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Fluxless Brazing of aluminum alloys using non vacuum electron beam by 60kV acceleration voltage

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Abstract. Lightweight construction materials, in particular aluminum alloys, have recently become more important as construction materials due to their low weight with high strength and sufficient wear and corrosion properties. In order to be able to use the advantages resulting from the use of aluminum alloys, powerful and reliable thermal joining methods are required which reduce the heat input into the component and thus the distortion and change the set structure as less as possible. New approach here is the NV-EB brazing at low acceleration voltage. In particular, two aspects must be solved for process-reliable brazing of aluminum alloys. On the one hand, the oxide layer on the surface of the aluminum workpiece must be removed. On the other hand, sufficient heat must be put into the solder and base material in order to both melt the solder and to heat the base material sufficiently, but below the solidus temperature. Often the “Nocolok” potassium tetrafluoroaluminate flux is used. In addition, the harmful to health cesium fluoroaluminate and mixtures of both fluxes are used. Apart from health aspects, the use of fluxes has led to increased pollution of an equipment and corrosion, which contributes to process instability. By reason of described above, the investigation of a fluxless brazing of aluminum alloys using non vacuum electron beam by 60kV acceleration voltage is of great interest.

1. Introduction

At the Institute of Material Science of the Leibniz Universität Hannover, systematic studies are conducted to study the potential of a non-vacuum electron beam with an accelerating voltage of 60 kV. Despite the lower power of the process compared to the NVEB by 175kV acceleration voltage, the main advantage is the reduction of x-ray radiation due to the lower accelerating voltage.This advantage is very important for industrial applications. On the other hand the lower the acceleration voltage is the smaller the construction of the beam equipment can be to reduce the weight of the moving parts.

The main problem in the brazing of aluminum alloys is the oxide layer (Al_2O_3) on the surface of the material, which has a higher melting point (2100 ° C) than aluminum (660 ° C). Usually the “Nocolok” potassium tetrafluoroaluminate flux is used to destroy this oxide layer. In addition, the harmful to health cesium fluoroaluminate and mixtures of both fluxes are used. Apart from health aspects, the use of fluxes has led to increased pollution of an equipment, which contributes to process instability. On that reason, the methods of the fluxless brazing has to be investigated. In the arc process, it is possible to achieve the destruction of the oxide layer by means of a DC + circuit or AC circuit with a large DC + part. Thanks to the cathodic cleaning effect caused by the arc, it is therefore possible to achieve that the aluminum oxide layer of the base material is removed and the aluminum surface can thus be wetted by the solder [1].

It was investigated the possibility of using an AC welding source for flux-free brazing of aluminum alloys with specially designed aluminum solder [1]. The soldering material used was in particular the ternary AlCuSi system, **Figure 1**. This material combination enables particularly low processing temperatures of up to 524 ° C in order to provide the largest possible process window for the soldering process. These materials have only a low formability in the alloyed state and thus can hardly be processed as solid wire. For this reason, this material system was manufactured at the IW as composite wire and its processing was tested. This composite wire consists of an AlSi or AlSiMg alloy in the core, the cladding is made of a Cu alloy, so that it can be processed in conventional wire feed units. The mixing of the materials in the liquid state only takes place directly on the workpiece surface, or during the material transfer. The solders can be processed without restriction with the electron beam in atmosphere [1].

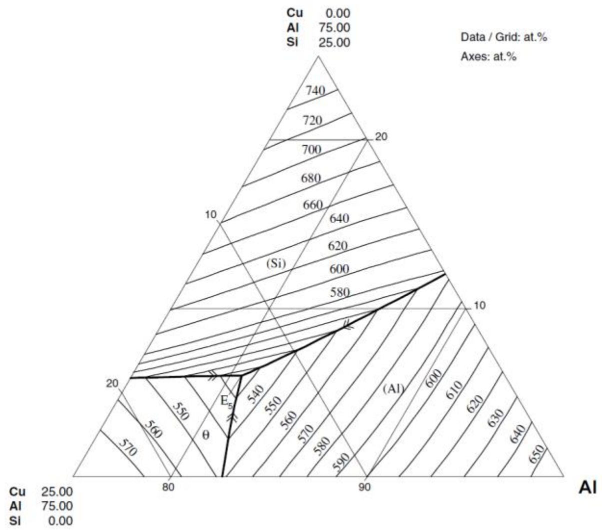

Figure 1: Part of the Al-rich region of the liquidus projection of the ternary phase diagram Al-Cu-Si [2]. The eutectic point E5 is at a composition of 80.6 at.% Al, 13.4 at.% Cu and 6.0 at.% Si, the melting point is 524 ° C.

