Non-vacuum electron beam welding and cutting of copper

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Abstract. Due to its physical properties, like high thermal and electrical conductivity copper is an indispensable material in many branches of industries. However the welding and cutting of copper and its alloys is challenging due to this properties and tendency to absorb gases resulting some defects like porosity or hot cracking. To prevent these, different requirements concerning the welding process have to be fulfilled. One requirement is the use of a highly concentrated heat input. The electron beam in atmosphere (NVEBW)is a suitable tool, which meets this requirement. This publication presents the advantages of NVEBW welding and cutting of copper. The experimental results of low-voltage (NVEBW) of copper will be shown and discussed too. The first portion studied the effects of varying power, travel speed and work distance on mechanical and electrical properties and structure of weldment at 175 kV accelerating voltage. The second portion studied the possibility of application of low-voltage 60kV NVEBW for welding of copper and influence of impurities in the copper on the welding parameters. The third portion studied the process of NVEB cutting of copper using the suction created by a local vacuum underneath the work piece. Experimental results of cutting with extremely high cutting speeds such as15m/min for 1.5 mm thick and 9m/min for 6mm thick copper will be representing.

1. Introduction
Copper materials are just as good weldable as steel materials taking into account the physical properties. However, a problem is the general tendency of non-ferrous metals to absorb atmospheric gases during welding; causing a reduction of the mechanical and technological properties of the weld seam. Therefore, all areas in which during welding occur the temperatures of more than 600 K must be protected from air access [1]. Other important properties for the welding of copper are its thermal conductivity as well as the thermal expansion. In comparison with alloyed steel, pure copper has an approx. 9 times higher thermal conductivity at room temperature (401 W/m°K for copper and 46 W/m°K 1132 for steel ) and a 13 times higher thermal conductivity at 1000 °C (352W/m°K and 27 W/m°K) respectively. [2]. Compared to steel, thermal expansion increases by 1.4 times and approximately twice as much as shrinkage during solidification [1, 3], which causes a large welding deformation. The high thermal conductivity leads to dissipation of a large part of the introduced energy into the surrounding base material. The dissipated energy is no longer available for melting the base material. In the liquid state copper tends to absorb gases from the atmosphere, including oxygen and hydrogen. Oxygen in solid copper at the solidification temperature of the eutectic (1065 °C) is only 0.09% soluble [4]. Already at low quantities is due to the eutectic reaction of the residual melt Cu formed oxide (Cu₂O). Hydrogen diffuses through the copper and reduced the inclusions of Cu₂O, forming H₂O (water), which then forms pressurized bubbles at the grain boundaries. This process can cause the grains to be forced
away from each other, and is known as steam embrittlement or "hydrogen disease". [4] Based on the foregoing, should be selected welding technology.

Arc welding of copper and its alloys is widespread but challenging due physical properties of copper. To prevent the welding defects different requirements of the welding process have to be fulfilled. One requirement is the use of a highly concentrated heat input to minimise of weld pool size. Laser welding and electron beam welding (EBW) are the suitable technologies, which meets this requirement. However, these technologies are not without drawbacks.

Due to low absorption at room temperature, copper materials are classified as difficult to weld with state-of-the-art lasers Fig.1. The low absorption also causes high sensitivity to variations in surface conditions. Green laser radiation shows a considerable higher absorption at room temperature. So for copper SE-Cu58 at wavelength 515 nm absorption riches 42.8% [5]. However, green lasers have relatively low power and can only be used on thin material.

Electron Beam Welding in vacuum (EBW) technology is an established and widely adopted technique in industry. There are numerous applications of EBW in electrical, nuclear and automotive industry. EBW equipment covers a range of power from 2 to 200 kW. Vacuum chambers with volumes ranging from several litres (in the electronics industry) to several hundred cubic meters (aviation structures, heavy, petrochemical and nuclear) industries allow welding material from a fraction of a millimetre to 200 mm in thickness [6].

