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Influence of direct electric current on wetting behavior during brazing

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Abstract The wetting behavior of liquid metals is of great importance for many processes. For brazing, however, a targeted modification beyond the adjustment of conventional process parameters or the actual set-up was not possible in the past. Therefore, the effect of direct electric current along the surface of a steel substrate on the wetting behavior and the formation of the spreading pattern of an industrial nickel-based filler metal was investigated at a temperature above $T = 1000\text{ °C}$ in a vacuum brazing furnace. By applying direct current up to $I = 60\text{ A}$ the wetted surface area could be increased and the spreading of the molten filler metal could be controlled in dependence of the polarity of the electric current. The electric component of the Lorentz force is supposed to be feasible reasons for the observed dependence of the electrical polarity on the filler metal spreading direction. To evaluate the influence of the electric current on the phase formation subsequent selective electron microscope analyses of the spreading pattern were carried out.

Keywords brazing, electric current assisted wetting, Lorentz force

1 Introduction

The wetting behavior of metallic substrates by liquid metals is decisive for many technical manufacturing

processes. As an example, processes like welding, brazing, casting, thermal spraying and their many variations can be mentioned [1–4]. The conventional methods to influence the wetting behavior in such processes are either adjusting the process parameters like temperature of the liquid metal and the substrate, the use of fluxes, or modifying the chemical composition of the liquid metal by adding alloying elements. Another already established and often used method is the modification of the solid interface by applying wettable coatings via thermal spraying or physical vapor deposition technology [1,5,6]. Regarding technical production processes a remarkable approach is the application of electric current at the interface between the substrate and the liquid metal. This approach is based on the effect of electrowetting, which can be described as modifying the surface tension between a solid and a liquid phase due to electric current at the interface. By this the wetting angle can be improved. This effect is applied in a wide range of applications like microfluid transport, lab on a chip devices, electronic displays, adjustable lenses, and tunable optical fiber devices [7–9]. In these fields of application, no interactions between the liquid and the solid phase occur. Only few publications describe the effect of applying electric current in technical production processes like brazing technology with possible interactions between the substrate and liquid metal [10–13]. In these publications, emphasis was placed on the potential effects of the electric current passing the brazing joint orthogonal to the joint plane. Improved wetting angle and enhanced formation of intermetallic compounds are the observed effects due to supposed electrowetting, electromigration and Marangoni convection. No publications are dealing with the influence of electric current along the interface. Thus, to investigate further possible effects, the focus of the current study is set on the influence of electric current along the brazing interface between the base material and filler metal. Beyond the benefits of applying electric current described in relevant literature like improving the wetting angle this approach enables the

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control of the wetting behavior including directing the filler metal spreading.

2 Experiments

The wetting experiments have been conducted in a PVA MOV 553 vacuum furnace (Wettnberg, Germany). To conduct electric current assisted wetting experiments an experimental setup was developed, Fig. 1. A Peak Tech I530 power source (Ahrensburg, Germany) was used to provide direct current (DC). The temperature and the electric current were measured with an HBM Quantum MX 840 B measuring amplifier (Darmstadt, Germany). To exclude the influence of Joule heating, the temperature was measured directly at the surface of the base material during the process. In order to avoid any influence of the electric current on the temperature measurement the thermocouple was covered in an alumina shell.

The utilized base material was a U-shaped structural steel AISI 1045. To ensure reproducible surface roughness the relevant surfaces of the base material were treated with grinding paper up to 1200 SiC before the experiments. The electric conductors were attached to the base material by screws. To consider possible influences of electromagnetic fields within the furnace the position of the samples was varied, Fig. 1.

The applied filler metal tape consisting of metallic filler metal powder and organic binder was B-Ni2 of Innobraz (Esslingen, Germany). According to the data sheet, the filler metal contains nickel, chromium, silicon, boron, and iron, as listed in Table 1. The specified melting range of the filler metal is $970\text{ °C} \leq \Delta T \leq 1000\text{ °C}$. The wetting process parameters are shown in Table 2.

To avoid a possible evaporation of the filler metal or the electric conductors the process, starting from the temperature of $T = 600\text{ °C}$, was carried out in an argon atmosphere with a static pressure of $p = 500\text{ mbar}$. Electric current was applied during the complete liquid phase of the filler metal.

