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Electrical contacting of High-Velocity-Air-Fuel sprayed NiCr20 coatings by brazing

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Abstract. Thermally sprayed heater coatings can be used to control the surface temperature of parts and tools. A crucial point for such applications that has been neglected in the past is a reliable electrical contact with the power supply. One possible solution is the soldering or brazing of cables and cable connectors onto the heater coating. In this study, the possibility of brazing cable connectors to High-Velocity-Air-Fuel sprayed NiCr20 coatings was investigated to ensure electrical contact. The eutectic Ag-Cu filler was used for the vacuum brazing process. The insufficient wetting of the filler on the as-sprayed coating surface and the favored wetting of this filler on the copper cable connector led to low joint quality. This joint was improved by grinding the coating surface and changing the cable connector’s material. Furthermore, measurements of the heater coatings’ electrical resistance confirmed that electrical contacting by brazing is possible without significant influence on the heater coatings’ properties.

1. Introduction
To prevent premature solidification of the melt and thus to enable the fabrication of thin-walled parts, in short cycle time by means of the die-casting process, increasing the surface temperature of the die-casting mold is sufficient. Among others, the concept of surface heating by means of a heater coating on the tool surface represents a time and energy-efficient solution, since the temperature of the interface between the tool and the melt and the heat exchange can be controlled directly. A typical structure of such a heating element is shown in figure 1. A bond coating is applied to the tool to ensure the following layers to adhere. For electrical insulation two ceramic coatings surround the heater coating.

![Figure 1. Schematic illustration of a coating structure of a heating element.](image-url)
One important component of the system is the heater coating, as the surface heating is realized with it. Thermally sprayed heater coatings have been investigated in numerous studies. The heater coating development by atmospheric plasma spraying (APS) [1] and High-Velocity-Oxygen-Fuel (HVOF) [2] was examined, inter alia, by Prudenzia et al. For the heater coating different feedstock materials have been investigated in the literature, which can be divided into two categories. One category of feedstock materials are ceramics, which have been investigated by M. Floristán et al. by the application of TiO$_2$ heater coatings onto Li$_2$O$_x$:Al$_2$O$_3$:SiO$_2$: glass substrate [3] and S. Schetitz et al. by examining TiO$_2$ and CrO$_2$-TiO$_2$ as feedstock material [4]. The other investigated group of materials used in these applications are metallic heater coatings. FeCr-alloys, CrAl-alloys and NiCr-alloys have been investigated by Killinger et al. [5]. Michels et al. studied the properties of NiCr20 coatings [6]. The authors have investigated the heating behavior of heater coatings [7] and their temperature distribution [8] in case of plasma sprayed TiO$_2$/Cr$_2$O$_3$ before.

Although the general feasibility of thermally sprayed coatings as a heating element has been investigated in the literature, little attention has been payed to the electrical contact to the coating. In the papers referenced here, it is not mentioned nor described in detail, how the electrical contact has been realized. In the industry, this variant of tempering has not been used so far and therefore no contacting concept has been implemented yet. Since the electrical contact is crucial for the functionality of the heater coating system and must be carefully adjusted for the aimed application, it is necessary to develop suitable concepts. Therefore, a possible contacting of the heater coating by brazing a connector is investigated in this paper. Generally, literature on the brazing of additional parts onto thermally sprayed coatings is sparse. In most cases, the filler metals were used as a thermally sprayed coating e.g. Nicolaus et al. [9]. The behavior of a coating onto which a brazing alloy has been applied by thermal spraying has been examined before. Bobzin et al. [10] and Zhao et al. [11] applied brazing alloy Al12Si on aluminium substrates. The substrates were coated with the brazing alloy by cold spraying process. In this paper, it will be investigated whether the filler metal can be brazed onto a thermally sprayed High-Velocity-Air-Fuel (HVAF)-NiCr20 surface coating and a sufficient connection can be achieved.

