## TABLE OF CONTENTS

# 1 INTRODUCTION

The spent fuel from Finnish nuclear reactors is planned to be encapsuled in thick-walled copper canisters and placed deep into the bedrock. The Posiva type canister consists of an internal cast iron insert and copper overpack of 50 mm thickness with double lids. The function of the canister is to isolate the spent fuel from the surrounding environment. The canister design, therefore, aims at providing with a high probability a corrosion lifetime of at least 100,000 years in the repository.

Copper and its alloys, especially thick-walled copper sections, are difficult to weld because of high thermal and electrical conductivities. The manufacturing methods of the copper canister have been widely studied and some studies are still going on. The objective of this study was to find out, if the narrow gap arc welding is suitable for the welding of thick copper sections.

Based on the existing knowledge from the open literature the arc welding of copper is cumbersome. The preheating temperatures required by the welding process are relatively high. Hence, the risk of hot shortness occurs. Gas shielding has to be adequate in order to avoid the risk of weld bead oxidation. This report includes a literature review of arc welding of copper.

The welding trials of this study were executed with 15 - 50 mm thick copper workpieces. Development work of the welding equipment was made in order that the welding trials could be executed. A narrow gap welding tool and a copper welding station were developed for the study.

The welding trials showed that the arc welding of thick copper is cumbersome and the welding environment and the welding parameters have to be strictly controlled.

# 2 LITERATURE REVIEW ON ARC WELDING OF COPPER

Copper (Cu) has a face-centered cubic (fcc) crystal structure up to its melting point, 1084.9 °C /Joseph 1998/. Hence, it is a monomorphic metal, whose mechanical properties cannot be improved by a conventional heat treatment. The mechanical strength of copper is not high, nor does it exhibit an upper yield point. Copper can therefore only be strengthened by means of cold work or alloying /Lindroos et al. 1986/.

Copper and its alloys can be divided into the following three groups: oxygen-free copper, phosphorous deoxidised copper and tough pitch copper. Tough pitch copper contains certain amount of oxygen. In phosphorous deoxidised copper the oxygen level has been significantly reduced by reduction with phosphorous. Oxygen-free copper is usually manufactured to high levels of purity by electrolytic refining. As it contains practically no oxygen, that would bind impurities as fairly harmless oxides, the copper content of certified oxygen-free copper is a minimum of 99.99 w-%. Pure copper is an excellent electrical conductor /Lindroos et al. 1986/.

## 2.1 Welding of copper

The following material properties must be taken into consideration when welding copper and its alloys /Cary 1998, Linnert 1994/:

1. High thermal conductivity
2. High thermal expansion coefficient
3. The heat of fusion of copper is relatively high
4. Relatively low melting point
5. Hot short (i.e., brittle at elevated temperatures)
6. Very fluid molten pool
7. High electrical conductivity
8. Much of its strength due to cold working

The coefficient of thermal expansion of copper is 17.7 * $10^{-6}$ 1/ºC between 25 - 300 ºC, the specific heat is 0.092 cal/g * ºC at 20 ºC and the heat of fusion is 50 cal/g /EWE-3/2.21-2.22 1999/. Because the heat of fusion of copper is relatively high, producing a molten pool calls for high arc energy. The high electrical and thermal conductivity of copper (approximately 395 W/m at room temperature) has a substantial effect on its weldability. The alloying elements bear an impact on the electrical and thermal conductivity of copper. Phosphorous decreases the electrical and thermal conductivity of copper significantly as shown in Figure 1 /EWE-3/2.21-2.22 1999/. Phosphorous also decreases weld bead oxidation and porosity /Lindroos et al. 1986/.

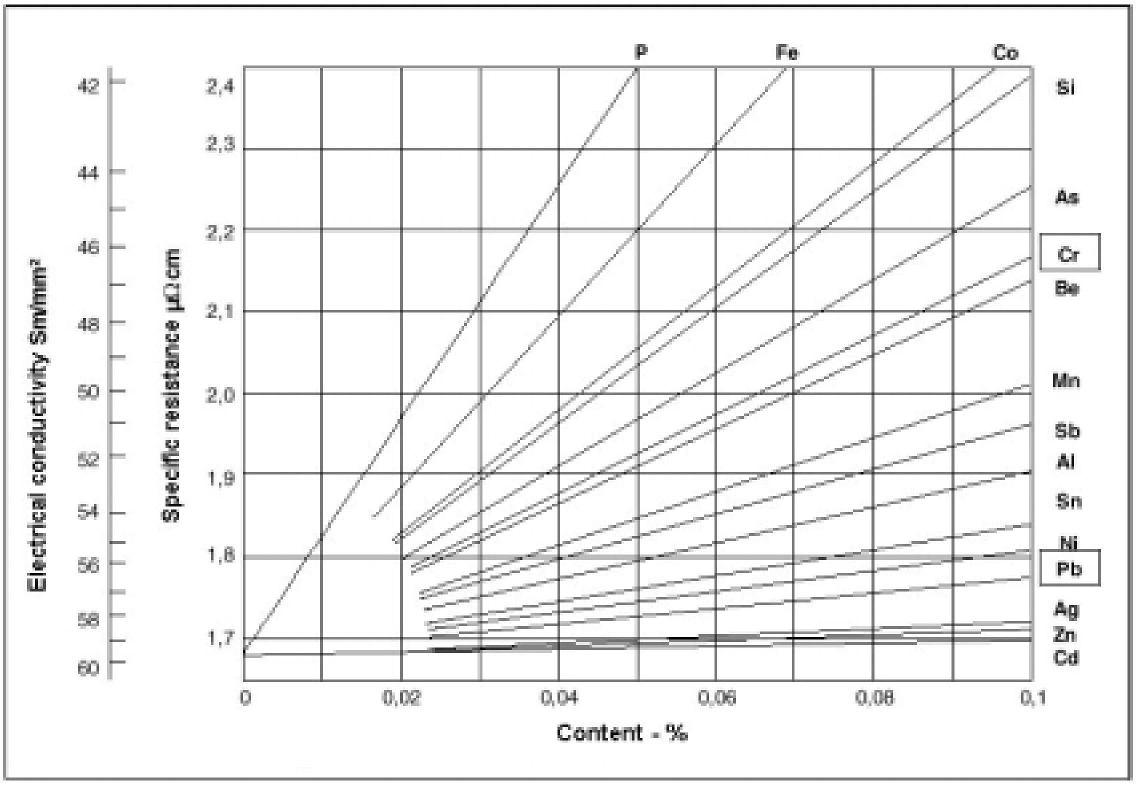

***Figure 1.*** *The effect of the alloying elements of copper on its electrical conductivity and specific resistance* /EWE-3/2.21-2.22 1999/.

Heat from the welding process is readily conducted into the parent material. The effective thermal conductivity depends primarily on the thickness or mass and temperature of the parent material. Preheating reduces the required arc energy needed to melt the material by reducing the temperature difference between the molten pool and the parent material /AWS 1996/.

Several copper alloys are strengthened by means of cold working. Subsequent heating of strengthened copper alloys softens them without exception. Hence, the heat affected zone (HAZ) after welding is softer and weaker than the unaffected parent material /AWS 1996/.

### *Viscosity*

The viscosity of the molten pool is an important property in welding metallurgy. The viscosity directly affects the intensity of the metallurgical reactions, the shape of the molten pool and the penetration. It also bears an impact on how easily the deoxidation products leave the molten pool, which affects the purity of the weld metal /Probst 1971/.

The viscosity of copper is approximately 15 % lower than that of iron, making the molten metal of copper very fluid. A large molten pool will easily run and an adequate fusion is hard to accomplish. The lack of a melting temperature range between the solidus and liquidus lines of the equilibrium phase diagram does not help the situation either /Nuotio 1993/.

### *Surface tension*

The behaviour of the molten pool has a great influence on the welding process. The characteristics of the pool are controlled by the welding parameters, shielding gas, shape of the electrode and surface tension of the pool itself /Nuotio 1993/. The significance of the surface tension in supporting and shaping the molten pool prior to solidification is emphasised, when the viscosity of the material decreases and the density increases. Forces opposite to the surface tension are the arc pressure, gravity, hydrostatic pressure of the molten pool and the inertial forces of the pool in motion /Nuotio 1993/.

Surface tension values of molten metals have been measured, despite the obvious difficulties of handling materials at elevated temperatures. Impurities, even in small concentrations, have been shown to have a significant effect on the surface tension. Pure iron, *e.g.*, has a surface tension of 1.8 N/m, while the surface tension of steel is reported to be 1.0-1.2 N/m. The surface tension values of various molten metals are depicted in Figure 2. According to Figure 2, the surface tension of pure copper is 1.3-1.4 N/m /Lancaster 1984/.

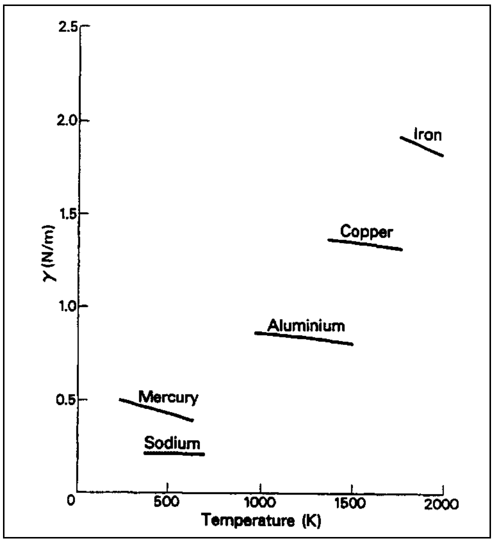

***Figure 2.*** *The surface tension values of various molten metals /Lancaster 1984/.*

### *Copper alloys*

The tough pitch copper is difficult to weld because of the presence of copper oxide within the material. In weld solidification, the copper oxide will form on the grain boundaries, which reduces ductility and tensile strength. Tough pitch copper alloys are hot short, meaning they become brittle at high temperatures /Cary 1998/.

Oxygen-free copper is not susceptible to this kind of embrittlement. However, adequate gas shielding is necessary in order to prevent airborne oxygen from entering the molten pool.

