation; passivation; electrochemical machining; ECM; abrasives; abrasive technology.

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Marcel Henerichs studied Mechanical Engineering at RWTH Aachen University, Germany. He worked in the research group for EDM and ECM technology and wrote his Diploma thesis on research of ECM dressing technology for metal bonded fine grinding wheels.

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## **1 Introduction**

Ceramic or cemented carbide tool inserts for glass moulding processes are difficult to machine. In order to achieve high geometrical and surface qualities during fine grinding operations smallest grain sizes have therefore to be used on grinding wheels. Diamond must be taken as abrasive material due to its highest hardness and good thermal conductivity. The application of metal bonded grinding wheels generally results in high wear resistances and profile constancies of the grinding wheels. The combination of very small grained diamonds and a metal bond causes great difficulties for conventional dressing.

Thus, effective trueing and dressing technologies must be developed especially when precise tool profile geometries are needed. Due to the electrical conductivity of the bond material the unconventional material removal processes ‘electro discharge machining’ (EDM) and ‘electrochemical machining’ (ECM) are often suggested as alternative technologies. The EDM process can efficiently be used as offline trueing and dressing process (Klocke et al., 2007a). The electrochemical process ‘electrolytic in-process dressing’ (ELID) can ideally be used as continuous dressing technology parallel to the grinding process (Ohmori and Nakagawa, 1990). The ability of ELID to improve the performance of precision grinding processes has been demonstrated in many publications within the last 20 years focusing on the ELID process, cf., for example Ohmori and Nakagawa (1995) and Lim et al. (2002).

Cast iron bonded grinding wheels are predominantly used for the ELID grinding process because of their superior oxidising behaviour. The influence exerted on the grinding wheels by various electrolytes has been investigated for different power supplies (AC, DC and pulsed DC) and peak currents (Ohmori and Nakagawa, 1997; Zhang et al., 2001).

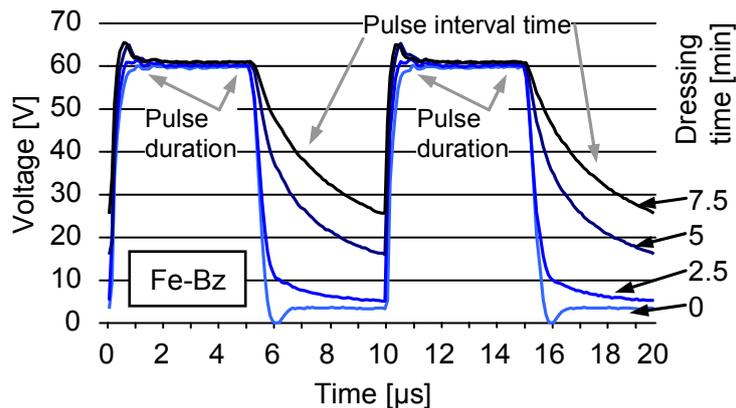
Bronze bonded grinding wheels can also efficiently be used for the described grinding task, as it is easier to modify their chemical composition – and therefore their bond hardness – to suit a specific grinding task. Additionally, the wheels can be sintered at lower temperatures, resulting in an easier production process. The general suitability of bronze bonded grinding wheels for ELID grinding is shown in Bifano et al., 1999 and Klocke et al., 2007b).

In this paper, further fundamental investigations on the capabilities of ELID for dressing of bronze bonded diamond grinding wheels are presented and the main influencing parameters are analysed.

## 2 Principle of ELID Dressing

The process is based on a metallic grinding wheel used as an anode while a copper or graphite electrode is used as a cathode. This electrochemical cell is positioned on the grinding wheel diametrical to the point of chip formation during the grinding process. The cooling lubricant used for the grinding process also serves as an electrolyte. A range of electrochemical reactions will occur, depending on the boundary conditions. The metal bond in the grinding wheel dissolves, according to the anode principle, in specific passive area, i.e., the section where oxide layers cover the anode. During ELID grinding, usually a pulsed voltage generator is used in order to generate the necessary electrolysis current. During the pulse duration (on-time) the nominal voltage is applied. During off-time the measurable voltage depends on the current thickness of the oxide layer, Figure 1.