2. Experimental and materials

2.1. Thermal spray process

The substrates are hot-working steel coupons made of X38CrMoV5-1. This steel was chosen because it is often used to produce modular die-casting tools. Before the thermal spraying processes, the substrates have been prepared by grit blasting with corundum with the fraction of F16. A bond coat made of NiCr20 and an insulation coating made of Al$_2$O$_3$ were first applied with APS, which is a common process for ceramic coatings, using a TriplexPro-210 gun (Oerlikon Metco Europe GmbH, Kelsterbach, Germany). The parameter sets used to apply these two coatings are listed in table 1. All parameters presented in this paper are based on previous studies performed at the Surface Engineering Institute, Aachen. During the deposition, the gun was mounted on a robot and traveled above the sample in a meandering path.
Table 1. Parameter set to apply the NiCr20 bond coating and the Al₂O₃ substrate insulation using APS.

| Parameter                        | Unit    | NiCr20 Bond coating | Al₂O₃ Insulation |
|----------------------------------|---------|---------------------|------------------|
| Normal particle size distribution| [μm]    | -53 +20             | -45 +20          |
| Flow rate of argon               | [SLPM]  | 70                  | 60               |
| Flow rate of hydrogen            | [SLPM]  | 0                   | 6                |
| Electrical current               | [A]     | 400                 | 450              |
| Spray distance                   | [mm]    | 120                 | 120              |
| Nozzle diameter                  | [mm]    | 9                   | 9                |
| Traverse speed of the gun        | [mm/s]  | 800                 | 800              |
| Offset of the meandering path    | [mm]    | 5                   | 5                |
| Rotation speed of the conveyor disk| [%]   | 15                  | 20               |
| Cooling                          | [MPa]   | 0.5                 | 0.5              |
| Flowrate of carrier gas argon    | [SLPM]  | 4.5                 | 5.5              |
| Passages                         | [-]     | 5                   | 9                |

The feedstock material used to apply the heater coating is also NiCr20, same as the material used for the bond coating but in this case with a nominal particle size distribution of -25 + 5 μm. To apply the heater coating onto the APS-sprayed insulation coatings the HVAF process was used with an AK 7 Gun (Kermetico Inc, Benicia, USA) equipped with a shortened 3L nozzle. The parameter settings used to apply the heater coating in this study are listed in table 2. As in case of the bond coat and the substrate insulation, the gun was carried by a robot and traveled in a meandering path. The HVAF process, which is used to achieve a low oxidation, necessitates the selection finer particle size for the heater coating compared to the bond coat.

Table 2. Parameter set for applying the NiCr20 heater coating.

| Parameter                        | Unit   | NiCr20 Heater coating |
|----------------------------------|--------|-----------------------|
| Normal particle size distribution| [μm]   | -25 +5                |
| Pressure of compressed air       | [MPa]  | 0.61                  |
| Pressure of propane              | [MPa]  | 0.55                  |
| Flowrate of carrier gas nitrogen | [SLPM] | 37.2                  |
| Spray distance                   | [mm]   | 250                   |
| Nozzle type                      | [-]    | shortened 3L          |
| Traverse speed of the gun        | [mm/s] | 1,000                 |
| Offset of the meandering path    | [mm]   | 5                     |
| Rotation speed of the conveyor disk| [rpm]| 3.5                  |
| Cooling                          | [MPa]  | 0.5                   |
| Passages                         | [-]    | 4                     |

The samples can be divided into two groups, one with the smaller dimension of 30 × 30 × 8 mm³ and the other one with the greater dimension of 100 × 18 × 8 mm³. The samples with the smaller dimension were named with prefix “A” followed by the sample number. The aim of the experiments done with the samples of group “A” is to investigate the brazing ability of the coating and to identify the suitable pretreatment for the brazing process. During the deposition of the heater coating, a mask was mounted on the sample surface, which reduced the heater coating to a dimension of 20 × 15 mm². This is necessary to prevent any electrical contact between the heater coating and the substrate. To optimize the brazing process in the experimental examination, two samples of the described dimension were ground
with 1,200# SiC abrasive paper before the brazing process. Figure 2 a) and b) shows the as-sprayed sample A1 and the corresponding height profile with the determined arithmetic average roughness Ra. The ground sample A3 is shown in figure 2 c) and d). The height profile and the corresponding roughness value Ra were measured using the Keyence VK-X200 (Keyence Corporation, Osaka, Japan).

![Figure 2](image)

**Figure 2.** a) as-sprayed sample A1 with b) corresponding height profile and c) ground sample A3 with d) corresponding height profile.