Deoxidised copper alloys are the best suited for welding of all coppers, because they do not suffer from hydrogen sickness. Hydrogen sickness occurs, when copper oxide is exposed to a reducing hydrogen gas at high temperature. Also, possible hydrogen from the welding environment can enter the molten pool, reducing copper oxide to copper and aqueous vapour /Cary 1998/.

### *Effect of oxygen*

Only a small amount of oxygen can dissolve into the solid copper, as shown in Figure 3. The solubility reaches its highest level (0.0036 %) at 1066 ºC. The solid solution α together with $Cu_2O$ forms an eutecticum at the oxygen content of 0.39 %. The proportion of $Cu_2O$ in the eutecticum is about 3.5 %, when the oxygen content of $Cu_2O$ is 11.2 %. This relatively small amount of $Cu_2O$-oxides disperses in the matrix formed by the solid solution α as globular enclaves. The eutecticum does not decrease the ductility of copper, if the amount of the eutecticum does not exceed 10 % in copper. However, oxygen containing copper is susceptible to hot cracking in welding above the eutectic temperature (1066 ºC), when the eutecticum at the grain boundaries dissolves. The eutectic structure can be decomposed by means of hot forming. Annealing coarsens the $Cu_2O$-oxides /Lindroos et al. 1986/.

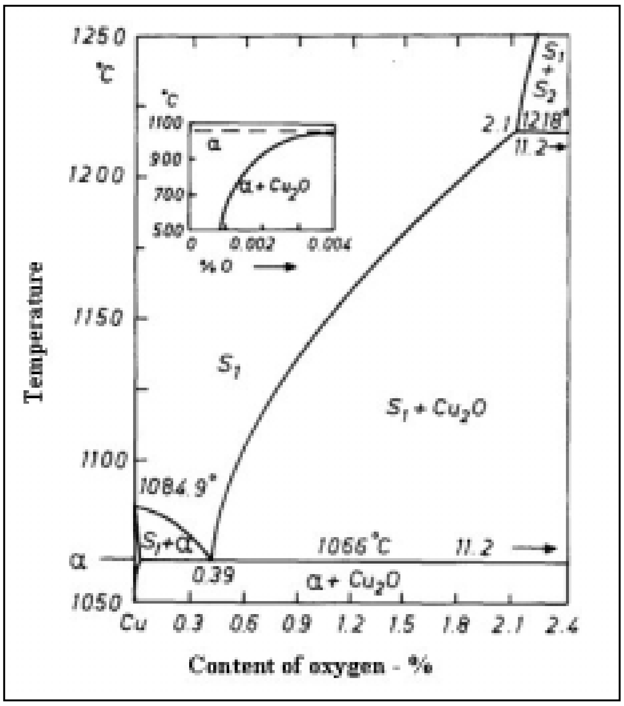

***Figure 3.*** *The Cu - O phase diagram on the copper side /Lindroos et al. 1986/.*

Oxygen may also be found as a free gas in the copper material. When the copper is heated, *e.g.*, during welding, the oxygen from the $Cu_2O$-oxides is released. The rapid solidification following welding entraps the oxygen in the metal, causing porosity of the weld /Solanki and Edkie 1999/.

Oxygen is the most harmful element in copper arc welding. Oxygen can cause porosity and reduce the strength of welds of certain copper alloys that do not contain sufficient quantities of phosphorous or other deoxidizers. Most commonly welded copper alloys contain deoxidizing elements - usually phosphorous, silicon, aluminium, iron or manganese. These elements will readily combine with oxygen and eliminate the potential for porosity. The same deoxidizers are also included in the filler metals. The soundness and strength of arc welds made in commercial coppers depend upon the cuprous oxide content. As the oxide content decreases, weld soundness increases /ASM 1993/. The presence of oxygen within the material makes copper susceptible to hydrogen sickness /Lindroos et al. 1986/.

### *Hydrogen sickness*

If a copper material contains oxygen, it is prone to hydrogen sickness. Elevating the temperature of the copper material causes the oxygen to react with hydrogen, forming water bubbles inside the grains as well as at the grain boundaries /Nakahara and Okinaka 1988/. The following steam reaction can occur, when hydrogen and oxygen are simultaneously in solution in molten or heated solid copper /Lancaster 1999/:

$Cu_2O + H_2 = 2Cu + H_2O$

Water exists as small droplets confined in closed holes /Koiwa et al. 1989/. Water bubbles, particularly those formed at the grain boundaries, lower the strength of copper considerably. This phenomenon is known as hydrogen sickness /Nakahara and Okinaka 1988/.

### *Hot shortness*

In a binary alloy solidification, the eutectic structure may not form at all, if the eutectic point is close to the other component as in Cu-Bi -system (Figure 4). The secondary phase solidifies as a film at the grain boundaries of the primary phase crystals. The phase diagram in Figure 4 shows, that copper and bismuth are almost non-soluble to each other at solid state and the eutectic point is situated at the copper content of 0.2 % /Lindroos et al. 1986/.

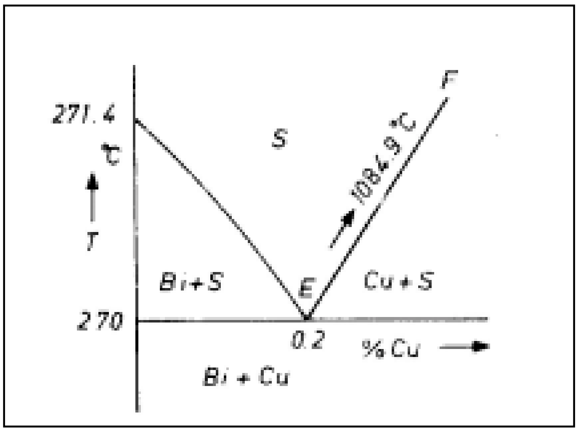

***Figure 4.*** *The Bi - Cu phase diagram on the bismuth side /Lindroos et al. 1986/.*

The melting point of bismuth is relatively low. Hence, the eutectic temperature of the Cu-Bi -system is low. If the temperature of material is elevated, the bismuth film in the grain boundaries melts and the copper material ruptures along the grain boundaries. This phenomenon is called *hot shortness.* If a copper material contains 0.002 % of bismuth, the risk of hot shortness occurs. Another impurity causing hot shortness is lead. The tough pitch copper tolerates bismuth and lead better. This is because the oxygen within the copper material forms stable oxides with bismuth and lead under 700 ºC /Lindroos et al. 1986/.

### *Groove preparation and alignment*

The grooves of copper welds are predominantly more open than those of the steel welds. This is due to the higher thermal conductivity and the loss of preheat from the weld joint. The thermal expansion of copper must also be considered when planning the groove. The groove must be dimensioned so as to accommodate a welding nozzle or tool allowing the material expansion due to preheating /Minnic 1996/.

Groove cleanliness is vital in copper welding. All traces of oil, grease, etc. must be thoroughly removed with acetone or alcohol. Groove edges that are prepared by the plasma arc cutting process or the carbon arc gouging process have a heavy oxide film on the surface. This surface should be thoroughly cleaned prior to welding to prevent dross and porosity in the final weld. The surfaces of the groove should also be free from ridges and other irregularities, as these easily harbour dirt. Additional corrosion products and possible scale are removed by suitable means, *e.g.*, immersion in pickling acid /Minnic 1996/.

### *Preheating*

Preheating is of paramount importance in the welding of copper. Insufficient preheating causes imperfect melting and inadequate penetration. Thick copper slabs require up to 540 °C preheating. Maintaining a sufficient interpass temperature can be difficult, due to the high thermal conductivity of the parent material. This difficulty can, however, be overcome by choosing an appropriate shielding gas. Helium has a high ionisation potential, which gives large heat input and, thus, simplifies the welding process. Hence, the use of pure helium in tungsten inert gas (TIG) welding or a mixture of helium and argon in metal inert gas (MIG) welding is recommended. The preheating temperature requirement for helium is 10 - 15 % lower than that of argon (see Figure 5) /EWE-3/2.21-2.22 1999/.

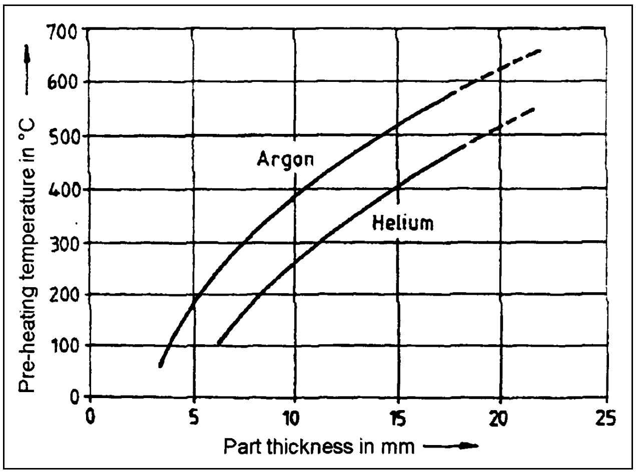

***Figure 5.*** *Preheating requirements of argon and helium /EWE-3/2.21-2.22 1999/.*

### *Gas-metal reactions and porosity*

Molten pool surface temperatures in TIG welding vary between 1350 and 1890 °C for welding currents between 100 and 450 A. At such temperatures, the affinity of copper for oxygen is low, and it does not react with nitrogen at all. Both oxygen and nitrogen may dissolve in the molten metal. The solubility limit of nitrogen in copper is, however, subject to debate /Lancaster 1998/.

Arc welding with an inert gas does not cause steam reactions in the parent material, whether it is deoxidised or not. The weld, however, is markedly porous if it is not deoxidised. Phosphorous is often inadequate for this purpose, and therefore the filler material contains either a combination of silicon and magnesium or titanium and aluminium. Despite the use of the aforementioned strong deoxidizers, manual TIG-welding can result in a porous weld, especially at the weld beginnings. Shielding gases used in copper welding are argon, helium and nitrogen. Argon and nitrogen are equal in properties, when it comes to porosity. Nevertheless, there are references which suggest, that helium gas-shielded welds are less susceptible to porosity than others. Tunnelled porosity, which is a phenomenon linked to turbulence in the molten pool, is encountered when the welding current is too high. For argon the risk becomes pronounced when the current exceeds 450 A, and for nitrogen the limit is 350 A /Lancaster 1999/.