The main disadvantage of EBW in a vacuum is the presence of a vacuum chamber, which increases the cost of equipment and reduces productivity. The preparation of edges for EBW requires high precision. As a rule, welding is performed with maximum joint opening of 1% of the material thickness, which requires milling of the edges. During the welding of copper in vacuum intense evaporation takes place. This evaporation cause’s formation of pores due to degassing of the molten metal in vacuum and to thinning of the weld seem. To reduce pore formation, it is necessary to increase the lifetime of the weld pool, which significantly reduces the welding speed. Reference [7] reports that defect-free welds of copper with thickness of 2-4 mm are obtained at speeds 0.3m / min or less.

Electron beam welding in the atmosphere (NV-EBW) is free of a significant part of the above disadvantages.

Non-vacuum electron beam welding employs essentially the same equipment as vacuum electron beam welding except that the working chamber is replaced by an orifice system [9, 10]. The electron beam emerges from the gun column via a series of differentially pumped vacuum stages, which are separated by small diameter orifices. Thus, the need for evacuation time is eliminated, as the orifice system and the generator column are permanently kept under vacuum. The very high welding speed and
adaptability to automation makes NV-EBW especially useful for mass production with very high output [11]. Welding speeds up to 60 m/min for 1 mm thickness sheet are possible, as well as welding with deep penetration up to 20 mm at 0.5 m/min, which is significantly higher than laser or EBW in vacuum [12, 13]. Compared to the laser beam or EBW, the electron beam on atmosphere has a more divergent profile. This guarantees a good gap bridging ability and the welding process has a wide tolerance towards inaccurate positioning. This technology is a promising alternative to laser and EBW in vacuum for welding and cutting of copper.

2. Experimental Setup
The welding tests were performed using a Non Vacuum Electron Beam Welding machine (PTR GmbH, Germany), located at the Institute of Materials Science at the University of Hanover, Fig. 2. The system has a maximum high voltage of 175 kV and beam power of 25 kW. For 3-D welding operations a CNC-work table with a travel length of 3.0 x 0.8 m in x-, y- direction can be used. A welding wire feeding system is fully integrated in the NVEB welder. Furthermore, the machine allows welding with pulsed beam current with variable frequencies between one and 999 Hz and pulse/break-ratios between 0 and 100 %. Principle set-up of NVEB is shown in Fig. 3.

![Figure 2](image)
**Figure 2** 175 kV-Non Vacuum Electron Beam Welding machine in the Institute of Materials Science, University of Hanover.

![Figure 3](image)
**Figure 3** Principle set-up of NVEBW facility.

Welding tests were performed on sheets of copper with thicknesses of 0.8; 1.5 und 6 mm. Physical properties and composition of copper samples are given in the Table 1.

| Cu-grade | Alloy components (mass fraction %) | Thermal conductivity W/m·°K | Specific electrical conductivity MS/m |
|----------|----------------------------------|-----------------------------|--------------------------------------|
| Cu-OFE   | –                                | 393                         | 58.0-59.1                            |
| Cu-HCP   | P: 0.002-0.007                   | 385                         | 57.0-59.0                            |
| Cu-ETP   | Bi: <0.0005                      | 394                         | 55-57                                |
|          | O: <0.0400                       |                             |                                      |
|          | Pb: <0.0050                      |                             |                                      |
| Cu-DHP   | P: 0.0150-0.0400                 | 305                         | 43                                   |

3. Welding tests at 175 kV accelerating voltage
In experiments on a setup with an accelerating voltage of 175 kV, the influence of welding parameters on the properties of welded joints was studied. The high efficiency, the material-independent energy coupling in connection with a high total available power of 175kV machine make it possible to realize
high welding speeds. The high thermal conductivity of copper leads to an increased dissipation of heat into the workpiece. Therefore, the relationship between thermal efficiency and welding parameters is very important. The thermal efficiency can be defined as being the ratio of the energy required to melt the weld bead to the total energy input over the same distance. The melting efficiency can be characterized used the linear energy, which representing the amount of energy per unit distance travelled. Figure 4 shows which linear energies have to be used to weld through 3 mm thick copper sheets using NVEBW. If one compares the necessary rated energy of 0.46 kJ / mm at 0.5 m / min, this can already be reduced to approximately one third (0.17 kJ / mm) at a welding speed of 4 m / min. Due to the high welding speed so less heat input into the workpiece can be achieved at the same penetration.

