R-03-25

Electron beam welding of copper lids

Status report up to 2001-12-31

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October 2003

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Summary

The report describes a summary of achieved results from 21 lid welds and numerous test block welds, performed at SKB Canister Laboratory in Oskarshamn for the period 1999-02-12 to 2001-12-31.

Good weld quality has been achieved and some welds fulfilled the preliminary interpretation criteria, but the weld process need to be further developed before process qualification.

Many different parameter settings have been tested and the influence on the weld profile has been mapped and documented. Deformations of the canister after welding have been measured and found to be very small. The preliminary inspection methods of the weld quality works satisfactory for the need of the development of the weld process.

The welding machine is a new design developed for welding of thick copper in reduced pressure and performs well, but suffers from teething problems, which has delayed the work with development of the weld process. The welding system needs to be further developed and improved to work more reliably in a production plant.

Contents

1 Introduction

This report describes a summary of achieved results from 21 lid welds and numerous test blocks performed at the SKB Canister Laboratory in Oskarshamn for the period 1999-02-12 to 2001-12-31.

More detailed results are described in the welding reports from every lid weld, reference [1–21]. The report also deals with experiences from the weld equipment during the same period.

A list of records from experimental welding in copper blocks is also included as an appendix to the report.

2 Process development

2.1 History

1982 SKB placed first EBW copper welding study with TWI.

1983 Attempt with High Vacuum EBW.
Root defect, gun discharging and cathode life problems.

1986 New indirectly heated diode gun.
Improved cathode life and beam stability.

1992 EBW High Power Non-Vacuum.
Improved weld profile but insufficient weld depth.

1994 Prototype 150 kW Inverter developed.
G*un discharging problems reduced.*

1995 Reduced Pressure H-V of canister lid.
Improved weld depth, acceptable weld profile.

1997 100 kW, 220 kV reduced pressure EB Machine delivered to Canister Laboratory.

1998 First 90 kW beam generated at 200 kV and 450 mA for a period of 7 minutes.

1999 Test welding of 10 Blocks and 4 Lids.
Weld profile and quality a problem.

2000 Gun modified → *Improved weld profile.*
Test weld of 21 Blocks and 10 Lids (no 5–14).
Developed weld process → *Improved weld quality.*

2001 Test welds of 21 Block and 7 Lids (no 15–21).
Measuring of beam profile with Beam probing.
Weld profile and quality still a problem.

2.2 Development goal

The main goal has been to fulfil the preliminary interpretation criteria in accordance with 2.7.1 in this report and to test the relationship between the welding machine parameter settings and the achieved weld profile and quality.

Another goal has been to achieve a round weld root with a tip radius ≥ 2,5 mm and a weld depth of ≥ 65 mm. The big tip radius empirically found to be needed to avoid internal cavities in the root area and is therefore of vital importance for achieving welds with good quality.

The objectives for each lid weld is described in a report before welding and the results analysis is described in a report after each welding.

2.3 Development status

Good weld quality has been achieved but the weld process can be further developed against improved weld quality and reduced heat input. A key issue is the cathode designs, which influences beam profile and beam stability. Good parameter stability of the welding machine is also important to determine the welding process parameters.

2.4 Joint design

The joint design was developed at TWI see figure 1. The gun is directed in the horizontal position and the beam first penetrates the outer part of the lid (7,5 mm) and then the joint face lid/cylinder (50 mm) and then stops inside the lid about 10 mm past the inner cylinder wall. The outer bar on the lid, called the fronting bar, prevents the weld melt from pouring out during welding. After welding, the lid is machined level with the outer cylinder wall.