### *Shielding gases*

All shielding gases used in copper welding are inert. They protect the molten pool against oxygen without reacting themselves with the parent material. Of the various inert gases used, argon produces the lowest arc voltage and power output for a given arc length and current flow. For nitrogen these values are the highest, but when using normal arc lengths, a too large welding voltage can blow the molten metal out of the pool. Using a higher arc length than usual can compensate for this detrimental effect, but this in turn can weaken the gas shielding. Of all shielding gases helium is the most advisable. It requires a lower preheating temperature than argon, while offering at the same time better penetration and higher travel speed. Helium also causes less oxide formation /Dahlgren 1997/.

Helium amplifies the purifying effects of the arc, which results in a superior outer appearance of the completed weld. Nitrogen enables the most efficient heat input and therefore also the smallest demand for preheating, but the appearance of the weld can be slightly defective with an increased risk of porosity /Dahlgren 1997/.

TIG welding, with helium used as the shielding gas, can be utilised for welding over 25 mm thick work pieces. The need for preheating decreases even for very thick sections, which efficiently reduces the risk of distortion and deformation caused by thermal expansion. It also reduces oxide formation and offers a more comfortable working environment /Dahlgren 1997/.

### *Hot cracking*

Copper and its alloys are susceptible to hot cracking if they contain a notable amount of impurities with a low melting point. Bismuth and lead are two examples of this type of impurities. The level of these impurities must therefore be kept as low as possible, in order to prevent cracking during welding or forming /Lancaster 1999/.

### *Tack welding*

Tack welding requires the following aspects to be considered /Minnic 1996/:
- All preheating of the material must be carried out before tack welding.
- Use the same filler material for tack welding as for the final weld.
- If the joint requires full penetration, the tack weld requires penetration.
- The tack welds should be made as small as possible.
- A fractured tack weld is not repaired, but replaced by another tack weld in the immediate vicinity.
- Never remove tack welds by grinding. If a tack weld must be removed, use a rotary file. Grinding grit and residue enter the final weld and weaken its properties.
- End craters, which represent the weakest spot in tack welds, must be avoided.

## 2.2 TIG welding

Conventional TIG welding can be carried out with either direct (DC) or alternating current (AC). When using DC, the electrode can either be negative (DCEN) or positive (DCEP). When welding copper, however, DC must be used and the electrode must be negative. This is explained by the fact that 70 % of the heat created during welding is absorbed by the anode while 30 % is absorbed by the cathode. Therefore, by making the electrode negative, we can achieve a better root penetration, decrease the heat load on the welding nozzle and lengthen the service life of the electrode. The effect of polarity in TIG welding is depicted in Figure 6 /ASM 1993/.

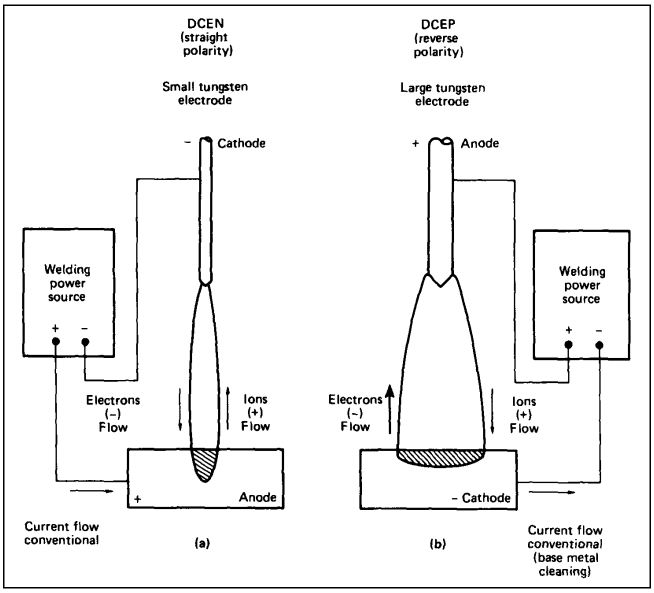

***Figure 6.*** *Effect of polarity switching in TIG welding /ASM 1993/.*

TIG welding is commonly utilised for materials with a section thickness of 3 mm or less. Helium is the recommended shielding gas when welding thicker plates. Helium enables a more fluid and purer molten pool since the access of oxygen to the pool is efficiently impeded. In comparison with argon, helium makes it possible to achieve better penetration or travel speed for the same welding current. Figure 7 shows shielding gas and preheating dependencies of penetration /AWS 1996/.

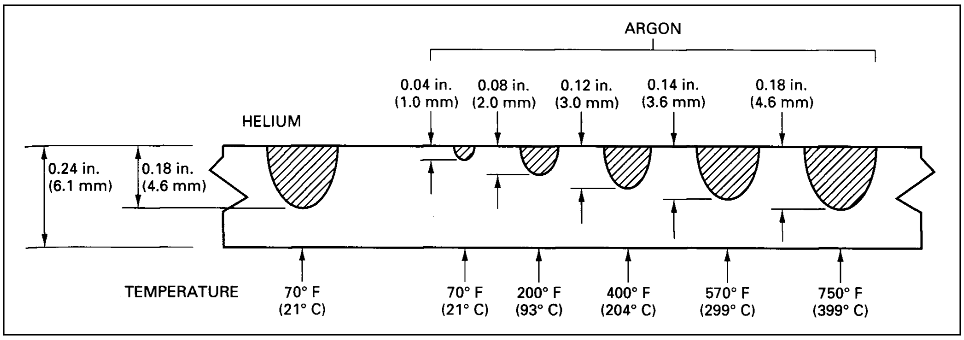

***Figure 7.*** *Effect of shielding gas and preheat temperature on weld bead penetration in copper in TIG welding with 300 A current at a travel speed of 20 cm/min /AWS 1996/.*

## 2.3 MIG welding

MIG welding is recommended for copper materials thicker than 3 mm. The biggest advantage of MIG welding, as compared to TIG welding, is its high deposition rate. Then the heat input is also higher than that in TIG welding. The wider HAZ of MIG welding may cause a problem in some applications /AWS 1996/.

Direct current and a positive electrode are used solely in MIG welding of copper.

MIG welding renders a high deposition rate and good joint properties. It requires low preheating and interpass temperature and results in small deformation. The shielding gases in MIG welding are the same as in TIG welding /Dahlgren 1997/.

Generally 90° single-U or single-V grooves with a root gap of approximately 3 mm are the best suited for thick joints to ensure adequate root penetration. Argon can be used as a shielding gas up to material thickness of about 25 mm with auxiliary preheat. The use of argon-helium mixed gases for thicker materials is especially beneficial since they decrease the need for preheating of thick joints without sacrificing the conditions that enable fine droplet transfer of the filler material. The fraction of helium in these gases can be as much as 50%. The stability of the arc is also improved. Mixed gases not only enable a higher travel speed than pure argon, but they also result in better penetration and a more favourable bead shape /Dahlgren 1997/.

Nitrogen bears a similar effect on the arc temperature and penetration to that of helium, but in MIG welding the use of it causes coarse metal transfer across the arc that can lead to rough weld deposits and spatter. Argon-based mixtures, with nitrogen content between 20 and 30 %, have been shown to exhibit deep root penetration without losing a fine droplet transfer, which is common to argon. Mixtures with more than 30 % nitrogen shift the deposit metal transfer from fine to coarse /Dahlgren 1997/.

## 2.4 Welding cases

### *Welding of thick copper*

A recent patent, approved and accepted in the United States of America, describes a process that enables the welding of thick-walled copper without the occurrence of weld bead oxidation or blowholes. The process can be carried out without preheating or grooving the copper workpieces. What it does require is carbon backing, which has been found to protect and shape the root of the weld. The patent also offers a solution for the necessity of preheating by raising the voltage exceptionally high, to about 37 - 45 V. The current is DC and the electrode is positive. The process has been applied both to TIG and MIG welding. In MIG welding the method enables a high melting rate of the filler metal and the purifying effect of the arc is good. Recommended shielding gases are helium-argon mixtures with 15 - 80 % helium. The patent states, that the method was developed for welding of pure or almost pure oxygen-free or deoxidised copper. It is possible to weld materials having a thickness of up to 25 mm, by one layer one side welding. Materials having a thickness of up to 100 mm are also possible to weld, when using multi-pass technique /Dahlgren 1997/.

Another welding process, originating from India, has been developed to join 10 - 60 mm thick copper short circuiting rings. The rings have formerly been manufactured by forging tough pitch copper, which is not readily welded. The new process has enabled implementation of weld production of 20 - 60 mm thick rings, despite the oxygen content typical of ETP copper and high thermal conductivity, which both complicate the welding process. ETP copper contains approximately 0,06 % oxygen. When the copper is heated, *e.g.*, during welding, the oxygen is released as follows:

$$\begin{aligned}&Cu_2O \rightarrow CuO + 2Cu \rightarrow\\&2CuO \rightarrow 2Cu + O_2 \rightarrow\\&O_2 \rightarrow (O) + (O)\end{aligned}$$

The rapid solidification following welding entraps the oxygen in the metal, causing porosity of the weld. Apart from this metallurgical dilemma, problems are also caused by the high thermal expansion of the material. Hence, studies have found preheating to be of vital importance in welding copper. Insufficient preheating easily leads to weld imperfections and porosity.

The chosen welding process was MIG welding, due to its high productivity. The composition of the filler material was noticed to greatly affect the soundness of the weld. Pure copper, which lacked sufficient deoxidising ability, caused centreline cracks in the weld. The shielding gas used was pure argon.

The criteria for a successful weld turned out to be a single V-groove, cleanliness of the groove surfaces and preheating to approximately 650 °C. The welding current was 310 - 350 A and the voltage 27,9 - 33,3 V. The gas (argon) flow rate was between 19 and 25 l/min /Solanki and Edkie 1999/.