The purpose of the work presented below is to investigate the possibility of using a low-voltage non-vacuum electron beam system for the brazing of aluminum alloys.

2. Set-up for experiments

2.1. Available equipment

At the Institute for Material Science at Leibniz Universität Hannover is available the NVEB welder PTR NV-EBW 25-175 TU. This system has following specifications:

- Maximum beam power – 24.5 kW
- Maximum beam current – 140 mA
- Accelerating voltage – 175 kV.

The principle set-up of the NVEBW system is shown in **Figure 2.**

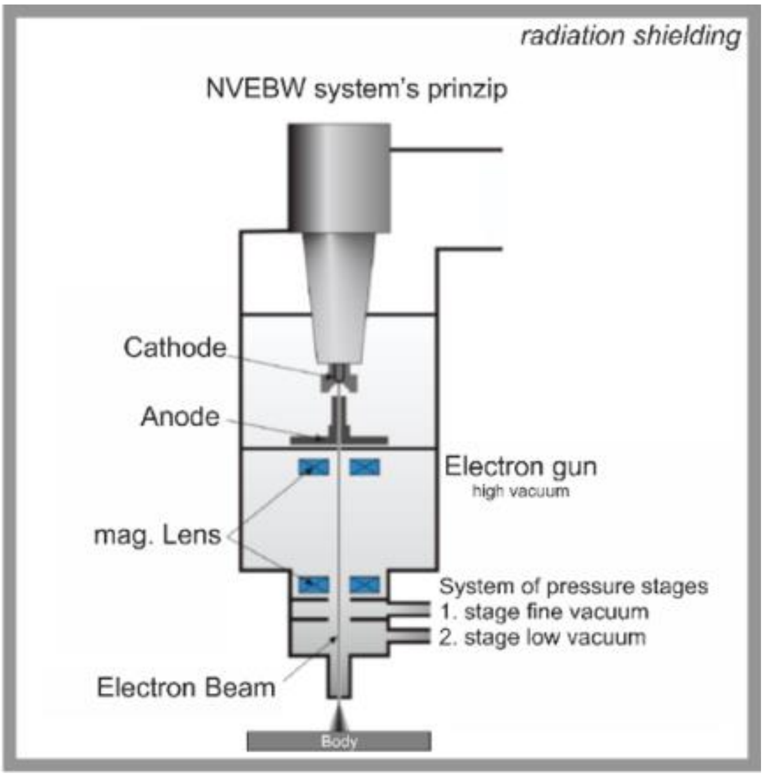

Figure 2: Illustration of the PTR NV-EBW 25-175 TU welder

The PTR NV-EBW 25-175 TU welder was accommodated for carrying out of brazing experiments using by 60kV acceleration voltage. To do this, the acceleration gap was reduced by increasing the length of the accelerating anode. Anodes with different lengths (+8, +13 and +18 mm) were created and then the efficiency was measured using a Faraday cup. The results of the measurements are shown in **Table 1**.

Table 1: Results of the efficiency and power measurements of the adopted NVEB system.

PTR-NVEB System Beam efficiency and power by 60 kV								
Beam current [mA]	**Efficiency [%]**				**Power [W]**			
	Original (0 mm) anode	**+8 mm anode**	**+13 mm anode**	**+18 mm anode**	**Original (0 mm) anode**	**+8 mm anode**	**+13 mm anode**	**+18 mm anode**
20	71,1	**75,8**	64,3	33,8	853	**910**	772	406
25	70,5	**76,9**	64,8	34,2	1058	**1154**	972	513
30	69	**80**	63,7	34,7	1242	**1440**	1147	625
35	67	**78,1**	66,8	37,4	1407	**1640**	1403	785

Measurements show that when the anode distance is reduced by 8 mm, the efficiency and power are the most optimal. Brazing experiments with an accelerating voltage 60kV were conducted on an adapted NVEB system.

2.2. Selection of material

For the investigation were selected 2 type of wire:

- Composite solder wire: AlCuSi
- Standard solder wire: AlSi12

The AlSi12 solder was chosen due to its low melting point, which is 575-585 ° C, while the melting temperature of the aluminum substrate is 615-655 ° C. The aluminum AW6063 alloy was used as the substrate. The chemical composition of all solders and the substrate is shown in **Table 2**.