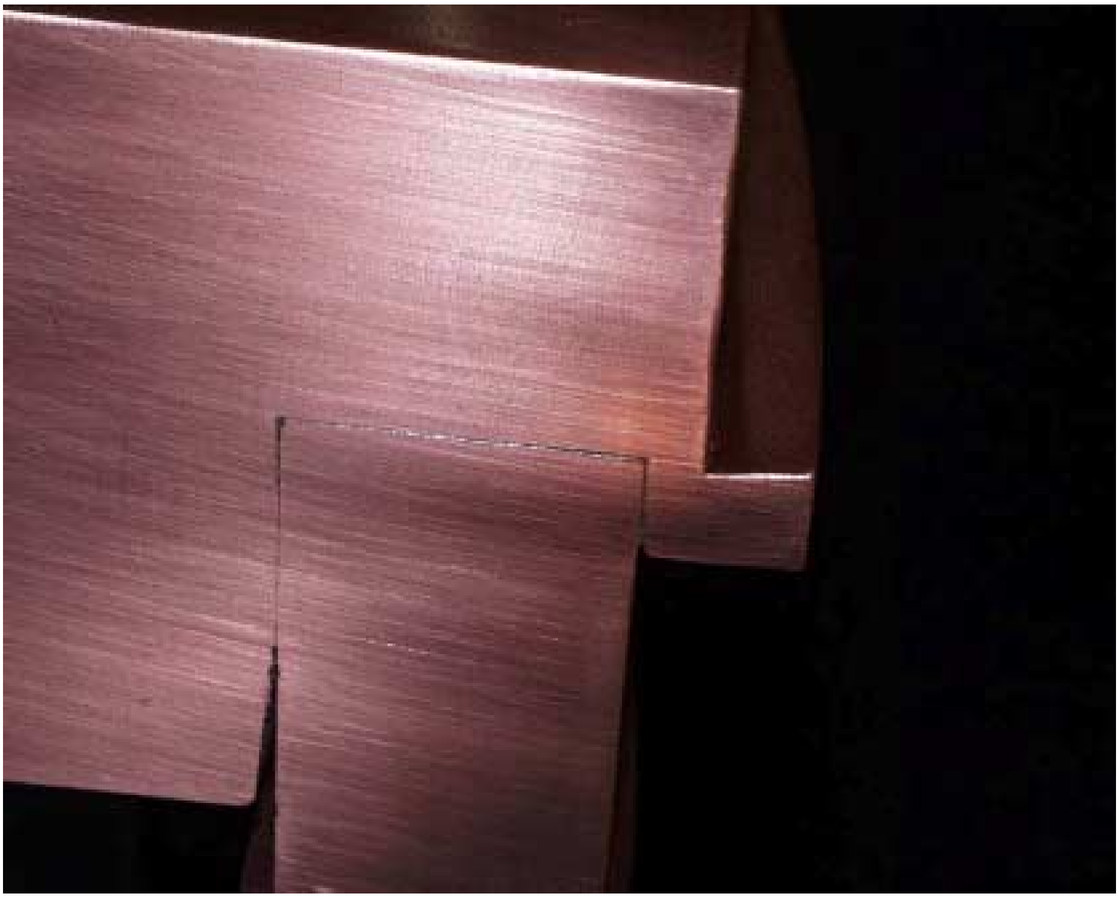


Figure 1: *Cross section of the joint design prior to welding.*

2.5 Process control

The welding process is controlled and monitored by two different computers.

1) A Siemens computer with the CNC-system Siemens 840C, runs the machine axes and the beam parameters. Every lid weld has a specific main welding computer program named by the lid no. For lid tack welding the standard computer program LID2TACK is used. All lid welding computer programs are stored on the Siemens computer hard disk.
2) A monitoring computer for data logging of the parameters used during the welding process. The monitoring program is a LabVIEW application. Labview is a general purpose programming system for data acquisition and instrument control. The program provides actual as well as historical information on the recorded data from the Siemens system. Data is logged and stored on the computer hard disk as an ASCII text file. This file is then processed in an Excel spreadsheet with charts, depicting the produced weld process.
3) All lid welds have also been video recorded using a colour TV-camera inside the chamber.

2.6 Development performance at TWI

The development of the joint design and the basic process of electron beam welding canister lids in reduced pressure are described in following reports:

- 220278 Welding lids onto 1,2 m (3 lids) and 2,4 m cylinders (1 lid and 1 bottom).
- 220745 Welding lids onto 5 m cylinders (2 lids and 2 bottoms).
- 220699 Inclined beam-lids to cylinders (3 lids).

REPORT TWI 220278/1/95 [44]

Weld trials were carried out on curved plates and on copper cylinders, 880 mm in diameter (three 1,2 m long and one 2,4 m long).

Weld no: W91/92/117/122/123/124/125/126/127/128.

Basic studies on the influence of various parameters:
Acceleration Voltage, Beam Current, Welding Speed, Beam Focus, Working Distance, Helium Flow, Weld Tilt, Beam Positioning, Beam Slope-up and Slope-down.

Temperature Measurements were taken on two of the lid welds W123 and W127.

The weld quality was examined by Radiographic and Ultrasonic C-scan and then by sectioning.