### 2.2. Brazing process

In this study the joint of electrical contacting by brazing was examined. The choice of a suitable filler metal should be made under the consideration of the application environment. According to the literature of Long et al. [12] and Norwood et al. [13], the surface temperature of casting dies during high pressure die-casting of aluminum alloys can reaches as high as $T \approx 450^\circ C$ – $500^\circ C$. Based on this condition the eutectic AgCu alloy (72 wt.-% Ag, 28 wt.-% Cu) was chosen as a foil filler metal, with the dimension of $7 \times 12 \text{ mm}^2$, to braze the electrical connector on the heater coating. The eutectic AgCu alloy, with its melting temperature of $779^\circ C$, is able to withstand the high temperatures of the die-casting process and the brazing temperature is low enough to keep the impact on the microstructure of the coating system as low as possible. The electrical contacts used in this study were common cable connectors, with and without copper cable attached, and a X5CrNi18-10 steel screw. The brazing process was carried out in vacuum furnace MOV 533T (PVA TePla Industrial Vacuum Systems GmbH, Wettenberg, Germany). The time-temperature setting of the brazeing process is shown in figure 3, the process was established in a previous project for a similar filler metal. The peak temperature is above the tempering temperature of the chosen X38CrMoV5-1 substrate. However, the focus of this study was to investigate the realization of a suitable bonding of the electrical connector to the heater coating by brazing. The future areas of application for the presented heating coatings are injection moulding and die-casting. In these applications, it is not practical to treat the entire tool in a brazing process, as only small areas of these tools need to be connected. These connections can then be brazed using laser brazing or induction brazing. Therefore, in this first step only the bonding mechanism of the AgCu filler metal to the connector and the NiCr20 heater coating are of interest.
Figure 3. Time-temperature setting of the brazing process.

Three samples of the group “A” were fabricated in this study. Sample A1, remained in as-sprayed state and was brazed with a cable connector with a copper cable inside. The surface of the heater coating of A2 was slightly grounded with 1,200# SiC abrasive paper. As electrical contact for A2, a cable connector without a copper cable was used. In case of A3 the cable connector was replaced by a steel screw. The parameter settings of the brazing process remained the same as for all specimens.

After the brazing ability examinations, two samples of same type with the greater dimension were fabricated to obtain a statistical validation. These two samples are named with the prefix “B” followed by the sample number. The longer shape of the samples in group “B” enables the deposition of a heater coating with the shape of a conducting track with the help of a corresponding mask. The samples were produced in the same manner and with the same parameter in table 1 and table 2. An overview of the fabricated samples is given in table 3.

Table 3. Overview of the fabricated samples.

| sample | preparation for brazing | electrical connector | sample shape         |
|--------|-------------------------|----------------------|---------------------|
| A1     | as-sprayed state        | Cu cable connector with copper cable | square brazing joint |
| A2     | grounded with 1,200 SiC | Cu cable connector without copper cable | square brazing joint |
| A3     | grounded with 1,200 SiC | X5CrNi18-10 steel screw | square brazing joint |
| B1.1   | grounded with 1,200 SiC | X5CrNi18-10 steel screw | conducting track    |
| B1.2   | grounded with 1,200 SiC | X5CrNi18-10 steel screw | conducting track    |

Additionally, an area of the heater coating was covered with an Al2O3 top insulation, which was necessary for further examinations. This top insulation was applied with the APS process using the same parameter sets as taken for the bottom insulation. The conducting track has two circular areas at its ends that function as the contact surface. The contact surfaces of the heater coating were also ground and steel screws were brazed to the sample with the same parameter sets as used before. Figure 4 shows a schematic illustration of these samples. The influence of the brazing process on the heater coating was investigated by testing the electrical resistance of the conducting tracks on B1.1 and B1.2 using four wire method with TM-508A (Isothermal Technology, Southport, United Kingdom).
3. Results and discussion

Figure 5 a) shows a closer view of sample A1 after the first brazing trial, in which the cable connector mounted with a copper cable was brazed onto the heater coating in the as-sprayed state. The area of the filler metal foil is still visible as a dark grey spot on the surface. Between the copper cables, a trace of the eutectic AgCu filler metal is visible. The capillary effect caused by the fine wires of the cable allows the filler metal to flow upwards along the cable connector, is one possible explanation for this phenomenon. Furthermore, a larger filler metal droplet on the surface of the heater coating is clearly noticeable. This droplet formation, as well as the visible gap between the cable connector and the coating, indicates poor wetting of the filler metal on the heater coating. This low wettability is probably caused by an oxide layer on the surface. Therefore, it must be concluded that this first brazing attempt was not successful.