In detail, electric current was applied during heating up from a temperature of $T = 900\text{ °C}$, during the brazing time, and during cooling down to a temperature of $T = 900\text{ °C}$, Fig. 2. Subsequent selective electron microscope (SEM) analyses of the spreading pattern cross sections were carried out with a Jeol JSM 7000F (Akishima, Japan).

3 Results and discussion

For the applied electric current of $I = 60\text{ A}$ (DC) the temperature measurements showed that the influence of Joule heating on the sample temperature is negligible for the case of utilized process temperature of $T = 1080\text{ °C}$. The measured surface temperature of the samples varied by a temperature difference of $\Delta T = 2\text{ K}$ around the process temperature. All samples with and without the application of electric current showed residues around the filler metal after the wetting experiments. It is supposed that these are binder residues and thus no effect of the electric current on the wetting behavior. Figure 3 shows macroscopic and light microscopic top view images of V1 and V2. Without the application of electric current during the wetting experiment the surface of the wetting pattern is slightly bigger than the original shape of the filler metal before the brazing process. Furthermore, in this case the spreading of the liquid filler metal takes place homogeneously in all directions, Fig. 3(a). When applying electric current of $I = 60\text{ A}$ during the wetting experiment the surface of the wetting pattern is approximately three times bigger than of the original shape of the filler metal and also bigger than the wetting pattern without the application of electric current. One reason for this can be the modification of the surface tension between the liquid filler metal and the solid base material. Moreover, the spreading of the liquid filler metal is directed significantly towards the negative pole of the base material. The spreading of the liquid metal towards the positive pole is suppressed compared to the case without the application of electric current, Fig. 3(b).

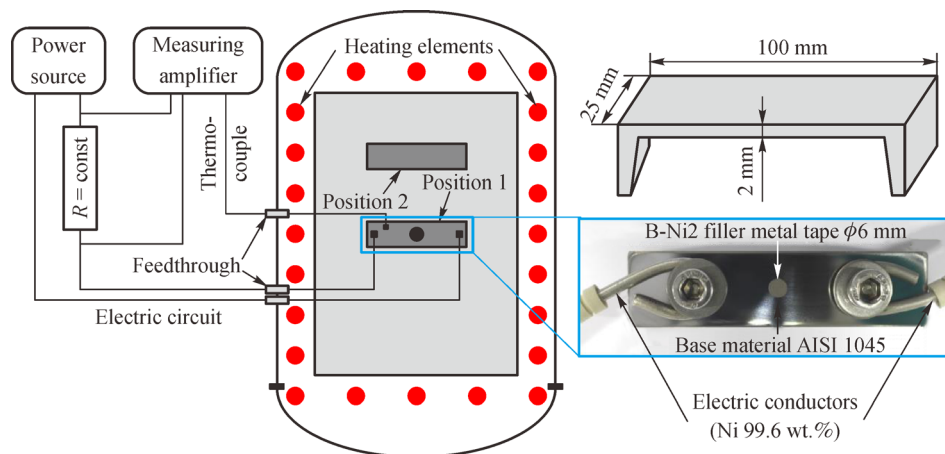


Fig. 1 Top view cross section schematic sketch of the experimental setup indicating the used position of the samples. R: Electric resistance.

Table 1 Chemical composition of B-Ni2 filler metal

Chemical composition	Weight percent/wt. %
Ni	balance
Cr	7.0
Si	4.5
B	3.1
Fe	3.0

A possible physical explanation may be the effect of electrolysis. Here, the remaining existing metal oxide could be reduced by the electric current. In this case the electrolysis process starts at the negative pole and propagates along the surface towards the positive pole leading to an oxide free and better wettable surface as time progresses. At some point the surface at both sides of the spreading pattern should be free of oxides which leads to better wetting on both sides of the spreading pattern. Due

Table 2 Wetting process parameter

Sample	Position	Electric current (DC)/A	Temperature/°C	Time/min
V1	Position 1	0	1080	10
V2	Position 1	60	1080	10
V3	Position 2	60	1080	10
V4	Position 2	-60	1080	10

