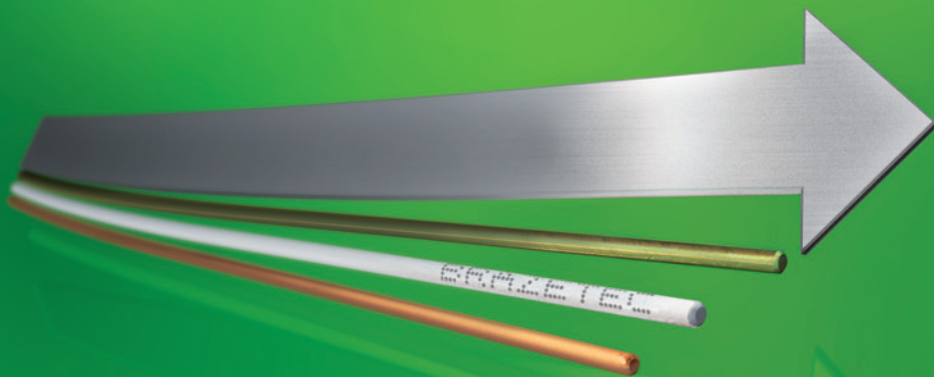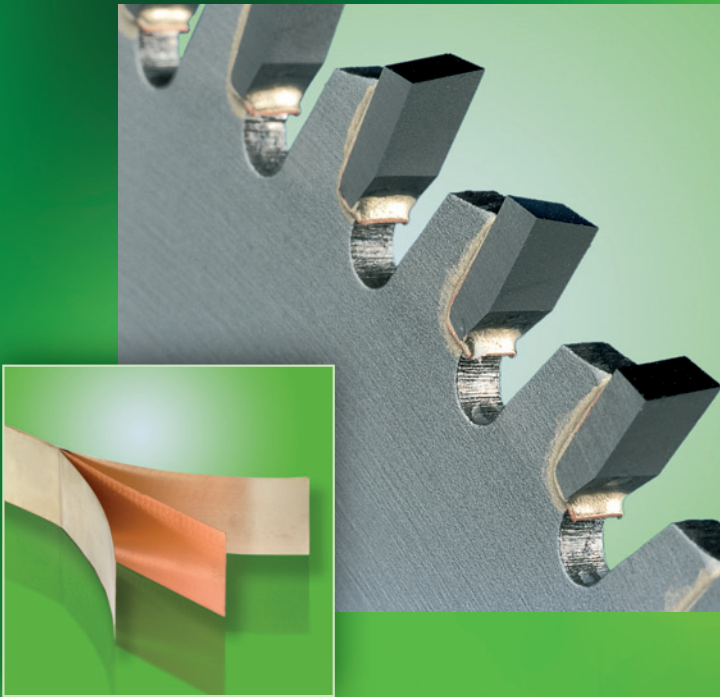# Brazing in the Tool Manufacturing Industry

Brazing is **BrazeTec**

Brazing is **BrazeTec**

Brazing in the
Tool Manufacturing Industry

by
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1. Introduction

Tools are used to make parts or components from various materials. Apart from hand tools such as hammers or files and forming tools for forging or casting, the majority of tools used for technical machining or separating processes are cutting tools. A distinction is made between milling, drilling, turning, grinding and other tools.

A common practice used to extend the life and, thus, the economic efficiency of a cutting tool is to apply a hard and wear-resistant cutting material to a substrate. Depending on the intended area of application and use, a cutting edge can be made of various materials ranging from carbides and diamonds to cubic boron nitride and ceramic materials. In any case, the quality of the tool largely depends on how well the cutting material is attached to the substrate. Brazing is one of the key bonding technologies because it produces excellent and highly rigid connections [1] the most stable of which are obtained by brazing with alloys at liquidus temperatures above 450 °C in conformity with DIN ISO 857-2. Various filler metals, fluxes and methods are available for brazing. In order to produce final products that meet strict quality requirements, all of these process materials need to be used in a consistent manner.

2. Basics for brazing tools

Thermal stress, induced during the joining process, should be reduced as much as possible.

2.1 Cutting materials

Generally speaking, cutting materials are materials whose properties enable the separating and machining of specific other materials.

Figure 1 shows that, in real life, most hard materials while being very hard have little ductility. The area of use thus sets physical limits beyond which a specific hard material is no longer suitable for a specific tool. Whereas diamonds, for example, are extremely hard and able to cut every other material, their relative brittleness makes them sensitive to impact which drastically restricts their practical use for wood working and other machining tasks. For example,

stones trapped in the wet wood areas of tree trunks and the like would splinter diamonds. Cemented carbides were developed to combine the positive properties of their carbide and metal components are a lot more appropriate for this kind of application. Their carbide phase provides hardness and resistance to wear, while their metal binder phase adds ductility and toughness.

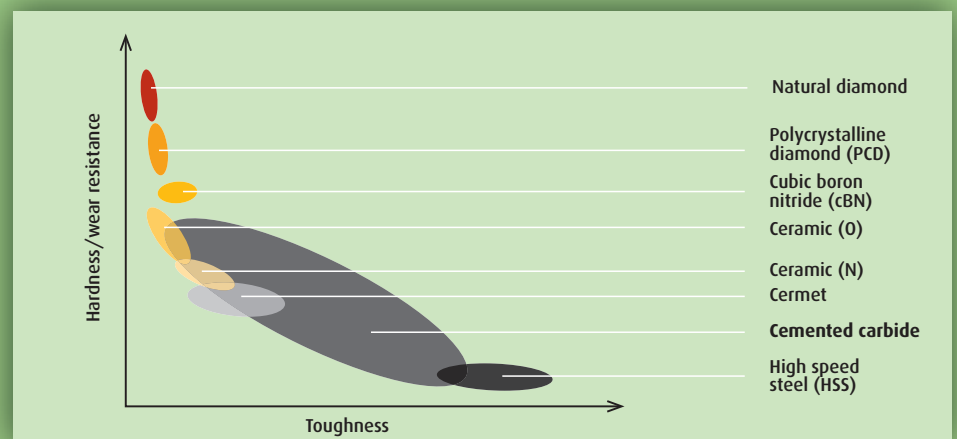**Figure 1 |** Hardness/wear resistance and ductility of some hard materials [2]

Natural diamond

Polycrystalline diamond (PCD)

Cubic boron nitride (cBN)

Ceramic (O)

Ceramic (N)
Cermet

Cemented carbide

High speed steel (HSS)

Hardness/wear resistance

Toughness

Table 1 | Code letters according to DIN ISO 513 [3] for the different groups of materials

Hard material	Code letters	Material group
Cemented carbides (carbides)	HW	Uncoated cemented carbide, main constituent: tungsten carbide (WC), grain size ≥ 1 µm
	HF	Uncoated cemented carbide, main constituent: tungsten carbide (WC), grain size < 1 µm
	HT (Cermets)	Uncoated cemented carbide main constituent: titanium carbide (TiC) or titanium nitride (TiN) or both
	HC	Cemented carbides as before but coated
Cutting ceramics	CA	Material group
	CR	Cutting ceramics, main constituent: aluminium oxide
	CM	Cutting ceramics, main constituent: aluminium oxide, reinforced
	CN	Cutting ceramics, main constituent: aluminium oxide plus other oxide constituents
	CC	Silicon nitride ceramics, main constituent: silicon nitride
Diamond	DM	Cutting ceramics as before but coated
	DD	Material group
	DP	Monocrystalline diamond
Boron nitride	BL	Polycrystalline diamond without binder
	BH	Polycrystalline diamond with binder
	BC	Material group

Table 2 | Composition of selected steels [4]

Tool steel	1.6582 (34CrNiMo6)		1.2003 (75Cr1)		1.2235 (80CrV)		1.8159 (51CrV4)	
Application	Hammer drills		Saw blades		Saw blades		Saw blades	
Element	min. in %	max. in %	min. in %	max. in %	min. in %	max. in %	min. in %	max. in %
Fe	rest	rest	rest	rest	rest	rest	rest	rest
C	0.30	0.38	0.70	0.80	0.75	0.85	0.47	0.55
Si	0.00	0.30	0.25	0.50	0.15	0.35	0.00	0.40
Mn	0.50	0.80	0.60	0.80	0.30	0.50	0.70	1.10
P	0.000	0.025	0.000	0.03	0.000	0.025	0.000	0.035
S	0.00	0.025	0.000	0.03	0.000	0.025	0.000	0.035
Cr	1.30	1.70	0.30	0.40	0.40	0.60	0.90	1.20
Ni	1.30	1.70	–	–	–	–	–	–
Mo	0.15	0.30	–	–	0.00	0.10	–	–
V	–	–	–	–	0.15	0.25	0.10	0.25

Standard DIN ISO 513 [3] is one of the references that classifies cutting materials for metal machining and other processes. It assigns letter codes which clearly identify all common hard materials. **Table 1** summarises the code letters of cemented carbides, cutting ceramics, diamond and boron nitride. The standard adds detail to the description by specifying the main machining category (P: steel, M: stainless steel, K: cast iron, N: non-ferrous metals, S: special alloys and titanium, H: hard materials) and the application category (01, 05, 10,... 50 (01: high wear resistance; 50: high toughness)), e.g. HW-P10 or HC-K20.

2.2 Steel qualities

The cutting materials are normally brazed onto steels of various qualities. **Table 2** summarises four examples of low-alloy tool steels used in carbide-tipped saw blades. The commonly used qualities support the assumption that they are generally fit to be brazed. In case higher-alloy steel grades are chosen, their wetting ability may be improved by modifying the brazing flux. Note that the steels are often tougher than the cutting materials brazed to them. This and the different coefficients of thermal expansion should be taken into account when designing the component to be brazed and when choosing the most suitable alloy.

2.3 Joining challenges

A major challenge of joining cutting materials to steels is the thermally induced tensions in the joint area which are often responsible for premature failure. They are due to the different coefficients of thermal expansion of the joined materials as shown in **table 3**. On cooling, once the filler metal has set, the two materials are rigidly linked to one another. As the temperature lowers, steel and cutting material will contract at different rates but since they are joined together, they are not able to shrink. The steel being prevented from contracting will produce tensile stress along the joining area. The cutting material will not contract as much and be buckled instead which leads to compressive stress. It will also be exposed to some bending stress which may provoke increased tensile stress on the cutting material's surface and ensuing cracks. The amount of thermally induced tensions can be assessed for every material combination by calculating the elastic modulus, the coefficient of thermal expansion, the thickness of parts, and the solidus temperature. Refer to **section 4.1.2** for an example [5].

Table 3 | Coefficient of thermal expansion of various tool materials

Tool material	Coefficient of thermal expansion in $10^{-6}K^{-1}$
Cemented carbide	5 – 7
Oxide ceramics	6 – 13
Cermet	7 – 10
Diamond	2 – 4
Boron nitride	5
Low-alloy steel	11 – 14

3. Brazing filler metals, fluxes and heating methods

In order to obtain a high-quality brazed connection, choose the brazing filler metals, brazing fluxes and heating methods matching the composition and geometry of the tool to be brazed as well as the conditions of its later use.

Table 4 | Brazing filler metal groups, primary and secondary alloy elements; bold print marks the groups used for the brazing of tools [6]

Brazing filler metal group	Main elements	Side elements
Silver	**Ag, Cu, Zn, Sn**	**Mn, Ni, Si**
Copper	**Cu, Sn, Zn, Si, Mn, Ni**	**Ag, Cu_2O, Fe, P**
Nickel	**Ni, Cr, B, P, Si**	**C, Co, Cu, Fe, Mo, Nb, W**
Aluminium	Al, Si, Cu, Zn	Bi, Fe, Mg, Ti
Magnesium	Mg	Be, Mn, Zn
Copper-Phosphorus	Cu, P, Ag, Sn	Ni, Sb, Si
Cobalt	Co, Cr, Ni, Si	B, W
Palladium	Pd, Ag, Cu	Mn, Ni, Co
Gold	Au, Cu, Ni, Pd	Ag, Co, Fe

Figure 3 | View of the layers of BrazeTec 49/Cu

3.1 Brazing filler metals

Their rigidity makes brazing filler metals the prime choice for the brazing of tools. The liquidus temperature is above 450 °C. You can generally choose from a large range of brazing filler metals depending on which metal elements they are based on. These groups are defined in DIN EN ISO 17672 [6] and other standards. **Table 4** summarises the primary and secondary alloy elements of the different brazing filler metal groups. Bold print marks the groups of silver, copper and nickel brazing filler metals used for the brazing of tools. Another group are the silver-/copper-based active brazing filler metals with titanium as the active element.
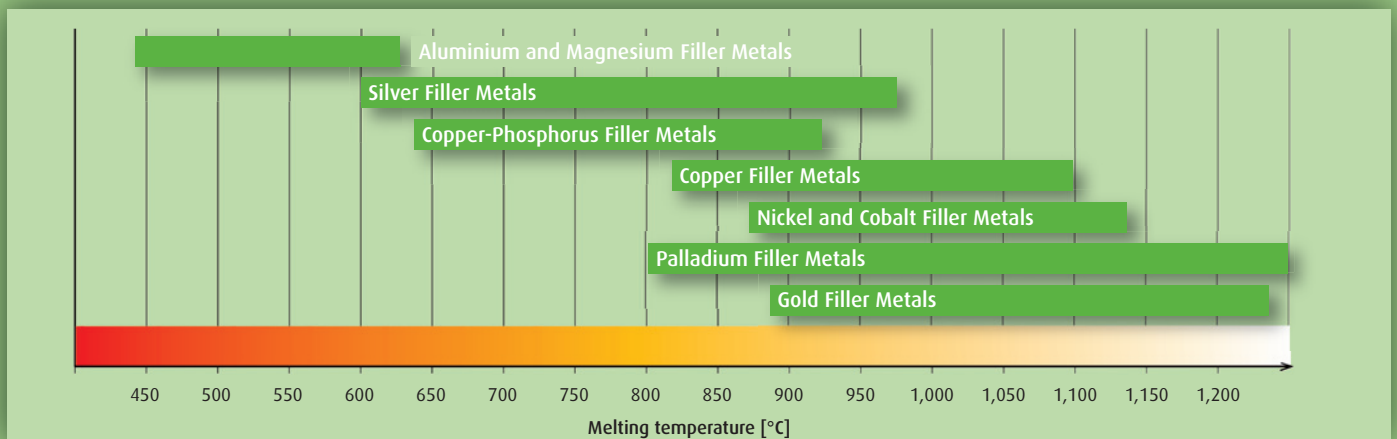
These are used for tools that, for example, ceramics, diamonds or cubic boron nitride (cBN) are to be joined to. **Figure 2** shows that, depending on their actual composition, the brazing filler metal groups have different liquidus temperatures which must be considered for both brazing and application.

