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Abstract (150 – 200 words)

Grinding and honing processes are quality-defining operations in the production of many modern products. Process performance and product quality are contingent on selecting the correct abrasive tool for a specific application. Thus, tools with different bonding systems are used, namely resin bonded tools, vitrified bonded tools, and metallic bonded tools. Tool manufacturers have great knowledge in the choice and intricate production of these bond types and their countless variants. Most bond systems pass through mixing, forming, pressing, heat treatment, and post-processing steps. Single-layer metallic bonds can be generated by electroplating or brazing processes. This article reviews the manufacturing of tools with different bonding systems and discusses their ingredients. Furthermore, the economic, environmental and social dimension of tool production and tool use are considered to understand sustainability issues of different bond types. The review of tool manufacturing is necessary to enable informed Life Cycle Assessments or other sustainability analyses for grinding or honing.

Keywords (4 – 6 words)

Abrasive tools, bonding, grinding wheels, bonding systems

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1 Introduction

Grinding is an important manufacturing process and defined by the specification of the tools used. Sustainability in grinding tools is gaining more attention [1]; therefore, grinding tool ingredients and manufacture have to be critically evaluated. Only few studies on the life cycle and sustainability of grinding tools have been conducted so far [1-4].

The bonding system of grinding tools has to fulfil many tasks, such as providing sufficient grit retention without untimely grit pullout and sufficient strength to transfer machining forces and centrifugal forces, allowing controlled bond erosion to expose new cutting edges, offering enough pore space to transport chips and cooling lubricant, providing adequate heat conductivity, providing thermo-shock resistance, and providing chemical resistance against metal working fluid [5,6]. The bond composition has to enable strong grit retention, optimum grit protrusion, and optimum self-sharpening abilities. The tool manufacturer has to find the appropriate compromise between hardness and erosion resistance [7]. Maximum grit retention capability is not synonymous with high performance in the abrasive process [5].

The bond material is chosen by the tool manufacturer with technological, economic, environmental and social considerations in mind. Main concerns are raw material price, availability and quality, and energy and labor costs. Furthermore, worker health, emissions, and legislation need to be considered. The bond system also affects tool conditioning which is comprised of tool sharpening and profiling. Tool conditioning affects tooling costs, tool wear, non-productive time, and final part quality, surface roughness and scrap rate.

Besides the primary bond ingredients, there are fillers, separator agents, auxiliary components, or even secondary abrasives in the bonding

composition to modify the abrasive tool. All ingredients need to be considered in their life cycle from raw material extraction to end of life as well.

In the following sections, the major bond types (resin bonds, vitrified bonds, metallic bonds) will be discussed. Sections 2-5 are organized by chemistry and then processing steps. Grinding tools with resin, vitrified and multi-layer metallic bond systems pass through similar manufacturing steps, such as mixing, forming, pressing, heat treatment, and post-processing [8]. All tool manufacturing processes include additional auxiliary steps such as raw material quality control, weighing, intermediate control steps, sieving, and stocking. Section 2 will discuss resin bonds. Section 3 will discuss vitrified bonds. Sections 4 and 5 will discuss metallic multi-layer bonds and metallic single-layer bonds. Section 6 will discuss rubber and hybrid bonds. And finally Sections 7 and 8 will present a discussion and a conclusion.

2 Resin bonds

Resin bonds have comparably high elasticity. Therefore, this bond type is selected for wheels that are subject to impacts, sideways load, sudden loads, or high cutting speeds. Typical applications are cut-off or roughing operations. In addition, resin bonds work well for finishing processes to achieve high surface quality. Bond elasticity, however, might have a negative effect on dimensional accuracy. [9]

Resin bonded wheels are easy to profile, but do not achieve a high enough grit protrusion through profiling. Therefore, they need an extra sharpening process. Furthermore, resin bonds are sensitive to heat. They start to degrade at temperatures above 200 °C and grit coatings help to dissipate the grinding heat.

2.1 Chemistry and Types of Resin Bonds

A resin bonded grinding wheel consists of abrasive grits in a resin bond with or without

fillers (**Fig. 1**). This wheel type has commonly a low porosity compared to vitrified bonded tools.

Fig. 1 Structure of a resin bonded tool

Resins are viscous liquids capable of hardening. They are polymers, i.e. large molecule chains composed of monomers. Monomers are substances with the elements C, H, O, N, Cl, S, or F, from which oligomers (“resins”) are synthesized [10]. These are then transformed to crosslinked, insoluble polymers in a second step, called curing, which optionally involves heat, catalysts, fillers, or pressure [10].

Resin bonds for abrasive tools consist of single resins or a resin combination with or without fillers. The resin itself is typically manufactured by esterification or soaping of organic compounds. Filler material has not only the task to reinforce the bonding in toughness, heat resistance, strength, and breakage safety, but also to support the grinding process as secondary abrasive [9]. Silicates, sulfides, halogenides increase the bonding strength and wear resistance and hinder the oxidative degradation of the resin [11]. In cut-off wheels, the resin bond is additionally enforced by body materials of glass fiber, linen cloth, etc.

Resin bonds can be divided into three classes based on strength and temperature resistance [9,12-15]:

- Phenolic resin,
- Polyimide and polyamide resin, and
- Epoxy or urethane resin, often called plastic bonds.