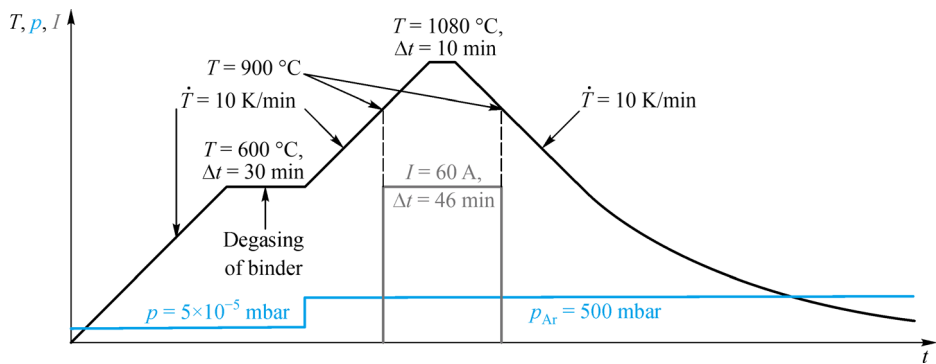


Fig. 2 Time vs. temperature, pressure, and electric current regime.

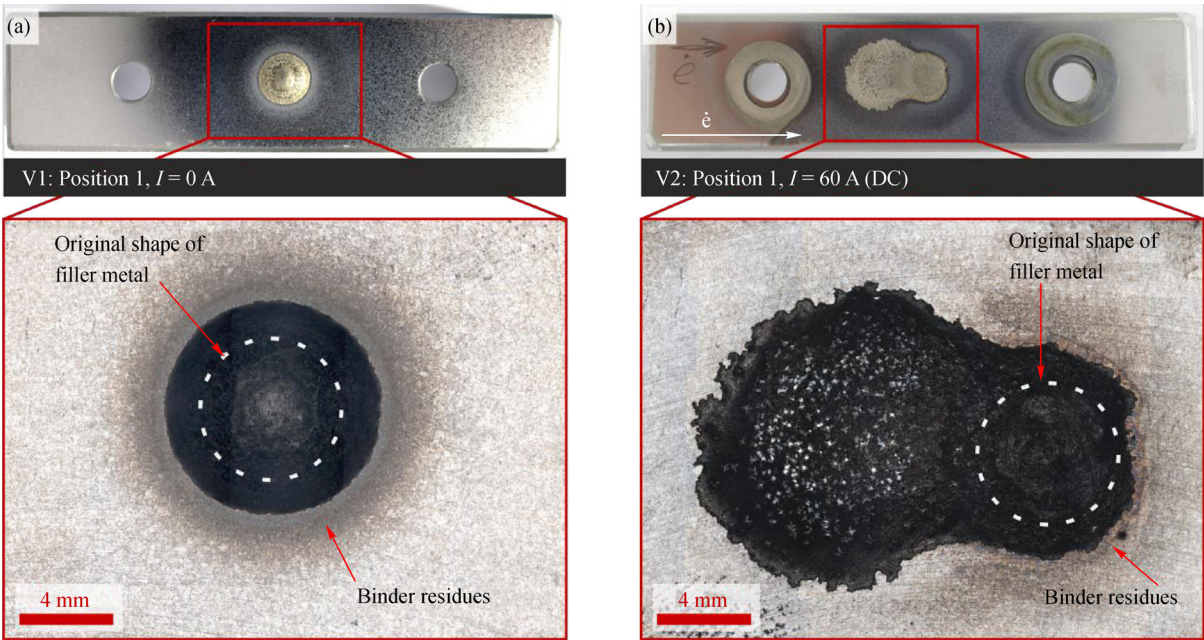


Fig. 3 Macroscopic and light microscopic top view image of the wetting pattern of (a) V1: Position 1, $I = 0$ A and (b) V2: Position 1, $I = 60$ A (DC).

to the observed suppression of the filler metal spreading towards the positive pole it is assumed that electrolysis is not the reason for the observed directed spreading of the filler metal.