Table 2: Chemical composition and melting point of the used materials [3,4]

Material	Chemical composition [wt.%]									Melting range [°C]
AW6063	Si 0,20-0,60	Fe 0,35	Cu 0,10	Mn 0,10	Mg 0,45-0,90	Cr 0,10	Zn 0,10	Ti 0,10	Al Rest	**615-655**
AlSi12 **Ø1,6 mm**	Si 12	Fe ---	Cu ---	Mn ---	Mg ---	Cr ---	Zn ---	Ti ---	Al 88	**580**
AlCuSi **Ø1,2 mm**	Si 8,40	Fe 0,08	Cu 20,24	Mn ---	Mg 0,91	Cr ---	Zn ---	Ti ---	Al Rest	**520-538**

3. Procedure of experiments

Principle set-up of the NVEB Brazing process is shown in **Figure 3**. Before the beginning of the brazing, experiments were conducted to establish the process limits. For the research, the following parameters were determined: I_{EB}-electron beam current [mA], v_b- brazing velocity [m / min], v_d- wire feed volocity [m / min], A_d- work distance [mm], β- angle of the wire feed [°], c- distance between the wire and the substrate [mm].

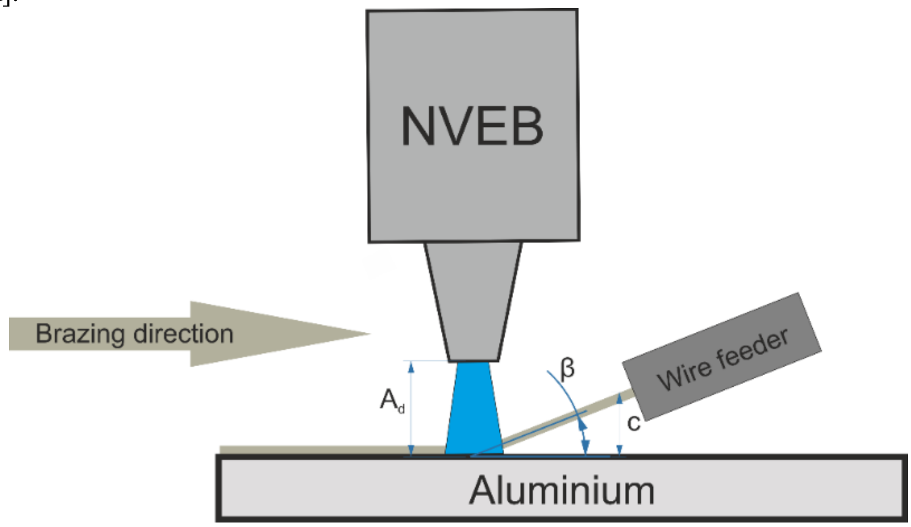

Figure 3: Principle of the NVEB Brazing process

Before carrying out the experiments, the aluminum surface was prepared by the following method [5], **Figure 4**:

1. First of all, a hot (50-80 °C) solution consisting of NaOH (120-200 g/l) and water
2. The sample is placed in the solution for 1-2 minutes depending on the condition of the sample surface
3. Immediately after etching process, the sample is thoroughly washed in cold, running water
4. The sample is then placed to neutralize in HNO_3
5. In the end, the sample is thoroughly washed in running water and quickly dried using hot air.
6. The above described method of surface preparation for brazing is used to remove the oxide film (Al_2O_3) and degreasing.

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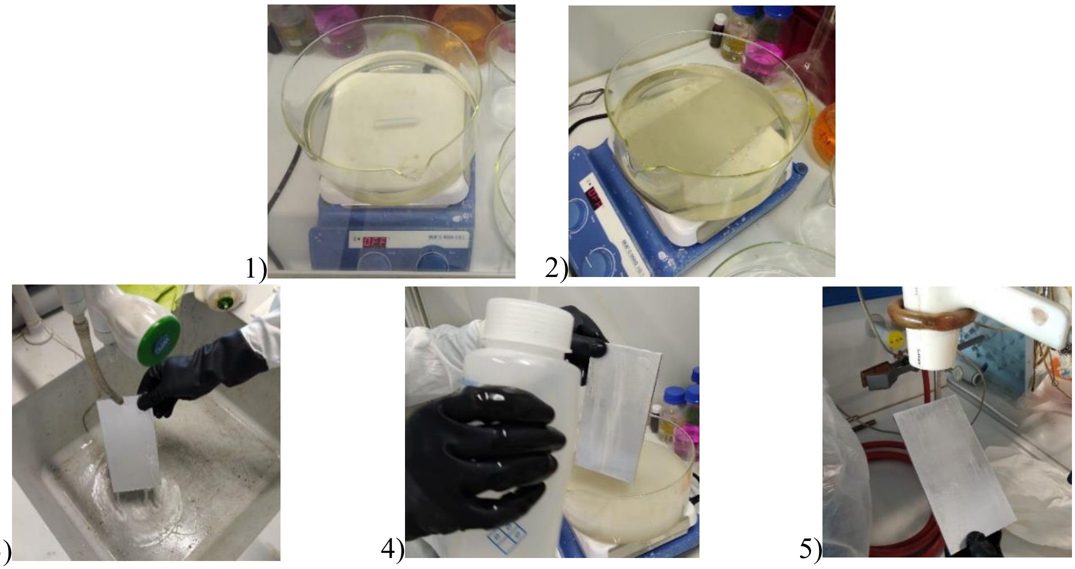