3.1.1 Silver-based brazing filler metals

Silver-based brazing filler metals are characterised by their relatively low solidus temperature between 600 °C and 970 °C, according to DIN EN ISO 17672. Since this allows brazing temperatures to be lower, there is less thermal exposure on the base materials and a lower level of residual stress in the components. Apart from silver, these alloys often contain copper and zinc. Adding nickel and manganese improves the wetting of carbides and other quite wetting-resistant materials and it increases the rigidity. Sandwich brazing filler metals are a special kind of silver-based filler metals. They consist of a copper foil with filler metal on either side (**figure 3**). Owing to the copper's high ductility, all residual stress produced when cooling down can be consumed by plastic deformation [1]. Silver-based filler metals are generally applied in air, inductively or with flame and by adding fluxes.

Figure 2 | Brazing filler metal groups specified in DIN EN ISO 17672 [7]

Aluminium and Magnesium Filler Metals
Silver Filler Metals
Copper-Phosphorus Filler Metals
Copper Filler Metals
Nickel and Cobalt Filler Metals
Palladium Filler Metals
Gold Filler Metals

450 500 550 600 650 700 750 800 850 900 950 1,000 1,050 1,100 1,150 1,200

Melting temperature [°C]

3.1.2 Copper-based brazing filler metals

The group of copper-based brazing filler metals used for tool brazing is characterised by a solidus temperature between approx. 970 °C and approx. 1,100 °C, i.e. considerably above that of silver-based alloys. The thermally induced stress is correspondingly higher and may reduce the strength of the compound. These brazing filler metals are normally processed in reducing gas, inert gas atmospheres or in a vacuum. Adding nickel increases the rigidity of copper-based filler metals. Adding further manganese to copper will lower the brazing temperature and enhance the wetting properties of steels [8].

Another common practice is to add phosphorus (e.g. copper-(silver)-phosphorus brazing filler metals). These alloys melt at temperatures between 645 °C and 920 °C, i.e. at much lower temperatures than the above copper-based brazing filler metals. However, phosphorus alloys should not be used for brazing materials containing iron, nickel and other materials commonly used in the tool manufacturing industry, the reason being that diffusion occurring during brazing will produce e.g. iron phosphide phases mainly in the joining layer near to the base material containing iron. The result would be a brittle joint.

3.1.3 Nickel-based brazing filler metals

Pure nickel is hardly ever used for brazing because its melting point is very high. As opposed to that, nickel-based brazing filler metals containing elements such as boron, phosphorus and silicon are commonly used because they make up eutectics that melt at relatively low temperatures. Adding chromium and other elements produces highly rigid nickel-based brazing filler metals both at room and high temperatures. They are also oxidation-proof and non-corroding. These alloys are processed in dry inert gas atmospheres or in a vacuum. Alloyed to nickel and chromium, the added semi-metals produce intermetallic hard phases which make comparatively brittle joints with these brazing filler metals. In many cases, brazing is therefore followed by heat treating the brazed components in order to make the connection tougher by diffusing the semi-metals out of the brazed seam [8]. Since the brittleness of the initial alloy prevents the application of conventional brazing foils, the use of nickel-based brazing filler metal pastes is common.

3.1.4 Active brazing filler metals

Active brazing filler metals have been developed to enable single-stage methods not involving pre-metallising for wetting and then brazing non-metal, inorganic materials, i.e. diamonds, cBN, ceramics and the like. Active brazing filler metals are normally based on a silver-copper system containing surface-active elements such as titanium, zirconium, niobium or hafnium. The industry in general and the tool manufacturing industry in particular most commonly use brazing filler metals containing titanium. The surface-active elements react to the non-metal material, allowing the remaining brazing filler metal to build up a wettable reactive surface. Even in alloys with a comparatively

Table 5 | BrazeTec fluxes for the tool manufacturing industry [18]

Flux	DIN EN 1045	Colour	Comments	Effective temperature range approx. [°C]
BrazeTec h 80	FH 10	white	For large surface and short brazing cycle; excellent flow properties	550 – 850
BrazeTec h 280	FH 10	white	Stabilised by binder for automatic application; for Co/Ni-coated cemented carbides	520 – 850
BrazeTec special h	FH 12	brown	Paste; general-purpose agent for brazing cemented carbides; very long duration of action, good flow properties	520 – 1,030
BrazeTec h 285	FH 12	brown	Stabilised by binder for automatic application	520 – 910
BrazeTec h 90	FH 12	brown	Powder; chemically activated for brazing cemented carbides that do not wet easily (TiC; TaC; low metal content)	520 – 850
BrazeTec h 900	FH 12	brown	Stabilised by binder for automatic application	520 – 850
BrazeTec special s	FH 20	brown	Paste; for high brazing temperatures	650 – 1,050

low melting point, this reaction will only start at brazing temperatures of about 850 °C [9] but temperatures of approx. 1,050 °C are no exception, depending on the material that the active brazing filler metal is linked to. Note that active brazing filler metals with a low titanium content will hardly flow and normally wet the base material only in places where they have been applied as a foil or paste prior to brazing.

3.2 Fluxes

Fluxes are inorganic salt mixtures whose job is to remove and prevent the building up of new oxide layers on the brazing surface. This requires them to be liquid at the relevant temperatures, to spread well across the base or brazing material, and to be easily displaced by the liquid filler metal. DIN EN 1045 [10] lists the fluxes suitable for brazing. It distinguishes fluxes of class FH used for the brazing of heavy metals (steels, stainless steels, copper and copper alloys, nickel and nickel alloys, precious metals, molybdenum and tungsten) from fluxes of class FL used for brazing aluminium and aluminium alloys.

Note that these agents often contain hygroscopic boron and/or fluorine compounds which need to be removed after brazing because of their corrosive nature. All fluxes listed in **table 5** for the brazing of heavy and specifically cemented carbides are corrosive. In rare exceptional cases, type FH 21 fluxes are used to braze tools. This type of agent is generally not corrosive such that it may stay on the brazed component. The brown fluxes of group FH 12 contain pure boron which has particular benefits for the brazing of cemented carbides. Automatically dispensing the flux is best achieved by means of fluxes such as BrazeTec h 280 paste, BrazeTec h 285 paste or BrazeTec h 900 paste which are stabilised with a binder.

3.3 Heating processes

The main heating methods used for the brazing of tools are induction, flame and furnace. Various criteria are available to help choose the most suitable. They include the heating speed, locality and homogeneity or the adjustability of the temperature profile. The heating speed depends on how the power is transferred to the component and other factors. Power transfer varies greatly with the method of heating as shown in **table 6**.

3.3.1 Induction brazing

Table 6 shows that heating something by induction transfers a lot of energy without coming into contact with the component.

Its major advantage is that it enables short process times because the heat is generated immediately inside the component without any need for actually transferring it. Since heating can be restricted to certain spots, it also prevents the warping of larger components. Note that only the immediate area surrounded by the inductor will be heated. This method yields highly repeatable results in identical components. When brazing compounds of dissimilar materials such as steel/cemented carbide compounds, the different materials will respond to a different degree such that they will not heat up at the same speed. Adapting the process (e.g. by inductor design, inductor position or process time) is the best way of taking account of this.

Table 6 | Power transfer under various methods of heating [11]

Method of heating	Supported power transfer [W/cm²]
Convection	0.5
Radiant heat	8
Conduction	20
Torch flame	1,000
Induction	30,000
Laser (CO2)	100,000,000
Electron beam	10,000,000,000

Figure 4 shows an inductor whose alternating electromagnetic field induces high eddy currents, I, into the component. Electric resistance, R, heats the components over the time, t, by the heat quantity, Q, in accordance with Joule's law:

$$Q = R * I^2 * t$$

The material's electric resistance, R, determines the heating speed.

Also note the skin effect generates higher-frequency alternating currents mainly on the surface of the conductive component. Further heat permeates towards the centre of the component. The heated surface area will be narrowed down with increasing frequency of the alternating field. Use the following equation to assess the effect:

$$d = V * f^{-\frac{1}{2}}$$

Where:

d: heated area

f: frequency [Hz]

V: variable representing the material's magnetic properties varying with the material and temperature (e.g. V = 0.17 in cold steel, V = 6.0 in hot steel > 800 °C, V = 1.8 for cemented carbide WC-4Co) [12].

Example:

An alternating field of a frequency of 50 Hz will heat an 800 °C steel sample about 90 mm deep. This depth reduces to about 0.65 mm at a frequency of 1 MHz [12].

The above equation suggests that the factor for steel (and other ferromagnetic materials such as cobalt or nickel) will change when the temperature rises above around 800 °C, the reason being the Curie temperature at which the base material's state changes from ferromagnetic to paramagnetic. Above this temperature, the material in question will be solely paramagnetic.

3.3.2 Flame brazing

Flame brazing involves a neutral or slightly reducing flame [13] set such that it heats the joining area to brazing temperature within the effective time of the brazing flux [7]. To ensure that larger components heat up homogeneously, a multi-flame burner may be used and its position varied [12]. This method has advantages over the induction brazing of steel/cemented carbide compounds because it directly heats the cemented carbide instead of relying on the indirect heat transferred by other metallic

material. It is faster than furnace brazing and may also be applied to localised spots. Remember, though, that the heated area is larger than that exposed to induction.

3.3.3 Furnace brazing

In electrically operated furnaces, the components are mainly heated by radiant heat but also by convection and conduction. **Table 6** illustrates that furnace heating transfers less heat than an open flame or induction such that furnace processes take longer. The advantage of furnace brazing is that the evenly arranged radiator elements distribute the temperature homogeneously and that the atmosphere (vacuum or inert gas) can be controlled. It also facilitates the monitoring and control of the process parameters and allows the brazing of many components in a single cycle.

Another fact to consider is that some brazing filler metal groups are not suitable for furnace applications because of the elevated vapour pressures of the alloy components (e.g. zinc) may lead to contamination depositing inside the furnace.

Figure 4 | Illustration of induction heating

Inductive heated component

Inductor
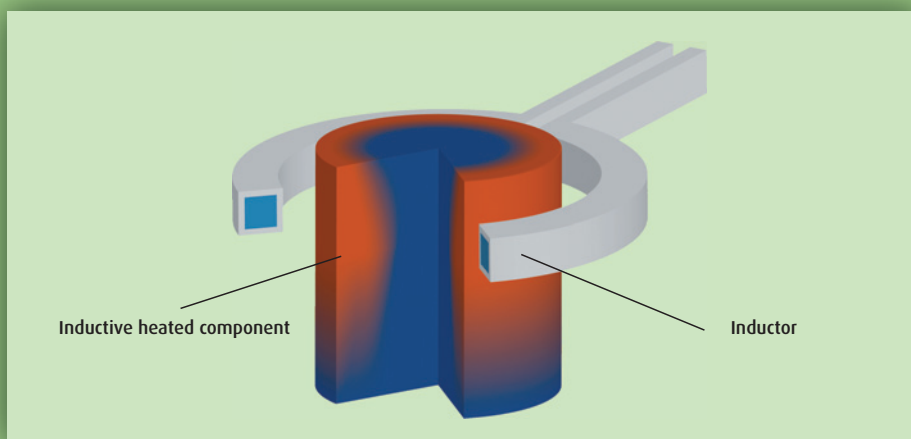
4. Brazing of different cutting materials

According to their properties cemented carbide, cermets, diamonds, cubic boron nitrides and ceramics have special requirements regarding the joining process and the selection of the brazing filler metals.

4.1 Cemented carbide

Cemented carbides are often used as cutting materials. Owing to their hardness and thermal strength, they are an excellent choice when it comes to milling, turning, drilling and sawing of metal, wood, plastic and other materials. As opposed to what their name suggests, cemented carbides do not consist of particularly 'cemented carbides' but they are sintered materials consisting of a hard phase (usually carbides) embedded in a metal binder. **Table 1** above shows that tungsten carbides are prevalent among the hard phases. Most binder matrices consist of cobalt and occasionally nickel and/or iron. Cemented carbides classify as P-type cemented carbides if some of the tungsten carbide is replaced with titanium, tantalum and/or niobium carbide. Cutting materials are called cermets if their hard phase is mainly made up of a titanium carbon nitride

embedded in a metal matrix. A cermet contains about 8% to 15% of metallic matrix, i.e. binder.

The performance of cemented carbide cutting faces largely depends on their composition and microstructure, e.g. the carbide grade it contains, the grain size and the binder content. The ideal microstructure of a cemented carbide consists of only two phases, i.e. the angular carbide and the binder. If the temperature rises too much, it may dissolve the original carbides and produce various complex carbides including the brittle η-phase. In order to improve their toughness, carbides of submicron grains have been developed by adding other carbides such as tantalum or niobium carbides. Various metals (cobalt, nickel, iron, chromium) may be added to the binder matrix. Of these,

nickel and chromium are particularly able to build up a passivating oxide layer on the surface and, thus, to improve the resistance to corrosion and oxidation [12] [15] [16].

Figure 5 shows an example of the influence of the tungsten carbide's cobalt content and grain size. In this example, the hardness is defined as the resistance another material must overcome to penetrate the sample. The bending strength describes the material's resistance to external loads and the associated tension and elongation. A material's fracture toughness is equivalent to its ability to resist crack expansion.

Sintered cemented carbide structures generally have grain sizes between 0.2 µm and 10 µm. Depending on the grade, the binder content may vary between about 2% and 30% [1] [17].