Another possible reason for the observed effect is the Lorentz force of the electric field via electrostatic attraction. Lorentz force is the combination of electric and magnetic forces on charged ions in electromagnetic fields. For the case of production processes like casting of metal alloys it was already shown that Lorentz force causes a melt flow of liquid metals which leads to grain refinement during the solidification [14–17]. Furthermore, the magnetic component of the Lorentz force is used for measuring contactless the flow of liquid metals like aluminum via Lorentz force velocimetry [18,19]. At a temperature of $T = 1080\text{ }^{\circ}\text{C}$ the relevant elements of the filler metal are not ferromagnetic due to their Curie temperature which is $T_{\text{Curie, Ni}} = 354\text{ }^{\circ}\text{C}$ for nickel and $T_{\text{Curie, Fe}} = 771\text{ }^{\circ}\text{C}$ in the case of iron [20]. Thus, in the present case the magnetic component of the Lorentz force may not influence the liquid filler metal. However, the electrical component of the Lorentz force is relevant in the present case. Therefore, the positive charged metal ions of the filler metal are moved in the direction of the negative pole and opposite to the direction of the electron flow due to the electrostatic attraction which is the electric component of the Lorentz force.

The influence of the electrostatic attraction on material transport in metals was already observed in electromigration processes. Electromigration is a current induced material transport in metals. Here, two main driving forces are differentiated [21–24]. The first one is the wind force which is the momentum transfer upon an impact of the electrons to the ions in an electric field and acts in direction

of the electron flow. To achieve a material transport by the wind force high current densities up to $J = 10^7\text{ A/cm}^2$ are necessary. Thus, the wind force is not relevant in the present case due to the low applied electric current and the observed filler metal spreading direction opposite to the electron flow. The second driving force in electromigration processes is the direct force which is an influence of the electric field on the ions in the material. This is also the electrical component of the Lorentz force. Since in the present case the material transport takes place by surface and not volume diffusion and in the case of a liquid filler metal the positive charged ions are not bound in a crystal lattice the influence of the applied electric field might be high enough to cause the observed directed material transport, Fig. 4.

To evaluate the influence of the electric current on the phase formation subsequent SEM analyses of the spreading pattern were carried out. Figure 5 shows SEM cross section images of V1 and V2. In both cases the interactions of the filler metal and the base material are very pronounced, which can be seen by comparing the original and the present interface. Thus, the base material was dissolved during the wetting process by the filler metal which leads to a higher amount of iron in the spreading pattern than specified in the datasheet of the filler metal.

Furthermore, in both cases intermetallic chromium rich borides can be detected in the spreading pattern. Figure 6 shows SEM cross section images and the corresponding energy dispersive X-ray (EDX) mappings at the initial position of the filler metal before spreading. Here the highest fraction of the chromium rich borides was found in the spreading pattern cross section for V1 and V2. Without the application of electric current, the fraction of chromium

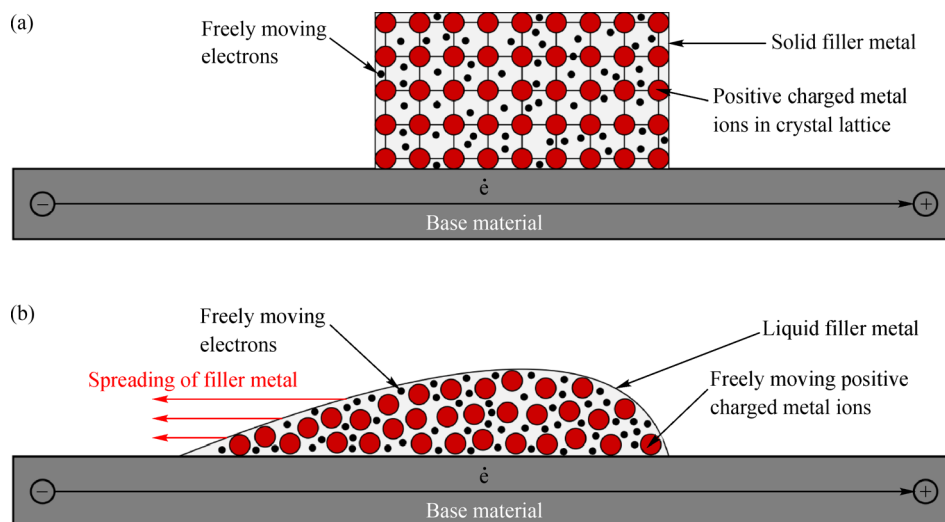


Fig. 4 Applied system with (a) solid filler metal and (b) liquid filler metal.