Figure 4: The process of preparing the aluminum surface for brazing

4. Determination of the process limits

4.1. Influence of wire feed

During experiments, the dependences between the main parameters were determined. The influence of the type of wire feeding, trailing or leading was firstly investigated. When using trailing wire feeding, the following defects were detected: frequent jamming of the wire feed, the accumulation of molten solder on the wire feed nozzle and the process became quite unstable. When using the leading wire feed, the following results were obtained: shade of the electron beam due to the tip of the wire, which can lead to poor preheating of the substrate and consequently a low surface wettability, but in spite of this process was much more stable.

The next parameters were investigated the wire feed angle and the distance between the substrate and the solder. The NVEB brazing process is very sensitive to wire feeding, namely the angle β should not exceed 10 ° and the distance „c“ should not exceed 1 mm, these parameters are the same for both wires AlSi12 and AlCuSi. When passing from these values, on the substrate surface are formed solder balls, or no connection to the surface. This is due to the fact that as the distance increases, the wire takes on a large amount of electron beam energy and the substrate does not have time to warm up, which leads to poor wetting.

4.2. Influence of the brazing parameters: beam current, work distance, process velocity and wire feeding.

For the brazing process, it is necessary to select a beam current such that the output power is sufficient for melting the solder, preheating the surface, and minimally depth of fusion of the base material. According to the experiment results, it was established that at a beam current of less than 24mA, there is no sufficient melting of the solder, for a high quality weld. The decreasing of the process speed, under 0.7 m/min, to increase the input energy, the wire does not melt, while the base material melts. During the establishment of the dependence between the wire feed velocity and the process velocity to obtain a stable weld, it was found that the wire feed velocity should not exceed the process speed. For the investigation of the influence of the working distance, the goal was to find the maximum distance at which the input energy would be sufficient to melt the wire and simultaneously preheat the base material without its melting. From the results it was found that the optimal work distance is 8mm.

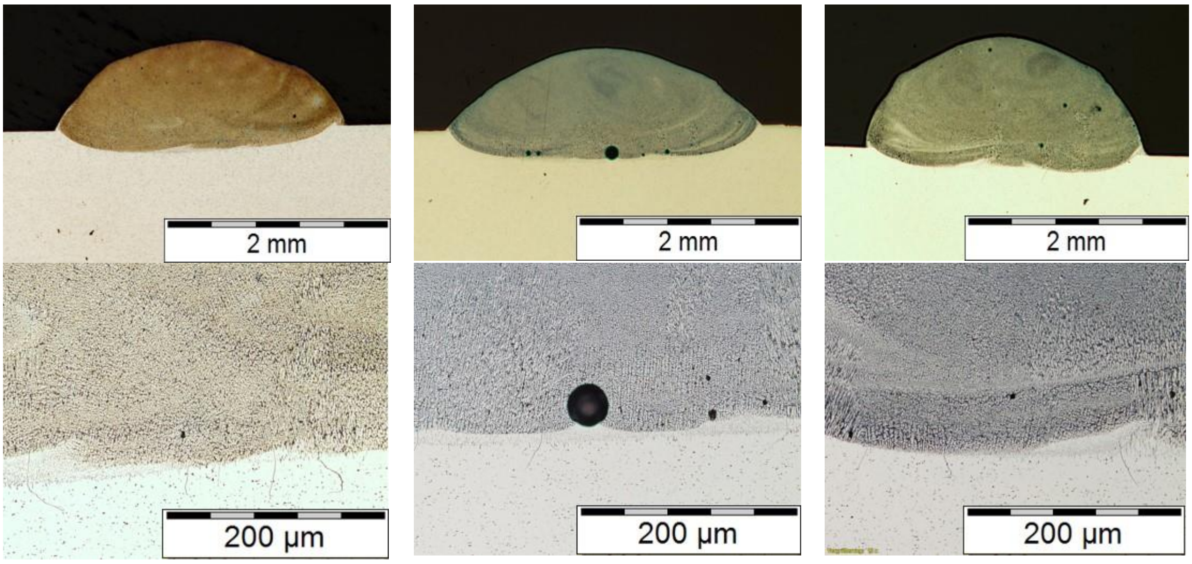
As a result of experiments, it was established that the optimal parameters of the process are: beam current 28-40mA, work distance 8 mm, the process velocity 1-2 m/min and the wire feed speed 1-2m/min and rate of energy input 54-144 J/mm.