*Shielding gas research*

Copper plates of the dimensions 80 × 60 × 6 mm were welded using different shielding gases and mixtures thereof. TIG welding with filler material was conducted in a 30° angle groove with a 2 mm root gap. Welding was carried out using the following gases and mixtures: 100 % He, 100 % Ar, 80 % He - 20 % Ar, 60 % He - 40 % Ar and 40 % He - 60 % Ar. Other parameters were: gas flow rate 15 l/min, welding current 160 - 165 A, voltage 15 - 18 V and travel speed 24 cm/min. Each weld required three beads /Camurri et al. 1996/.

The chemical composition of the welds was analysed for all elements except oxygen. Furthermore, the welds were examined by means of radiography as well as tensile and hardness testing.

Due to preheating, the parent material undergoes severe oxidation, its initial oxygen content being almost doubled, which in the form of copper oxide $Cu_2O$, dispersed in the matrix, does not reduce ductility /Camurri et al. 1996/.

Inspection revealed that the welds appeared good, with uniform beads, without projections, undercutting or surface porosity. The tensile strength of the parent material was reduced and the ductility was increased due to the preheating /Camurri et al. 1996/.

The radiographic images showed that the specimens welded with a pure shielding gas (100 % He or 100 % Ar) did not exhibit porosity. Specimens welded with gas mixtures exhibited porosity evenly distributed in the weld. The results of the mechanical tests were better for the specimens welded with a pure shielding gas, especially the ones with 100 % He. The results of the tests are displayed in Table 1 /Camurri et al. 1996/.

***Table 1.*** *Mechanical properties of copper specimens welded with different shielding gases /Camurri et al. 1996/.*

| Gas | Tensile strength MPa | Elongation to fracture % | Hardness HV |
|---|---|---|---|
| 100 % He | 227 | 36.5 | 83 |
| 80 % He – 20 % Ar | 179 | 19.6 | 84 |
| 60 % He - 40 % Ar | 174 | 20.3 | 84 |
| 40 % He – 60 % Ar | 194 | 30.2 | 84 |
| 100 % Ar | 202 | 35.9 | 84 |

The objective of the study was to establish how well TIG welding with filler material applies to copper welding. The best results were attained for welding with pure helium as the shielding gas, and then the mechanical properties of the weld were the same as those of the preheated parent material. All specimens exhibited a similar dendritic microstructure with columnar grains in the weld bead, where potential porosity caused by entrapped gas weakens the properties of the weld /Camurri et al. 1996/.

# 3 THE SCOPE OF THE TEST PROGRAM

The spent fuel from Finnish nuclear reactors is planned to be encapsulated in thick-walled copper canisters and placed deep into the bedrock. Outokumpu Poricopper Oy and Posiva Oy have done joint research and development work in copper canister manufacturing technology. Joining of thick copper sections is not straightforward, when using existing welding methods due to the high thermal conductivity of copper /Aalto 1998/.

The possibilities of EB-welding and friction stir welding for the copper canister manufacturing have been studied. The main objective of this test program was to develop suitable equipment for arc welding of thick copper and to find a suitable range of parameters for copper arc welding. The test program consisted of following sections:

1. A literature review on arc welding of copper.
2. The development of the welding equipment including the welding torch and the copper welding station.
3. Welding trials with small workpieces.
4. Metallographic examination.
5. Written report of the test program.

# 4 THE WELDING EXPERIMENTS

Heat from the welding process is readily conducted into the parent material in TIG welding of copper. Heat brought through tungsten electrode to the workpiece transfers rapidly from the molten pool into the parent material. Hence, achieving the molten pool calls for very high arc energy. That is the main difficulty of copper arc welding.

Thick copper plates (over 8 mm) are normally preheated up to 300 - 400 °C before welding. At this temperature range the heat energy input is sufficient for producing the molten pool and the filler material melts adequately. 90° single-U or single-V grooves are the best suited for thick joints.

## 4.1 Preliminary trials

The first preliminary welding trial was executed with one TIG welding torch in order to define the sufficient workpiece surface temperature for welding. According to the trial results the sufficient surface temperature range is 300 - 500 °C before welding, otherwise the welding process will fail.

The second preliminary welding trial series was executed to find out how the shielding gas affects the heat input and the root penetration. The trials were executed with pure argon, pure helium and with mixtures of helium and argon: 30% He - 70% Ar, 50% He - 50% Ar, 75% He - 25% Ar. The best penetration and highest heat input were achieved with pure helium. However, it was observed that helium as a shielding gas does not increase enough the heat input for welding with one torch without preheating. Thus, the next trials were executed with two cascade welding nozzles in the same tool, the first nozzle for preheating and the second for welding. The objective was to find out if it is possible to weld the workpiece without preheating it with an external device.

It was observed that a narrow gap TIG welding torch calls for two cascade welding nozzles, one for preheating and the other for welding. The welding trial was executed with two separate power sources and with two welding nozzles in the same tool as shown in Figure 8. Welding current for the first nozzle was 250 A and 300 A for the second nozzle. It was observed that the first nozzle (preheating arc) increases significantly the melting efficiency of the second nozzle.

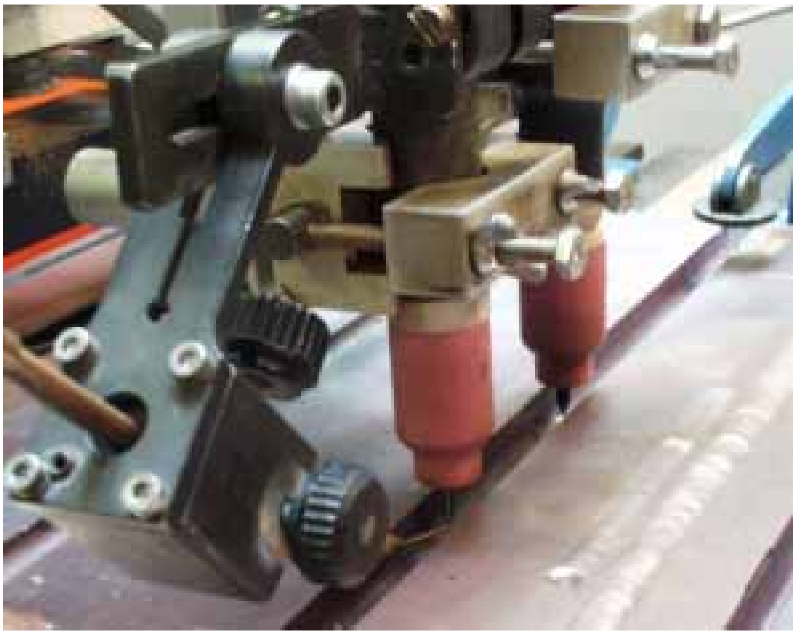

***Figure 8.*** *Two TIG welding nozzles in the same tool.*

The next welding trial was executed with the welding equipment described above with 4-5 mm U-groove using manual filler material feed (Ø 2,5 mm). According to the trial results, the filler material melts adequately in the groove, when using parameters described above. Another objective of the trial was to examine, what is the effect of the distance between the two electrodes on the melting efficiency. According to the trial results, the distance between the two electrodes should be as small as possible. The maximum distance between the two electrodes is 50 mm. If the distance is under 30 mm, the arc performance of both electrodes decreases.

## 4.2 The first version of narrow gap TIG welding torch

Based on the preliminary trial results it was decided to develop a narrow gap tandem welding torch. The torch includes two cascade welding nozzles and the filler material feed is in the middle as shown in Figure 9. The filler material feed is situated between the two electrodes because of gas shielding and better filler material feed control. The filler material conductor is replaceable and adjustable vertically and horizontally. The filler material conductor structure has to be firm so that it does not tremble during the welding process. The main parts of the narrow gap welding torch consist of copper and they are coated with boron nitride using High-Velocity Oxy-Fuel coating method. The main parts are coated because of insulation.

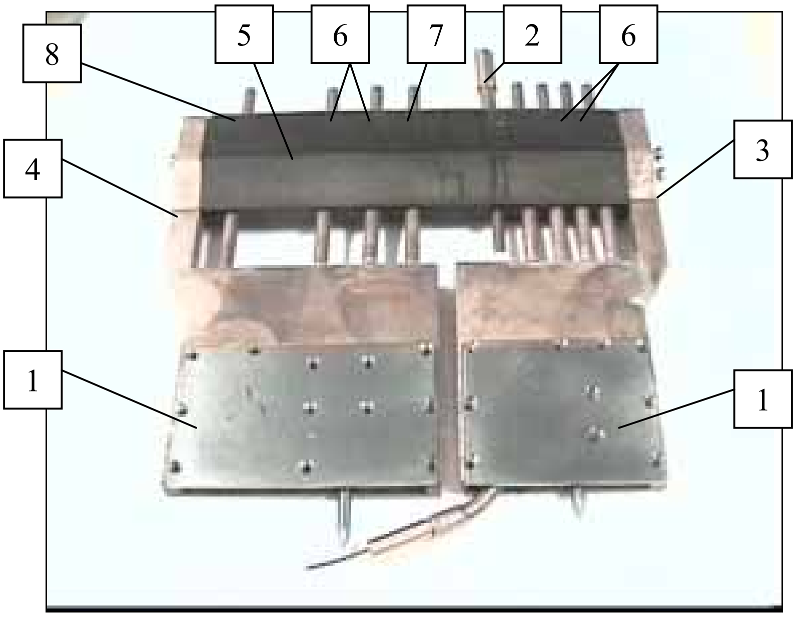

***Figure 9.*** *The narrow gap TIG welding tool.*

Part list of the tool:

1. Replaceable gas nozzle
2. Filler material feed conductor
3. Conductor rail of the first nozzle
4. Conductor rail of the second nozzle
5. Insulated adapter
6. Cooling water input and output
7. Gas input
8. Gas input

Problems occurred, however, when firing the arc with a high frequency spark. The boron nitride coating was imperfect and the arc ignited between the gas nozzle and the workpiece. Furthermore, the temperature of the molten pool surface is so high, that copper from the molten pool evaporates and forms a copper coating on the gas nozzle. Thus, firing the arc has to be executed with electrode contact instead of high frequency spark. However, firing the arc with the electrode contact was not possible due to the features of the welding equipment.

The narrow gap welding torch was recoated with aluminium oxide using High-Velocity Oxy-Fuel coating method because of the problems described above. However, the problems continued to occur. Based on the trial results firing the arc with high frequency spark is unreliable. It was concluded that copper is not the best structural material for the welding torch. Basically the material selection and the structure of the narrow gap welding torch call for further research.