**Figure 1** Development of voltage signals during ELID (see online version for colours)



ELID parameters:  $U = 60 \text{ V}$ ;  $\tau = 0.5$ ;  $f = 100 \text{ kHz}$   
 $\alpha = 100^\circ$ ; Gap = 0.5 mm  
 Electrolyte: Cimiron CG-7:water = 1:50

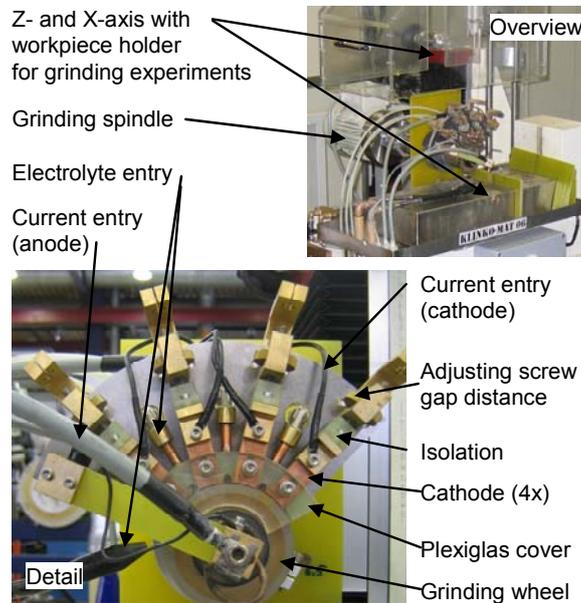
For a very thin oxide layer just at the beginning of the ELID dressing process the voltage signal is falling down to zero for the pulse interval time (off-time). With a dressing time based growing of the oxide layer an electrical capacitance is formed. Through this, the voltage drop during pulse interval time depends on oxide layer thickness. The oxide layer that forms acts as an isolating covering. The electrical conductivity of the grinding wheel surface and therefore the electrolysis current decreases as oxide layer thickness increases. On the other hand, the oxide layer is relatively easily removed mechanically during the grinding process. When the current therefore increases again, the anodic dissolution is restarted, so the self-regulating dressing process is in dynamic equilibrium. The measurable total average voltage is representing a simple monitoring parameter for oxide layer thickness.

### 3 Experimental set-up

In order to perform fundamental investigations on the capabilities and mechanisms of ELID for dressing of bronze bonded diamond grinding wheels, the following purpose-built equipment was used. A comprehensive electrical power supply allows the variation of nominal voltage, pulse frequency and duty factor  $\tau$  (ratio of pulse duration and pulse cycle time) in a wide range.

In addition to the electrical process parameters, a special test rig allows the defined variation of all other important parameters (number of cathodes – wrap angle  $\alpha$ , gap distance, electrolytic coolant, grinding wheel) and the simple and reproducible measurement of the dressing process. While voltage and current can be measured by appropriate process monitoring equipment the oxide layer thickness can be determined by measuring grinding wheel diameter changes with a micrometer gauge, Figure 2.

**Figure 2** Purpose-built ELID-grinding test rig (see online version for colours)



**Table 1** Bronze bonds used in experiments

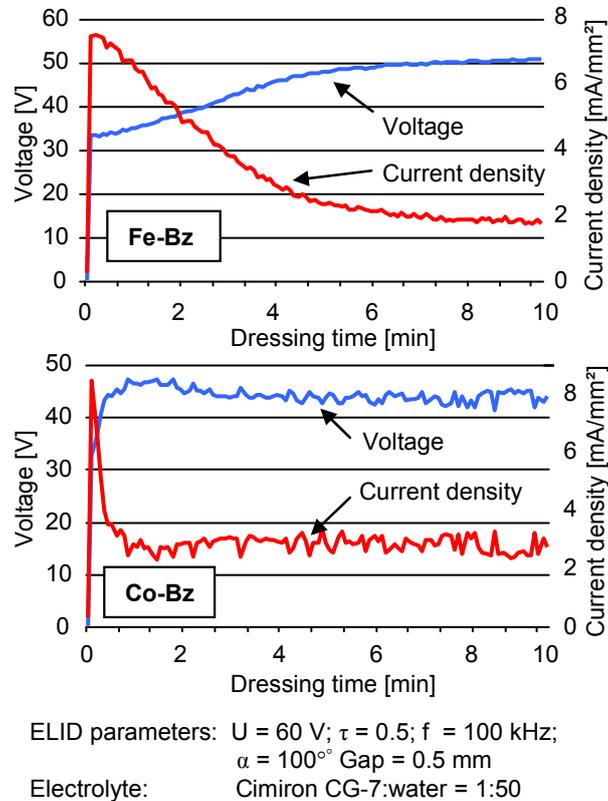
<i>Denotation</i>	<i>Metal composition of bond</i>
Fe-Bz	70% Fe, 30% Bz (Cu-Sn)
Co-Bz	70% Co, 30% Bz (Cu-Sn)
Cu-Bz	85% Cu, 15% Sn