4.3. Metallographic analysis of samples from AlSi12

To analyze the effect of the beam parameters on the brazing process using AlSi12, macro- and microsections were produced, which are shown in **Figure 5**.

Proceeding from the obtained macro- and microsections, it can be seen that in the boundary zone of the brazing joint there is a small porosity. The formation of pores during the welding or brazing of aluminum alloys is mostly based on the presence of interstitially hydrogen. The appearance of hydrogen is connected with several causes, such as a contaminated surface of the material or solder (fat and oil) and a damp atmosphere. In order to avoid this, it is necessary to preheat the base material more strongly or to use a shielding gas [6].

On microsections can be seen the formation of cracks in the boundary area. The reason for this, for example, can be the thermal effect of the electron beam or stress, which are formed during the solidification of the wire, because of its high amount on silicon.



AlSi12 Ø1,6 mm
60 kV, 28 mA,
v_L:1,5 m/min, v_D:1,5 m/min
Wetting angle: 60,4°
Depth of fusion: 209 µm

AlSi12 Ø1,6 mm
60 kV, 30 mA,
v_L:2 m/min, v_D:1,5 m/min
Wetting angle: 46.4°
Depth of fusion: 263 µm

AlSi12 Ø1,6 mm
60 kV, 30 mA,
v_L:2 m/min, v_D:2 m/min
Wetting angle: 79.3°
Depth of fusion: 160 µm

Figure 5: Macro- and microsections of AlSi 12 with Ø1.6 mm

4.4. Metallographic analysis of samples from AlCuSi

On **Figure 6** are shown macrosections of samples using composite solder wire AlCuSi.

AlCuSi, Ø1,2 mm
60 kV, 35 mA,
v_L:1 m/min, v_D:2 m/min
Wetting angle: 52°
Depth of fusion: 489 µm

AlCuSi, Ø1,2 mm
60 kV, 30 mA,
v_L:1 m/min, v_D:2 m/min
Wetting angle: 68°
Depth of fusion: 377 µm

Figure 6: Macrosections of AlCuSi with Ø1.2 mm

On macrosections can be seen multiple pore formation. As in the case of AlSi12, the reason for the appearance of pores is due to the presence of hydrogen in the melt.

4.5. Influence of the inclined beam on the brazing process

The use of a direct beam may not be sufficient to preheat the base material before the solder wire is welded onto it. To improve the preheating of the base material, an inclined beam can be tested. **Figure 7** shows the process setup. In case of inclined electron beam, it is necessary to heed of the change of power distribution in the electron beam spot and in the beam itself. A qualitative representation of the power distribution is shown in **Figure 8.**