The copper cable was removed from the cable connector for sample A2 to investigate whether the capillary effect caused by the copper wires was the main reason for the poor bonding between the cable connector and the heater coating. In addition, the surface of the heater coating was lightly ground with a 1200# SiC abrasive paper to remove the oxide layer. Figure 5 b) shows a closer look at the sample A2. A droplet formation on the surface of the heater coating can also be seen here, but it is not quite as pronounced as in the previous trial. The visible gap between cable connector and heater coating also indicates a weak connection of the two components. Therefore, the quality of the connection still remained insufficient despite the two chosen measures.

To examine the underlying mechanisms in more detail, cross sections of the brazed position were prepared. The brazing gap of sample A2 was examined closely under the scanning electron microscope
(SEM), as shown in figure 6 a) and figure 6 b). Both images confirm that the filler metal only partially connects the cable connector with the heater coating. This poor connection is not sufficient to guarantee a functional electrical contact of the resistance heating element. The SEM images also indicate that most of the filler metal disappeared from the brazing gap even without the cable.

![Figure 6. SEM images of the brazing gap of sample A2 in a) central position and b) side position.](image1)

Figure 6. SEM images of the brazing gap of sample A2 in a) central position and b) side position.

Figure 7 shows another SEM image of the A2 sample, in which a bright film at the edge of the cable connector is visible. Apparently, the filler metal flowed upwards along the surface on the side of the cable connector.

![Figure 7. SEM image of sample A2 at the side of the cable connector.](image2)

Figure 7. SEM image of sample A2 at the side of the cable connector.
The cylindrical section of the cable connector was cut and its surface was examined. In addition to the SEM images of the lateral surface of the cable connector, energy dispersive X-ray (EDX) measurements were carried out at selected positions to provide evidence of AgCu filler metal on the lateral surface of the cable connector. SEM images were taken at the middle section and the section far from the heater coating surface. Figure 8 shows two examples of the SEM images taken at these two sections. The EDX measurement points were marked with arrows on the images.

**Figure 8.** EDX analysis of A2 copper cable connector after brazing process at a) middle section and b) far section. Measurement points are marked with arrows.

Table 4 shows the results of the EDX analysis. It is evident that even at the far section silver can be detected on the surface of the cable connector. It can be concluded that even without the copper wire inside the cable connector the filler metal flowed up and along the surface of the cable connector due to its excellent wettability on the cooper connector. Thus, there is not enough filler in the gap between the cable connector and the coating to form a satisfactory connection. Therefore, neither grinding nor removing the copper cable from the connector are sufficient to achieve a satisfactory connection.

**Table 4.** EDX results of the side surface of the cable connector.

| Position | Element [wt.-%] | Ag | Cu | Al | O |
|----------|-----------------|----|----|----|---|
|          | Ag              | 92.60 | 3.74 | 3.66 |
|          | 92.57 | 4.10 | - | - | 3.33 |
|          | 93.44 | 6.52 | - | - | - |

Based on the results obtained with A1 and A2, a steel screw was used as the connector for A3 to prevent the upward flow of the filler metal. On the other hand, the HVAF-sprayed NiCr20 heater coating was further ground with 1200# SiC abrasive paper until most of the coating surface appears glossy. The aim is the removal of most of the surface oxide to further increase the filler metal’s wettability on the coating. Likewise, the lower arithmetic average roughness Ra of the ground sample, which is shown in figure 2 b) and d), should result to a better wettability. Figure 9 illustrates the new trial with sample A3. Neither droplet formation nor a gap between the screw and the coating is visible.
The investigation of A3 indicates that the use of a steel screw and the thoroughly grinding of the heater coating’s surface can ensure a good bonding between the screw and the coating. Therefore, this concept was used to fabricate the samples B1.1 and B1.2. A closer look at the brazing gap of sample B1.1 using SEM in figure 10 a) shows that the filler metal has completely filled the gap between the screw and the heater coating and has distributed itself homogeneously. The filler adheres well to both. The wetting of the screw and the coating surface therefore is satisfactory. The closer observation of the interface between the filler metal and the heater coating shows, that the filler metal was able to penetrate into the coating along the splat boundaries by capillary effect, see figure 10 b). Furthermore, EDX results, which are shown in table 5, confirm that silver can be detected in the gap. A solid bonding was formed.