Figure 5 | Cemented carbide properties in relation to their cobalt content and the size of tungsten carbide grains [17]
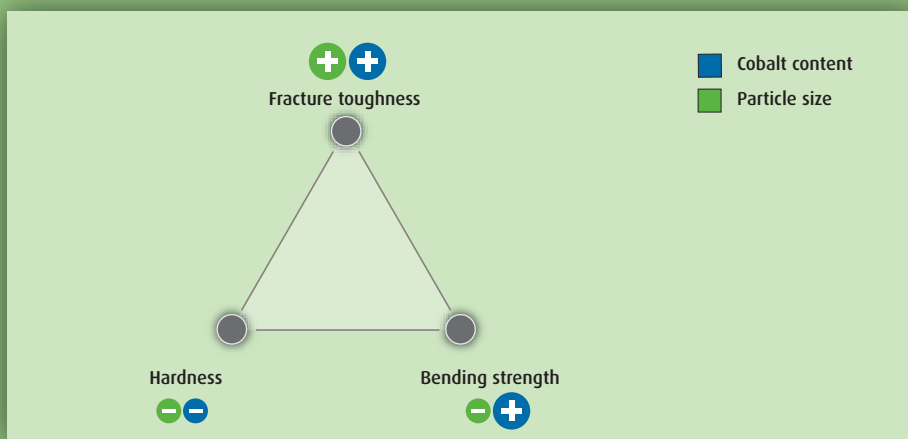
Figure 6 | Standard delivery forms of BrazeTec silver-based brazing filler metals

4.1.1 Brazing of cemented carbide and cermets

Owing to their high non-metal content, cemented carbides in general and cermets in particular are difficult to braze using conventional brazing filler metals. Controlling the brazing process must also aim to reduce metallurgic interaction between the metallic binder matrix and the carbide as well as the generation of thermally induced tension. In some cases, the cemented carbide surface is sandblasted to improve its wetting by the molten brazing filler metal. Coating the cemented carbide surface with a cobalt or nickel layer is another method of significantly improving its wettability. This method specifically applies to cemented carbides with a very low metal binder content. These metal coatings have another important

effect: they prevent oxidation when the cemented carbide heats up during the brazing process [18]. The majority of brazing filler metals for cemented carbides are silver-based as they have a relatively low melting point and may be processed without any specific fluxes or methods. Adding nickel and manganese often improves the wetting of carbides, specifically of carbides that do not wet well such as titanium carbide. Second to the silver-based brazing filler metals are some copper-based alloys [1] [12]. **Table 7** lists some examples. A special matter are sandwich brazing filler metals consisting of an interlayer of copper foil surounded on boths sides from brazing filler metal.

Silver-based brazing filler metals plus fluxes are usual processed by induction heating in normal atmosphere. While FH 10-type

general-purpose fluxes are the standard choice, special flux grades of type FH 12 to DIN EN 1045 may be used to address the needs of specific joining parameters [18]. Refer to **table 5** for details. Flame brazing is not very common. You are generally advised against using silver-based brazing filler metals in furnaces because process cycles are fairly long compared to induction brazing cycles and may cause the zinc to vaporise from the brazing filler metal. A good choice for furnace brazing is the zinc-free BrazeTec 6488 special brazing filler metal. Depending on the final quality of brazing, brazed connections produced with silver-based brazing filler metals may achieve a shear strength between about 150 MPa to 300 MPa [22].

Maganese alloyed copper brazing filler metals make up another group of alloys for the

Table 7 | Brazing filler metals for brazing cemented carbides [29]

Brazing filler metal	ISO 17672	Comment	Melting range ISO 17672 approx. [°C]	Melting range DSC [1] approx. [°C]	Brazing temp. approx. [°C]	Shear strength [2] [MPa]	Composition in weight-%					
							Ag	Cu	Zn	Mn	Ni	Else
BrazeTec 6488	–	Zn-free brazing filler metal; suitable for TiN coatings and stainless steel	–	730 – 780	770	> 150	64	26	–	2	2	6 In
BrazeTec 5081	Ag 450	Mn-free brazing filler metal	660 – 705	670 – 730	700	> 230	50	20	28	–	2	–
BrazeTec 4900	Ag 449	Most commonly used brazing filler metal, general-purpose brazing filler metal	680 – 705	680 – 705	690	> 250	49	16	23	7.5	4.5	–
BrazeTec 4900A	–	Wider melting range than BrazeTec 4900	–	670 – 720	710	> 240	49	27.5	20.5	2.5	0.5	–
BrazeTec 2700	Ag 427	Low Ag content, high brazing temperature	680 – 830	690 – 850	800	> 250	27	38	20	9.5	5.5	–
BrazeTec 21/80	Cu 595	Zn-free for furnace brazing	965 – 1,000	970 – 1,005	990	> 200	86	–	12	2	–	–
BrazeTec 21/68	–	Zn-free for furnace brazing	–	980 – 1,020	1,020	> 200	87	–	10	–	–	3 Co

1) Schnee, Wiehl, Starck 2014 [40]   2) Compound 1.2210 & K10; brazed area 8 x 8 mm; shear tester: Gerling GLFP

$$\Delta l_{St} = \alpha_{St} * L_{0,St} * \Delta T = 14 * 10^{-6} K^{-1} * 25 \text{ mm} * (680 - 20)K = 0.23 \text{ mm}$$

Formula 1 | Calculation of the elongation of steel at a solidus temperature of 680 °C (brazing filler metal)

$$\Delta l_{CC} = \alpha_{CC} * L_{0,CC} * \Delta T = 4.7 * 10^{-6} K^{-1} * 25 \text{ mm} * (680 - 20)K = 0.08 \text{ mm}$$

Formula 2 | Calculation of the elongation of cemented carbide at a solidus temperature of 680 °C (brazing filler metal)

brazing of cemented carbides. These brazing filler metals are used to produce large quantities of hammer or percussion drills, rock chisels and drills. Brazing is performed at approx. 1,000 °C. Since this brazing temperature is very high compared to that of the silver-based filler metal grades, brittle phases and high thermally induced tension in the compound can be avoided only by strict adherence to the brazing process parameters. These brazing filler metals are mainly used in inert gas or vacuum furnaces but can sometimes be used with induction heating.

4.1.2 Thermal effects and stresses

As mentioned in **section 2.3**, joining cutting materials to steel will generate high thermally induced stresses. They are due to the different coefficients of thermal expansion of the joined materials. Cemented carbide coefficients are between 5 and 7 · 10^{-6} K^{-1} while steel coefficients are between 11 and 14 · 10^{-6} K^{-1}, the consequence being that steel expands and contracts more than twice that of the cemented carbide. Use the following equation to calculate the expansion:

$$\Delta l = \alpha * l_0 * \Delta T$$

Where:

Δl: change in length

α: coefficient of linear thermal expansion

l_0: initial component length

ΔT: difference in temperature

Assuming a brazed compound of steel (1.8159) and a cemented carbide (K10) has an edge 25 mm long and is cooling down after brazing. At 680 °C (solidus temperature of silver-based brazing filler metal BrazeTec 4900), i.e. at the temperature at which the two materials are firmly joined, the elongation is calculated for steel with **formula 1** and for cemented carbide with **formula 2**.

Refer to **table 8** to find the elongations of these mating materials for different brazing filler metal systems and, thus, different solidus temperatures.

Table 8 | Elongation of base materials during joining

Material		Steel: 1.8159	Cemented carbide: K10	Difference between steel and cemented carbide
Dimension at room temperature	[mm]	25	25	0.0
Coefficient of expansion α (alpha)	[10^{-6}K^{-1}]	14	4.7	8.3
Dimension at $T_{Sol. \text{ BrazeTec } 4900}$ = 680 °C	[mm]	25.23	25.08	0.15
Dimension at $T_{Sol. \text{ BrazeTec } 21/68}$ = 980 °C	[mm]	25.34	25.11	0.23
Dimension at $T_{Sol. \text{ E-Cu } 58}$= 1,083 °C	[mm]	25.37	25.13	0.24

$$\frac{1}{R} = \frac{(\alpha_{St} - \alpha_{CC}) * \Delta T}{\frac{2}{h_{CC} + h_{St}} \frac{l_{CC}}{A_{CC}} \left(1 + \frac{l_{St} * E_{St}}{l_{CC} * E_{CC}}\right) \left(1 + \frac{A_{CC} * E_{CC}}{A_{St} * E_{St}}\right) + \frac{h_{CC} + h_{St}}{2}}$$

Formula 3 | Calculation of the bending of the compound

For as long as the two materials are not firmly adhered, as shown on the far left in **figure 7**, they are free to expand without building up tension. When the molten brazing filler metal deposited between them solidifies again, free expansion is no longer possible. Since the cemented carbide contracts less than the other material, a kind of bimetal effect transfers tensile stress through the steel and into the cemented carbide. Cemented carbides are known to be sensitive to tensile stress and the stress built up now may cause irreversible damage to the cemented carbide which may consequently, crack. Sooner or later, this will lead to a cemented carbide failure in operation [18]. A simulated cooling process of a steel/cemented carbide sample – see on the right

of **figure 7** – revealed that where more tension is generated on the upper side of the cemented carbide there is a greater risk of cracking.

By means of appropriate simplifying equations, the amount of tensile or compressive stress in this kind of compound can be approximately calculated. They are based on the bimetal effect of two base materials which are firmly connected to one another and assumed to behave perfectly elastically.

In accordance with **figure 8**, [20] and [21], the system under analysis is found to bend as follows:

The tensile or compressive stress in the layers equates as:

$$\frac{1}{R} = \frac{M_{CC}}{l_{CC} * E_{CC}} = \frac{M_{St}}{l_{St} * E_{St}}$$

and

$$F_{ax} = (M_{CC} + M_{St}) \frac{2}{h_{CC} + h_{St}}$$

into

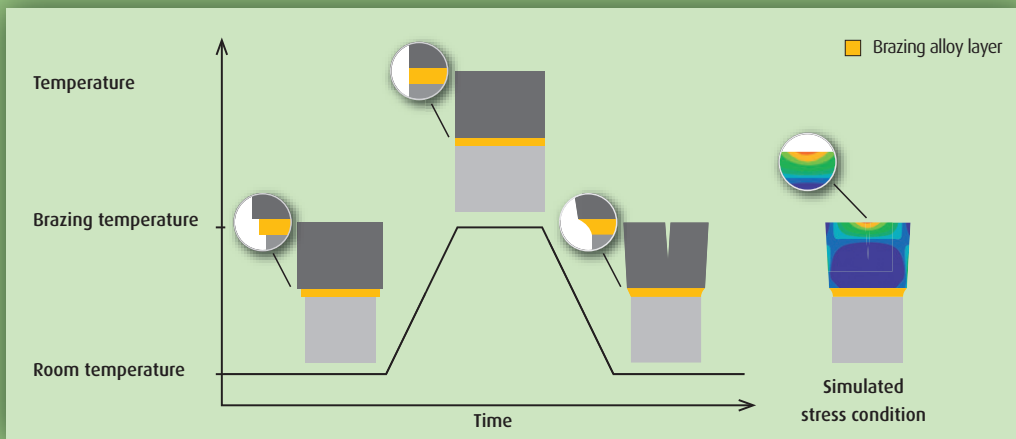$$\sigma_{.max/min;\, i} = \sigma_{ax,i} \pm \sigma_{b\,max,i}$$

where

$$\sigma_{ax,i} = \frac{F_{ax}}{A_i}$$

and

$$\sigma_{b\,max,i} = \frac{M_i}{l_i} \frac{h_i}{2}$$

Figure 7 | Schematic view of how different coefficients of thermal expansion affect a cemented carbide/steel compound brazed using a conventional brazing filler metal [18]

Temperature

Brazing alloy layer

Brazing temperature

Room temperature

Time

Simulated stress condition

The following applies to a compound of steel 1.8159 and cemented carbide K10:

$\alpha_{CC} = 4.7 \cdot 10^{-6}$ K^{-1}; $\alpha_{St} = 14 \cdot 10^{-6}$ K^{-1}

$E_{CC} = 600$ GPa; $E_{St} = 210$ GPa

$L_0 = 1$ mm

$h_{CC} = 1$ mm; $h_{St} = 3$ mm

$T_1 =$ solidus temperature of brazing filler metal system

$T_2 = 20$ °C

Under the above constraints, the low-melting silver-based brazing filler metal BrazeTec 4900 (solidus temperature: 680 °C) generates a tensile stress of approx. 85 MPa on the cemented carbide surface. Taking the same two base materials, an increase in the brazing filler metals' solidus temperature to 980 °C (BrazeTec 21/68) the tensile stress increases by about 50% to 120 MPa and, if the temperature rises further to 1,083 °C (BrazeTec E-Cu 58) the stress increases by 60% to 135 MPa. Designers must therefore take account of these changes in the tensile stress when modifying the brazing filler metal system (**figure 9**).

The above calculation assumes a thickness ratio of 1 : 3 (cemented carbide : steel). Extending the above equation to further thickness ratios soon reveals that this ratio has a major influence on whether or not the cemented carbide surface (in the case of a saw tooth: the cutting surface) is exposed to tensile or compressive stress (**figure 9**). The different graphs generally support the approximate conclusion that a thickness ratio of about 1 : 3 (cemented carbide : steel) may be considered ideal because it generates almost zero stress in the cemented carbide surface. This is opposed by maximum tensile stress at a ratio of about 1 : 1 which should therefore be avoided if at all possible.

Whenever a compound is pre-stressed by this kind of thermally induced stress, it sometimes only takes a small external load to cause the compound to fail. Thus, in order to maintain a low level of such thermally induced stress, steel/cemented carbide compound should be produced by means of a brazing filler metal with as low a brazing temperature as possible. Note, though, that real-life tensile or compressive stress readings will generally be lower because some of it will be dissipated by the ductile brazing filler metal present in the joining layer.