2.1.1 Phenolic resin

Phenolic resin bonds, in particular phenol-formaldehyde resin bonds, are the most common resin bonds; tools made of this bonding type represent the largest market segment for conventional wheels after vitrified tools [11-13]. Originally, this bond type was known as bakelite and for this reason retains the letter “B” in many

wheel specifications [5,10]. In comparison to other resins, phenolic resin is less expensive and easier to mold [16]. Phenolic resins are obtained by the reaction of phenol and aldehyde [10]. Safety is critical in phenol synthesis, because the oxidation takes place close to the flammability limit and the unstable material cumene hydroperoxide is used [10].

The phenolic resin bond for grinding wheels contains liquid phenolic resin (resole type) and powdered phenolic resin (novolak type), straight and modified phenolic resins, powdered resins with wetting agents, or low melting phenolic resin combined with powdered phenolic resin [10]. Various modifications with epoxy resins, rubber, polyvinyl butyral, etc. are possible [10]. Furthermore, phenolic resin bonds for superabrasives are enhanced by SiC grits and solid lubricants [17].

Phenolic resins are cured at around 150 °C to 200 °C through polycondensation [11,5]. Gardziella et al. [10] give detailed compositions of the single liquid and powdered resins used for the production of abrasive tools.

2.1.2 Polyamide and polyimide resin

Polyimides are polymers with a noncarbon atom of nitrogen in one of the rings in the molecular chain [18]. Polyamide-imide are members of the same polymer family and contain aromatic rings and nitrogen linkages [18].

Polyamid and polyimide bonds have a higher toughness, thermal resistance and elasticity than phenol resin bonds [12]. For example, polyimide bonds have 5 to 10 times the toughness of phenolic bonds and can withstand temperatures of 300 °C for 20 times longer than phenolic bonds [13]. The higher price however reduces the use of this bonding system type to special applications and superabrasives [13]. Polyimide resin is a dominant bond type for high-production carbide grinding especially for

cutting-tool flute grinding [13] and for lubrication-cooled cut-off grinding.

2.1.3 Epoxy or urethane resin

Epoxy or urethane wheels are the softest of resin bonded wheels. With conventional abrasives, they are popular for double disc and cylindrical grinding. With superabrasives, epoxy or urethane bonds appear to be limited to micron diamond grain applications for the glass and ceramics industries [5].

Epoxy resins are characterized by their epoxide group which consists of oxirane rings ($-\text{CH}_2-\text{O}-\text{CH}_2-$) [18]. The epoxy resin then is hardened with a fluidic hardener to a polymer [9,12].

2.2 Manufacturing of resin bonds

Resin bonded grinding tools are manufactured via mixing, pressing and hardening at temperatures up to 200 °C (**Fig. 2**) [9]. Resins consist normally of the two main components resin and hardener. Mixing both parts results in the reactive resin material. During hardening, the resin's viscosity rises and a duroplastic material is generated.

Fig. 2 Manufacturing of resin bonded tools after [6,8,10,16]

2.2.1 Mixing and molding

Mixing is often done in several steps, wet mixing, dry mixing, and final mixing (**Fig. 2**). In the wet mixing step, abrasive grits and liquid resins or furfural, a wetting agent, are combined [9,10]. The abrasive grits will be coated so that the powder resins and fillers will cleave easier onto the grit surface. Wetting agents also improve the aggregation of grits. In addition, the abrasive tool can be handled in its raw, so called "green" state [8,9].

Powder resin on phenol basis and fillers are mixed dry before they are combined with the wet mixture composed of abrasives and wet resins. Additives are included to support the

mixing process by improving the pourability and storage life of the mixture and reducing the clumping tendency [10]. Examples for additives are powdered additives, silica and silica derivatives [10]. The mixing process is continued until a homogenous, pourable mixture emerges [9]. Dust is a safety issue during handling of powder resins. Therefore, antidusting agents can be useful additives to minimize dust [10]. Before pressing, body material such as glass cloth for cut-off wheels or aluminum bodies for superabrasive wheels can be imbedded [11].

2.2.2 Pressing

The bond and grit mixture can be either cold pressed and subsequently hardened in a furnace, or as hybrid-process the bond and grit mixture are hot pressed and hardened on a press with a heating plate. **Fig. 3** shows an example setup for pressing an abrasive layer onto a grinding wheel body. Conventional wheels are either hot or cold pressed and hardened at 140 - 200 °C [9,15]. Most superabrasive wheels and dense, low porosity conventional wheels are produced by hot pressing at 160 - 175 °C [15,10]. In the case of superabrasive wheels with a diameter below 200 mm, the abrasive layer can be pressed directly onto the tool body [6]. Epoxy or urethane bonds are casted or joggled in molds where they are hardened at temperatures of 20 - 80 °C [9,12].

Fig. 3 Pressing of resin bonded tools

Cold pressing is done on hydraulic presses with compression strength of 15 - 30 N/mm² [6,10]. Pressing time ranges from 5 - 50 seconds and depends on the dimensions and shape of the abrasive tool, grit size, mixture plasticity and distribution [10]. In hot pressing, the pressing times are determined to be about 30 - 60 seconds per millimeter of wheel thickness [10]. The pressing process works either on a defined volume or with a defined pressure [9].

2.2.3 Curing

The curing process causes the resin bonds of the grinding tool to harden. The resin curing process has to follow a defined temperature profile to achieve desired tool properties. Several chemical processes happen during curing depending on the actual temperature [9,10]:

- 70 - 80 °C: The resin bond starts to flow and transforms into a fused mass. Water in the phenol resin evaporates and the resin hardens [9].
- 110 - 120 °C: Hexamethylenetetramine decomposes and induces the hardening process of fused powder resin. Gas is liberated, particularly ammonia (NH_3). [9,10]
- 170 - 180 °C: The structure finally hardens and crosslinking of the phenol resin takes place [9]. Overcuring should be avoided because overcured tools exhibit reduced strength [10].
- 180 - 200 °C: Benzylamin structures split and result in new ammonia generation. The resin bond becomes brittle, but also thermally more stable [9].
- The final temperature level (165 - 170 °C, 175 - 180 °C, or 185 - 195 °C) affects the final tool properties (hardness, toughness, brittleness) considerably [10].