A special ELID cooling lubricant Cimiron CG-7 was used during the series of experiments presented in this paper. The dilution rate with water was 1:50. The resulting pH-value was 10.4 and the specific electrical conductivity was 1.5 mS/cm. The circumferential grinding wheels had a diameter of 75 mm and a width of 2 mm. The rotational speed during experiments was 7,000 rpm. Three different types of sintered bronze were selected as grinding wheel bond material, Table 1.

#### 4 Analysis of passivating behaviour

The three different types of bronze bonds were investigated regarding their passivating behaviour due to oxide layer growth during ELID pre-dressing (no parallel grinding process). The pure bronze (Cu-Bz) showed a fast anodic dissolution of the grinding wheel bond material without the ELID-typical formation of an oxide layer. The current density over time decreased due to a fast growth of the electrolytic gap between anodic metal bond of the grinding wheel and the cathode. Therefore, the total electrical resistance of the electrolyte increased resulting in a current decrease. As Cu-Bz showed no closed oxide layer formation, this fast and extensive anodic dissolution of the grinding wheel bond took place preventing an efficient ELID dressing process.

**Figure 3** Influence of bond material (see online version for colours)



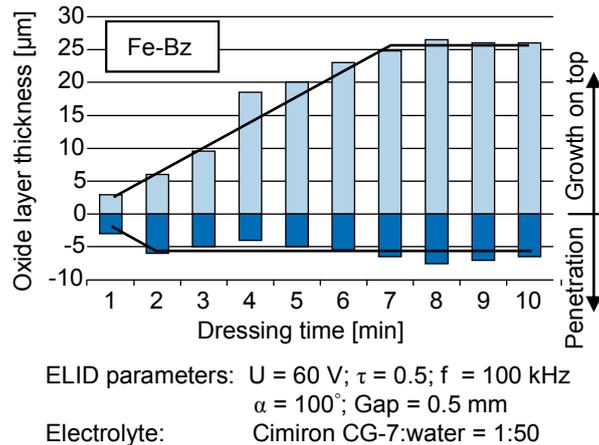
The two other bond materials showed the ELID-typical decrease of current density and the increase of the average voltage over dressing time, cf., Ohmori and Nakagawa (1997) and Klocke et al. (2007b). In parallel, an adequate oxide layer formation took place, Figure 3.

During the complete dressing time of ten minutes virtually stable levels for average voltage and current density were achieved for both bond materials representing the adequate ELID pre-dressing of the grinding wheels. Comparing the results for both bond materials it can be concluded that for the cobalt-based (Co-Bz) a much faster passivation

takes place. A very fast current density decrease – even down to the stable level – takes place during the first minute of dressing. This effect can be explained by very efficient electrochemical anodic reactions for the Co-Bz. On the surface, the generation of the oxide layer takes place very fast resulting in an increase of electrical resistance and a decrease of electrolysis current. In contrast to this, the according chemical reactions for the iron-based (Fe-Bz) last for about seven minutes until a sufficient oxide layer thickness is achieved.

From former investigations (Klocke et al., 2007b) it is known that for Cimiron CG-7 an efficient oxide layer growth during ELID dressing is connected with the anodic deposition of molybdenum out of the fluid. The molybdate ( $\text{MoO}_4^{2-}$ ) in the electrolyte combines with the iron or especially the cobalt to form a mixed oxide that settles on the surface. Thus for the oxide layer formation during ELID dressing it can be distinguished between a penetration of the oxide layer into the anodic grinding wheel bond and a growth on top of it, Figure 4. The growth on top can directly be measured after the experiments by determining the grinding wheel diameter increase with the micrometer gauge. For the measurement of the penetration depth the oxide layer has to be removed mechanically before measurement.