Figure 8 | Bimetal effect of steel (below) and cemented carbide (above) under thermal load [19]
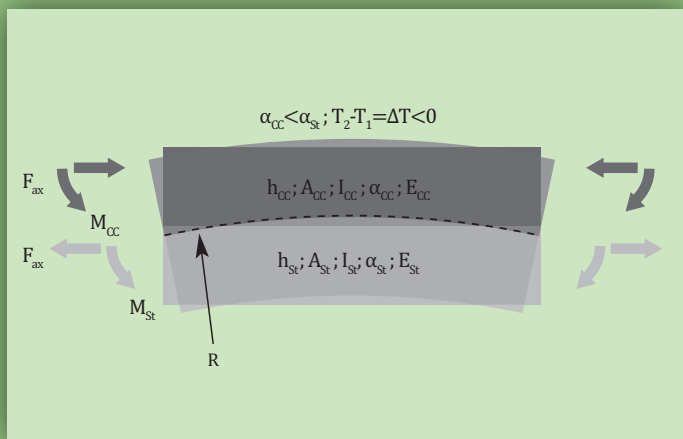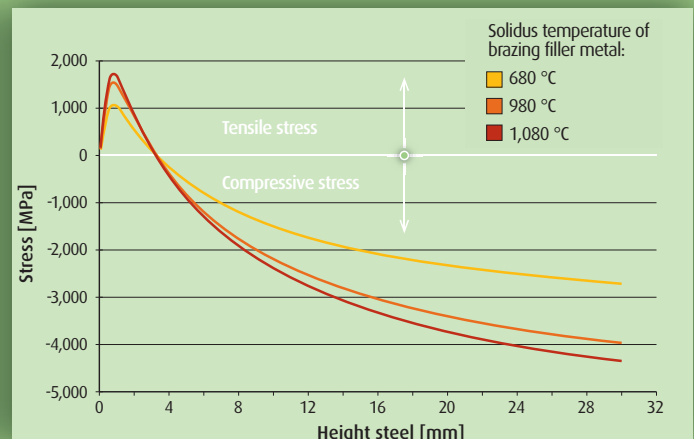

$\alpha_{CC} < \alpha_{St}$; $T_2 - T_1 = \Delta T < 0$

h_{CC} ; A_{CC} ; I_{CC} ; α_{CC} ; E_{CC}

h_{St} ; A_{St} ; I_{St} ; α_{St} ; E_{St}

F_{ax}

M_{CC}

F_{ax}

M_{St}

R

Figure 9 | Stress state in a cemented carbide surface 1 mm thick connected to steel layers of varying thicknesses

Solidus temperature of brazing filler metal:
680 °C
980 °C
1,080 °C

Tensile stress

Compressive stress
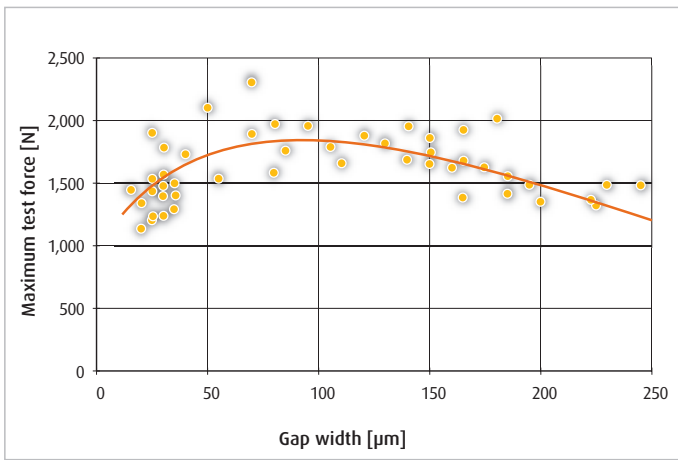
Stress [MPa]

Height steel [mm]

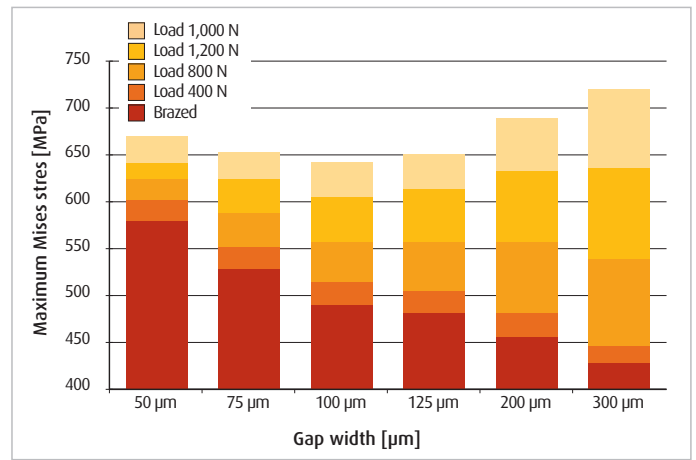Figure 10 | Test forces as a function of the brazing gap size for brazing filler metal BrazeTec 4900 [23]

Figure 11 | Calculated maximum Mises stress in brazing filler metal BrazeTec 4900 as a test force function of the brazing gap size [23]

In order to minimise the stress, try using a brazing filler metal with as low a solidus temperature as possible and producing a very wide brazing seam containing a rigid and easily deforming brazing filler metal whose plastic deformation will dissipate the stress. Gap sizes between 0.1 mm and 0.2 mm are enough for brazed areas less than 100 mm² in size [8] [5].

Tests carried out using the silver-based brazing filler metal, BrazeTec 4900, revealed that maximum test forces occur with fairly little variance under bending stress at gap sizes near to 100 µm. Forces reduce at gap sizes lower than 70 µm and higher than 125 µm (**figure 10**). This gradient results from the stresses in the braze metal. **Figure 11** – and the calculation for the purely brazed state – shows that the stress in the braze metal decreases versus an increasing gap size. On the other hand, the braze metal in wider gaps must consume more stress when the compound is exposed to external loads. Thus, minimum stress is found at a gap size of about 100 µm, a finding that corresponds to rigidity values of **figure 10**. **Figure 12** confirms that the stress in the braze metal is lowest under a load of 1,500 N and a gap size of 100 µm. Looking at the 300 µm braz-

ing gap size you will clearly see the higher stress level, mainly along the edge of the braze metal.

Brazing larger areas will require much wider gap sizes. However, these will not be possible owing to the higher stress level in the braze metal and the incomplete filling of the gap to be expected because of an insufficient capillary action of silver-based brazing filler metals. This issue may be addressed by inserting a section of sheet or wire gauze made of a ductile and higher-melting material of by using a sandwich brazing filler metal [8] [5].

Figure 12 | Calculated maximum Mises stress distribution in brazing filler metal Ag 449 under 1500 N as a test force function of the brazing gap size [23]
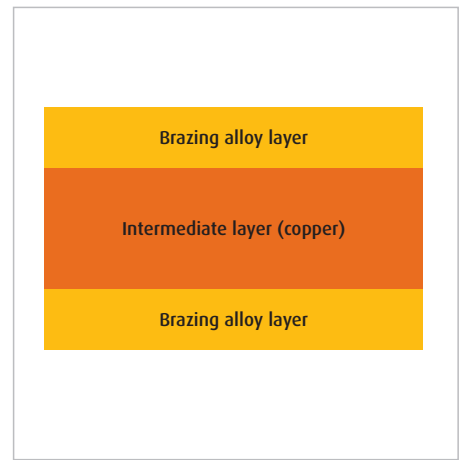

T = 50 µm   T = 100 µm   T = 300 µm
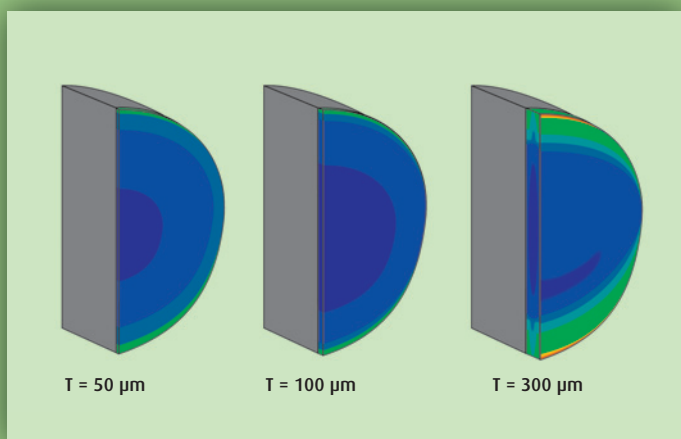
4.1.3 Sandwich brazing filler metals

As their name and **figure 13** suggest, sandwich brazing filler metals are characterised by their sandwich structure. The core is an interlayer with normally a silver-based brazing filler metal on either side. Their standard thickness ratio is 1 : 2 : 1 (brazing filler metal : interlayer : brazing filler metal). Other thickness ratios are also available.
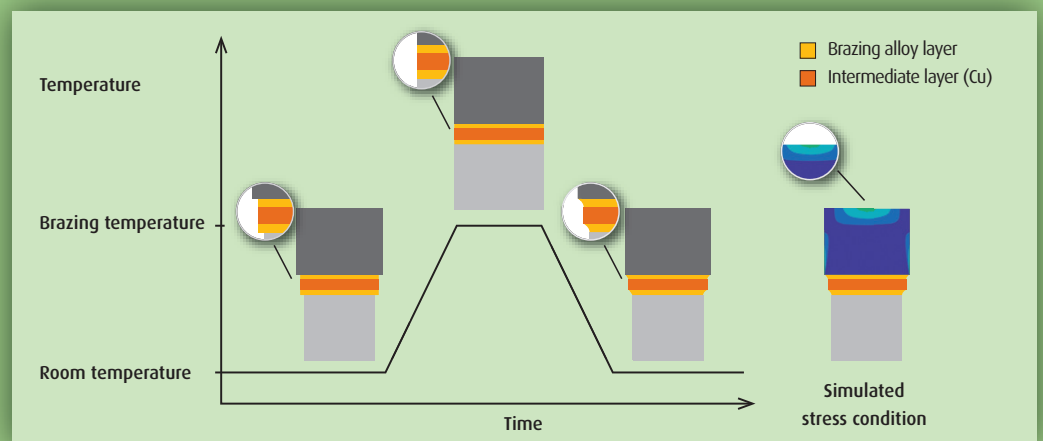
The purpose of the copper or special-alloy interlayer is to absorb stress that may occur at the cooling stage. A nickel mesh may also be put in as a spacer that ensures that the gap between steel and cemented carbide is of a constant and reproducible width.

On the right of **figure 14**, you see a stress simulation in the cemented carbide after cooling down a cemented carbide/steel compound made with a sandwich brazing filler metal. Dark blue marks areas without any tensile stress, orange red marks high-stress areas. Obviously, a sandwich brazing filler metal in the middle section of the cemented carbide produces a much smaller area with little tensile stress than a conventional brazing filler metal (**figure 7**). Furthermore, the side of the cemented carbide is exposed to considerably lower forces.

Figure 14 | Schematic view of how different coefficients of thermal expansion affect a cemented carbide/steel compound brazed using a sandwich brazing filler metal [18]
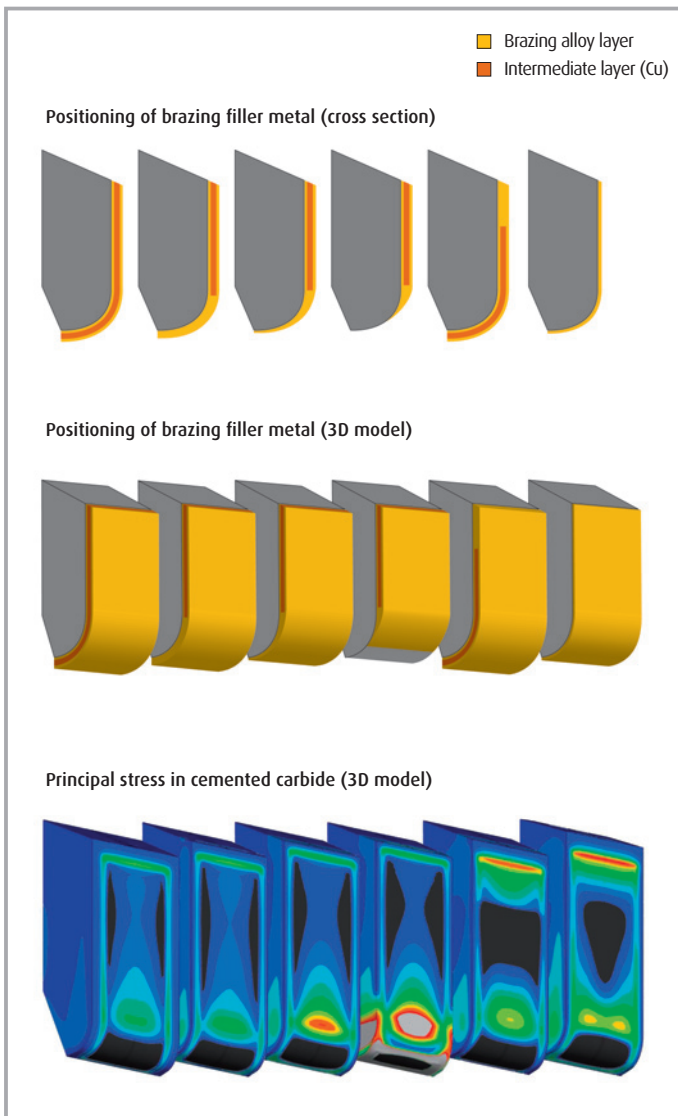
Legend:
- Brazing alloy layer
- Intermediate layer (Cu)

Positioning of brazing filler metal (cross section)

Positioning of brazing filler metal (3D model)

Principal stress in cemented carbide (3D model)

Figure 16 | top: Geometry of samples with different sandwich brazing filler metal positions; bottom: calculated maximum main stress in brazed samples, scale: 0 – 250 MPa [24];

The sandwich brazing filler metal's shear strength is commonly limited by the strength of the interlayer. The results of the four point bending tests in **figure 15** confirm that using special-alloy interlayers (e.g. BrazeTec 49/Cu^{plus}) help to increase the joints shear strength by more than 25% compared to a normal copper interlayer (e.g. BrazeTec 49/Cu), i.e. from about 150 MPa to approx. 180 MPa.