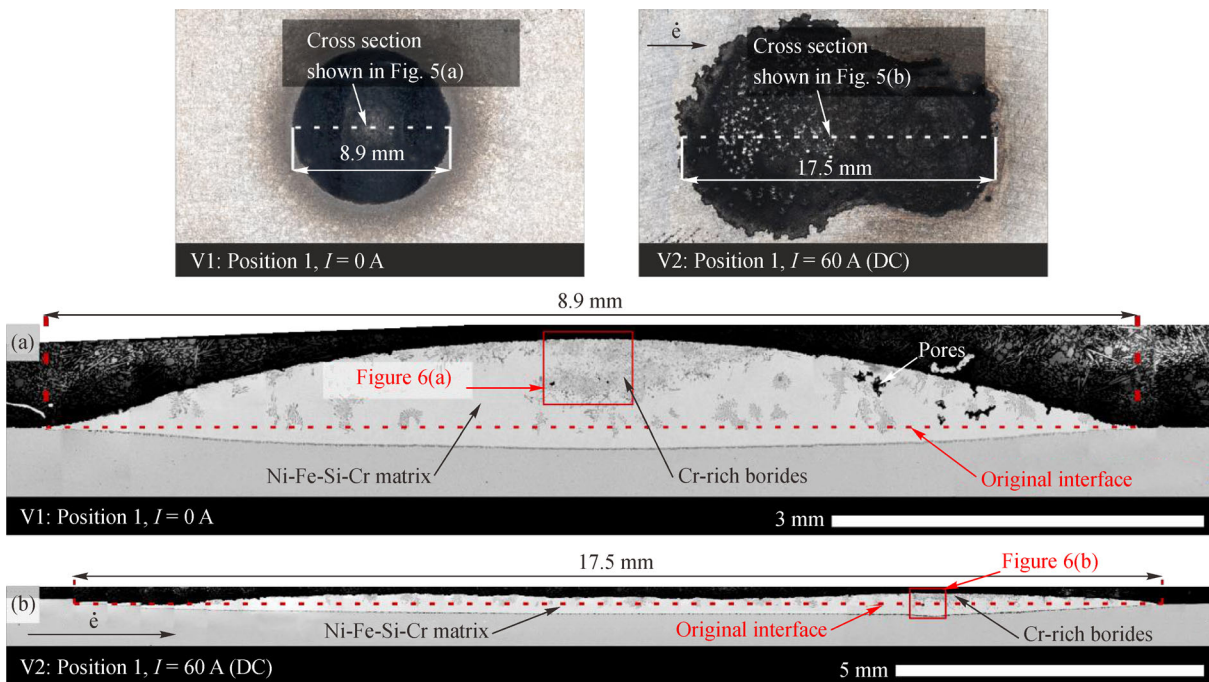


Fig. 5 Selective electron microscope cross section images of (a) V1: Position 1, $I = 0$ A and (b) V2: Position 1, $I = 60$ A (DC).

rich borides is higher in contrast to the application of electric current. Whether the difference in the spreading pattern morphology can be attributed to the application of electric current or the enhanced melt pool dynamics due to electric current and thus a spatially higher interface will be investigated in the future.

Figure 7 shows macroscopic and light microscopic top view images of V3 and V4. In both cases the wetted area is larger with the application of electric current and the spreading of the filler metal takes place in direction of the respective negative pole due to the supposed Lorentz force. In addition to that, in both cases the spreading also takes place orthogonal to the electric current direction. Thus, there is a force which acts orthogonal to the direction of the electric current and does not depend on the polarity of the direct electric current. Therefore, the force has to be external respectively to the sample and the electric current. The spreading of the filler metal is directed away from the heating elements. For these reasons, an influence of a temperature gradient due to the position of the sample near the heating elements can be excluded. Due to the higher spatial proximity of the sample at position 2 to the heating elements compared to position 1, the electromagnetic fields at position 2 are more pronounced. At the process temperature of $T = 1080$ °C the relevant elements are not ferromagnetic due to their Curie temperature which is $T_{\text{Curie, Ni}} = 354$ °C for nickel and $T_{\text{Curie, Fe}} = 771$ °C for iron [20]. Thus, a direct influence of the electromagnetic fields within the furnace on the spreading of the filler metal can be excluded. However, the electromagnetic fields may

influence and displace the electric field lines within the base material. By the displacement of the electric field lines the spreading of the filler metal is influenced, Fig. 8.