**Figure 4** Oxide layer growth over dressing time (see online version for colours)

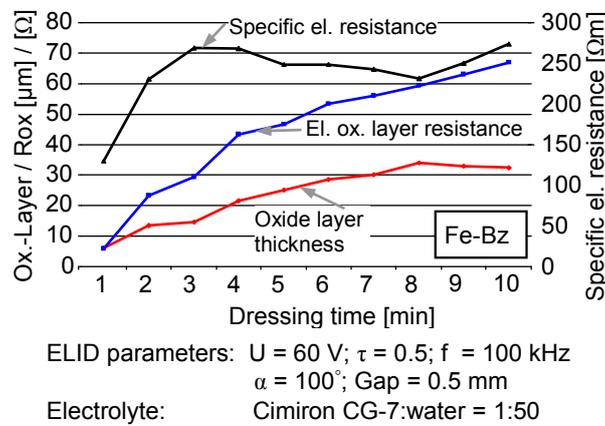


In Figure 4 the oxide layer growth over dressing time is shown for Fe-Bz under given ELID parameters (results from a total of ten dressing experiments stopped after given time). Within the first two minutes the oxide layer mainly grows down to the penetration depth by the conversion of the bond material to oxide layer through the anodic reaction. After these initial reactions the penetration depth is kept constant for the rest of the dressing time. In addition, the deposition of molybdenum out of the fluid takes place by the electrolysis. Due to the additional masses the growth effect can be explained. By the constantly growing oxide layer thickness over dressing time the electrical resistance of the oxide layer increases reducing the according electrolytic current, Figure 5.

Thus, after a specific dressing time the electrolytic process stops when achieving the stable levels of average voltage and current density, respectively, Figure 3. The calculated specific electric resistance of the oxide layer achieves a constant level after the initial reactions representing a more or less homogeneous layer growth. While the oxide

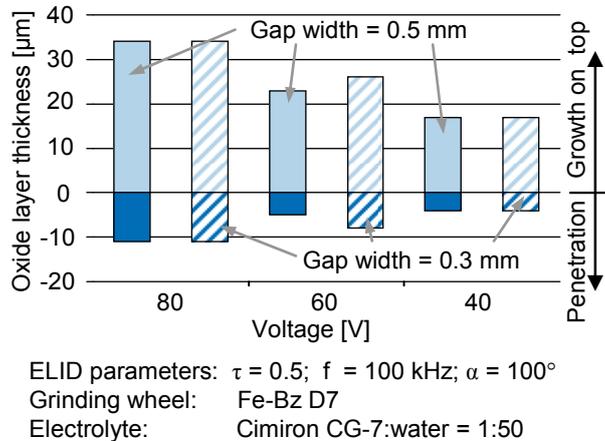
layer growth on top of the initial surface has a minor influence on the grinding process – it can just mechanically removed by the grinding process – the penetration depth determines the amount of dressing in order to remove bond material and to achieve new grit protrusion. In order to keep an economic dressing process, this penetration depth must be kept to a defined level in the order of magnitude of the average grit size. During a later in-process dressing process the resulting constant reduction of grinding wheel diameter over time (dynamic equilibrium of new penetration through mechanical removal of the covering oxide layer and new deposition of a covering oxide layer) must be compensated through an appropriate grinding process adjustment.

**Figure 5** Development of electrical resistance over time (see online version for colours)



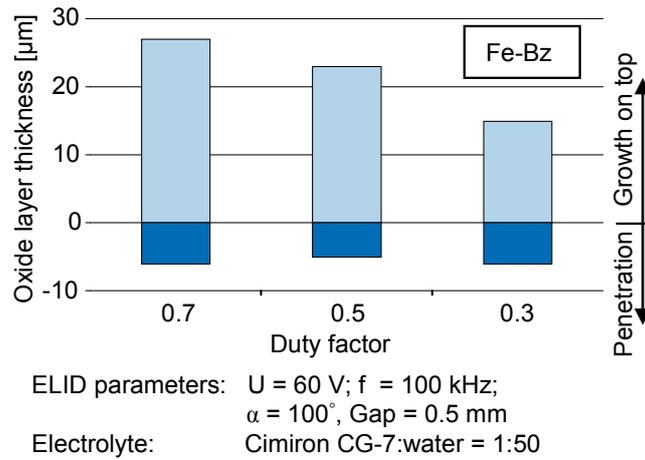
The size of the penetration depth can mainly be influenced by the chosen ELID dressing voltage, Figure 6. A high nominal voltage is resulting in a bigger penetration depth and a bigger amount of total oxide layer growth. The initial gap width between the anodic grinding wheel and the cathode electrode has virtually no influence on the growth behaviour. The total electrical resistances of the oxide layers formed during the dressing process are much bigger compared to the initial differences in electrical gap resistances.