Several factors should be considered before using a sandwich brazing filler metal. One major point is where to place it. **Figure 16** suggests that the position of the sandwich brazing filler metal or the central layer clearly affects the stress in a brazed cemented carbide saw tooth. Stresses in these areas are higher if there is no interlayer and they will again increase considerably if the gap becomes narrower in these areas. Only if the sandwich brazing filler metal and the

Figure 15 | Test forces as a function of the brazing gap size for the sandwich brazing filler metal of [23]

Legend:
- BrazeTec 49/Cu
- BrazeTec 49/Cu^{plus}

y-axis: Maximum bending force [N]
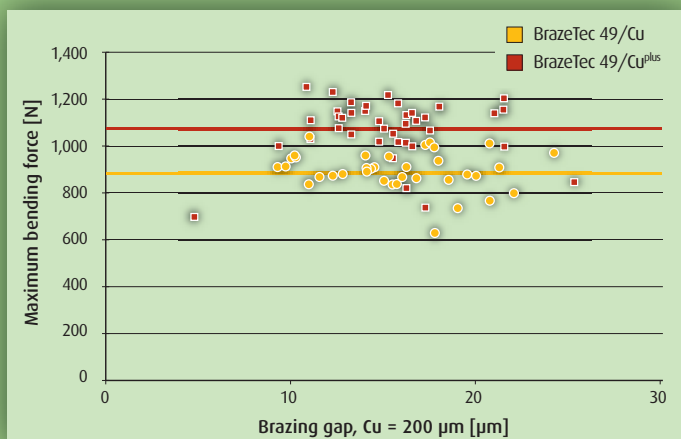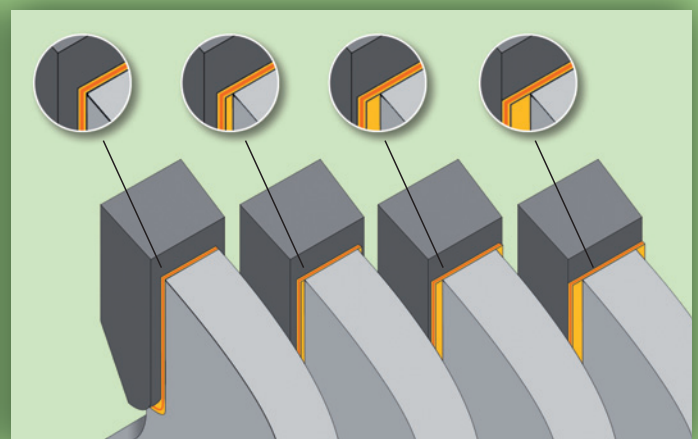x-axis: Brazing gap, Cu = 200 μm [μm]

Figure 17 | Base saw blade brazed using BrazeTec 49/Cu strips of varying widths

central layer completely wrap around the saw tooth (left) will the stress be as low as it could be. In case the brazing filler metal fails to completely enclose the tooth or if the central layer ends too soon, much stress will occur on both the brazed side (middle and right) and the cutting surfaces. **Figure 16** shows that the stress may easily increase by about 60% (from 150 MPa to 250 MPa) which, in turn, also increases the probability of a fracture by approx. 3,000% (calculation based on Weibull's theory) [24].

Another factor affecting the stress in the entire brazed compound is the width of the strip of brazing filler metal (**figure 17**) [25]. Simulating the stress distribution in a base saw blade (made of CrV4) 3.5 mm thick with a brazed cemented carbide tooth of size 10.5 mm x 5.3 mm x 3.0 mm (CERATIZIT KCR06) reveals that the stress in the steel significantly increases with the strip width,

whereas, at a strip width of 4 mm, the stress in and elongation of the brazing filler metal is at a minimum. Compared to the steel, however, the stress is on a similar level in strips of all widths. Whereas the strip width does not affect the stress in the copper interlayer, the elongation decreases as the width of brazing filler metal strips increases (**figure 18**). At a strip width of 4 mm in the above example, maximum stress occurs in the brazing filler metal near the cemented carbide and minimum stress in the widest strips under analysis. As in the steel, the tensile stress in the cemented carbide increases with the width of the brazing filler metal strip until the stress peaks in the root area of the tooth flanks. There is no major change in the stress found in the front faces of the cemented carbide tooth.

To conclude: a compromise has to be found for the different stress states in the brazed

compound. Generally speaking, the sandwich brazing filler metal should overlap by 0.25 mm on either side of the saw blade as this would support an optimum stress distribution in both materials. It would also make the process as such more reliable because it would ensure that the brazing filler metal strip will completely fill the gap even if it moves slightly.

Figure 18 | Elongation of the copper interlayer in strips widths between 3.5 mm and 5.0 mm (0 – max. 14%) [25]
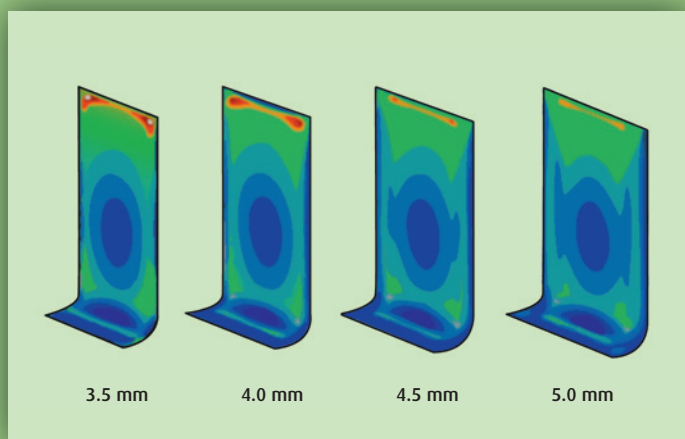

| 3.5 mm | 4.0 mm | 4.5 mm | 5.0 mm |

Figure 19 | Tensile stress in the cemented carbide tooth in strips of varying widths [25]

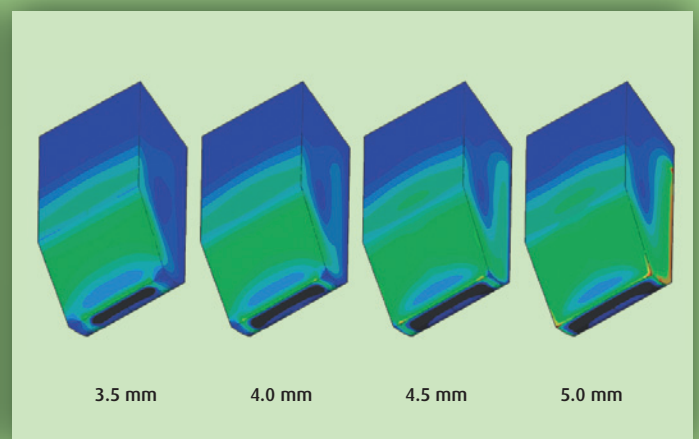| 3.5 mm | 4.0 mm | 4.5 mm | 5.0 mm |

Table 9 summarises the composition of various sandwich brazing filler metals and their brazing temperatures. Special applications in medical, plastics and other technologies have strict requirements regarding the corrosion resistance of the stress-levelling effect of the interlayer. Pure copper often fails to meet these requirements. Using interlayers of copper/nickel/iron alloys (e.g. BrazeTec 49/CuNiFe) allows the successful brazing of cemented carbides.

4.1.4 Characteristics of special applications

The many tasks are accomplished by using different cutting materials, modified cutting materials or extra coatings. Therefore brazing may have to be re-thought.

Assuming you wish to improve the wear resistance of cemented carbides by depositing a hard material layer from the vapour phase such as titanium carbide (TiC), titanium nitride (TiN) or titanium aluminium nitride (TiAlN), you will have to take account of the process constraints of the PVD coating method (Physical Vapour Deposition). Your choice of brazing filler metal must consider the ensuing high process temperatures that will increase the vapour pressure of brazing filler metal components or the intended processing in a vacuum. As a typical element of low-melting silver-based brazing filler met-

als, zinc for example generates a vapour pressure of approx. $1 \cdot 10^{-5}$ mbar at about 200 °C. This normally exceeds the initial pressure of common PVD processes. The zinc vapour pressure will increase at higher temperatures and lower pressures. This may be assumed to jeopardise the coating quality and the strength of the brazed connection. Thus, cemented carbides intended for this kind of coating process should be brazed using a zinc-free silver-based brazing filler metal; for example BrazeTec 6488 or BrazeTec 64/Cu (**table 7** and **table 9**).

Accurately controlling the brazing temperature is a must. Brazing fairly small pieces of cemented carbide, as predominantly used for turning and milling tools for wood machining, may be done without sandwich brazing filler metals as described earlier. If so, you may opt for the low-melting silver-based brazing filler metals BrazeTec 5600 or BrazeTec 5507 (**table 11**) whose brazing temperature is approx. 20 °C lower than that of BrazeTec 4900 [18].

4.2 Diamond & Polycrystalline diamond (PCD)

Diamond is the hardest known material. It is used as an abrasive and a cutting material. While diamonds are generally chemically stable in contact with inorganic acids for example, at higher temperatures they easily

react to carbide formers such as iron, nickel, cobalt, tungsten or chromium. This limits the use of diamond-doted tools to non-ferrous metals such as aluminium or copper and to non-metal materials such as glass and carbon fibre, carbides and stone.

In practice, there are numerous diamond variants which may be used as natural or synthetic monocrystalline diamonds whose hardness depends on the direction of load application. And there are polycrystalline diamonds (PCD) consisting of many crystals with a random orientation embedded in a metal or ceramic matrix (binder) which causes their behaviour to be isotropic. As in the cemented carbides, the properties of polycrystalline materials depend on the ratio of hard material and binder, the grain size and other factors. PCD is brazed to the tool as compacted segments sometimes sintered onto a cemented carbide substrate. You may also consider using the CVD method when depositing diamond layers.

Diamonds provide excellent hardness and high thermal conductivity. Thus, the heat generated when cutting is immediately discharged from the cutting face. The big disadvantage of diamonds is their high brittleness. However, typical failures can be strongly influenced in PCDs or by defects and secondary phases.

Table 9 | Sandwich brazing filler metals for the brazing of cemented carbides [29]

Brazing filler metal	Intermediate layer	Melting range DSC [1] approx. [°C]	Brazing temp. approx. [°C]	Shear strength [2] [MPa]	Composition in weight-%					
					Ag	Cu	Zn	Mn	Ni	Else
BrazeTec 49/Cu	Copper interlayer	670 – 720	710	> 150	49	27.5	20.5	2.5	0.5	–
BrazeTec 49/Cu^{plus}	Reinforced copper interlayer	670 – 720	710	> 180	49	27.5	20.5	2.5	0.5	–
BrazeTec 49/CuNiFe	Copper interlayer of increased corrosion resistance	670 – 720	710	> 150	49	27.5	20.5	2.5	0.5	–
BrazeTec 64/Cu	TiN-coatable copper interlayer	730 – 780	780	> 150	64	26	–	2	2	–
BrazeTec 49/NiN	Ni matrix interlayer, stabilised gap	670 – 720	710	> 150	49	49	20.5	2.5	0.5	6 In
BrazeTec Cu/NiN	Copper interlayer	1,085	1,100	> 200	–	100	–	–	–	–

1) Schnee, Wiehl, Starck 2014 [40]   2) Compound 1.2210 & K10; brazed area 8 x 8 mm; shear tester: Gerling GLFP

Most PCDs contain 5 – 10% by volume of binder but PCDs made of synthetic diamonds may have further impurities caused by metal and graphite from the process of synthetic production. The metal binder normally resides on the grain boundaries. It influences the strength of the diamonds in that it supports the conversion into graphite and, owing to the different coefficient of expansion, adds stress to the material if used at high temperatures. This can be avoided by chemically removing the binder from the grain boundaries or by using binder materials with a more equivalent coefficient of expansion such as silicon carbide [15].

4.2.1 Brazing of diamonds & Polycrystalline diamond (PCD)

When using thermal methods to join diamonds you must be aware that, under specific thermal and pressure constraints, diamonds will change their crystalline structure or may oxidise. At temperatures above 600 °C, for example, diamonds and atmospheric oxygen react to produce CO_2. At higher temperatures, diamonds may also convert back to graphite. The actual conversion temperature depends on various factors such as the ambient atmosphere. In a pure inert atmosphere, a natural monocrystalline diamond will turn into graphite at about 1,600 °C; in a vacuum (at a pressure of $5 \cdot 10^{-4}$ mbar) it converts back at about

1,500 °C. Under atmospheric conditions, this temperature may be as low as 1,000 °C [12] [26] or, depending on process conditions, even as low as 750 °C [15] to generate a significant graphite share.

The wetting of diamonds largely depends on the interaction of the diamond and the material it is in contact with. Two brazing filler metal grades are used for brazing diamonds: nickel-based brazing filler metals containing carbide-forming elements such as chromium, boron and silicon [12] [27] and so-called active brazing filler metals containing surface-active elements such as titanium or zirconium [12]. These elements may react to the non-metal, inorganic materials, e.g. diamond or ceramics. The resulting reaction layer can be wetted by the remaining brazing filler metal which only contains a few active elements. Since the active elements are characterised by their oxygen affinity and since the elements should be prevented from setting early by reacting to oxygen, the process is carried out in a vacuum at min. $5 \cdot 10^{-4}$ mbar or in an inert gas atmosphere [26]. Nickel-based brazing filler metals are a good choice when it comes to improving the wear resistance of the brazed-on diamond grains [12]. Compared to brazing with nickel alloys, active element brazing benefits from the lower brazing temperatures near 900 °C and the active brazing filler metals' higher ductility,

both of which reduce thermally induced stress. While active brazing filler metals such as BrazeTec CB 4 are often used as a brazing foil, there are also active brazing filler metal pastes such as the nickel-based alloy and active alloys that can be applied (semi-)automatically by a dispenser and screen printing.

It has been mentioned earlier that brazing filler metals containing carbide-forming elements such as titanium, zirconium, chromium, boron and silicon are used to braze diamonds. They produce a carbide layer upon contact with the diamond. Use the Gibbs free energies shown in **figure 20** to assess the carbide types that are actually produced. The lower the Gibbs free energy reading for carbide generation, the more likely it is that this particular carbide will actually be formed. According to the Gibbs free energy, a nickel-based brazing filler metal plus chromium and boron is more likely to produce $Cr_{23}C_2$ than Cr_3C_2, B_4C or nickel carbide at a brazing temperature of about 1,000 °C.