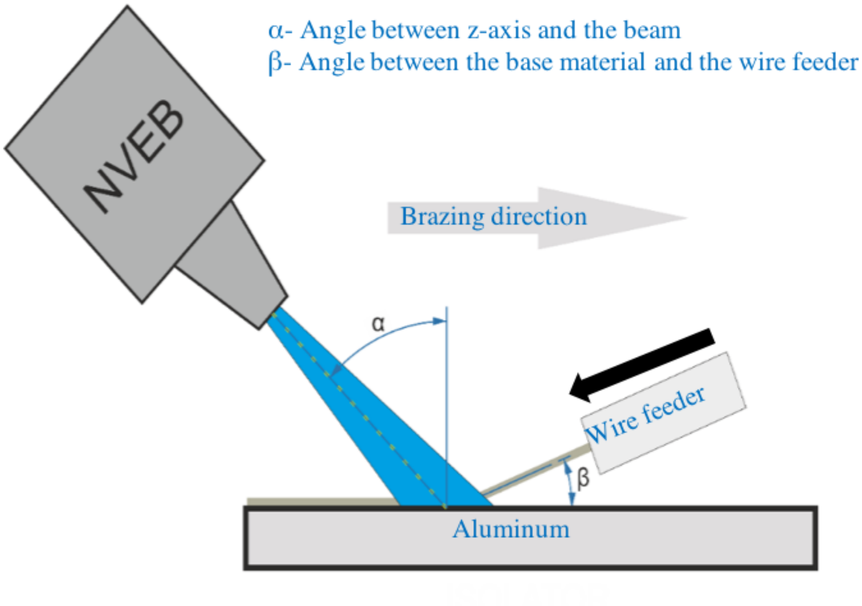


Figure 7: Principle of the NVEB Brazing process with inclined electron beam

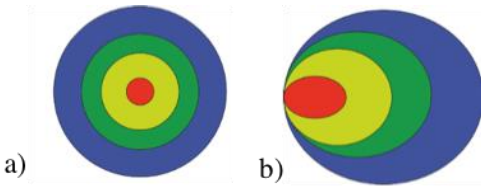
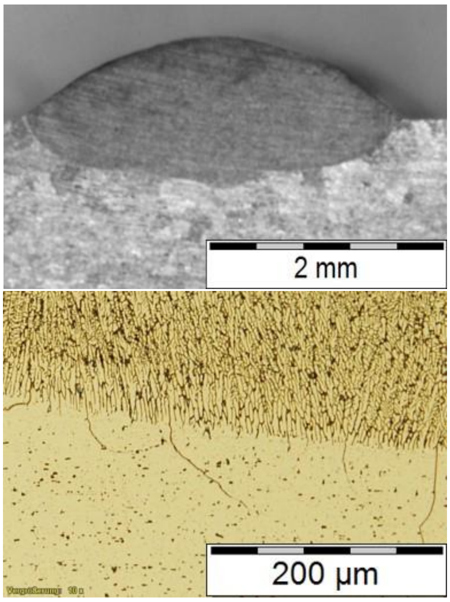


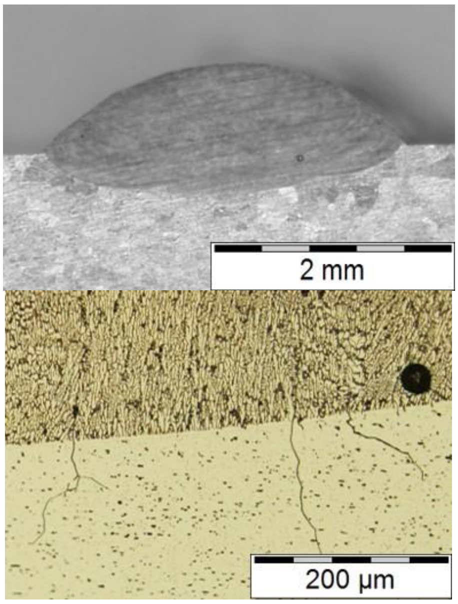
Figure 8: Qualitative representation of the power distribution of a) straight und b) inclined EB

The experiments showed good wettebility and good seam formation at α = 5-20°. Then a metallographic study was carried out to analyze the brazing seams, **Figure 9**.

Metallographic analysis showed that the use of an inclined beam positively affected the wetting angle with the surface and reduced the formation of pores in the seam, but increase depth of fusion.



60 kV, 35 mA,
v_L:1,5 m/min, v_D:1 m/min
Wetting angle: 36°
Depth of fusion: 444 µm



60 kV, 40 mA,
v_L:2 m/min, v_D:2 m/min
Wetting angle: 44,5°
Depth of fusion: 382 µm

Figure 9: Metallographic analysis of samples produced by inclined electron beam**.**

5. Cathodic cleaning of the surface

5.1. Set-up for experiments

For the fluxless brazing using NVEB by 60 kV acceleration voltage was investigated the effect of cathodic cleaning using an additional plasma arc. To carry out experiments on cathodic cleaning, a current was applied between the outlet nozzle and the base material (biaspotential). The process chain is shown on **Figure 10**.