## 4.3 Welding trials with filler material feed

In order to find out the suitable angle and position for the filler material feed, a welding trial was executed with 1.2 mm diameter filler material feed using a MIG welding equipment. The filler material type used in the trials was Esab OK-Autrod 19.12, which is best suited for pure copper arc welding. The filler material was manually fed using a MIG welding torch. The filler material feed speed was 3 m/min, workpiece thickness was 12 mm and the trial was welded in a 6-7 mm semi-circular shaped groove. The travel speed was related to the workpiece heating. An average value for the travel speed was 10 cm/min with welding currents of 250 A for the first nozzle and 280 A for the second nozzle.

Based on the trial results, the filler material can be fed almost vertically. The filler material should be positioned in front of the molten pool. If the filler material is positioned directly into the molten pool, the speed of the filler material melting process alternates because of the heating effect of the arc. A stand for the filler material feed was installed beside the welding tool. If the filler material feed speed is too high, the size of the molten pool increases and the electrode may collide with the molten pool. The collision short-circuits the system and the arc will go off. Moreover, large size of the molten pool can cause a lack of fusion defect.

It was observed in additional trials that the filler material melts and becomes oxidised before it enters the molten pool. Hence, the filler material feed system should be cooled and insulated from radiation heat. It was also presumed that the feed of the filler material should be pulsed.

Best results were achieved with a high travel speed and low welding run with relation to the filler material feed speed and welding current. If the travel speed is too low when welding the capping run, the edges of the groove melt and the welding process becomes more complicated. Moreover, the risk of the undercut increases.

The amount of the shielding gas is a significant factor. The temperature and the uniformity of the arc increase, if the flow of the shielding gas decreases. However, adequate gas protection for the welding process is necessary in order to prevent airborne oxygen from entering the molten pool.

## 4.4 Welding trials with two nozzles

The next trial was welded in a U-groove with the width of 10 mm and the depth of 15 mm. Workpiece material was oxygen-free copper and the workpiece thickness was 50 mm. The length of the workpiece was 500 mm and the width of the workpiece was 300 mm. The trial was executed with two cascade welding nozzles and with 1.2 mm diameter filler material feed. The shielding gas was pure helium. The workpiece was preheated 10 min with welding nozzles with the current of 300 A on each nozzle. The average temperature of the workpiece was 100 °C after preheating. The travel speed was 5 cm/min. During the trial, the size of the molten pool decreased and finally the parent material did not melt at all. The filler material could not be fed because the molten pool was not present. The next trials were executed with elevated welding currents. The results of the trials are shown in Table 2.

***Table 2.*** *The molten pool characteristics of 50 mm thick copper plates.*

| Welding arc, A | Preheating arc, A | The molten pool characteristics |
|---|---|---|
| 350 | 300 | The parent material did not melt |
| 350 | 350 | The molten pool width 3 mm |
| 350 | 400 | The molten pool width 3 mm |
| 400 | 400 | The width of the molten pool increased slightly |
| 400 | 450 | The width of the molten pool increased slightly |

Welding with the filler material feed was not possible because the filler material cooled the environment and the parent material did not melt, when feeding the filler material. The electrodes endured, however, the welding with 400-450 A current. The gas protection for the welding process was adequate. Hence, oxidation and cracking was not observed in the workpiece.

The heat input and the preheating were not adequate. The heat transfers rapidly and three-dimensionally in thick copper workpieces. The heat transfer was explored with a mathematical model. The model was used to calculate the temperature of the material as a function of the distance when using the welding current of 250 A and the travel speed of 50 mm/min. The temperature distribution in 30 mm thick copper workpiece calculated by the model is shown in Figure 10. It was observed that the distance between the two electrodes should be less than 30 mm when welding 30 mm thick or thicker copper workpieces. If the distance, however, is under 30 mm, the arc performance of both electrodes decreases. According to the trial results, the benefit of the preheating arc is not significant. It was decided that the following trials shall be welded with one welding nozzle and the preheating process is executed with a heating device.

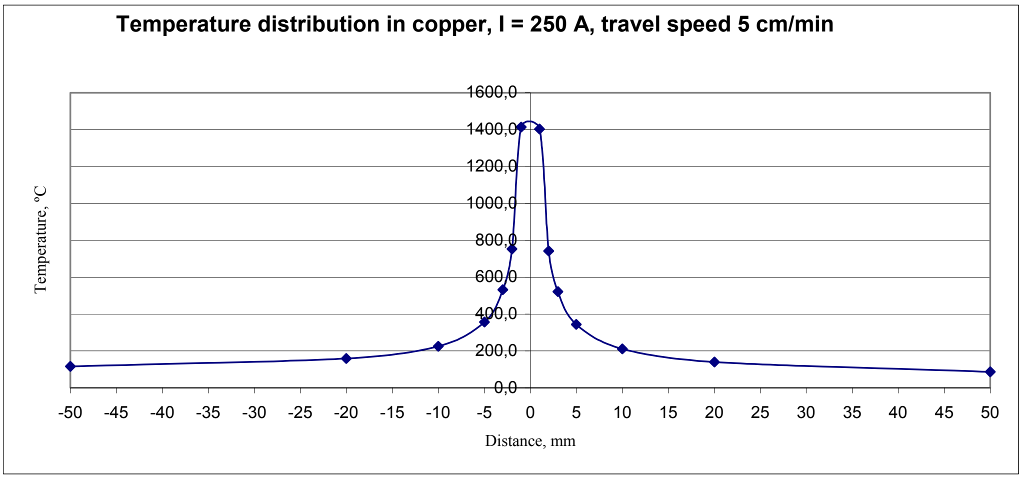

***Figure 10***. *The calculated temperature distribution in 30 mm thick copper workpiece.*

Conclusion of the trials was that the welding of 50 mm thick copper workpieces is impossible with the available welding equipment. The focus of the test program was directed at the narrow gap TIG welding with one welding torch and 15-25 mm thick copper workpieces.

The first trial was executed on the surface of a 15 mm thick workpiece to find out the adequate preheating temperature for producing a molten pool. The length of the workpiece was 500 mm and the width of the workpiece was 300 mm. Travel speed was 5 cm/min, welding current was 350 A and the length of the welding run was 10 cm. The shielding gas was pure helium with the flow rate of 20 l/min. The welding tool was set in motion 10 s after firing the arc. The trials were executed with preheating temperatures of 50 °C, 200 °C, 250 °C, 300 °C and 350 °C. The width of the welds increased towards the end because the temperature of the workpiece elevated during the welding process.

The workpiece was insulated with bricks as shown in Figure 11. The workpiece was preheated in each trial 50 °C above the desired temperature. After preheating the workpiece was air-cooled to the desired temperature. The alternations of the temperature values were registered with a thermocouple.

***Figure 11.*** *Preheating arrangements for the welding trials.*

There is interdependence between the welding current, the molten pool size and the preheating temperature. If the welding current is increased, the size of the molten pool increases. The controllability of the molten pool decreases thereby introducing the risk of lack of fusion. The shape of the molten pool should not be spherical in order to ensure a successful joint with the parent material. If the preheating temperature is elevated, the size of the molten pool increases. According to the trial results, the most suitable welding parameters for 15 mm workpiece are 350 A for the welding current and 250 °C for the preheating temperature.

The role of the filler material feed is significant. The filler material cools down the welding environment. The next trials were executed to explore the significance of the filler material feed. The filler material feed was pulsed with speed of 2,5 m/min, the travel speed was 5 cm/min, welding current was 350 A and the shielding gas flow speed was 20 l/min. The preheating temperature was 250 °C.

The gas shielding was started 9 s before welding and the welding tool was set in motion 10 s after firing the arc. The welding bead became relatively high.

The travel speed was increased up to 10 cm/min in order to accomplish a lower welding bead. Preheating temperature was elevated up to 300 °C. It was observed that the filler material feed speed should be decreased, since the arc energy was not adequate for melting the filler material. A suitable value for the effective filler material feed speed was 164 cm/min (pulsed), when the filler material feed speed without pulsing was 216 cm/min.

## 4.5 Welding fumes and ultraviolet radiation

The local exhaust could not be used in the trials, because the gas protection for the welding process failed when using the local exhaust. The temperature of the molten pool surface is so high in copper arc welding, that copper from the molten pool evaporates and a health hazard occurs. Hence, fresh air hose breathing apparatus had to be used during the trials because of the welding fumes. The level of ultraviolet radiation is also high because of the high welding currents. The trials were then executed in an insulated cell, which was specifically built for this purpose. Health hazards related to the copper welding processes call for further research, in general.

## 4.6 Copper welding station

The final copper welding equipment built during this study included two TIG welding power sources (Esab Pro TIG 450 and Kemppi PRO-TIG 400) with the capacity of 400 A current of 100% duty cycle. The filler material feed is automatic and can be pulsed. The filler material feed angle can be adjusted manually. The welding torch is mounted on a guide rail. The system includes two cameras for monitoring the welding process. One of the Pro TIG equipment’s features is the AVC system, which adjusts the torch automatically in vertical direction based on the variation of the welding voltage. Real time adjustment of the welding parameters is possible with the equipment. Preheating was executed with Heatmaster HM 100 device. The copper welding station is an insulated cell with local exhaust. The station is shown in Figure 12.