Curing can also happen dielectrically with radio frequency and microwave heating [15,19]. These methods need the existence of a significant electrical loss factor, which is common with phenolformaldehyde resin [19].

2.3 Fillers in Resin Bonds

Fillers in resin bonds have several tasks in both manufacturing phase and grinding operation: They induce porosity, reinforce bond properties, change aesthetics, and more [20]. Common fillers in resin bonded grinding tools are cryolite (Na_3AlF_6), pyrite (FeS_2), zinc sulfide (ZnS), lithopone (ZnSBaSO_4), potassium fluoroborate and potassium chloride (KAlF_4 , K_3AlF_6),

potassium sulphate (K_2SO_4), and mixtures of these materials (KCl) [9,10,21]. The toxic materials antimony trisulfide (Sb_2S_3) and lead chloride (PbCl_2) were used in the past, but are substituted by special iron halides and others [10]. The percentage of fillers and resin bond varies with the grinding tool hardness and density. A common abrasive grit content ranges from 65 – 95 w%, with resin content below 8 w% and filler content below 3 w% for soft wheels and resin content below 18 w% and filler content below 20 w% for hard wheels [9,10].

Fillers can induce porosity [20]. Basic oxides, such as CaO and MgO , are fillers that accelerate the hardening process [9]. However, CaO should only be applied to grinding tools for dry grinding operations, because CaO fillers can hydrate and transform into CaCO_3 in contact with cooling lubricant [9].

Fillers are either reinforcing agents in the bond by improving toughness, heat resistance, strength and burst resistance or they support the grinding process as secondary abrasive [9,10]. Glass chips reinforce wheels around the inner diameter [16]. Fine metal powder of high thermal conductivity can be introduced into the bond to improve the tool's heat absorption in the machining process [22]. An example is fine silver powder, mesh size 325 or finer [23]. In addition, fine silicon carbide grits act as bond strengtheners [22]. Fillers in the form of solid lubricants can lead to reduced friction at the wheel-workpiece interface, fewer loading of the wheel by grinding swarf, and preserved sharpness of the abrasive grits [22].

3 Vitrified Bonds

Vitrified bonds are thermally highly stable. The first vitrified bonded CBN grinding wheels needed separate profiling and sharpening processes [24]. However, this problem has been overcome by new bonding compositions. Modern vitrified bonded grinding wheels are

easy to profile and sharpen in one step. Grit retention in vitrified bonds is partially mechanical because the bond encloses the grits. In addition, the bond often reacts chemically with the grit surface.

3.1 Chemistry and Types of Vitrified Bonds

Vitrified bonds consist of silicates (red and white clay), kaolin (also known as white clay, $\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$), field spar (KAlSi_3O_8 - $\text{NaAlSi}_3\text{O}_8$ - $\text{CaAl}_2\text{Si}_2\text{O}_8$), quartz (also known as silicon oxide, SiO_2), and frits, i.e. pre-molten bonding components [25-28]. The bond is sintered at temperatures above 800 °C and results in a structure where the grits are enclosed by the bond (**Fig. 4**). The bond-bridges between grits leave room for pores. Due to the high sintering temperatures, reactions between grits and bond are likely. In contrast to resin and metallic bonds, vitrified bonds have a significant amount of pores.

Fig. 4 Structure of a vitrified bonded tool

Vitrified bonds vary in their appearance due to the proportion of ingredients and sintering conditions. The two bond type extremes are melted bonds and sintered bonds [6,11,29]:

- Melted or fusible bonds are glassy bonds with a high amount of glass phase [30]. They result from a high proportion of clay and frits as raw materials. During sintering, the bond material completely melts, flows around the grits, and reacts with the grit surface [31].
- Sintered bonds occur as porcelain bond type with a small amount of glass phase. A high proportion of fieldspar and a low amount of frits causes this bond type. The abrasive grits are only held together by partially molten bond material. The volumetric proportion of bond material and the firing temperatures are comparatively high [11]. This bond type is used for critical grinding operations

with low forces and for silicon carbide tools [11].

3.2 Manufacturing of Vitrified Bonds

First, the bond components and abrasives are mixed and filled into a mold, either by a casting process in the case of clay-like bonds or by a molding process (**Fig. 5**). Pressing compacts the material and produces the so-called “green body”. The green body is then dried and sintered. Next, the grinding wheel is machined to its final profile before the final quality control.

Fig. 5 Manufacturing of vitrified bonded tools after [6,8]

3.2.1 Mixing

The proportion of grit, bond, and pore volume defines structure and hardness of a grinding tool. The right amount of bond components and grits are weighted and mixed. Even if the various ingredients have different size, density, form, and weight the mixture has to be controlled that it is homogenous and without agglomerations, doing so ensures the final abrasive tool has a homogeneous cutting edge distribution [32]. Furthermore, the mixing process must not demix the components, induce changes in the mixture, or produce heat [8].

In the first step, coarse particles are made sticky by mixing them in for example a water dextrose solution [8,33]. Fine components are added afterwards and stick to the prepared coarse components [8,33]. Lubricant is added to control and avoid aggregation [32]. Aqueous phenolic resin binders are one example for temporary binders [34].