4 Summary and conclusions

An experimental setup for electric current assisted wetting and brazing was presented. Using the experimental setup, electric current assisted wetting experiments were carried out in which, in contrast to the relevant literature, direct current was applied along the interface between the base material and filler metal. The results showed an unusual significant influence of electric current on the size of the wetted area and in addition to that a dependence of the filler metal spreading direction on the polarity of the direct current. The Lorentz force is supposed to be the responsible physical effect for the observed directed filler metal spreading. Comparable observations of the influence of metallic melt by the Lorentz force have already been made in technical production processes such as casting, but not yet for brazing. Furthermore, a dependence of the filler metal spreading direction on the base material position in the furnace was observed. Here it is assumed that the position-dependent electromagnetic fields in the furnace displace the electric field lines in the base material and thus the filler metal spreading. The effect of enhanced and directed filler metal spreading might be a valuable tool for brazing technology concerning overcoming insufficient filling of the brazing gap due to manufacturing tolerances

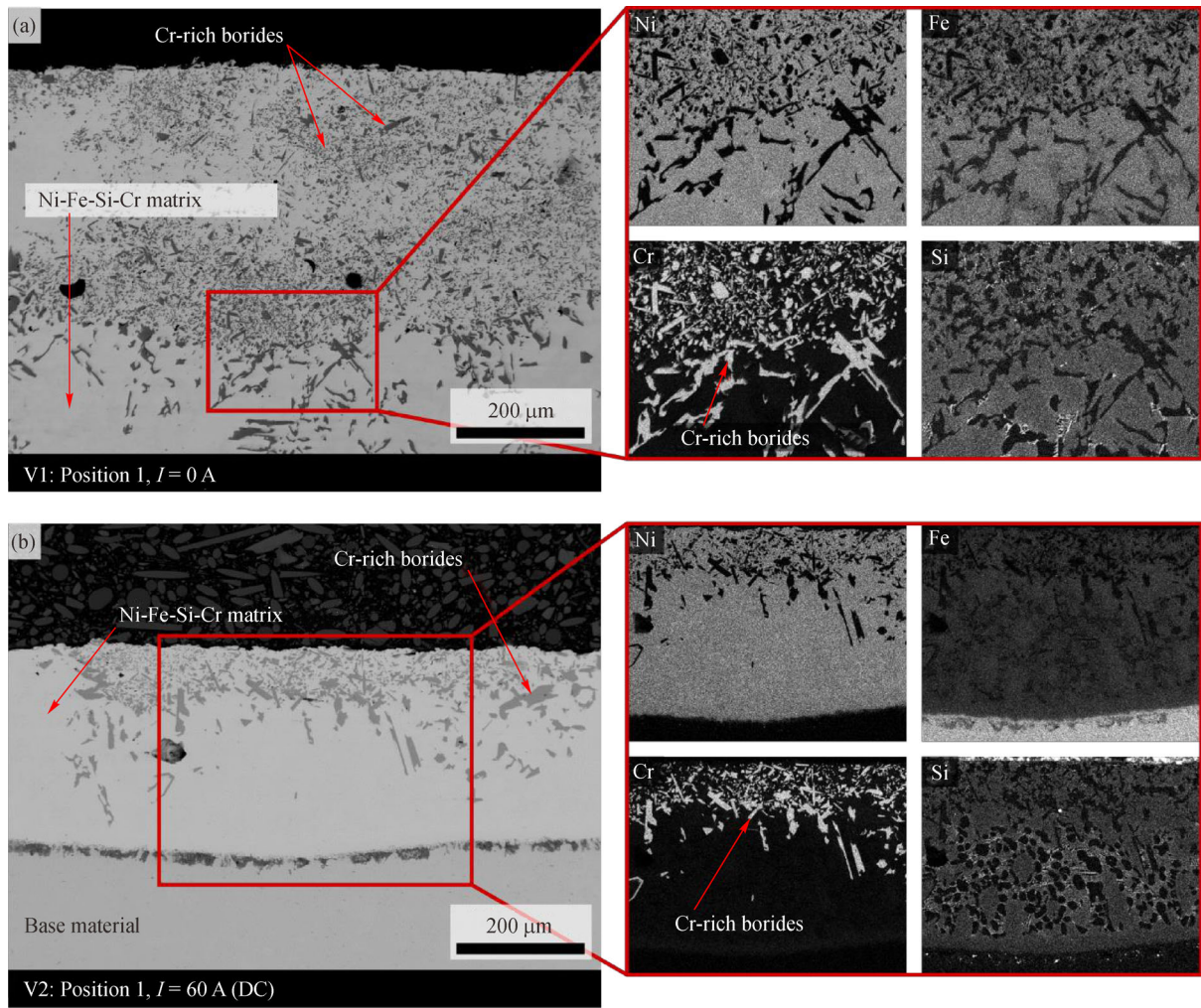


Fig. 6 SEM cross section images and EDX-mappings at filler metal initial position of (a) V1: Position 1, $I = 0$ A and (b) V2: Position 1, $I = 60$ A (DC).