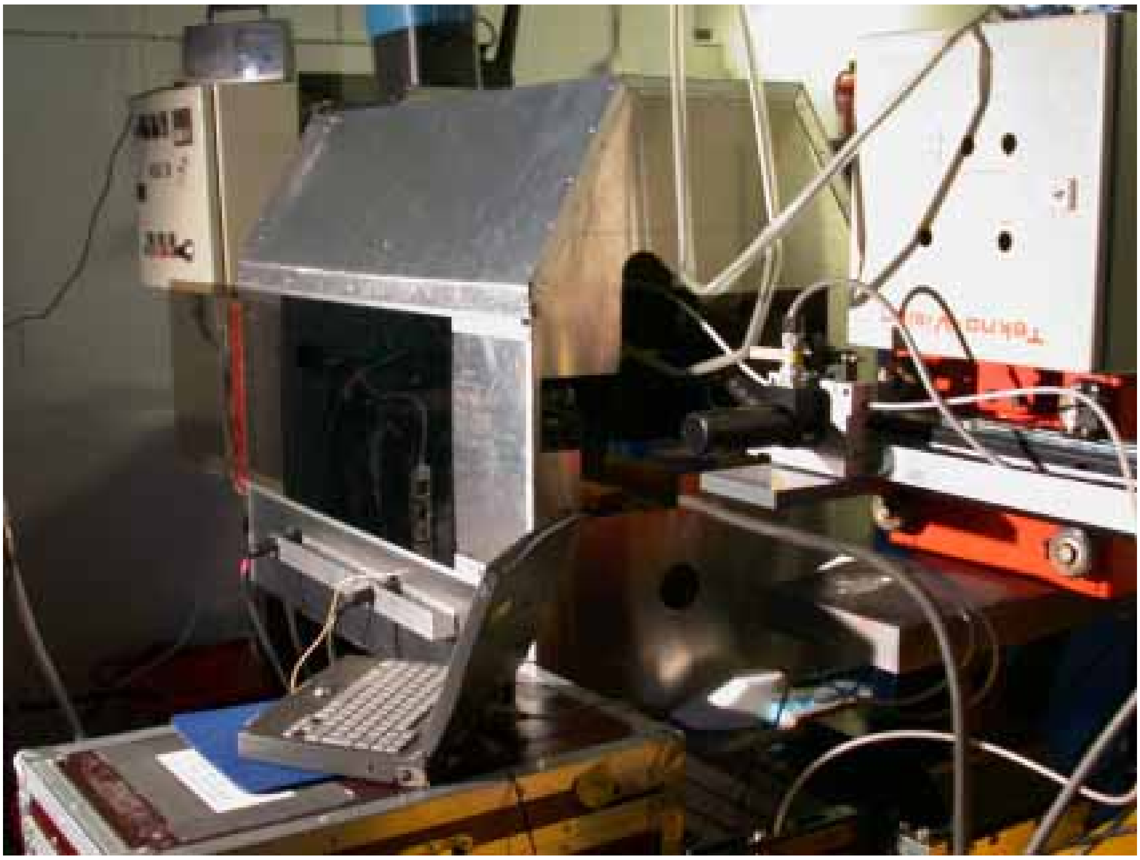

***Figure 12.*** *The copper welding station.*

The objective of the welding trials was to find out a range of parameters suitable for welding 25 mm thick copper workpieces with one welding nozzle. The first trial was executed with 400 A welding current without the filler material feed. The length of the workpiece was 500 mm and the width of the workpiece was 300 mm. The shielding gas was pure helium (flow rate 20 l/min) and the welding tool was set in motion 10 s after firing the arc.

The preheating temperature was initially meant to be the only adjustable parameter. However, the arc voltage and the travel speed had to be adjusted as well due to the blowholes. The arc voltage had to be increased in order to prevent the electrode from colliding with the molten pool. One reason for the problems was that helium as the shielding gas calls for higher arc voltage than argon and the AVC system of the Pro TIG equipment is optimised for argon.

## 4.7 Blowhole phenomenon

The molten metal of copper workpieces is very fluid. At normal arc length the arc force is so great that it often expels the molten metal from the pool. In order to reduce this force, it is necessary to hold a very long arc, thereby introducing the risk of loss in shielding. On the other hand, thick workpieces call for high arc voltage. Hence, TIG welding of thick copper is fairly cumbersome. The travel speed did not seem to have a significant effect on the blowhole phenomenon. Because a melting temperature range between the solidus and liquidus lines of the equilibrium phase diagram does not exist, it was presumed that the molten metal solidifies before it enters back to the pool.

The shielding gas may be one of the reasons for blowholes. Hot welding atmosphere may cause whirlpools, thereby introducing the risk of loss in shielding. The objective of the next trial was to find out if the shielding gas system is working properly and has no leaks. The welding trial was executed using stainless steel. According to the trial results the shielding gas system was working properly.

Another reason for the problems may be too high heat input. Helium has a high ionisation potential, which gives a higher heat input than argon. The next trials were performed with the mixture of helium and argon (50% - 50%) on the surface of 25 mm thick copper. In the first trial the preheating temperature was 100 °C, the travel speed was 100 mm/min, the arc voltage was 14,0 V and the shielding gas flow rate was 18 l/min. The welding current was pulsed. The trial was started with the welding current of 200 A, but it was increased up to 400 A, because the parent material did not melt until the welding current reached 350 A. The second trial was executed with the preheating temperature of 200 °C and with the welding current of 400 A. However, the blowhole phenomenon occurred again in the second trial.

The large arc energy is presumably the main reason for the blowhole phenomenon in copper welding. The molten metal is highly fluid and it solidifies rapidly. If the welding current remains high and even, the arc force expels the molten metal behind the arc constituting a pile of solidified material behind the arc and a blowhole in front of the arc. The blowhole phenomenon is shown in Figure 13. It was presumed that pulsing the welding current might improve the situation. With pulsed welding current the size of the molten pool and the arc pressure decrease and the molten pool is more controllable.

***Figure 13.*** *Blowholes in copper workpiece.*

The next two trials were executed with pulsed welding current on the surface of the 25 mm thick copper workpiece. The length of the workpiece was 500 mm and the width of the workpiece was 300 mm. The peak current was 400 A, inter-pulse current was 200 A and the inter-pulse time was 0,3 s. Shielding gas was a mixture of helium and argon (50% - 50%) and the arc voltage was 14,0 V. The preheating temperature in the first trial was 200 °C and the welding tool was set in motion 10 s after firing the arc. The weld was fairly clean, but the size of the molten pool was too little for the filler material feed.

The second trial was executed with the preheating temperature of 250 °C. The blowhole phenomenon occurred during the peak current. The preheating temperature of 250 °C had caused the occurrence of oxide layer on the surface of the workpiece. It was presumed that $H_2O$ produced by the steam reaction described in Section **2.1** caused porosity.

The trials were continued with variable pulse parameters and preheating temperatures. It was also discovered that increasing the preheating temperature over 200 °C causes the occurrence of weld bead oxidation. A suitable range of parameters for welding of thick copper workpieces with filler material feed could not be found during the test program.

# 5 RESULTS

## 5.1 Preliminary trials

According to the preliminary trial results, the suitable preheating temperature range for thick copper plates is 300 - 500 °C. The best penetration and highest heat input were achieved with pure helium. Helium as shielding gas, however, calls for higher arc voltage than argon, thereby introducing the risk of blowhole phenomenon.

## 5.2 Welding equipment

A narrow gap tandem welding torch was developed for test program. The torch includes two cascade welding nozzles and the filler material feed is in the middle. The torch is shown in Figure 6. Problems occurred, however, when using the narrow gap tandem welding torch. Firing the arc with the torch was uncertain and the coating of the torch was imperfect. Basically the material selection and the structure of the narrow gap welding torch call for further research. Some of the trials were executed with conventional TIG welding torches.

A copper welding station was developed for the trials. The station is described in Section **4.6**. The copper welding station served its purpose well. A slight problem occurred with the automatic torch adjusting system of the welding equipment, because it was optimised for welding with pure argon as shielding gas.

## 5.3 Welding trials

### *50 mm thick workpieces*

The welding of 50 mm thick copper workpieces is impossible with the available welding equipment. Without the filler material feed the width of the molten pool was only 3 mm. The filler material cooled the environment and the parent material did not melt when feeding the filler material even with the maximum welding current of the welding equipment.

### *15 mm thick workpieces*

Travel speed was 5 cm/min, welding current was 350 A and the length of the welding run was 10 cm. The shielding gas was pure helium with the flow rate of 20 l/min. The welding tool was set in motion 10 s after firing the arc. Other parameters and observations are shown in Table 3.

***Table 3.*** *The width of the welds in 15 mm thick copper workpiece.*

| Number of weld in Figure 14 | Welding current, A | Preheating temperature, ºC | Observations | Width of the weld, mm | | |
|---|---|---|---|---|---|---|
| | | | | start | middle | finish |
| 1 | 350 | 200 | The preheating temperature is inadequate, the size of the molten pool is too little | 7.6 | 10.6 | 13.8 |
| 2 | 350 | 250 | The preheating temperature is adequate | 7.6 | 10.9 | 13.8 |
| 3 | 350 | 300 | The preheating temperature is adequate | 10.0 | 13.4 | 16.4 |
| 4 | 400 | 350 | The preheating temperature is adequate | 11.0 | 14.0 | 17.9 |

The width of the welds increased towards the end because the temperature of the workpiece elevated during the welding process. Hence, controlling the welding process is cumbersome. The welds are shown in Figure 14.

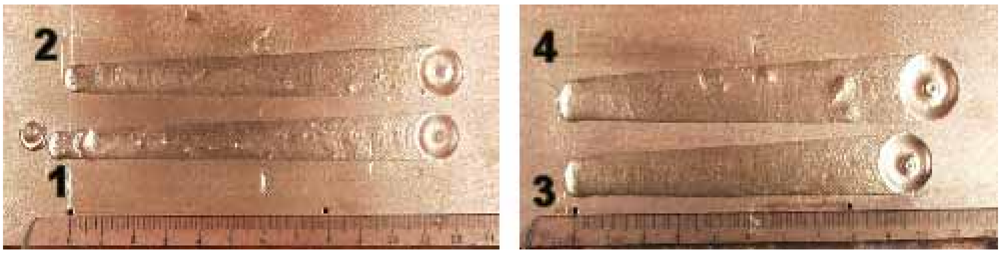

***Figure 14.*** *The width of the welds in 15 mm thick copper. The numbers in Figure refer to Table 3.*

### *25 mm thick workpieces*

The trials were executed on the surface of 25 mm thick oxygen-free copper workpiece to discover a range of parameters suitable for welding 25 mm thick copper workpieces with one welding nozzle. The first trial was executed with 400 A welding current without the filler material feed. The shielding gas was pure helium (flow rate 20 l/min) and the welding tool was set in motion 10 s after firing the arc. Other parameters and the trial results are depicted in Table 4.