Figure 4. Linear energy vs welding speed for 3 mm DHP- copper

Despite the large power reserve of NV EB welder, an increase in welding speed has a limit. The welding speed is limited of such weld bead instability as humping or undercut bead. Humping can be defined as periodic undulations of the weld with undercutting along the edges of the weld seem Fig.5. Until now, there is no generally accepted theory of the origin of humping. The Rayleigh instability mechanism bears apparent similarities to the humping phenomenon, so it has been adopted and extended by many researchers to explain and describe the shape of molten beads deposited on a solid surface and also to determine conditions for instability by capillary forces [14, 15]. Other models are based on the flow of molten metal in a weld pool due to the Marangoni effect [16, 17]. Two main factors: the welding speed and penetration affect the shape of the weld. With the increase in the penetration depth, the threshold speed of undercuts and humping decreases. In our experiments with 3 mm thick, through-welded sheets at working distance of 15 mm with welding speeds up to 8 m/min no humping has been observed. At penetration depths in the range of 6 mm, the formation of humping could be observed at the welding speed of 3 m / min. In general, humping comes out of the weld pool dynamic, so factors that affect the dynamics may also have an effect on humping. This includes the working distance as a parameter, which influences the beam diameter and the power density via the scattering in the atmosphere.

In our experiments the copper sheets of 1.5mm, 3 mm, 6 mm and 10 mm were examined Fig 6,7. The welding parameters are given in the Table 2. Due to its low viscosity, copper melt tends to flow out of the weld. For the 3 mm sheets, a sagging of the weld root of 0.2 mm to 0.3 mm can be observed. For sheets with a thickness of more than 3 mm, a bath support must be used.
Table 2. Welding parameters for copper sheets at NVEBW with 175 kV accelerating voltage

| Material | Thickness (mm) | Beam current (mA) | Welding speed (m/min) | Work distance (mm) | Remarks |
|----------|----------------|-------------------|-----------------------|-------------------|---------|
| DHP 1.5  | 45             | 10                | 15                    | good              |
| DHP 1.5  | 67             | 14                | 15                    | undercut          |
| DHP 1.5  | 90             | 15                | 20                    | humping           |
| DHP 3    | 80             | 8                 | 15                    | good              |
| ETP 6    | 103            | 5                 | 8                     | good              |
| ETP 10   | 140            | 2                 | 10                    | good              |

Figure 5. The Humping on 1.5 mm DHP-copper, a) welding bead b) cross-section of hump, (beam current 90 mA, work distance 20 mm, welding speed 15m/min)

Figure 6. Weld seam and macro-section of 6 mm ETP Plate (welding speed 5m/min, working distance 8 mm, beam current 103 mA)

Figure 7. Weld seam and cross-section of 1.5 mm DHP-copper, (beam current 45 mA, work distance 15 mm, welding speed 10m/min)
In the cross section of the welded joint Fig. 8, can be seen the fusion zone (FZ) consists of columnar crystal which crystal axes are directed normal to the diffusion line, and HAZ which grain size was slightly affected by the heat input applied during the welding. The Cu2O inclusions in the weld were not detected.

As mentioned above, oxygen has a negative effect on the properties of copper. In conventional non-vacuum electron beam welding, the welding process takes place under atmospheric conditions without protective gas coverage. Since oxygen has an influence on the properties of the joint, such as pore or crack formation, finally, the uptake of oxygen has been considered using the example of the oxygen-containing copper Cu-ETP. Compared with the base material with oxygen content of 89 ppm, an increase to about 225 ppm oxygen content in the weld metal was detected. Additional, experiments were carried out under atmosphere of argon. Wherein only a slight increase in the oxygen content in the weld to about 108 ppm oxygen was found.

