Feasibility study of fluxless brazing cemented carbides to steel

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Abstract. One of the most important brazing processes is the joints between cemented carbides and steel for the tool industry such as in rotary drill hammers or saw blades. Even though this technique has already been used for several decades, defects in the joint can still occur and lead to quality loss. Mostly, the joining process is facilitated by induction heating and the use of a flux to enhance the wetting of the filler alloy on the surface of the steel and cemented carbide in an ambient atmosphere. However, although the use of flux enables successful joining, it also generates voids within the joint, which reduces the strength of the connection while the chemicals within the flux are toxic and polluting. In this feasibility study, a fluxless brazing process is used to examine the joint between cemented carbides and steel for the first time. For this, ultrasound is applied during induction heating to enable the wetting between the liquid filler metal and the surfaces of the cemented carbide and steel. The ultrasound generates cavitations within the liquid filler metal, which remove the oxides from the surface. Several filler metals such as a silver based alloy Ag449, pure Zn, and an AlSi-alloy were used to reduce the brazing temperature and to lower the thermal residual stresses within the joint. As a result, every filler metal successfully wetted both materials and led to a dense connection. The ultrasound has to be applied carefully to prevent a damage of the cemented carbide. In this regard, it was observed that single grains of the cemented carbide broke out and remained in the joint. This positive result of brazing cemented carbides to steel without a flux but using ultrasound, allows future studies to focus on the shear strength of these joints as well as the behavior of the thermally induced residual stresses.

1. Introduction
Ultrasonically-assisted brazing enables the production of dense joints in an ambient atmosphere without the use of a flux. For this, a sonotrode initiates vibrations in the brazing gap. These high frequency vibrations have two positive effects on the wetting behavior of the materials by generating cavitation in the liquid filler metal. This cavitation break and remove oxide layers and additionally reduce the surface tension of the liquid filler metal. This allows the liquid metal to wet the surfaces. According to Crawford [1], flux-free soldering with the aid of ultrasound was already applied in Germany in 1936, but most recently this approach became a niche application used only by a few companies [2, 3]. In the past decades, several investigations were conducted to analyze the mechanisms of a fluxless soldering and brazing process. Table 1 provides a summary of published studies regarding fluxless brazing with the assistance of ultrasound. It is obvious that most lightweight materials such as Al, Ti, Mg, and its alloys as well as materials, which also resisted oxidations in an ambient joining process such as SiC or WC were analyzed. The brazing temperature for the process depends on the used filler alloy and ranges between 380 °C and 750 °C.
Table 1. Summary of published investigations regarding fluxless brazing with the assistance of ultrasound.

| No. | Material          | Filler alloy       | Temperature (°C) | Year | Source |
|-----|-------------------|--------------------|------------------|------|--------|
| 1   | 1. Al, 2. Copper  | 1. Zn-Al, 2. Pb-Sn | 482              | 1976 | [1]    |
| 2   | Al-Si-Mg          | -                  | Melting Point    | 1994 | [4]    |
| 3   | Al-MMC            | Zn with SiC        | 420              | 2011 | [5]    |
| 4   | Ti₆Al₄V and Al₄Cu₁Mg | Zn-based | 383-403          | 2011 | [6]    |
| 5   | Al                 | Zn₈₆Al₁₄ | 410-470          | 2012 | [7]    |
| 6   | WC-Co and BeCu    | AgCuZnCd          | 640-750          | 2012 | [8]    |
| 7   | Ti₆Al₄V           | Al₈₈Si₁₂         | 600              | 2013 | [9]    |
| 8   | Al an Cu          | Zn₀₇Al₃           | 420              | 2013 | [10]   |
| 9   | Al an Cu          | Zn₀₇Al₃           | 400-480          | 2014 | [11]   |
| 10  | SiC and Ti₆Al₄V   | AlSnZnMg          | 620              | 2013 | [12]   |
| 11  | Mg                 | Zn-based           | 350              | 2013 | [13]   |
| 12  | Al₂O₃             | AlCu₄₋₂Mg₁₋₅      | 700              | 2014 | [14]   |
| 13  | Al and Ti         | AlSiZnCuNi+Sn     | 517              | 2016 | [15]   |
| 14  | SiC               | Al₈₈Si₁₂         | 620              | 2015 | [16]   |
| 15  | TiAl₆V₄           | Al₀₇₃Mg₂₅Cr₀₃     | 660-680          | 2015 | [17]   |

The publications mainly show the significant advantages of an ultrasonically assisted brazing process, since it produces an almost void-free joint even with materials that are difficult to wet, such as SiC, WC, or sapphire. But none of the performed studies deals with the joining process between cemented carbides and steel. A successful application of this ultrasonically assisted technology on brazing cemented carbides to steel would significantly enhance the quality of the joint as a dense structure without any voids would provide a much better mechanical fatigue behavior. Cemented carbides are further known for their complex wetting behavior, which could be improved by ultrasound. Additionally, the reduction of the use of toxic materials such as the flux would be an advantage for many producing companies.