3.2.2 Casting

Casting is applied for bonds with high clay content since only these can be held in suspension [6]. The casting process is more

expensive and therefore is being replaced by molding processes [6].

3.2.3 Molding and pressing

Most vitrified bonded tools are manufactured by molding. In the past, the mixture was formed into the mold manually; today fully or partially automated systems supply and disperse the mixture into steel molds. The mixture has to be filled into the mold homogeneously and without demixing, which is done by conveyor belts, vibrating trough, or other supply systems. The filling height is leveled with sheets. Molding gets more complicated for complex grinding tools such as wheels with different layers for crankshaft grinding, different hardness areas for raceway grinding, or large width for centerless grinding. [8]

The pressing process defines density distribution and thus the specific characteristics of the component [35]. The pressure is an important factor for tool quality and commonly not published. Today, computer controlled hydraulic presses between 500 kN to 45 MN are in use [8]. Commonly, the target volume, not the target pressure, controls the pressing process. Segments for superabrasive wheels are pressed with hydraulic or pneumatic presses or by hand at comparatively low pressures (max. 50 N/mm²).

Inevitable friction between the dies, molds, and powder leads to density gradients, which can result in sintering distortions and inhomogeneous material properties [35]. Additives like paraffin, polysaccharide, silicon oil, wax, and polyethylene emulsions lubricate the mixture and therefore support the pressing process [32]. Oscillations of about 60 Hz can be superimposed to the pressing process and enhance the density distribution [35].

Hot pressing is used for high density tools [6]. Hot pressing of diamonds in vitrified bond produces wheels of low porosity. Using graphite

molds enables higher sintering temperatures in the hot pressing process. However, as the graphite molds are of low strength, the process has to be heated above regular sintering temperatures to limit pressing pressures [5]. As consequence, the bonds are densified with less than 2 % of open porosity.

3.2.4 Drying

In the drying or de-binding process, water from the temporary binders is expelled [8]. Drying is conducted in a special drying furnace or in the sintering furnace during the general heat-up period. Drying will occur at temperatures between 200 and 600 °C which depends on tool ingredients, composition, and application.

3.2.5 Sintering process

During sintering, the bond components melt and flow around the abrasive grits. Bonds with a large amount of clay melt at higher temperatures; bonds with more frit content melt at lower temperatures [36]. The mechanisms of melting, wetting, re-solidification, and forming of bonding-bridges between grits are highly complex [32,37]. The bond mixture is formed into non-uniform glass of complex composition including several ceramic bond minerals that form during the sintering process [28]. For example, Jackson studied the vitrification behavior of sintered and fusible bonds for conventional grinding wheels [30]. Bot-Schulz analyzed the chemical reactions and sintering mechanisms for varying bonding composition for white corundum and Sol-Gel-corundum [32].

One problem in manufacturing of vitrified bonded tools is shrinkage after melting and sintering. A higher amount of abrasives and secondary abrasives reduces the shrinkage, but might have a negative effect on the grinding tool performance. Pore builders are designed to burn to create voids, which sometimes collapse during the sintering shrinkage. New approaches to reduce sintering shrinkage and act as

dimensional stabilizing additive are to use fired clay ("grog") or crushed firebricks in sizes between 30 - 200 μm . Cerium oxide, andalusite, sillimanite, willemite, or a combination thereof. [38]

Several chemical processes happen during sintering [32]:

- 20 - 600 °C: Free and bound water dissolves. The temporary binders burn out. Quartz changes volume at 573 °C. Gas pressure and volumetric shrinkage lead to high internal stresses in the tool.
- 600 - 900 °C: Carbonates, organic material, chemically combined water in the clay, and other volatile materials drive out.
- Chemical reactions between grits and bond are possible.

The sintering temperature must not harm the abrasive grits by inducing unwanted oxidization or other chemical reactions. The bonding systems for CBN and diamond have to fuse together under lower forming pressures and vitrification temperatures than for conventional grits [39]. Because CBN is thermally more stable than diamond, CBN grits can be used with a wider range of vitrified bonds [36]. Special coatings protect CBN grits from chemical reactions above 800 °C with the water and alkali in most frits [36]. For diamond wheels, a non-oxidizing atmosphere is applied to enable a sintering temperature higher than the diamond oxidation temperature of around 700 °C.

Different furnace types are used depending on application and batch size. Continuous furnaces, also called tunnel furnaces or traveling kiln, are often used for the mass production of conventional grinding wheels and can be 70 m long. Periodic hood-type furnaces are used for smaller batch sizes. In general, about 80 % of the inner furnace volume can be used for producing products. Additional accessories enable special gas atmospheres in the furnace or pressure

control. Furnaces are heated by electrical energy, with gas or oil [6]. Gas furnaces are typically less expensive but they cannot be used for all processes.

The temperature distribution is not constant along the furnace cross-section. Temperature fluctuations inside the furnace should not exceed ± 10 °C. A smaller range enhances process capability. Tool properties can depend on their position within the kiln [40].

The temperature curve has to be controlled precisely. The rate of heating, peak temperature, and isothermal soaking time define the grinding wheel properties [30]. The temperature profile consists of a heating, soaking and cooling phase. The total time can be 100 h [8]. For example, corundum wheels in a tunnel furnace are heated up to 1260 °C over 1 to 2 days, held for about 12 hours at the maximum temperature, then slowly cooled down [36]. The cooling process has to be carefully controlled to avoid thermal stresses or cracking of the wheels [36]. The cooling process can take weeks for very large wheels [36].