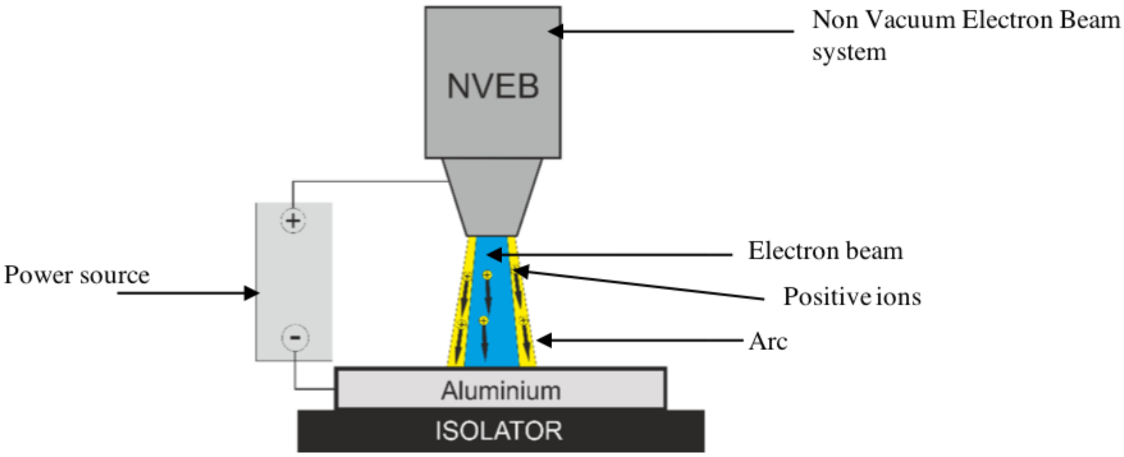


Figure 10: Experiment set-up of a hybrid process with arc and electron beam

The idea is intensification the cathodic cleaning effect by striking an arc between the workpiece and the beam nozzle. Under the hypothesis, the ions from the electron beam plasma can be used for cathodic cleaning of the workpiece surface during NV-EB brazing of Al alloys by 60kV acceleration voltage. Already Arata showed that it is possible to generate an arc discharge up to 450 mA in parallel with the electron beam, without strong deflection of the electron beam through the magnetic field of the arc [7]. There are no further investigations if this effect can be exploited technologically. E. Abramian and G.

Kuleschov reported successful combination of EB in the atmosphere and an arc up to 500 A [8]. A. Hershcovitch showed successful welding experiments using this hybrid method (arc and electron beam) [9].

As a source of electrical current for the experiments was used laboratory DC power supply SM120-13 with max. voltage 120V and max. current 13A. Negative pol was connected to an isolated substrate, the positive pol was connected to the output nozzle, **Figure 11**. The first results using the available nozzle showed that the arc can be ignited at a low work distance, beneath 1 mm. Because of this fact, the output nozzle has to be reconstructed. For this, a concept was developed, where a tungsten inlet is used to ignite an arc and can be inserted mechanically, **Figure 11**. Using this concept makes it possible to rapid replace the W-inlet after its wear.

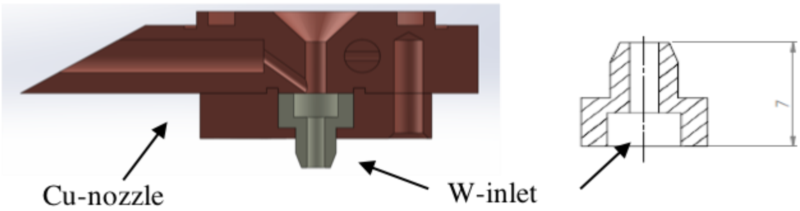


Figure 11: CAD representation of Cu-orifice with a tungsten (W)-inlet

Initially, experiments were conducted without the introduction of solder wire. To determine the working distance, a ramp was programmed along the vertical axis. The initial work distance is 2mm then during the process, the EB moves along a horizontal axis and synchronous the working distance increases to 10mm, **Figure 12.**

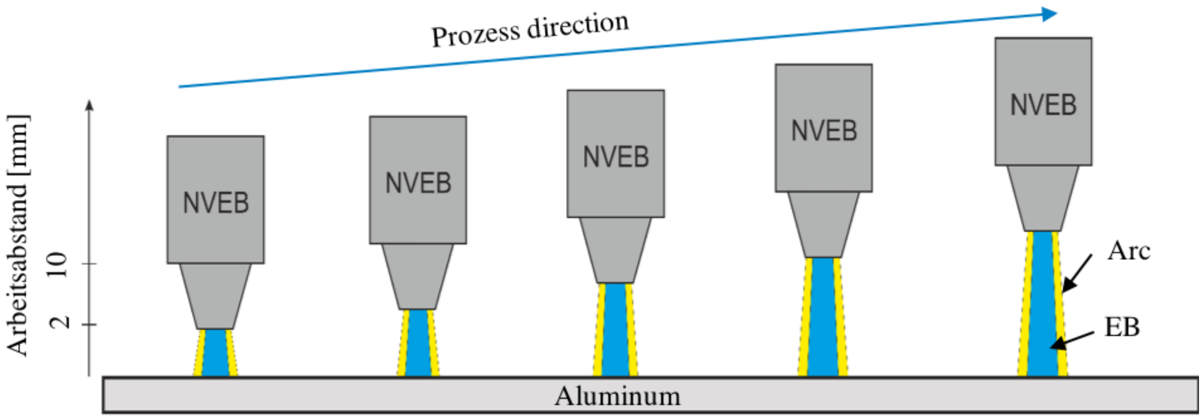


Figure 12: Procedural principle of a programmed ramp.