One challenge when developing a steady bonding process is the oxidation behavior of the steel surface during heating. On the one hand, the cavitation will remove the oxides, but on the other hand too many oxides will decrease the joint quality. The presented papers do not provide any experience concerning this circumstance.

2. Experimental
The cemented carbide of the grade K10 (DIN ISO 513:2014-05) and the tool steel UNS T11302 were selected as base materials due to their wide distribution for industrial applications. The properties of the cemented carbide are listed in table 2. The cemented carbide consists of tungsten carbide with 5.6 m% of cobalt as binder, and has a hardness of at least 1730 HV30. The thermal expansion coefficient in a temperature range between 20 and 400 °C is 4.9*10⁻⁶K⁻¹ due to the low proportion of the binder metal. The composition of the tool steel is listed in table 3. This steel grade is an alloy with tungsten, molybdenum, chromium, and vanadium. These alloying elements function as carbide formers and reduce the grain size to enhance the wear resistance of this material. The thermal expansion coefficient of the steel is 12.5*10⁻⁶K⁻¹ for the same temperature range as measured for the cemented carbide. Due to the difference in the expansion coefficients, residual stresses will occur after
the solidification of the liquid filler alloys and affect the strength of the formed joint, especially during the cooling stage.

Table 2. Properties of the cemented carbide K10 DIN ISO 513:2014-05 [18].

| Grade | Carbide | Grain size (μm) | Binder | Proportion of the binder (m%) | Density (g/cm³) | Hardness (HV) |
|-------|---------|----------------|--------|-------------------------------|----------------|--------------|
| K10   | WC      | 0.8-1.3        | Co     | 5.6                           | 14.95          | 1730         |

In the past, filler alloys, which contain a certain amount of cadmium, were used to reduce the brazing temperature and to ensure a strong joint. Since the restriction of using cadmium, higher temperatures are needed to produce sufficient joints with other filler metals, but the process became more complex by handling the residual stresses. Using the ultrasonically assisted brazing process, the lower melting point of other filler alloys could reduce the residual stresses and, additionally, might increase the strength of the joint by providing a larger bonding area due to the reduction of voids.

Table 3. Composition of the tool steel UNS T11302 in m% [19].

| Steel     | C    | W    | Mo   | Cr  | V   | Mn  | Si   |
|-----------|------|------|------|-----|-----|-----|------|
| T11302    | 0.9  | 6.4  | 5.0  | 4.3 | 1.9 | ≤0.4| ≤0.45|

For this investigation, three different filler alloys were selected to analyze their behavior in an ultrasonically assisted brazing process joining the cemented carbides to the tool steel. The chosen filler alloys are listed in table 4. A pure zinc foil was chosen as first filler metal due to its low melting temperature of 420 °C. The second filler was a eutectic aluminum and silicon alloy with a melting temperature of 577 °C. The last filler, a silver based alloy named Ag 449 according to DIN EN ISO 17672 has a melting range from 680 to 705 °C and is commonly used in industrial applications of these joints.

Table 4. Used filler alloys and melting range.

| Filler alloy | Melting range (°C) | Application |
|--------------|--------------------|-------------|
| Zn           | 420                | 250 μm - foil |
| Al_{58}Si_{12} | 577                | 100 μm - foil |
| Ag 449       | 680-705            | 100 μm - foil |

The experiments were carried out in two different setups to analyze the characteristics of each process. The cemented carbides had a size of 10x10x5 mm and the steel of 10x10x3 mm. The specimens were polished and stacked together. The foils of the filler alloys were cut to fit the brazing gap.

The different brazing setups are shown in figure 1. An induction coil provided the heat for the process. In the first setup A the coil was placed below the sample holder and the heat was transferred through the holder to the specimen. The specimen was only fixed with the holder without any additional force to prevent a movement during the applied ultrasound. This setup was successfully tested in different studies for ultrasonically assisted brazing processes [7, 11, 14] and the reason, why it was used for the first brazing experiments of this investigation. A thermocouple measured the temperature close to the brazing gap. The sonotrode was placed on the specimen when the specimen reached the melting temperature of the filler alloy and the ultrasound was activated for 20 s. The heating device was switched off 5 s before the ultrasound, so that the vibrations were still active during the cooling process. The sonotrode was set to a frequency of 20 kHz and an amplitude of 6 μm. In the second setup B, the induction coil was placed directly around the specimen to induce faster heating. Screws were used to fix the specimen. The sonotrode was placed on the upper plate to induce
the ultrasonic vibrations. The steel plate was placed on the top to induce the ultrasound into the joint and to protect the brittle cemented carbides from vibrations.