Figure 20 | Gibbs free energy for carbide generation at various temperatures [15]
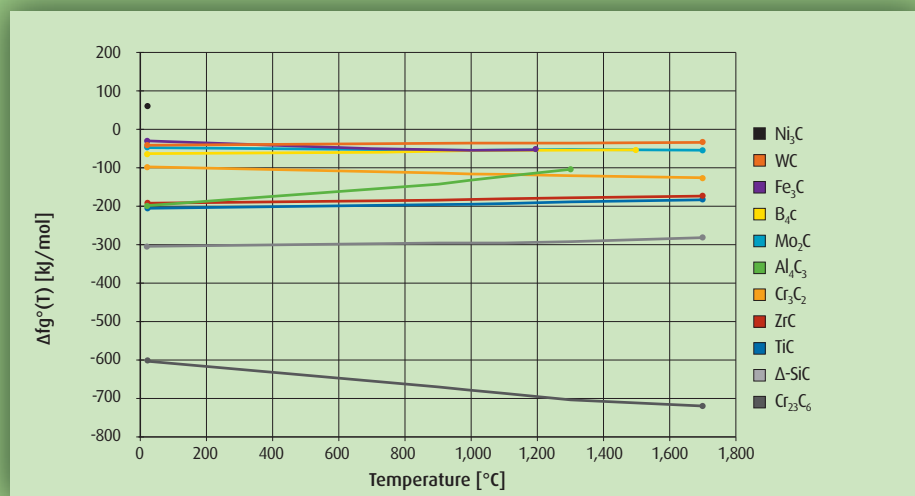
You will have to distinguish between the brazing of diamond grains and compact PCD layers. There is no restriction on using the brazing filler metals of **table 10** for brazing grains. Use the active brazing filler metals from the table for brazing pure PCD layers.

PCD layers may also be sintered onto cemented carbides. In this process, the binder will diffuse from the cemented carbide into the diamond compound where it will again produce a joint. You are generally advised against overheating the diamond bodies because this will cause the diamonds to convert into graphite which may cause PCD layers to separate from the cemented carbide [28]. Because of the different coefficients of expansion, the resulting compound should be allowed to slowly cool down in air in order to avoid premature failure by thermally induced stress [16].

Brazing filler metals with a high silver content and melting points up to a maximum of 750 °C plus the appropriate fluxes are used to link the sintered-on PCD layers to the tool. Wetting of the base materials may be improved by adding manganese [29]. **Table 11** lists a number of recommended brazing filler metals. However, not all of these are actually suitable for brazing sintered PCD layers. BrazeTec 5507 (higher silver content) and BrazeTec 4900 (containing manganese and nickel) have given positive results for this kind of application. Some of the fluxes of **table 5** are recommended, specifically BrazeTec special h, BrazeTec h 80, BrazeTec h 90 and BrazeTec h 285. PCD layers, like cemented carbides, are brazed with induction heating.

Another way of applying diamonds to tools is as diamond segments which are characterised by a low diamond content (approx. 10%) embedded in a cobalt or bronze matrix. In this case, the joining task is to wet the matrix metal. Such segments are often mounted on cutting wheels, for example. In order to obtain highly rigid and reproducible connections without causing thermal damage to the diamond segment binder, you should consider your choice of brazing filler metal and brazing process.

4.3 Cubic boron nitride & Polycrystalline cubic boron nitride (PcBN)

Cubic boron nitride (cBN) is only half as hard as diamond but twice as hard as the other materials and is therefore the second-hardest known material. It is used in a similar way to diamonds. cBN is brittle when exposed to impact loads. Just like a PCD, a PcBN is a material whose crystals are orientated randomly in a metal matrix. But with regard to secondary phases, particle size distributions and particle concentrations, PcBN has more variants than PCD. Like PCD, PcBN is sometimes sintered onto a cemented carbide before it is brazed.

Owing to its very slow reaction to iron, nickel and cobalt alloys, cBN may be used to process these elements. It does, however, respond quickly to materials such as titanium and zirconium under formation of nitrides or borides.

4.3.1 Brazing of cubic boron nitride

Apart from brazing-on grains, you may use compacted segments. The latter are often applied to a cemented carbide substrate whose high rigidity and little expansion produces low thermally induced stress in the resulting compound.

Table 10 | Brazing filler metals for brazing ultra-hard materials [22]

Nickel-based brazing filler metal	ISO 17672	Comment	Melting range ISO 17672	Brazing temp.	Composition in weight-%				
			approx. [°C]	approx. [°C]	Ni	Cr	Fe	Si	B
BrazeTec 1002	Ni 620	Dispenser & screen printing paste	970 – 1,000	1,050	82.4	7	3	4.5	3.1

Active brazing filler metal	ISO 17672	Comment	Melting range	Brazing temp.	Composition in weight-%				
			approx. [°C]	approx. [°C]	Ag	Cu	Ti	–	–
BrazeTec CB 4	–	General-purpose active brazing alloy foil	780 – 820	850 – 950	70.5	26.5	3	–	–
BrazeTec CB 10	–	General-purpose active brazing alloy paste for screen printing and dispensing	780 – 820	850 – 950	64.8	25.2	10	–	–

cBN is a lot more resistant to oxidation and conversion into hexagonal boron nitride than diamond. An oxide layer protects it up to a temperature of 1,300 °C. Conversion will only start above that temperature. Again, the actual conversion temperature depends on the atmosphere which varies from 1,525 °C after 12 hours in nitrogen [26] to 1,700 °C in air [15]. With regard to its thermal and chemical resistance, polycrystalline cBN is not affected by the binder phases.

cBN is chemically extremely stable which is why it cannot be brazed using conventional brazing filler metals. Prior to brazing, cBN is sometimes coated with nitride- or boride-forming materials such as nickel or titanium and then brazed with conventional brazing filler metals.

Just like diamonds, however, it is normally processed using active brazing filler metals based on a silver-copper-titanium system.

For this purpose, recommended active brazing filler metals are the BrazeTec alloys of **table 11**.

Nickel-based brazing filler metals cannot be used because the enthalpy for chromium nitride formation is -121 kJ/mol [30] and,

thus, a lot higher than the enthalpy for cBN formation (-266.8 kJ/mol [31]) which results in energetic disadvantages. The result of this fact is that there will be not be a linking re-action layer. As a general rule, you may also enhance the brazed material's hardness by adding hard material powder or hard metals such as molybdenum or tungsten.

The same silver-based brazing filler metals as for the PCD/cemented carbide layers or the cemented carbides can be used to braze the PcBN layers sintered onto a cemented carbide substrate.

Table 7 and **table 11** list the recommended brazing filler metals. Again, PcBN brazing should be performed at as low a temperature as possible to prevent the PcBN from coming off the cemented carbide substrate [26]. Brazing in a vacuum is used occasionally.

4.4 Brazing of ceramics

All ceramic tools are made from ceramic raw material powders which are formed into the target shape, compacted and then baked. Various routes are available, depending on the type of ceramics and intended use. Hot-isostatic press-forming is a particular way of

producing dense components with isotropic properties. Refer to **table 1, page 8** to find the main two grades used as cutting ceramics for tools: aluminium oxide and silicon nitride ceramics. Al_2O_3 is appropriate for the use as monolithic ceramic with an Al_2O_3 content > 99% or as a reinforced ceramic that other ceramic substances such as titanium or silicon carbide fibres are added to. Apart from pure silicon nitride you will also find sialon, a ceramic composition of Si_3N_4 and Al_2O_3 or aluminium nitride. Another option is to use Si_3N_4 reinforced with metal carbide fibres [15]. Adding further oxides, carbides or fibres and modifying the production route generally and clearly enhanced the materials' performance and fracturing characteristics [26].

Table 11 | Brazing filler metals for brazing sintered-on PCD layers and segments containing diamond [29]

Brazing filler metal	ISO 17672	PCD on cemented carbide	Diamond segments	Comment	Melting range ISO 17672 approx. [°C]	Melting range DSC [1] approx. [°C]	Brazing temp. app. [°C]	Composition in weight-%					
								Ag	Cu	Zn	Mn	Ni	Sn
BrazeTec 5507	Ag 155	brazeable	brazeable	low melting point	630 – 660	650 – 670	660	55	21	22	–	–	2
BrazeTec 4900	Ag 449	brazeable	brazeable	good wetting	680 – 705	680 – 705	690	49	16	23	7,5	4,5	–
BrazeTec 4404	Ag 244	–	brazeable	highly ductile and rigid	675 – 735	675 – 735	730	44	30	26	–	–	–

1) Schnee, Wiehl, Starck 2014 [40]

Ceramic cutting materials are characterised by their hardness under heat, chemical and thermal strength and wear resistance. As opposed to conventional tools, these materials are a good choice for materials which are too hard for standard tools or for working at high processing speeds which will produce temperatures beyond the practical limits of other cutting materials. They also benefit from homogeneous cuts within close tolerance.

Tools of monolithic or TiC-reinforced aluminium oxide are used for tempered steel, cast iron and nickel-based super alloys, while the SiC fibre-reinforced Al_2O_3 components are used for tempered steel up to 65 HRC and nickel-based super alloys. Silicon nitride-based ceramics are appropriate within limits because they tend to chemically react with the materials to be processed. They are therefore mostly used for cutting cast iron and nickel-based super alloys only. Their chemical resistance can be improved by adding aluminium oxide or by coating them with TiC-TiN or TiC-Al_2O_3 systems [15].

Like the other cutting materials, ceramics are not used for complete components but as in- serts in the widest sense of the word attached to a metal substrate. In some cases, it may be enough to screw the cutting inserts to the substrate. Permanent connections, however, are best obtained by brazing the ceramic parts.

4.4.1 Brazing filler metal materials and brazing process

Since their binding structure disallows the wetting of ceramic materials by conventional brazing filler metals, active brazing filler metals are used instead for the brazing of diamonds. The process as such is detailed in **section 4.2** but assumes the reaction of the ceramic materials with surface-active elements such as titanium. The active BrazeTec silver-copper-titanium brazing filler metals of **table 10** are used either as a foil or paste.

4.4.2 Thermal effects and stresses

As specifically described in **section 2.3**, compounds of cutting materials and steels often produce thermally induced stress caused by differences in the coefficients of thermal expansion. The same applies to ceramic/metal compounds, because the coefficient of expansion of ceramics is much lower than that of the most steels (**table 12**). The brazing seam is too narrow compared to the rest of the component and therefore unable to dissipate the stress generated when the component cools down. The effect is a complex distribution of partial high stresses throughout the entire compound.

A consequence of the high stress levels is that the rigidity of ceramic/metal compounds is lower than that of ceramic/ceramic compounds. **Figure 21** shows the example of a four point bending test. Compared to ceramic/ceramic compounds, the bending strength of ceramic/metal compounds with silicon nitride is approx. 15% lower and that of SiC/metal compounds 50% lower.

Table 12 | Linear coefficient of thermal expansion of various ceramic and metal materials

Ceramic material	Linear coefficient of thermal expansion [$10^{-6}K^{-1}$]	Metal material	Linear coefficient of thermal expansion [$10^{-6}K^{-1}$]
Diamond	1.3	FeNiCo	5.9
SiC	4.6	FeNi	8.0
Si_3N_4	3.0	C45	11.0
Al_2O_3	8.0	C45	11.0
ZrO_2	9.8	1.4301	16.0

Figure 21 | Four point bending resistances of actively brazed ceramic/ceramic and ceramic/metal joint [32]
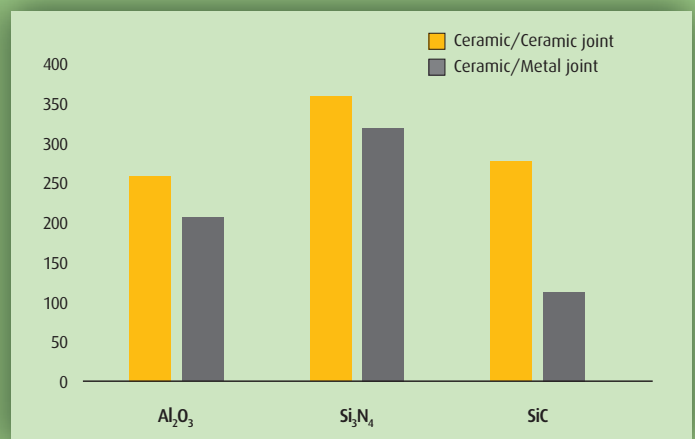
4.5. Examples of applications

Saw blade

Material	Cemented carbide (CoCr matrix) steel
Brazing filler metal	BrazeTec 49 / Cu
Flux	BrazeTec h 285
Atmosphere	Air
Method of heating	Induction

TiN-coated drill bit

Material	Cemented carbide (Co matrix) steel
Brazing filler metal	BrazeTec 6488
Flux	BrazeTec h 285
Atmosphere	Air
Method of heating	Induction

Paper knife

Material	Cemented carbide (Co matrix) steel
Brazing filler metal	BrazeTec 49 / Cu
Flux	BrazeTec h 285
Atmosphere	Air
Method of heating	Induction

Chisel

Material	Cemented carbide (Co matrix) steel
Brazing filler metal	BrazeTec 21/68
Flux	BrazeTec s
Atmosphere	Nitrogen
Method of heating	Induction, furnace

Core drill
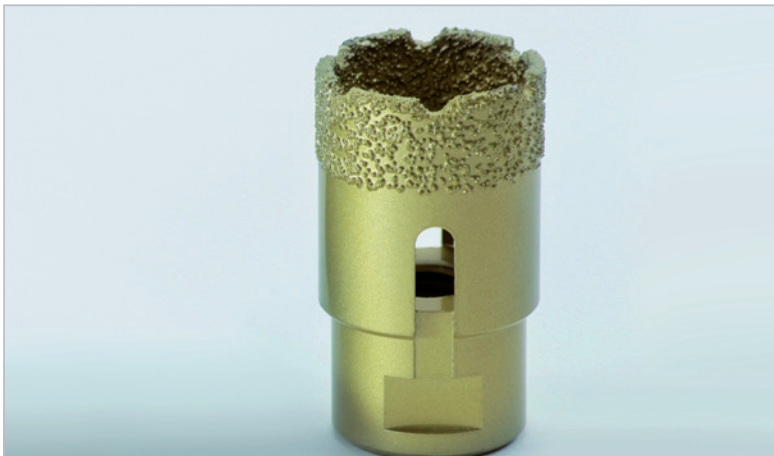
Material	Diamonds, steel
Brazing filler metal	BrazeTec P 1002.1
Flux	none
Atmosphere	Argon 4.8, vacuum $< 10^{-3}$ mbar
Method of heating	Furnace