4. Welding Experiments with acceleration voltage 60 kV

Among in electron beam welding experts, it is considered impractical to use an accelerating voltage of less than 150 kV for NVEBW, because due to the strong scattering of a low-energy beam in the atmosphere, the power density in the work area is not high. On the other hand, the requirements for the X-ray protection can be reduced and EB Generator can be small. For some applications such as brazing or welding of thin materials NVEBW at low acceleration voltage is of the great interest. Recently, in the Institute of Materials Science at the Leibniz University Hannover were carried out successful experiments on welding in the atmosphere at an accelerating voltage of 60 kV [18]. In the experiments, copper sheets of DHP and ETP grades with a thickness of 0.8, 1.5 and 2 mm were used. The maximum welding speed on sheets with a thickness of 0.8 mm reached 9 m/min. The welding parameters are presented in Table III. Fig 9,10,11 shown cross-section welds obtained at a welding speed of 2.6 and 9 m/min and a working distance of 10, 6 and 4 mm respectively. An inhomogeneous weld without full penetration was observed by welding of 2 mm sheets Fig 12. The weld width was wider at the area near the ending point than the starting point area since the material at the beginning of seam is cold; the beam energy is insufficient to melt the metal.
Figure 11. Cross section welds of Cu-DHP 0.8 mm, 9m/min, 60kV, 120mA, 4mm

Figure 12. An inhomogeneous weld of 2mm Cu-ETP.

Figure 13. Copper sample 0.8 mm thick after tensile strength testing

Tensile strength testing of the welds of 0.8 mm ETP copper was conducted in compliance with the DIN EN ISO 6892-1 at room temperature using universal tensile testing machine Zwick Z100 operating with a crosshead speed of 0.5 mm/s. Dimensions of a tensile testing sample are illustrated in Fig.13 Results of tensile strength testing are summarized in Table 3.

Table 3. The tensile test of the weld samples

| Nr. | $R_{p0.2}$ [MPa] | $R_m$ [MPa] | Failure area |
|-----|----------------|------------|--------------|
| base | 186.01 | 252.42 | base |
| 3    | 137.78 | 165.95 | FZ |
| 9    | 151.87 | 188.99 | FZ |
| 16   | 137.82 | 146.19 | FZ |

The tensile strength of the weld reduced average 23% in comparison with the base material. The sample failed at the centre of the FZ, as indicated in Fig. 13. Fig. 14 shows the comparison of mechanical properties between welded samples and a reference sample.

Figure 14. The comparison of mechanical properties between welded samples and a reference sample

5. Electrical conductivity of the weld

Figure 15 shows a diagram for measuring the electrical conductivity of welded samples. The voltage drop was measured at a distance of 100 mm and 10mm at the current of 100 amperes for 2 seconds are shown in the Table IV. In the weld area, there is a slight increase in voltage drop compared to the base metal. The electrical properties of pure copper will only be affected when impurities are formed in the welds. The electrical measurement showed that welds was not significantly modified after the NV EB welding process.
Table 4. The voltage drop at the 100A current

| Nr. | spec. | voltage drop mV (10mm) | voltage drop mV (100mm) |
|-----|-------|------------------------|--------------------------|
| 3   |       | 2.15                   | 18.11                    |
| 9   |       | 2.06                   | 18.07                    |
| 16  |       | 2.16                   | 18.09                    |
| Ref.|       | 1.95                   | 18.10                    |

6. Electron beam cutting

Most thermal cutting processes employ a concentrated gas jet directed onto the process zone to remove molten metal from the kerf. Contrasting to conventional cutting processes, we were able to realize a cutting process that utilizes a local low vacuum underneath the process zone. This is achieved by creating an area of low-vacuum between 100 and 500 mbar using a sliding seal. The electron beam melts the material and due to the pressure gradient between two sides of the workpiece induces a strong gas flow across the melting front, carrying molten and evaporated metal as well as smoke away from the kerf. This approach avoids high stagnation pressure, which will increase the beam power density and therefore will achieve very high cutting speeds. The gas flow can interact precisely at the melt front and will force the molten metal downwards. In another way than for a trailing gas jet, there is no dependence on the direction of the cut, so that curved contours can easily be realized. Experimental set-up for NVEB cutting with local suction were developed in Institute of Material Science of Leibniz University of Hannover. [19, 20]. It is important to remark that this method requires no change to the beam generator or pressure stage system of the original NVEB welder. Cutting experiments have been done with copper plates of 6 mm thickness. The 6 mm plates could be safely cut with a speed of 9 m/min at a working distance of 2 mm. The cut edges show a small ridge of residual melt droplets at the bottom edge. Macro- and micro-section examinations of these specimens show no sign of thermal influence induced by the cutting process Fig.16,17. The cut surface shows typical cutting grooves for such materials, the JIS-B0601 (1994) roughness Rz is 135µm Fig.18 The width of the kerf is 1.4 mm on the top cut edge and 1.00 mm at the bottom cut edge measured from the macro-section profile. This agrees with an EN ISO 9013 quality grade of 3 for angular deviation.