3.2.6 Frits

Frit is a generic term for a material that is generated by blending minerals, oxides, and other inorganic compounds, heating to at least melting temperature, cooling, and pulverizing [41]. An example frit production process is given as follows: Melting of the ingredients above 1,150 °C, holding at the temperature for 4 h, water quenching, crushing, and pulverizing of the material.

Frits for the manufacturing of grinding wheels consist commonly of boron silicates or magnesium glass [32]. In addition, frits also contain TiO_2 , feldspar, borax, quartz, soda ash, red lead, zinc oxide, whiting, antimony trioxide, sodium silicofluoride, flint, cryolite, and boric acid [41]. In producing grinding tools, frits act as flux agents and change the properties of the

vitrified bond, for example by lowering the sintering temperature [28].

3.2.7 Flux agents

In addition to frits, siliceous clay with low melting point is considered as 'flux agent' and minimizes the surface tension at the interface between bond and abrasive grit [39]. Lithium for example is one of the most expensive flux agents, but can decrease softening and melting point, viscosity, as well as heat expansion coefficient [32].

3.2.8 Porosity builders

In vitrified bonded wheels, the natural packing of the abrasive particles leaves certain porosity [42]. Additional pore builders produce higher porosity when they sublime or burn off during the sintering process. Pore builders are typically either hollow particles or fugitive materials [13]. Hollow particles such as hollow ball corundum, glass beads, or mullite maintain a stronger wheel structure [13]. Conventional fugitive pore builders include nut shell powder, sugar, starches, polymeric materials, plastic granulate, naphthalene, wax balls, etc. [38,42]. Fugitive pore formers allow flexible pore shapes and sizes [13].

Naphthalene is a fugitive pore builder, which boils at 218 °C [43]. Because naphthalene is regarded as carcinogenic, tool manufacturers attempt to substitute it with natural components, supercritical CO₂, liquid CO₂, or other materials [42,43].

Other substances that build pores during the tool production are often organic such as wood shavings and salt. Variations in pore distribution can lead to non-uniform tool shrinkage in the manufacturing process, especially for tools produced at high temperatures. This is a result of two factors. First, the effective thermal expansion coefficient of a composite body depends on the relative contents of the various components. Second, denser zones with fewer

pores undergo a more thorough sintering action with stronger contraction. [44]

3.2.9 Finishing

Superabrasive tools are produced in segments and rings which are connected to a wheel body. Conventional grinding wheels are machined to achieve the final dimensions and tolerances.

4 Metallic Multi-layer Bonds

Metallic bonds are either multi-layered (produced by sintering or infiltration) or single-layered (produced by electroplating or brazing) [13]. They are only applied to superabrasive grits because conventional grits wear too quickly to use the bonding strength to full capacity.

Metallic bonds provide high grit retention and low wear during grinding. However, a copper bonding might smear during grinding. Metallic bonds can have very low porosity, so that fillers in the bond are added for lubrication during grinding.

Metallic bonded tools are difficult to condition mechanically [45]. Electro physical and electro chemical processes can be applied due to the electrical conductivity of the metallic bond and are used in many different set-ups [45].

4.1 Chemistry and Types of Metallic Bonds for Multi-layer Abrasive Tools

Metallic multi-layered bonds consist of various alloys such as copper/tin-bronze (Cu/Sn), cobalt-bronze (Co/Cu), tungsten carbides (W/WC) or alloys from the iron-copper-tin-system (Fe/Cu/Sn) [6,7]. Common Cu/Sn alloys have a ratio of 85:15 or 80:20 Cu to Sn with fillers and additional alloys [13]. The binder needs to have good wettability for the abrasive grits.

Iron and alloys with iron content may cause undesired reactions with diamond grits due to the iron's affinity for carbon [7]. Besides high wear resistance and toughness, tungsten builds an advantageous, small interface layer of

tungsten carbide with the diamond grits [7]. Therefore, the bond retention is not only mechanical but also chemical. Moreover, auxiliary metal powders on the basis of cobalt, nickel, copper, iron, and mixtures of copper-nickel-zinc, copper-zinc and copper-manganese optimize bond retention [7].

As discussed, metallic bonds have strong grit retention and are wear resistant against the chips of brittle, short-chipping materials. The high hardness becomes a disadvantage in tool conditioning. Nevertheless, metallic bonds can be modified to be brittle and dressable, for example by increasing the Tin (Sn) content or adding Silver (Ag) embrittles bronze bonding [13].

4.2 Manufacturing of Metallic Bonds by Infiltration

Metallic bonding by infiltration is used mainly for dressing rollers and special applications [6]. Infiltrated bonds are also used for superhard honing sticks (bronze, Cobalt-bonding), stone drilling crowns, or saws.

Grits, bond material, and fillers are either mixed and filled into the die or the grits are first fixed onto the bottom of the die and the matrix powder is added afterwards (**Fig. 6**). A defined amount of hard solder and flux (often copper, nickel or zinc alloys) is added. Finally, the die form is heated in continuous ovens with inert gas or by induction [7,46]. The solder has a relatively low melting point. Therefore, the molten solder penetrates the matrix powder by capillary forces. The resulting matrix is strong and highly wear-resistant [46]. The tool body can be connected to the abrasive layer simultaneously by brazing. Subsequent to the heating process, pressure can be applied to further influence the tool characteristics [7].

Fig. 6 Manufacturing of metal bonded tools by infiltration after [6], [7], [46]

4.3 Manufacturing of Metallic Bonds by Sintering

Sintered bonds are produced by mixing of metal powder and abrasive grits, molding, either hot pressing or cold pressing, and sintering (**Fig. 7**). In exceptional cases, the metallic powder is mixed with an organic binder (paraffin oil and / or wax granule). This binder helps to produce a green compact, which can be handled, and vaporizes in the sintering process [7]. The binder also leaves pore space, which might be infiltrated with a soldering agent.