Figure 9. Sample A3 after brazing process.

Figure 10. a) SEM image of brazing gap and b) EDX analysis of sample B1.1 after brazing process.
Table 5. EDX results of sample B1.1.

| Position | Element [wt.-%] |  
|----------|----------------|
|          | Ag      | Cu    | Ni   | Cr |
| 1        | 90.80   | 5.15  | 4.05 | -  |
| 2        | 3.79    | 80.55 | 15.66| -  |
| 3        | -       | -     | 81.45| 18.55|

Further cross section of B1.1 was also examined by SEM, see figure 11 a). Furthermore, the boundary layer of the coating is dissolved by the filler metal. A closer look at the boundary layer, as shown in figure 11 b), reveals that the filler metals nearly reaches the insulation coating. This diffusion process results in the formation of a solid bond.

Figure 11. a) SEM image and b) closer SEM image of the B1.1 sample.

To investigate the influence of the brazing process on the functionality of the heater coating as a resistance heating element, the electrical resistance of samples B1.1 and B1.2 was measured before and after the brazing process. To verify the electrical resistance measurement both samples were fabricated similar. Table 6 shows that there are no significant differences in electrical resistance between measurements. Although the filler metal infiltrated the coating, this phenomenon only takes place in the connection area. The microstructure of the linear section of the conducting track should remain mostly uninfluenced, since the electrical resistance of the coating show almost no difference before and after the brazing process. Therefore, it can be assumed that the electrical contacting of the NiCr20 heater coating by brazing seems promisingly.

Table 6. Electrical resistance measurement.

| Sample | Electrical resistance [mΩ] |
|--------|---------------------------|
|        | Before Brazing | After brazing |
| B1.1   | 455            | 464           |
| B1.2   | 534            | 534           |
4. Conclusions and Outlook
As the electrical contacting of the thermally sprayed heating elements has only been investigated to a very limited extent so far, it is necessary to examine the possibilities of contacting further. The aim of this study was to investigate the brazing of cable connectors onto a HVAF sprayed heater coating to realize an electrical contact. For this purpose, a multilayer resistance heating element was fabricated. A NiCr20 bond coating and a Al2O3 insulation coating were applied using the APS process. The subsequent NiCr20 heater coating was applied via HVAF process. An electrical connector was brazed onto the heater coating with a eutectic AgCu filler metal. The braze gap and the bonding mechanism of the connector to the coating were analysed. The results can be summarized as follows:

- An as-sprayed coating surface has an oxide layer, which greatly reduces the wettability of the coating. The wettability can be increased by grinding the surface.
- Cable connectors made of copper are unsuitable for the studied case, since the filler metal’s excellent wettability on copper leads to its upward flow during the brazing process and an insufficient bonding to the heater coating. Replacing the cable connector with a steel screw prevents this phenomenon and sufficient bonding can be achieved.
- If the coating surface is sufficiently wetted, the filler metal penetrates the heater coating and forms a firm solid bonding.
- The filler metal AgCu (72 wt.-% Ag, 28 wt.-% Cu) is a suitable material selection for the combination of a NiCr20 heater coating and a X5CrNi18-10 steel screw.
- The used brazing process has no significant influence on the electrical resistance of the HVAF sprayed NiCr20 heater coating.

After the coating surface was ground and a steel screw was used as an electrical connector, the brazing process enabled a satisfactory connection to the heater coating. In further studies, the developed contacting must be validated in heating cycle tests. Thereby it must be examined whether this contacting can withstand requirements and high heating rates. In future studies it must also be investigated if the presented combination can be bonded using laser or induction brazing. These processes would prevent an improper heat affection of the tools in the intended applications.

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