***Table 4**. The welding parameters for 25 mm thick copper workpiece.*

| Number of weld in Figure 15 | Preheating temperature, ˚C | Travel speed, mm/min | Arc voltage, V | Observations |
|---|---|---|---|---|
| 1 | Room temperature | 100 | 16 | Clean and narrow weld |
| 2 | 100 | 100 | 16 | Blowholes at first, then clean weld |
| 3 | 150 | 100 | 17 | Blowholes during the whole weld |
| 4 | 200 | 100 | 19 | Blowholes |
| 5 | 220 | 50 | 19 | Blowholes |
| 6 | 250 | 100 | 20→22 | Blowholes |
| 7 | 300 | 100 | 22 | Blowholes |
| 8 | 350 | 50-100 | 22 | Blowholes |
| 9 | 400 | 50-100 | 22 | Blowholes, depth of a single hole 4-5 mm and width 7 mm. |

The size of the molten pool was too small for the filler material feed (approximately 3 mm) in welds 1 - 2. The blowhole phenomenon occurred in the welds 3 - 9. The arc energy is presumably the main reason for the blowhole phenomenon. The welds of the trials are shown in Figure 15.

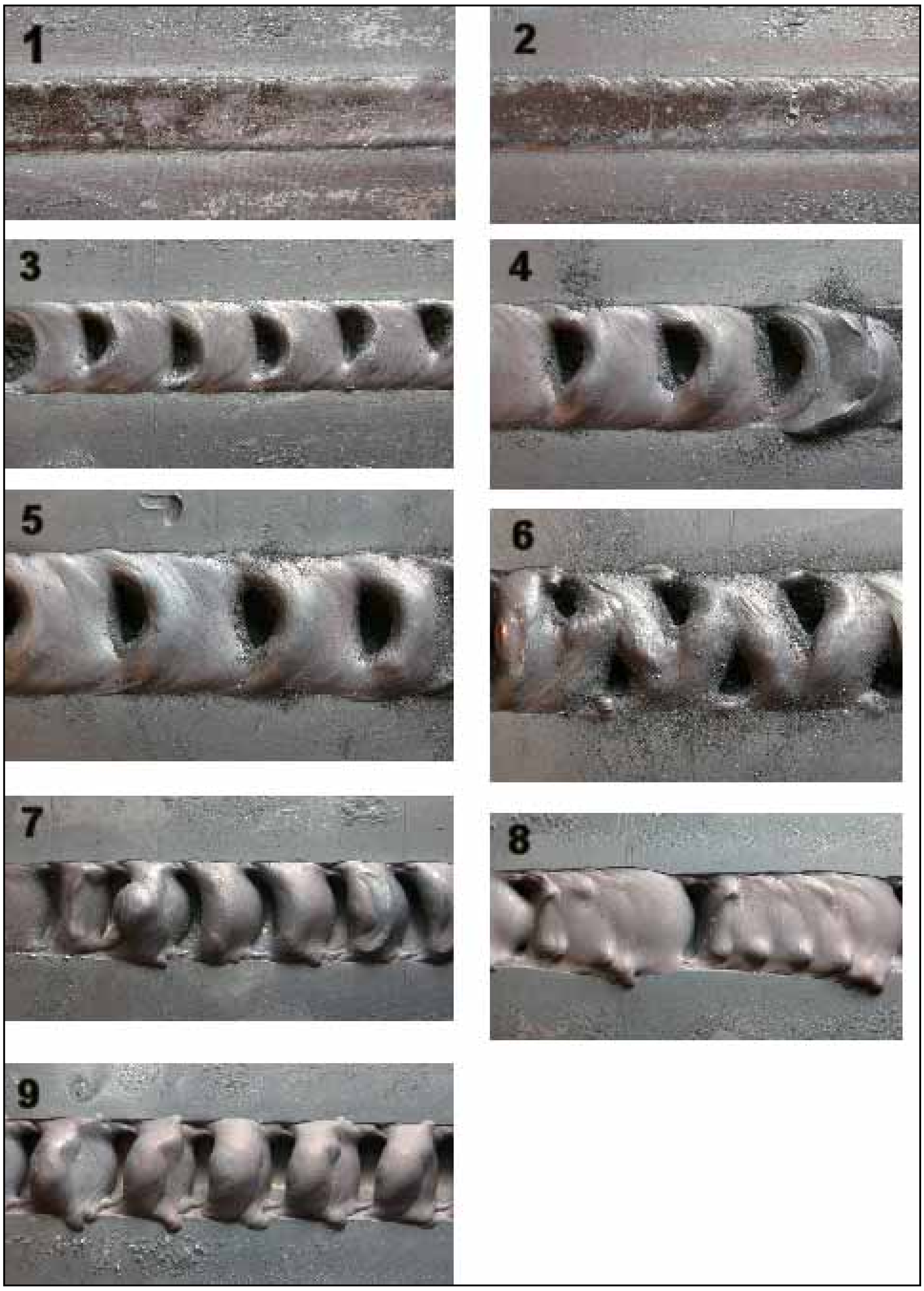

***Figure 15.*** *The welding trials for 25 mm copper workpiece. The numbers in Figure refer to Table 4.*

### *25 mm thick workpiece welded with the mixture of helium and argon*

In order to reduce the arc energy the next trials were executed with the mixture of helium and argon (50% - 50%). The parameters for the trials are depicted in Table 5.

***Table 5.*** *The welding parameters for the 25 mm thick workpiece welded with the mixture of helium and argon.*

| Number of weld in Figure 16 | Welding current, A | Arc voltage, V | Travel speed, mm/min | Shielding gas, l/min | Preheating temperature, °C |
|---|---|---|---|---|---|
| 1 | 200 -> 400 | 14 | 100 | 18 | 100 |
| 2 | 400 | 14 | 100 | 18 | 200 |

The size of the molten pool was smaller than with pure helium. In the second trial with the preheating temperature of 200 °C the blowhole phenomenon occurred. The welds are shown in Figure 16.

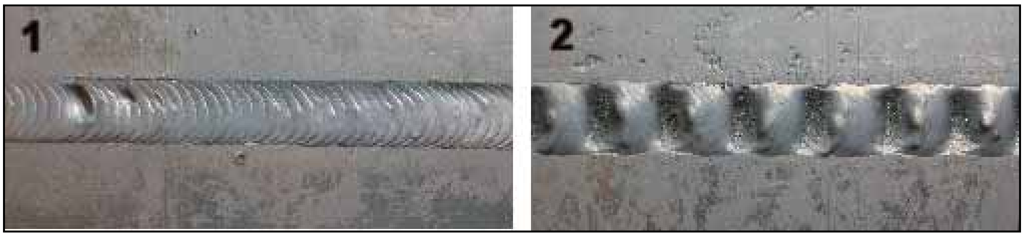

***Figure 16.*** *The welds in 25 mm thick copper workpiece. The numbers in Figure refer to Table 5.*

### *25 mm thick workpieces welded with pulsed welding current*

It was presumed, that pulsing the welding current may improve the situation. With pulsed welding current the size of the molten pool and the arc pressure decrease and the molten pool is more controllable. The inter-pulse time in the trial was 0,3 s and the shielding gas was a mixture of helium and argon (50% - 50%). The other parameters are depicted in Table 6.

***Table 6.*** *The welding parameters for the 25 mm thick workpiece with the mixture of helium and argon.*

| Number of weld in Figure 17 | Welding current, A | | Arc voltage, V | Travel speed, mm/min | Shielding gas, l/min | Preheating temperature, °C |
|---|---|---|---|---|---|---|
| | Peak | Inter-pulse | | | | |
| 1 | 400 | 200 | 14 | 100 | 18 | 200 |
| 2 | 400 | 200 | 14 | 100 | 18 | 250 |

In the first weld the size of the molten pool was too little for the filler material feed. The quality of the second weld was poor. The preheating temperature of 250 °C had caused the occurrence of oxide layer on the surface of the workpiece. It was presumed that $H_2O$ produced by the steam reaction described in Section **2.1** caused porosity. Blowhole phenomenon occurred also. The welds are shown in Figure 17.

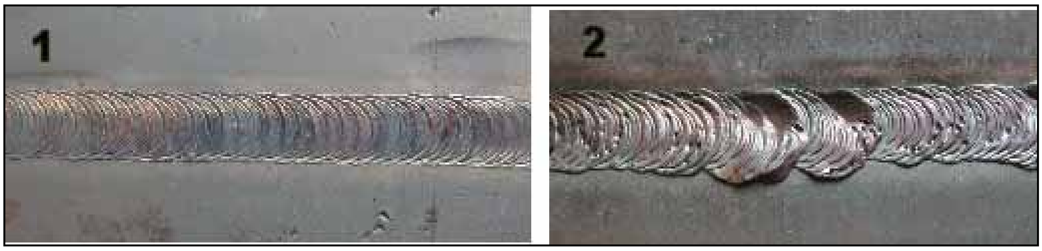

***Figure 17.*** *The welding trials with the pulsed welding current. The numbers in Figure refer to Table 6.*

## 5.4 Metallographic examination

Because a suitable range of parameters for welding of thick copper workpieces with filler material feed could not be found during the test program, the quality of the trial welds was poor according to the visual inspection. Hence, it was not necessary to perform metallographic examination for the workpieces.

# 6 DISCUSSION

Arc welding of copper is cumbersome. The high electrical and thermal conductivity of copper has a substantial effect on its weldability. Heat from the welding process is readily conducted into the parent material, causing possible imperfections. Because the heat of fusion of copper is relatively high, producing a molten pool calls for high arc energy. The welding current of 450 A (which is the maximum value with the available equipment) is inadequate for arc welding of 50 mm thick oxygen-free copper workpieces.

Preheating is of paramount importance in the welding of copper. Insufficient preheating causes imperfect melting and inadequate penetration. On the other hand, if the preheating temperature is increased over 200 °C the risk of weld bead oxidation occurs. Because of the high thermal conductivity the size of the molten pool increases easily towards the end of the weld because the temperature of the workpiece elevates during the welding process. Hence, controlling the welding process is cumbersome and it calls for real-time adjustment of the welding parameters.