Fig. 7 Manufacturing of sintered metal bonded tools after [6] [7]

In the cold pressing method, the green compact is taken out and sintered in a melting oven under inert gas atmosphere [7]. Sintering takes place with or without form [7]. Iron or steel compacts are sintered at 1,100 °C [47]. Bronze bondings are easy to process and press and are sintered at temperatures between 500 - 700°C.

In the hot pressing method, the mixture is compressed under additional heat directly in the graphite form. Three heating types, namely inductive heating, indirect, and direct resistance heating can be used in hot pressing [48].

5 Metallic Single-layer Bonds

For tools with just one single layer of abrasive grits, tool life can be a major determining factor and is impacted by grit strength. Electroplated grits are held mechanically, brazed grits are held mechanically and chemically.

5.1 Chemistry and Types of Metallic Bonds

Single layer metallic bonds have a layer height of only the average grit size and a high grit protrusion of 20 - 70 % of the grit diameter. Because of the high grit performance, single layered wheels are limited to superabrasives.

The metallic single-layer bonds are produced by electroplating, brazing, or electroless plating.

5.2 Manufacturing of Metallic Bonds by Electroplating

Electroplating is based on the cathodic metal deposition from a watery electrolyte. A metallic layer can only be deposited on a workpiece, if there are enough electrons to discharge the metal ions within the watery solution. Depending on the origin of the electrons, a distinction is drawn between chemical metal deposition (without external voltage source) and electrochemical metal deposition (with external voltage source). [49]

Fig. 8 Manufacturing of electroplated tools

The tool body is covered with superabrasive grits and placed into the electrolytic bath [6] (**Fig. 8**). The area to be coated needs to be surrounded by a sufficient amount of grits, which can present a big amount of fixed capital [17]. The bath consists of a watery solution of metal salts from the deposited metal, such as Ag, Co, Cu, Ni, Au salts [50,51]. In general, the anode consists of the bond material and the tool body acts as cathode. The direct current (DC) voltage leads to precipitation of Ni at the tool body. After the initial bonding of the grits, the excessive grits are removed and the process is continued until the desired plating depth is reached [6]. The first bonding phase needs a motionless bath; the second phase of layer growth can work with higher power and bath circulation [49]. The plating depth leaves about 50 % of the grit exposed (**Fig. 9**) [5].

Fig. 9 Structure of an electroplated layer after [5]

5.3 Manufacturing of Metallic Bonds by Brazing

Brazing is a soldering process at higher temperatures. Because the grits are held mechanically and chemically in the bond, grit exposure can be higher than for electroplated wheels leading to bigger chip space (**Fig. 10**) [5]. Chemically bonded grits allow for even thinner bonding layers than electroplated grits [52]. This has advantages of higher chip storage space and achievable material removal rate.

Fig. 10 Structure of a brazed layer after [5,53]

The wheel body material acts as substrate for the brazing process and has to be cleaned before brazing [53]. The solder, also known as braze material, is deposited on the body (**Fig. 11**). This can be done by spreading the solder as powder. The abrasive grits are either deposited along with the solder or fixed temporarily before the brazing takes place. Brazing is done at temperatures of up to 1,000 °C; the solder builds up around the grits and puts them under tensile stress when cooling [5]. The mechanisms within the brazing process include complex steps, such as dissolution of the substrate, diffusion of elements, formation of reaction products, and wetting phenomena [53].

Fig. 11 Manufacturing of brazed bonded tools after [53,52]

6 More bond types

6.1 Rubber bonds

Rubber bonds are another type of organic bonds [14]. Rubber bonds were once prominent for grinding of bearings and cutting tools, but today are mainly used for cut-off wheels and control wheels in centerless grinding [36]. Rubber bonded tools are manufactured by mixing of

grits with synthetic rubber or vulcanized natural rubber and sulphur, then rolled into sheets with the required thickness, and cutting out the desired shape (**Fig. 12**). Thin wheels are then directly vulcanized under pressure at 150 - 275 °C. In the case of thick wheels, the sheets are first stacked to the final wheel width and then vulcanized [36].

Fig. 12 Manufacturing of rubber bonded tools after [6]

6.2 Hybrid bonds

Hybrid bonds of a resin and a metallic phase are generally used for superabrasive tools [54]. The metallic phase can be either a filler or a binding component to enhance grit retention depending on specification or manufacturing conditions [17]. In the 1970s, a hybrid bond from interpenetrating bronze and epoxy resin was invented and is used for the grinding of carbide cutting tools [54,55]. The porous metal bond is manufactured by cold pressing and sintering; the resin component is vacuum casted to infiltrate the pores [54,55]. Another composition of a hybrid bonding consists of bronze and polyimide phases [54].

7 Discussion

7.1 Economic sustainability

The type of bonding is commonly determined by tool application and technological performance and not so much by tool price. Nevertheless, the costs for a grinding or honing tool are mainly impacted by the costs of the ingredients and costs of processing. The ingredient prices result from raw material extraction and material processing. For example, many raw materials in vitrified bonding systems are still obtained from natural resources because of the lower price, although synthetic materials ensure better constant quality [32].

The heat treatment processes in tool manufacturing are major cost factors within processing costs. Different heat treatment processes use different temperatures and processing times and therefore the energy demand varies. For example, resin bonds might be cured for 24 h at a maximum temperature of 190 °C, whereas vitrified bonds are processed for up to 100 h and maximum temperatures up to 1,250 °C [8].