5.2. Results

The results of the experiment revealed the following dependences: between the beam current and the work distance to the cleaning effect; understanding of arc ignition at a low work distance and stable conditions of the arc; between the arc current and the work distance for different beam currents (25-60mA).

According to the results it was revealed that the ignited arc at the 2 mm work distance can be kept without a significant current drop up to the 6 mm work distance, **Figure 13**. By a visual analysis of the surface, it can be observed the treated surface, which indirectly indicates the presence of cathodic cleaning effect, **Figure 14**.

After the input of the solder wire, the arc is ignited between the filler wire and the base material, which deflects the electron beam. To avoid this, further sealing of the filler wire is necessary.

Figure 13: Dependence between I_{lb} and A_d by I_s=40mA

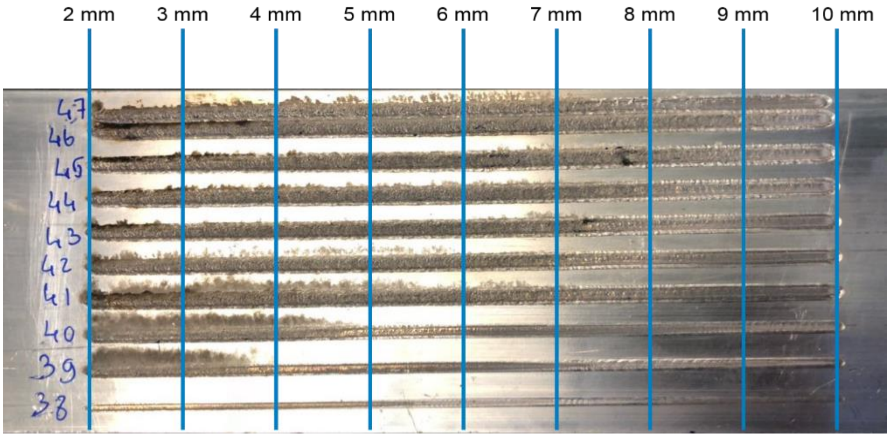


Figure 14: Treated surface after NVEB-arc hybrid process

6. Conclusions and outlook

NVEB by 60kV acceleration voltage is a capable for brazing of aluminum alloys. During the experiments a range of samples using 2 different wires, solder wire AlSi12 and composit wire AlCuSi, on the aluminum alloy AW6063 was carried out.

The primarily investigations shows:

- The brazing process using NVEB by 60kv is very sensitive to wire position. A wire position should have max. angel 10° and max. distance of 1 mm between wire and base material. A wire should put into the middle of the electron beam spot. This geometrical characteristics are necessary for obtaining a high quality weld seem or braze.
- The process limits of the beam parameters are found in the following range: rate of energy input – 54-144 J/mm, beam current – 28-40mA, process and wire feed velocity – 1-2 m/min.
- The experiments with the AlSi12 solder wire shows good wettability parameters and seam formation. The weld seems have light porosity, cracks and light depth of fusion.
- The experiments with the AlCuSi composite wire shows good wettability parameters and seam formation. The weld seems have a porosity and light depth of fusion
- The presence of porosity indicates the amount of hydrogen or different surface impurities (oil or fat) during the brazing process.

- An application of the inclined electron beam gives the better wettability of the AlSi12 solder wire on the base material, but increases the depth of fusion.
- For the effect of the cathodic cleaning was construct a W-inlet and impelled into the NVEB system. For the understanding of the cathodic cleaning using W-inlet were carried out the following dependences: between beam current and work distance; understanding of arc ignition at a low work distance and stable arc conditions; between the arc current and work distance at different beam currents (25-60mA). The base material surface after the hybrid process (arc and non-vacuum electron beam) has a treated surface, which can may indicate a cleaned surface from the aluminum oxide (Al_2O_3).

Further investigations are planned as follows:

- Further experiments with inclined electron beam to avoid the depth of fusion.
- Decrease of a porosity amount in the brazed seam using the shielding atmosphere.
- Carrying out the tensile tests of brazed joints
- Isolation of the solder wire for the brazing investigations using NVEB by 60kV with cathodic cleaning effect.

7. Acknowledgments
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