![Figure 1. Experimental setups of the ultrasonically assisted brazing process.](image)

### 3. Results and discussion

In figure 2, the temperature measurement of the thermocouple is visualized for both brazing setups. The heat needs at least 420 s to heat the specimen to 700 °C in setup A as the specimen holder has to be heated up as well. Due to the long heating time, many oxides were formed on the surface of the steel and exhibit a proper wetting of the filler metal, even with the assistance of the ultrasound. In this regard, the heating speed was significantly increased by the brazing setup B so that the temperature of 700 °C was reached in 7 s.

![Figure 2. Trend of the heating stage of both brazing setups.](image)

The first setup A was used to form a brazed joint between WC-Co and WC-Co with the selected filler alloys to study the effect of the ultrasound on this material, which is usually difficult to wet with liquid fillers. Anyway, it was not possible to form a dense joint between steel and a cemented carbide, because the heating was too slow and too many oxides were formed on the surface of the steel. Figure 3 shows the joint that was produced with a zinc filler metal and a process temperature of 450 °C. The ultrasonic vibration was activated until the zinc solidified. The cross-section shows the dense structure of the joint. Both surfaces of the cemented carbides were well linked to the solidified filler metal. The width of the joint decreased to 145 µm. Within the joint, a lamellar structure is noticeable. This structure resembles a freeze-frame of the vibrations within the joint, respectively, the interferences of the ultrasonic waves in the liquid metal. Here, particles of the cemented carbide and of ZnO have accumulated on the dead centers of the waves to form this unique structure.
By switching to setup B, it was also possible to braze the cemented carbide to steel by using different filler metals. In this regard, figure 4 shows the cross-section of the brazed joint, which was produced by using the Zn filler metal at a process temperature of 450 °C. This process formed a dense structure without any voids. Both the steel and the cemented carbide were connected to the filler metal. At the interface of the cemented carbide, single broken WC grains can be identified within the brazements. The joint gap has a width of 250 µm. The shadows at both interfaces are related to the preparation as the filler metal is much softer than the cemented carbide and the steel, so that a hollow was formed in the joint.

The cross-section of the joint with the Al₈₀Si₁₂ filler alloy and an increased process temperature of 600 °C in figure 5 reveals a dense almost eutectic structure without any voids as well. Some solid solutions of Al and Si, which have a different composition than the eutectic of Al and Si, can be recognized in the filler. Actually, no dense intermetallic layer of iron aluminide was formed at the T11302 interface. This was probably because the brazing process was fast enough or the cavitation helped to prevent a forming of these brittle phases, which decreased the strength. In this brazement, the brazing gap reached a width of 54 µm. Additionally, some WC-Co particles can be found in the joint, which certainly broke from the surface of the cemented carbide due to the ultrasonic vibrations.
Ag 449 formed a tight joint at a brazing temperature of 850 °C, figure 6. In this case, the brazing gap reached a width of 33 µm. It is obvious that no single WC grains but large WC-Co particles were broken out of the surface of the cemented carbide and stuck in the joint. In fact, the used cemented carbide is very sensitive to ultrasonic vibrations and cracks are easily induced during the process due to the brittleness of the cemented carbide.

4. Conclusion and Outlook
This feasibility study analyzed the ultrasonically assisted brazing process to join cemented carbides to steel. Starting from a brazing setup that was used in former studies for ultrasonically assisted brazing processes, the heating was too slow to ensure a fast brazing process and the oxidation of the steel surface prevented a tight joint due to the long heating time. The oxidization does not affect the cemented carbide during the heat treatment and the cavitation of the induced ultrasonic vibrations enabled a sufficient wetting of the liquid filler metal instead of using a hazardous flux. By improving the brazing setup to accelerate the heating, the oxidation of the steel was minimized, and a successful brazing to cemented carbide was realized with different filler alloys. The different filler enable an improvement of the residual stresses within the joint due to the lower brazing temperatures compared to commonly used silver based alloys. In addition, a rupture of some WC grains or bigger cemented carbide particles was observed within the joint.

In this regard, it is necessary to study if the vibrations affect the strength of the cemented carbides by micro cracking or if the particles are just released from the surface of the cemented carbides. In this case, the vibration parameters have to be improved to enable a good wetting of the filler alloys on both surfaces and to minimize the weakening of the cemented carbide. In addition, shear tests will be
performed to measure the strength of the joint and to investigate if an improved performance can be obtained utilizing this new process handling when compared to the use of fluxes.

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