7.2 Environmental and social sustainability

Bond ingredients might be health endangering, such as Li, CaO, B₂O₃ in vitrified bonds or heavy metals in metallic bonds [43]. Workers need to be protected during handling of potentially dangerous material. However, substituting these risky ingredients might reduce the residuals intensity and direct hazards from these materials, but indirectly this might lead to higher tool manufacturing costs.

Pore builders are important fillers in bonded grinding tools. The prominent chemical naphthalene is hazardous to workers and the environment. Ongoing attempts to substitute naphthalene, e.g. with renewable material, indicate the problem to find a solution with technological similar results [42].

Particulate matter (PM) might occur from handling of loose abrasive grits and bond components [56]. Heat treatment processes such as curing of resin bonded tools or sintering of vitrified bonded tools emit the main emissions in grinding tool production, in particular volatile organic compounds (VOC) or products of combustion, such as CO, CO₂, NO_x, SO_x, and PM [56].

During the manufacturing of resin bonded tools, emissions form from formaldehyde and phenol. These emissions can be reduced to follow air standards by thermal after-burning [9]. However, investment and energy costs for the after-burning systems are relatively high and not

feasible for small and medium sized companies, who will likely use absorption methods with activated-carbon filters [9].

Likewise, the electrolytic baths in producing single layer metal bonded tools need to be maintained carefully to keep workers and local communities safe.

8 Conclusion

The life cycle of abrasive tools depends largely on the bonding type. Resin, vitrified and metallic multi-layer bonds have common processing steps such as mixing, molding, pressing, heat treatment, and post-processing, but manufacturing times and ingredient costs can differ considerably. For any formal Life Cycle Assessment of grinding or honing tools, all steps and materials need to be considered and monitored. This paper provides a comprehensive overview on the different bonding systems and affiliated tool manufacturing processes. Specific details are however the manufacturers' expertise.

Future studies should try to integrate life cycle costs, social and environmental life cycle assessments.