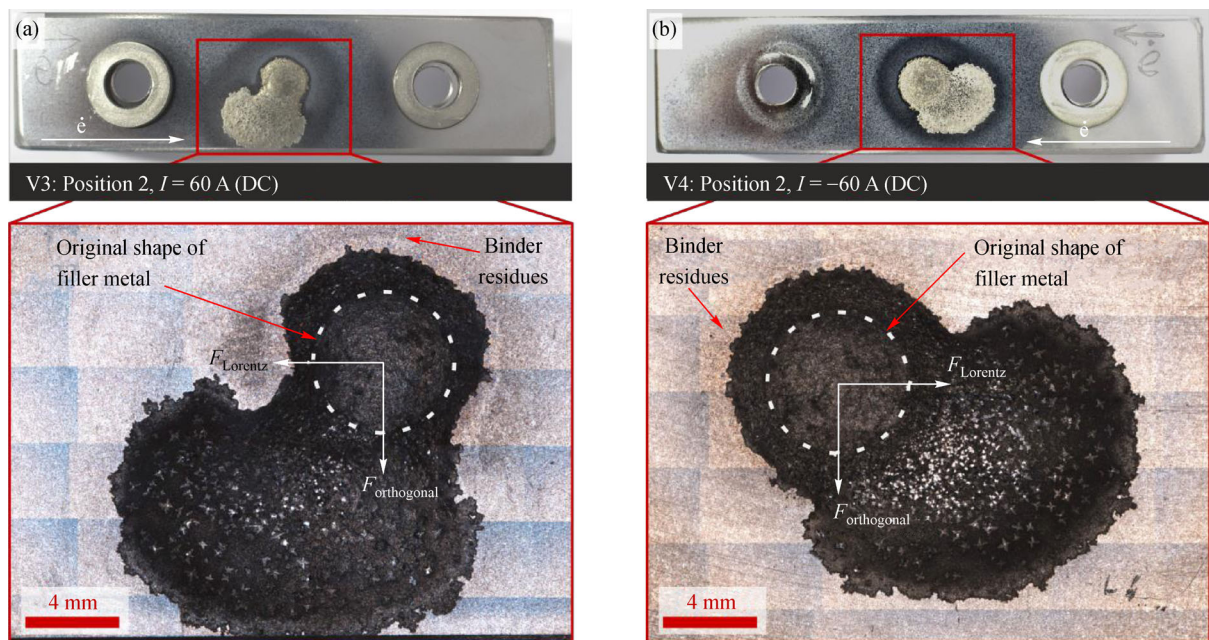


Fig. 7 Macroscopic and light microscopic top view image of the wetting pattern of (a) V3: Position 2, $I = 60$ A (DC) and (b) V4: Position 2, $I = -60$ A (DC).

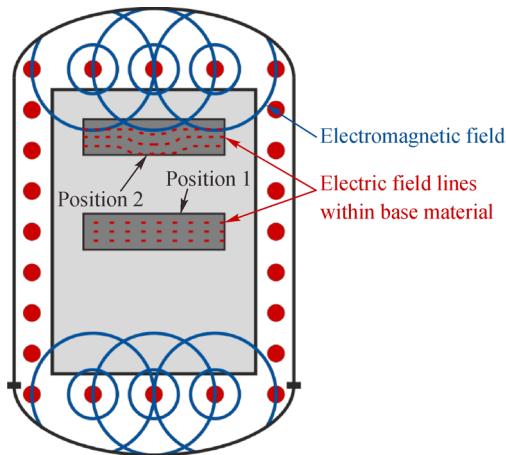


Fig. 8 Schematic sketch of electromagnetic fields in the furnace indicating the displacement of the electric field lines within the base material at position 2.

of the brazing components or component distortion during the brazing process.

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