Cutting wheel
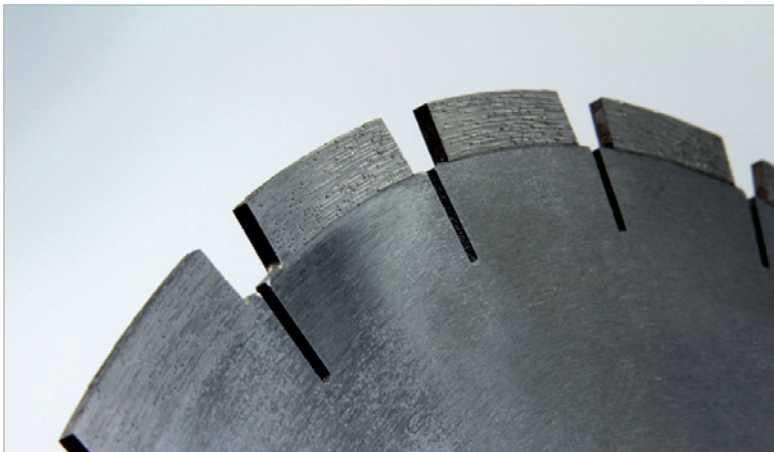
Material	Diamond segments (Co, Cu, Fe, Sn matrix) steel
Brazing filler metal	BrazeTec 5507
Flux	BrazeTec h 80
Atmosphere	Air
Method of heating	Induction

Cutting disk

Material	Diamonds, steel
Brazing filler metal	BrazeTec P 1002.1
Flux	none
Atmosphere	Argon 4.8, vacuum $< 10^{-3}$ mbar
Method of heating	Furnace

Milling cutter

Material	PCD sintered onto cemented carbide / steel
Brazing filler metal	BrazeTec 4900
Flux	BrazeTec special h paste
Atmosphere	Air
Method of heating	Induction

Cutting insert
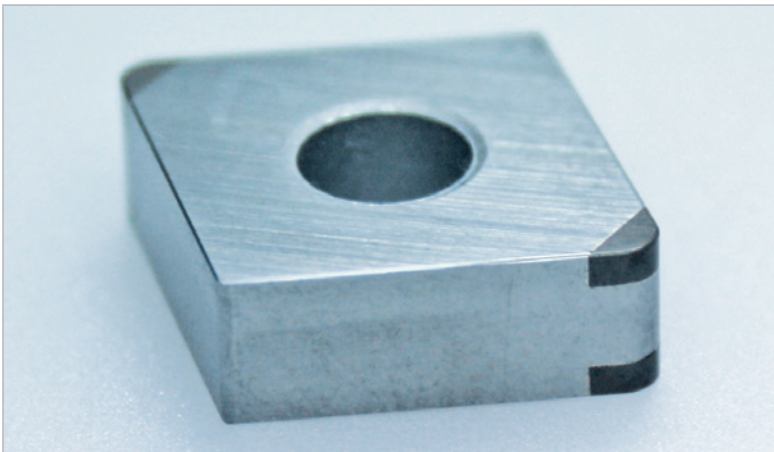
Material	PcBN/steel
Brazing filler metal	BrazeTec CB 10 paste
Flux	none
Atmosphere	Argon 4.8, vacuum $< 10^{-3}$ mbar
Method of heating	Furnace

5. Process optimization

Quality criteria for identification of improvement are the filling degree of the brazing gap, a low porosity, certain mechanical properties needed for the application or a good surface of the brazing seam.

Table 13 | Induction brazing faults – root causes and corrective actions [11]

Fault	Root cause	Corrective action
The brazing filler metal failed to flow properly	A badly adjusted inductor caused differences in the heating process.	Run a test to correctly adjust the inductor.
	The gap size has been set wrongly or the gap becomes wider in the direction of brazing filler metal flow.	Maintain the set gap sizes.
	Incorrect flux.	Use the BrazeTec fluxes recommended in table 5, page 12.
	Too much grease/oil on the surface of the parts to be brazed together consumed some of the flux's effect.	Always degrease the components prior to brazing.
	Oxide left on the surface.	Oxide layers can be reduced by brazing in a reducing atmosphere (in a furnace).
	The base material (e.g. cemented carbide with a low binder content) does not wet well.	Improve wetting by applying cobalt or nickel coatings.
The brazed joint is not stable enough	The work-piece was moved while the brazed joint was setting; brittle brazing filler metal is often found in alloys with a large melting interval.	Brazed parts should not be removed from the holding device until the brazing filler metal has fully set; avoid vibrations while the alloy is solidifying.
	Flux is enclosed in the brazing filler metal because of an improper brazing design; for example, the brazing gap may be too narrow or grooves run across the brazing gap in the direction of alloy flow; this will allow the alloy to cover flux inclusions.	Adapt the component design to the needs of brazing.
	Wrongly applying the brazing filler metal caused gas escaping from some flux components to be entrapped without being able to evaporate when the alloy solidified.	Check for the correct brazing temperature, specifically when using brazing filler metals containing zinc.
	Excessive brazing temperature - the boiling point of some brazing filler metal components was exceeded; some of the brazing filler metal evaporated and the remaining alloy fails to provide the specified strength.	Induce less HF energy or adjust the inductor to ensure that the brazing temperature is correct and that all of the part is heated smoothly.
	Someone tried to speed up the cooling process when the brazing filler metal stop flowing; this caused contraction cracks in the alloy.	Do not speed up the cooling process.
	The heat expansion of the parts to be brazed was not taken into account – the brazing gap is too narrow after heating stopping the brazing filler metal from flowing properly.	Calculate the correct brazing gaps with regard to the effects of thermal expansion.
	Incorrect flux; the brazing filler metal failed to flow properly.	Use the fluxes recommended by BrazeTec.
Highly oxidised brazed joint and environment	Brazing was performed in a normal atmosphere and using a brazing filler metal with too high a melting point.	Use a low-melting brazing filler metal or perform brazing in an inert gas atmosphere or in a vacuum.
	The heating cycle was unnecessarily long.	Check your process engineering; if complicated brazing processes require long heating cycles, try to perform them in an inert gas atmosphere or to apply more flux to the critical points.

5.1 Process errors of induction brazing – causes and solutions

Induction heating is particularly prone to tarnishing problems. **Table 13** summarises the root causes of some faults and suggests corrective actions.

5.2 Potential loss of strength when using copper-based brazing filler metals

Assuming copper-based brazing filler metals are used to braze cemented carbide-to-steel connections, setting up the process inappropriately may reduce the strength of the brazed joints. Tests with a copper-nickel-silicon brazing filler metal showed that extending the holding time from 5 min. to 60 min.

reduced the average shear strength from about 300 MPa to about 180 MPa. In samples with a copper-manganese-nickel brazing filler metal, the average strength was reduced from about 250 MPa at a brazing temperature of 1,000 °C to less than 200 MPa at 1,090 °C. In both cases, the reduction in strength was caused by an iron/cobalt phase that formed at the cemented carbide's abutment face in conjunction with a brittle η-carbide phase forming inside the cemented carbide [1]. The carbon concentration reduces from the cemented carbide towards the low-alloy steel which supports the carbon's tendency to diffuse into the steel. Although the copper brazing filler metal is unable to dissolve the carbon, the emerging iron/cobalt phases provide bridges between the cemented carbide and the steel which

the carbon can use for migration [1] [33]. The cemented carbide starts losing its carbon and carbon depletion supports the formation of brittle η-carbide phases such as Co_6W_6C, Co_3W_3C and Co_2W_4C [34] which jeopardise the compound's mechanical strength. Although closely related, these three carbides behave very differently. Co_3W_3C, for example, is unstable below 1,000 °C and reverts into Co_6W_6C, WC and cobalt.

5.3 Pyrometer for optimised temperature control

A pyrometer is often used to measure the temperature of cemented carbide samples brazed by induction because it provides a non-contact means of measuring. Prior to measuring using a pyrometer, be sure to set the emission rate which is the reference

Figure 22 | Pyrometer temperature reading with reference to the emission rate set for a sample of an actual surface temperature of 730 °C [29]
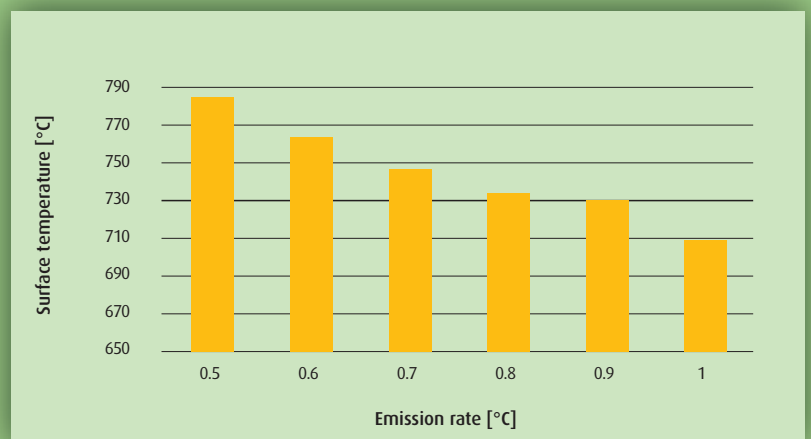
variable for assessing an object's ability to radiate heat. This step is adjusting the measurement to the object. Failure to do so will distort the result as shown in **figure 22**. In this case, the temperature probe measured a surface temperature of 730 °C, but the set emission rate made the pyrometer show a reading varying between 709 °C and 785 °C. Note that the emission rate may be influenced by the component surface and that heating the samples may change the colour on the component surface which, in turn, may distort the reading.

Brazing may face a number problems. The sections below discuss various general issues of process control but also very specific challenges that need to be addressed when brazing cemented carbides, e.g. by optimising the brazing process.

5.4 Effects of overheating diamond segments with a high binder content

As previously discussed in **section 4.2.2**, brazing diamond segments with a high binder content but low cobalt content presents quite a challenge. In order to explain why the brazed compounds are of little strength, segments were analysed whose binder consists of 40% cobalite HX and 60% bronze which results in a cobalt content of less than 20% [35]. The BrazeTec 4900 brazing filler metal was used to join diamond segments to steel samples. The brazing temperature was found to have a major impact on the compounds' shear strength. A pyrometer was used to measure the sur-

face temperature of the diamond segment. Highest shear strengths were found at a surface temperature of 620 °C which allows us to assume that both the brazing filler metal and the surfaces to be wetted had a brazing temperature of 690 °C which is perfect for the brazing filler metal. Further increasing the temperature reduced the shear strength (**figure 23**) readings by overheating the brazing filler metal which caused some manganese and nickel to diffuse from the brazing filler metal into the base material.

Figure 23 | Shear strength of a diamond segment/steel compound brazed with BrazeTec 4900 as a function of the measured surface temperature of the segment [35]
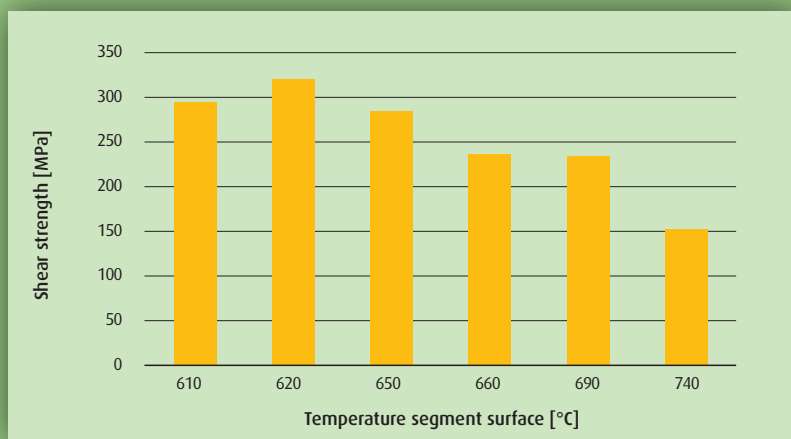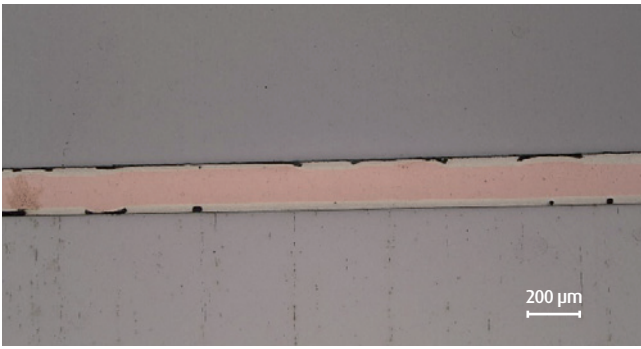
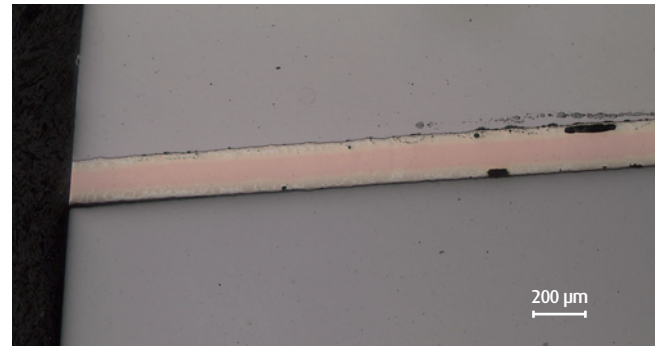**Figure 24 |** Brazing BrazeTec 49/Cu at 750 °C in a 10-second cycle

Figure 25 | Brazing BrazeTec 49/Cu at 850 °C in a 600-second cycle

5.5 Effects of overheating sandwich brazing filler metals

Sandwich brazing filler metals such as BrazeTec 49/Cu or BrazeTec 64/Cu are brazing filler metals with a copper layer in the middle. Since the silver-based brazing filler metal component melts during the brazing process, there is a risk of the copper layer alloying with, or "disappearing" into, the brazing filler metal under certain process conditions [36].

Our investigations revealed that this only happens if the brazing filler metal overheats significantly or if the brazing time is very long. Assuming that a component is brazed by induction, the brazing time will be within the range of seconds which will cause no damage (**figure 24**). We found no major alloying of the copper layer and the brazing filler metal up to a temperature of 950 °C with 10 minutes brazing time (**figure 25**). After just 3 minutes, an obvious effect was found at a higher brazing temperature (1,100 °C) (**figure 26**). Applying this finding to the BrazeTec 64/Cu brazing filler metal which is also used in furnaces with potentially longer brazing cycles suggests using as low a brazing temperature as possible in order to avoid these dissolving effects.