Figure 16. Macro-section of NVEB-cut of 6 mm thick ETP-copper with 9 m/min at 24.5 kW.

Figure 17. Micro-section of NVEB-cut of 6 mm thick ETP-copper with 9 m/min at 24.5 kW. (mag x50)

Figure 18. 3D laser scan of the cut edges.
7. Conclusions
1. The non-vacuum electron beam (NVEB), due to its high power density, is a suitable tool for welding and cutting copper.
2. Due to the high welding speed and small size of the weld pool, the influence of the welding cycle on the material properties is minimal.
3. Welding speed is limited by the appearance of humping.
4. A low-energy beam with an accelerating voltage of 60 kV allows welding of copper sheets up to 2 mm thick with high speed.
5. No significant changes of electrical resistivity and chemical composition of welds were observed after welding.
6. A new cutting method with local low vacuum underneath the process zone allows cutting of 6mm copper at speeds up to 9 m / min with high quality cuts.

References
[1] Schulze G 2004 Die Metallurgie des Schweißens 3 Auflage (Berlin: Springer-Verlag).
[2] Handbook of chemistry and physics 2007 88th. edition (CRC Press).
[3] Dorn L 1987 Metallphysikalische Vorgange beim Schweißen von Kupfer und Kupferlegierungen– Werkstoffliche, Grundlagen. Schweißen und Schneiden Nr.12 39.
[4] Schweifen von Kupfer und Kupferlegierungen, Deutsche Kupferinstitut Informationsdruck i.12 Auflage 2009.
[5] Englerra S, Ramsayera R, Poprawe R 2011 Process studies on laser welding of copper with brilliant green and infrared lasers Physics Procedia 12 339–346.
[6] Dobeneck D 2007 An international history of electron beam welding, 1st edition (Germany: Pro-beam AG).
[7] Nazarenko O et.al. 1987 Electron beam welding [in Russ.] (Kiev: Naukova Dumka).
[8] AKELA LC 2019 Laser diode cutting. URL: https://www.akelalaser.com/markets/industrial/ diode-laser-cutting/.
[9] Arata Y, Tomie M 1970 Some fundamental properties of non-vacuum electron beam JWS September.
[10] Powers D E 1997 Nonvacuum electron beam welding enhances automotive manufacturing Welding Journal 76.
[11] Hinse-Stern A, Schwab U 2004 Elektronenstrahl-Schweßen an Atmosphäre (NVEBW) von Modulträgern 6 International Konferenz Strahltechnik 26.04–28.04.2004.
[12] Draugelates U et.al 2000 Hochgeschwindigkeit Elektronenstrahl-Schweßen von Aluminium unter Atmosphärendruck Schweßen und Schneiden 52.
[13] Bach Fr.-W, Beniyash A, Lau K, Konya R 2009 Non-vacuum electron beam welding of structural steels Paton Welding Journal May.
[14] Arata Y Tomie M 1970 Some fundamental properties of non-vacuum electron beam JWS September.
[15] Bradstreet B J 1968 Effect of surface tension and metal flow on weld bead formation Weld J 47 (7) 314–22.
[16] Mills K G, Keene B J 1990 Factor affecting variable welding penetration International Material Review 35 185-216.
[17] Reisgen U et al 2012 A Investigation of factors influencing the formation of weld defects in non-vacuum electron beam welding The Paton Welding Journal 2 11-18.
[18] Hassel T, Klimov I, Beniyash A 2018 Beam extraction using non vacuum electron beam by reduced acceleration voltage beam technologies and laser application Journal of Physics Conf Series 1109.
[19] Hassel T, Murray N, Klimov G, Beniyash A 2016 Cutting and welding of high-strength steels using non-vacuum electron beam as a universal tool for material processing World Journal of Engineering and Technology 4 598-607.

[20] Beniyash A, Murray N, Klimov G, Hassel T 2017 Using a non-vacuum electron beam as a universal tool for material processing In Proc. 2nd International conference on Electron Beam Wielding (14.11.2017-17.11.2017) (Moscow: MPEI).