The large arc energy together with the rapid solidification of copper is presumably the main reason for the blowhole phenomenon in copper welding. The molten metal is highly fluid and it solidifies rapidly. If the welding current remains high and even, the arc force expels the molten metal behind the arc constituting a pile of solidified material behind the arc and a blowhole in front of the arc. The molten metal of copper workpieces is highly fluid. A large molten pool will easily run and an adequate fusion is hard to accomplish. At normal arc length the arc force is so great that it often expels the molten metal from the pool. In order to reduce this force, it is necessary to hold a very long arc, thereby introducing the risk of loss in shielding. On the other hand, thick workpieces call for high arc voltage. Hence, TIG welding of thick copper is fairly cumbersome. The travel speed does not seem to have a significant effect on the blowhole phenomenon. Because a melting temperature range between the solidus and liquidus lines of the equilibrium phase diagram does not exist, the molten metal solidifies easily before it enters back to the pool.

The arc welding of thick copper should be executed in pure argon atmosphere in order to prevent airborne oxygen from entering the molten pool. The preheating temperature should be elevated up to at least 600 ºC when welding thick copper sections. At high preheating temperatures the arc energy can be decreased thereby decreasing the risk of the blowhole phenomenon. When preheating is used, the parent material adjacent to the joint should be heated uniformly to the temperature. The temperature should be maintained until the joint is completed. On the other hand, high preheating temperatures may introduce the risk of the hot shortness.

More promising results have been achieved in thick copper welding with electron beam welding (EBW) and friction stir welding (FSW) techniques. Posiva Oy and Outokumpu Poricopper Oy have achieved good results in the field of EBW with their “Development of EB-welding method for massive copper canister manufacturing” joint project. Tests carried out at The Welding Institute (TWI) have demonstrated that both EBW and FSW are potentially suitable to produce high integrity joints in 50 mm pure copper. Only the powerful, intense EBW heat sources are capable of making these welds. Both FSW and EBW equipment are already installed in SKB's canister laboratory at Oskarshamn, and FSW welding trials are ongoing at TWI using a purpose built machine on testpieces representative of complete canisters. Practical experimentation has shown that EBW and FSW of 50 mm section copper, despite their essentially disparate natures, involve a similar heat input to the canister. In both EBW and FSW there is significant heat flow well ahead of the weld due to the relatively low welding speed, high heat input, and high thermal diffusivity of copper /Andersson et al. 2000/.

# 7 CONCLUSIONS

The conclusions obtained from the experiments on arc welding of thick copper are as follows.

(1) The suitable preheating temperature range for thick copper plates is 300 - 500 °C.

(2) The welding current of 450 A is inadequate for arc welding of 50 mm thick oxygen-free copper workpieces even when using high preheating temperatures.

(3) With 15 mm thick copper workpieces the width of the welds increases easily towards the end because the temperature of the workpiece elevates during the welding process. Hence, controlling the welding process is cumbersome and it calls for real time adjustment of the welding parameters.

(4) Increasing the material thickness introduces the risk of the blowhole phenomenon. The large arc energy needed for welding thick workpieces is probably the main reason for the blowhole phenomenon.

(5) The arc welding of thick copper workpieces is cumbersome, in general. More promising results have been achieved in thick copper welding with electron beam welding (EBW) and friction stir welding (FSW) techniques.

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## APPENDIX 1: DEVELOPMENT PLAN FOR NARROW GAP ARC WELDING OF COPPER

The narrow gap arc welding experiments of thick copper sections evidenced that the welding process is cumbersome. Some thoughts arose during the test program. It was not possible, however, to execute all the desired experiments with the existing resources. Some of the observations from the executed trials and subjects that call for further research for successful narrow gap arc welding of thick copper sections are as follows:

### *Gas shielding*

Copper is susceptible to weld bead oxidation if temperature exceeds 200 ºC. Hence, the arc welding of thick copper should be executed in an insulated cell in pure shielding gas atmosphere in order to prevent airborne oxygen from entering the molten pool. Helium has a high ionisation potential, which gives larger heat input than that of argon. The risk of the blowhole phenomenon, however, increases with helium because of the larger arc energy. The welding process is easier to control with argon. Hence, the pure argon atmosphere is preferable.

### *Preheating*

The preheating temperature should be at least 600 ºC when welding thick copper sections. With high preheating temperatures the arc energy can be decreased thereby decreasing the risk of the blowhole phenomenon. When preheating is used, the parent material adjacent to the joint should be heated uniformly to the temperature. The temperature should be maintained until the joint is completed. This may require cooled backing during the welding process.

### *Travel speed*

With the thick copper workpieces the width of the welds increases easily towards the end because the temperature of the workpiece elevates during the welding process. Hence, controlling the welding process is cumbersome and it calls for real time adjustment of the welding parameters. One solution for the problem may be the adjustment of the travel speed. If the travel speed is elevated during the welding process, the heat input decreases, and the weld bead may be uniform throughout. This issue calls for further research.

### *Oscillation*

Oscillating the welding tool may decrease the blowhole phenomenon. If the welding electrode is oscillated orthogonally towards the welding direction 1 - 1.5 mm, the shape of the molten pool becomes wider and the arc pressure decreases. The molten metal bonds possibly also better with the edges of the groove when oscillating the welding electrode.

### *Narrow gap welding tool*

A narrow gap welding tool including two cascade welding nozzles was developed for the narrow gap arc welding experiments of thick copper sections. The coating of the tool was imperfect and the arc ignited between the gas nozzle and the workpiece. The welding tool could not be coated successfully with the available coating methods. Hence, the structure of the tool should be different. The welding electrodes should be insulated from the welding tool with a ceramic collar. This should prevent the arc from igniting between the gas nozzle and the workpiece.

The arc performance could be possibly improved with a specific shielding gas system. The system would include a normal gas shielding coming out from the gas nozzle (possibly argon). In addition, there would be a small flow of helium gas coming out between the welding electrode and the ceramic collar. The shielding gas system is depicted in Figure 1. This issue, however, calls for further research.

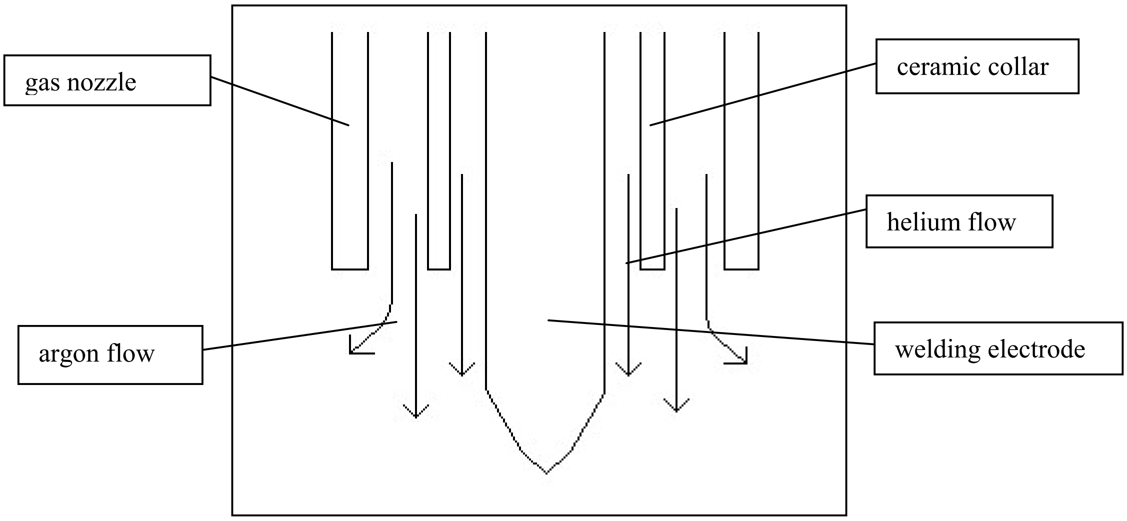

*Figure 1. The gas shielding system.*

### *Electrode*

Thoriated tungsten electrode or lanthanum oxide alloyed tungsten electrode is preferred for copper welding for its better arc performance, longer life and greater resistance to contamination.

The rake angles of the electrodes were tested with 400 A current. The trial was executed with 30 mm thick copper workpiece. The arc time for each workpiece was 10 min.

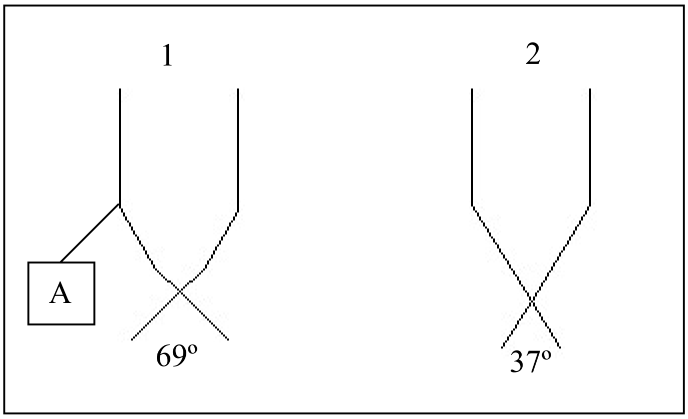

*Figure 2. The shapes of the welding electrodes.*

The trials evidenced that the head of the electrode retains its shape better with larger spread angles of the electrode. If the shape of the head of the electrode changes, the arc performance decreases causing welding defects. Electrode 1 retained its shape well in the trials, but electrode 2 did not. Hence, the head of the electrode should be obtuse in the narrow gap arc welding of copper. The best angle for the head of the electrode calls for further research.

It was also found out, that if the edge between the electrode and its head is rounded (A in Figure 2) instead of angular, the arc performance is better.

### *Filler material*

The welding trials were executed with the filler material type Esab OK-Autrod 19.12. Based on the knowledge obtained from Outokumpu Poricopper Oy inadequate preheating temperature together with unsuitable filler material is one reason for the blowhole phenomenon. Thick copper sections are best welded with deoxidizing filler materials which prevent the steam reaction. The viscosity conditions of the molten pool can also be influenced with a suitable filler material.

In some trials, the molten pool could not be produced with the filler material feed because of the inadequate heat input. Based on the experience obtained from Outokumpu Poricopper Oy increasing the angle between the welding electrode and the filler material may help for solving the problem. This issue also calls for further research.