5.6 Copper interlayer failures

A failing brazed joint of a tool brazed using a sandwich brazing filler metal will normally be caused by a failure of the copper interlayer. Comparing the strength of the base materials in the joining area reveals that the copper layer is characterised by its lower strength. This is only logical since the task of the interlayer, or rather its intrinsic ductility, is to absorb any thermal stress induced during the brazing cycle. Its comparatively low strength turns the interlayer into the rated break point of the joining zone. There are various potential causes for the damages described, ranging from brazing as such to the product's end use (in-service overload). **Figure 27** shows an example of a failure in the copper interlayer caused by overloading the cemented carbide saw tooth.

5.7 Badly placed sandwich brazing filler metals

Section 4.1 discussed that brazing cemented carbides to steel transfers thermally and mechanically induced forces directly into both base materials. In order to specifically dissipate the thermal stress, the use of a sandwich brazing filler metal was recommended which ideally covers the entire joining area

Figure 28 | Cemented carbide saw tooth brazed using fully applied BrazeTec 49/Cu [37]

Figure 29 | Cemented carbide saw tooth brazed using BrazeTec 49/Cu but directly in contact with the steel substrate [38]

Figure 26 | Brazing BrazeTec 49/Cu at 1,100 °C in a 180-second cycle

Figure 27 | Cemented carbide saw tooth brazed using BrazeTec 49/Cu showing a failed joint in the copper interlayer [37]

(**figure 28**). In case there is no brazing filler metal or copper interlayer between the cemented carbide and the steel, i.e. if the joined materials directly contact one another (**figure 29**), the stress can no longer be dissipated as much as needed. Assuming the compound is later exposed to further loads, the segment may fail or separate from the substrate at a specific critical load.

Figure 30 shows another example of a totally failed cemented carbide saw tooth. In this case, the sandwich brazing filler metal was too short with a double amount put in on one side of the saw tooth root. There was thus no stress-relieving copper interlayer in the brazing area on the back of the tooth. Furthermore, the gap in this area was extremely narrow and just filled with a little silver-based brazing filler metal from the sandwich brazing filler metal. The stress

states shown in **figure 16** suggest that, because of the restricted stress dissipation, inappropriate stress occurred on the back of the cemented carbide saw tooth. This led to fairly small shearing forces causing a cemented carbide failure. This issue may be addressed by ensuring that the entire length of the joining area is actually filled with the sandwich brazing filler metal.

5.8 Badly shaped saw blade body

The saw's blade body should be adapted to the shape of the cemented carbide [39]. Its seating on the steel should fit the shape of the cemented carbide. All joining surfaces should be consistent. Irregularities or even defects may reduce the quality of the joining area. A critical factor is the correct shape of the radius at the base of the cemented

carbide seating (**figure 31**). If this radius is badly shaped as shown, a cavity will occur along the radius. Although, prior to brazing, a strip of brazing filler metal was inserted along the entire section, there is a risk of the amount of brazing filler metal not completely filling the cavity or of the brazing filler metal having flux or gas entrapped in it. Comparing the surfaces of cavity and gap, you will see that the cavity will soon make up a large share, the consequence being that less surface area is actually joined inside the brazing gap which may reduce the compound's strength.

Figure 30 | Cemented carbide saw tooth brazed using BrazeTec 49/Cu. Cemented carbide damaged by an incorrectly placed sandwich brazing filler metal strip [37]
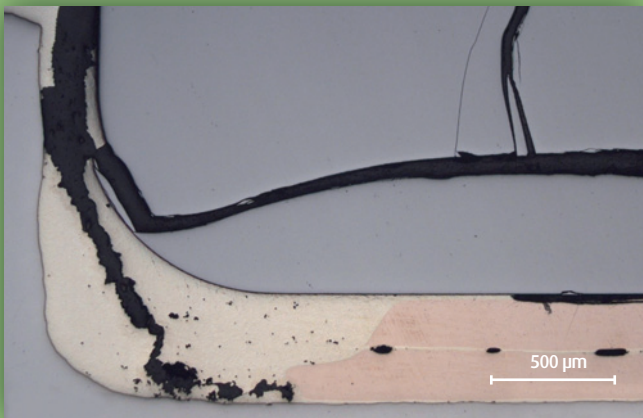

Figure 31 | Badly shaped saw blade body

6. General recommendations

Table 14 | List of brazing processes and hard materials

Hard material	Application	Brazing filler metal	Flux	Method	Atmosphere	Comment
Cemented carbide	Drill (bit)	BrazeTec 4900	BrazeTec special h	Induction, flame	Air	–
Cemented carbide	Saw blade, paper knife	BrazeTec 49/Cu BrazeTec 49/Cu^plus	BrazeTec h 285	Induction, flame	Air	–
Cemented carbide	Surgical instruments	BrazeTec 49/CuNiFe	BrazeTec h 285	Induction	Air	Interlayer, increased corrosion resistance
Cemented carbide	TiN-coated tools	BrazeTec 6488	BrazeTec h 285	Induction, flame	Air	–
Cemented carbide	Chisel	BrazeTec 21/80	BrazeTec s	Induction, furnace	Nitrogen	–
Cemented carbide, low binder content	Milling cutter, saw blade, drill bit, hammer drill	BrazeTec 4900 BrazeTec 49/Cu BrazeTec 21/80	BrazeTec h 900	Induction, flame	Air	Flux for activating the cemented carbide surface
Cermet	Saw blade, milling cutter	BrazeTec 49/Cu BrazeTec 4900	BrazeTec h 900	–	–	Flux for activating the cemented carbide surface
Diamond	Core drill bit, cutting discs	BrazeTec P 1002.1	–	Furnace	Argon 4.8, vacuum	–
PCD / cBN	Indexable tip	BrazeTec CB 4	–	Furnace	Argon 4.8, vacuum	–
PCD / cBN sintered onto cemented carbide	Milling cutter	BrazeTec 5507 BrazeTec 4900	BrazeTec special h	Induction	Air	–
Diamond segments	Cutting wheel	BrazeTec 5507	BrazeTec h 80	Induction	Air	–
Ceramic	Ceramic blade	BrazeTec CB 10	–	Furnace	Argon 4.8, vacuum	–

Table 15 | General recommendations for the brazing of hard material

Hard material	Brazing filler metal systems acc. to DIN EN ISO 17672:2010				Brazing method		
	Silver-based brazing filler metals	Copper-based brazing filler metals	Active brazing filler metals	Nickel-based brazing filler metals	Induction	Flame	Furnace
Cemented carbide	•	•	–	–	•	•	•
Cermet	•	–	–	–	•	•	•
Diamond - pure	–	–	•	•	–	–	•
- in metal matrix (diamond segments)	•	–	–	–	•	•	–
Polycrystalline diamond (PCD) - pure	–	–	•	–	–	–	•
- sintered onto cemented carbide	•	–	–	–	•	–	–
Cubic boron nitride (cBN)	–	–	•	–	–	–	•
PcBN (PcBN sintered onto cemented carbide)	•	–	–	–	•	–	–

Literature

[1] Weise, W., Koschlig, M., Herzog, H., Beuers,J.: Einsatz innovativer Lote in der Schneidtechnik; Tagungsband „Hart- und Hochtemperaturlöten und Diffusionsschweißen", DVS-Berichte Band 192, S. 62 – 67 (1998)

[2] CERATIZIT: Hartmetall für die Holzbearbeitung

http://www.ceratizit.com/services/downloads/?fileid=20&lang=en_file&cHash=3145b211f0464caa43895c07e598bd72

[3] DIN ISO 513:2014: Klassifizierung und Anwendung von harten Schneidstoffen für die Metallzerspanung mit geometrisch be-stimmten Schneiden – Bezeichnung der Hauptgruppen und Anwendungsgruppen

[4] Stahlschlüssel, Verlag Stahlschlüssel Wegst GmbH (2013)

[5] Mahler, M., Zimmermann, K. F.: Löten von Hartmetallen, Technik die verbindet, Band 30, S. 238, Degussa AG (1975)

[6] DIN EN ISO 17672:2010-11, Hartlöten – Lote

[7] Schnee, D.: BrazeTec Präsentation „Grundlagen des Lötens", Hartlötseminar, Technische Akademie Esslingen (2014)

[8] Müller, W., Müller, J.U.: Löttechnik: Leitfaden für die Praxis, S. 128 – 131 für Mg- und Ag-Lote, S. 167 – 174 für Ni-Basislote, S. 197 – 199 Hartmetalle, DVS Verlag GmbH (1995)

[9] DVS Merkblatt 3102: Herstellen von Keramik: Keramik- und Keramik- Metall-Verbindungen durch Aktivlöten, Verlag für Schweißen und verwandte Verfahren DVS Verlag GmbH (2005)

[10] DIN EN 1045:1997-08: Flussmittel zum Hartlöten – Einteilung und technische Lieferbedingungen

[11] Benkowsky, G.: Induktionserwärmung, Verlag Technik GmbH, S. 11 – 23, (1990)

[12] AWS C3 committee: Brazing Handbook, S. 409 – 434 Löten von Cermets und Hartmetallen, S. 430/31 Induktion, S. 623 – 635 Löten von Diamanten, American Welding Society (2007)

[13] DVS Merkblatt 2602: Hartlöten mit der Flamme, Verlag für Schweißen und verwandte Verfahren DVS Verlag GmbH, (2001)

[14] Schnee, D.: Grundlagen des Lötens, Umicore AG & Co. KG, 2. Auflage (2013)

[15] Davis, J. R.: Tool Materials, S. 42 – 53 über Hartmetalle, S. 67 – 76 Keramiken, S. 77 – 84 Beschichtungen für Schneidstoffe, S. 85 – 100 Diamant und CBN, S. 101 – 109 Schleifanwendungen, S. 381 – 382 Löten, ASM International (1998)

[16] Roberts, P.M.: Industrial Brazing Practice, CRC Press LLC (2004)

[17] Raßbach, S.: Hartmetall – ein moderner Hochleistungswerkstoff und seine Perspektiven, Vortrag, Ceratizit (2002)

[18] Schimpfermann, M., Bronny, M.: Hartlöten von HW-Schneidwerkzeugen, HOB – Die Holzbearbeitung, Ausgabe Mai (2011)

[19] Öry, H.: Leichtbau I, II, Umdruck zur Vorlesung an der RWTH Aachen, S. 256 – 257, (1985)

[20] Timoshenko, S.P, Boodier, J.N.: Theory of Elasticity, McGraw-Hill (1987)

[21] Timoshenko, S.P: Analysis of Bi-Metal Thermostats, J. Opt. Soc. Am. 11, S. 233 – 255, (1925)

[22] Lieferprogramm BrazeTec (2013)

[23] Schnee, D., Zenk, C., Magin, M., Rassbach, S., Hafner, T., Meyer, U.: Optimized Brazing Gap Width for Cemented Carbide Tipped Saw Blades, Proceedings of the 5th International Brazing and Soldering Conference, IBSC 2012 USA, S. 149 – 155, (2002)

[24] Magin, M., Rassbach, S.: Stress Analysis on Brazed Hardmetal Saw Teeth, 17. Plansee Seminar, Reutte (2009)

[25] Schnee, D., Zenk, C., Magin, M., Rassbach, S., Hafner, T., Meyer, U.: Einfluss der Bandbreite von Schichtloten auf die Festigkeit der Verbindung von Hartmetall und Stahl bei Sägeblättern, Tagungsband „Hart- und Hochtemperaturlöten und Diffusionsschweißen", DVS-Berichte Band 263, S. 226 – S. 229, (2010)

[26] Sekulic, D. P.: Advances in brazing – Science, technology and application, Woodhead Publishing Limited, S. 160 – 191 CBN; S. 423 – 467 Löten von Schneidstoffen, (2013)

[27] Peaslee, R. L.: Brazing Footprints: Case Studies in High-Temperature Brazing, Wall Colmonoy Cooperation, S. 204 – 207, (2003)

[28] Bex, P. A., Shafto, G. R.: Einfluss von Temperatur und Wärmebelastungsdauer auf das Einsatzverhalten von PKD-Werkzeugen, Diamant-Information M 38, Ademant-Seminar, S. 12 – 18, (1984)

[29] Schimpfermann, M.: BrazeTec Präsentation „Löten in der Werkzeugindustrie", DGM Seminar „Löten – Grundlagen und Anwendungen", RWTH Aachen (2014)

[30] Juza, R.: Nitrides of Metals of the First Transition Series, Advances in inorganic chemistry and radiochemistry, Vol. 9, Academic Press New York, S. 81 – 131, (1966)

[31] Gavrichev, K. S.,. Solozhenko, V. L, Gorbunov, V. E., Golushina, L. N., Totrova, G. A., Lazarev, V. B.: Low-temperature heat capacity and thermodynamic properties of four boron nitride modifications, Thermochimica Acta, 217, S. 77 – 89, (1993)

[32] N.N.: BrazeTec Präsentation „Aktivlöten", Umicore Ag & Co. KG (2014)

[33] Lugscheider, E.: Abschlussbericht zum Forschungsvorhaben: Hartlöten von hartmetallbestückten Bauteilen und Werkzeugen (2002)

[34] Ettmayer, E., Suchentrunk, E.: Über die thermische Stabilität der Eta-Carbide, Monatshefte für Chemie, 101, S. 1098 – 1103, (1970)

[35] Schnee, D.: Technical report, BT-BC-2009-12-18-Sn, Umicore AG & Co. KG (2009)

[36] Starck, S.: Technical report, BT-BC-2011-08-20-Sk, Umicore AG & Co. KG (2011)

[37] Schimpfermann, S.: Batch card, LK-2013-0088, Umicore AG & Co. KG (2013)

[38] Ries, H.: Batch card, LK-2014-0006, Umicore AG & Co. KG (2014)

[39] Schimpfermann, S.: Batch card, LK-2014-0083, Umicore AG & Co. KG (2014)

[40] Schnee, D., Wiehl, G., Starck, S.: Development of Ag-Cu-Zn-Sn brazing filler metals with a 10 weight-% reduction of silver and same liquidus temperature, 2014 International conference on Brazing,..., Beijing (2014)