9 References

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Fig. 1

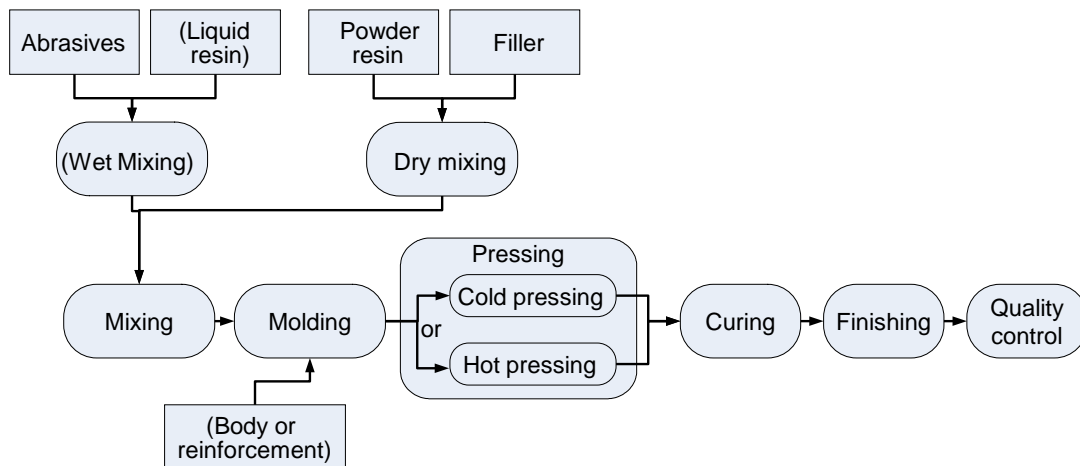


Fig. 2

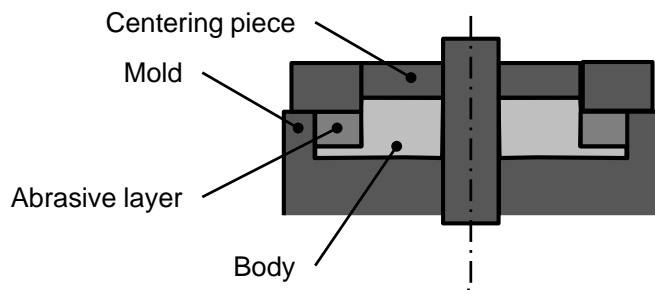


Fig. 3

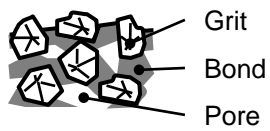


Fig. 4

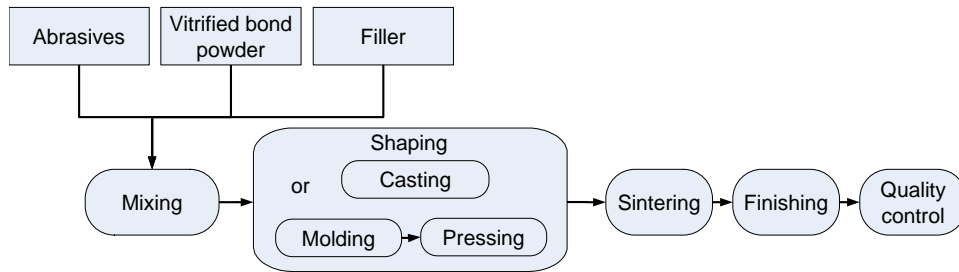


Fig. 5

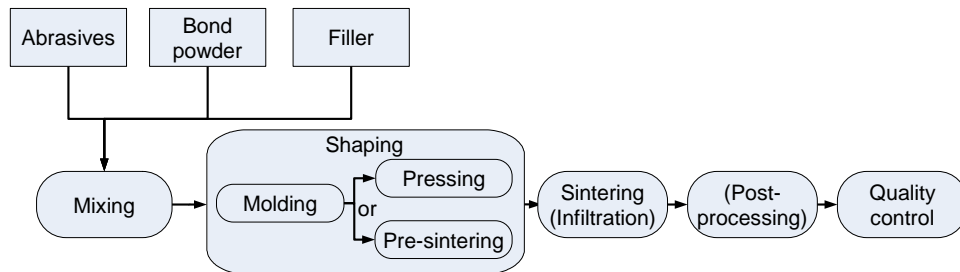


Fig. 6

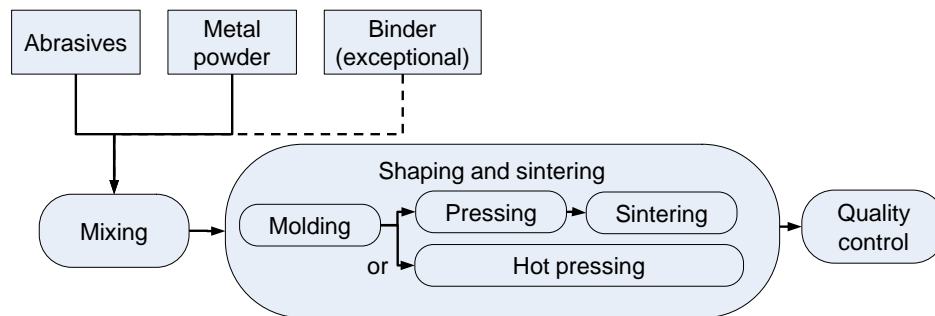


Fig. 7

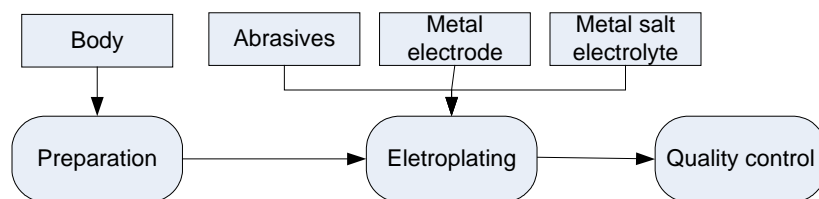


Fig. 8

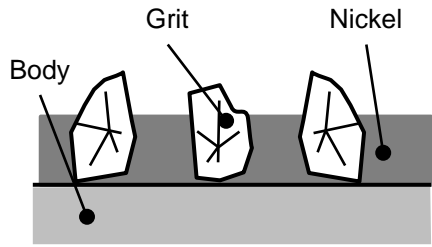


Fig. 9

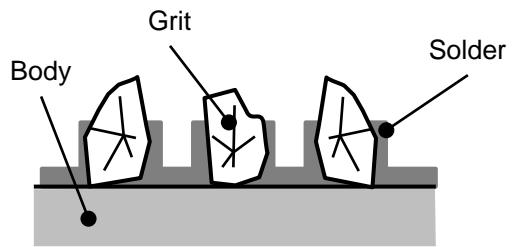


Fig. 10

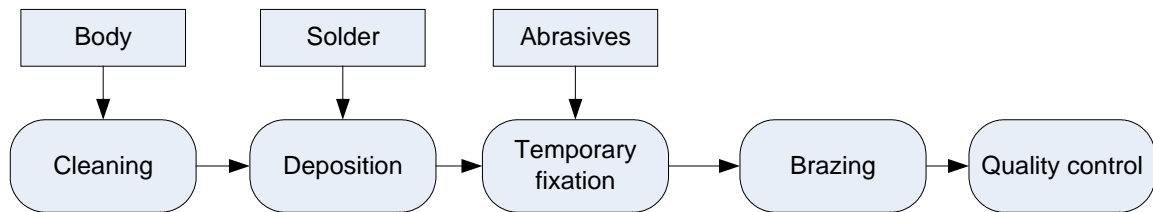


Fig. 11

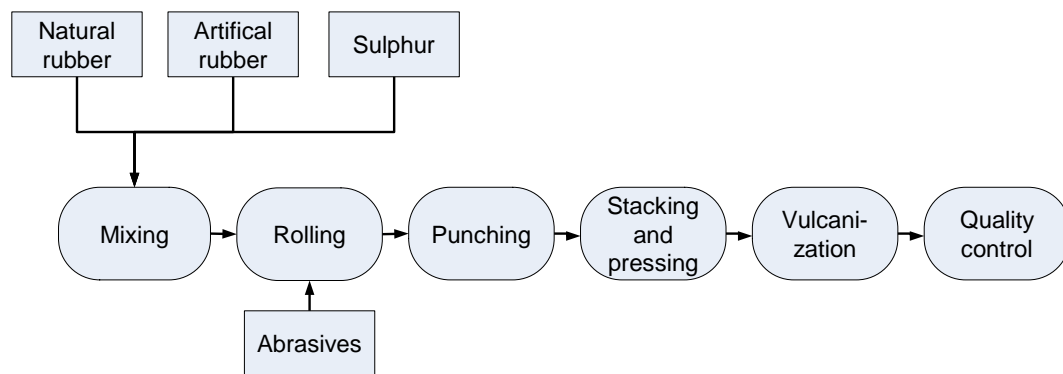


Fig. 12