**Figure 6** Influence of voltage and gap width (see online version for colours)

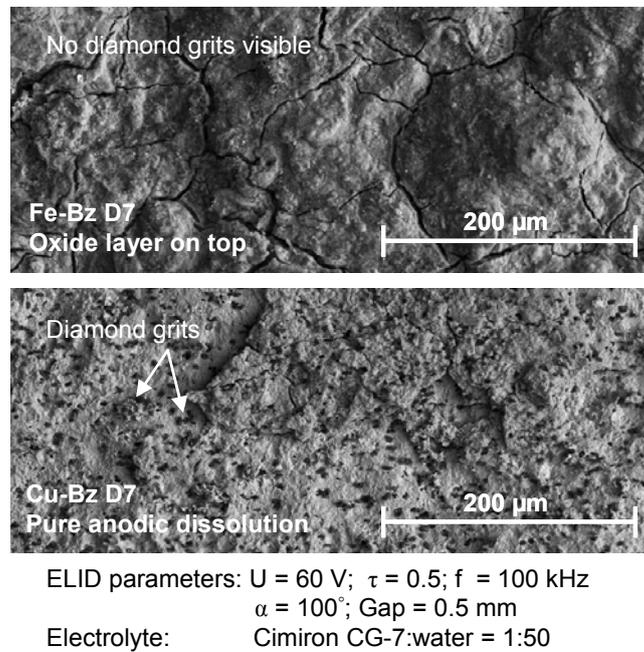


Also the duty factor has virtually no influence on the penetration depth. Only the amount of oxide layer growth depends on the duty factor, Figure 7. The wrap angle  $\alpha$  of the cathode was not varied during these investigations. From theoretical analysis it can be concluded that with a bigger wrap angle the anodic reactions will take place faster or will reach a bigger amount, respectively. Also from theory it can be concluded that the rotational speed of the grinding wheel will have no influence on the effective electrolytic time, cf., Ma et al. (2007).

**Figure 7** Influence of duty factor (see online version for colours)



**Figure 8** Oxide layer formation for different bronze bonds



In Figure 8 SEM pictures of different bronze bonded grinding wheel surfaces after ELID pre-dressing are shown. The used diamond grits have an average diameter of 5–10  $\mu\text{m}$  and a concentration of 12.5 vol%.

The top picture shows the surface of a grinding wheel with a Fe-Bz bond material. An oxide layer has formed on top of the initial grinding wheel surface. Thus, no diamond grits are visible. The comparatively rough topography can be explained by a locally different anodic reaction and oxide layer growth of different micro phases of the sintered grinding wheel.

The bottom picture of Figure 8 shows the surface of a grinding wheel with a Cu-Bz bond material. During the ELID-dressing operation a pure anodic dissolution takes place without oxide layer formation. Thus, a lot of diamond grits are visible as small black spots in the according backscattering SEM image. Under these conditions no economic precision grinding is possible due to a too fast dissolution of the bond material. No self-regulation with the oxide layer resistivity takes place.

## 5 Application

The adapted ELID dressing process for bronze bonded fine grinding wheels has been successfully applied to precision grinding operations of cemented carbide tool inserts for glass moulding operations, Figure 9.

**Figure 9** ELID grinding of a cemented carbide tool insert (see online version for colours)



### Workpiece:

- Material: WC
- Geometry: R =100mm,
- Surface quality: Ra=5nm

### Grinding wheel:

- Co-Bz D3 C35

### ELID-parameters:

- Cimiron CG-7 (1:50)
- U=60V;  $\tau=0.1$ ; f=100kHz
- $\alpha=100^\circ$ ; Gap=0.4mm

## 6 Summary

This paper presents an assessment on the capabilities of ELID for dressing bronze bonded grinding wheels. Three different types of bronze bonds have been analysed regarding their process performance. In addition, the main influencing parameters of the electrochemical dressing process on penetration depth and total oxide layer thickness are presented.

Fe-Bz and Co-Bz bronze bond types showed good performance regarding oxide layer formation during the ELID pre-dressing. An extensive oxide layer growth prevents the

metal bond from a too fast anodic dissolution. In contrast, Cu-Bz showed no closed oxide layer formation resulting in an extensive anodic dissolution of the grinding wheel bond preventing an efficient ELID dressing process.

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