Parameter settings at the lid weld trials as follows:

Acceleration Voltage	220 kV	Beam Current	340 mA
Welding Speed	250 mm/min	Helium Flow	2 l/min
Working Distance	100 mm	Beam Focus Q1	1,160 → 1,225 A at 005 → 340 mA
Weld Tilt position downwards	2°	Beam Focus Q2	Full beam current 1,450 A Slope out 1,450 → 1,550 A
Chamber pressure	0,16 mbar	Beam Positioning	3 mm above front bar
Slope in distance	60° rotation	Slope out distance	60° rotation

21 conclusions is mentioned in the report, some of them as follows:

1) A weld with a penetration of 70 mm, width of 10 mm and a round-bottomed profile can be made using 75 kW beam power.
2) Root porosity can be eliminated, by using suitable beam focus parameters.
3) Porosity in the body of the weld occurs randomly and no weld conditions have been found to control it completely.
8) Beam slope in and slope out parameters has been established. Beam focus must be altered during slope out to avoid root porosity defects.
9) A fronting bar is necessary to support the top bead.
11) Shrinkage of the weld metal leads to a reduction of the lid diameter of 0,78 mm and shrinkage across the weld of 0,62 mm.

According to the radiographs and the ultrasonic inspections there were severe cavity and porosity formations in some areas of the weld.

REPORT TWI 220745/1/96 [90]

Weld trials were carried out on one EB fabricated copper cylinder and on one extruded copper cylinder, both cylinders ∅ 880 mm in diameter and 5 m long.

Weld no: W139/153 lid welds and W133/145 base welds.

Some conclusions as follows:

- For the lid/base weld, sufficient weld depth > 65 mm with a round bottom weld profile can be achieved.
- Ultrasonic NDT revealed defects in all four lid and base welds, thought to be porosity ranging in size from the limit of detection 0,1 to 20 mm.
- In the first lid weld, the effects of EB gun discharging led to multiple defects and surface braking voids. In the other three welds there were no gun discharge events.
- There is a close correlation between the fit up of the lid or base and the number and size of defects.
- Attempts to repair near surface defects by re melting in a normal HV position were only partially successful
(HV position = Gun in horizontal and Canister in vertical position according to figure 22).
- Trial melt runs into solid material were largely defect free and had a smooth top bead.
- Lid to cylinder welds generally exhibited numerous gross porosity defects and the surface was often covered with spatter and metal explosion.
- Cleaning of the joint surfaces is critical. An experiment showed that using wire wool as the cleaning abrasive was better than Scotchbrite cleaning material.

REPORT TWI 220699/1/97 [89]

Weld trials were carried out on curved plates and on copper cylinders ∅ 880 mm in diameter, 1,2 m long.

Weld no: W231/234/237 lid welds and W188-217 block welds.

Principle conclusions when using a 37° downward tilting beam as follows:

1) Penetration depth is not significantly altered compared with HV welding at similar powers.
2) The effect of welding parameter variations is similar to that found in HV welding.
3) Periodic metal expulsion from the weld pool leaves surface cavities, which cannot be filled by subsequent cosmetic pass, the cause remains unclear and needs further investigation.
4) Root porosity is much less of a problem than with HV welding, becoming apparent only if the root radius is < 1 mm.

2.7 Development performance at SKB

The process development has mainly been performed using full size copper lids and short copper cylinders (length 1–2 m) 1,050 mm in diameter. Experimental welding has also been done in copper blocks with the size of 30–100 kg. Due to thermal effects, the weld profile in copper blocks is different from the weld profile in lids with the same parameter settings. Therefore these tests have only been used as a guide and to establish a qualitative understanding.

The welds have been inspected with RT and UT, both before and after machining of the lid outer surface. Some of the welds were also inspected using eddy current (ET) to detect small close to surface defects. Macro sections have been taken out from all welds by drilling with a core drill. The macro sections have then been cut in two halves machined, polished and etched so the weld profile could be viewed. The weld profile has been examined and measured under a microscope.

The shrinkage of the lid diameter and height has also been measured as well as the axial and radial distortion.

A list of operations has been created unique for every lid weld. That list has to be followed when producing a lid weld, and the operator has to sign the list after every performed operation.

2.7.1 Preliminary interpretation criteria [46]

The weld quality has been examined using NDT. In order to get a uniform interpretation for the NDT, has preliminary interpretation criteria been established. These criteria are based on conservative estimations of allowable discontinuities in the weld and some investigations concerning the NDT-methods ability to detect and size discontinuities. Some of the weld trials have been performed for beam parameter trials and some to fulfil these criteria.

The main principles of the criteria's for the work at the Canister Laboratory are shown in figure 2 below, where the red line represents the report level for the NDT and the blue line represents the maximum allowable discontinuity size in the weld.

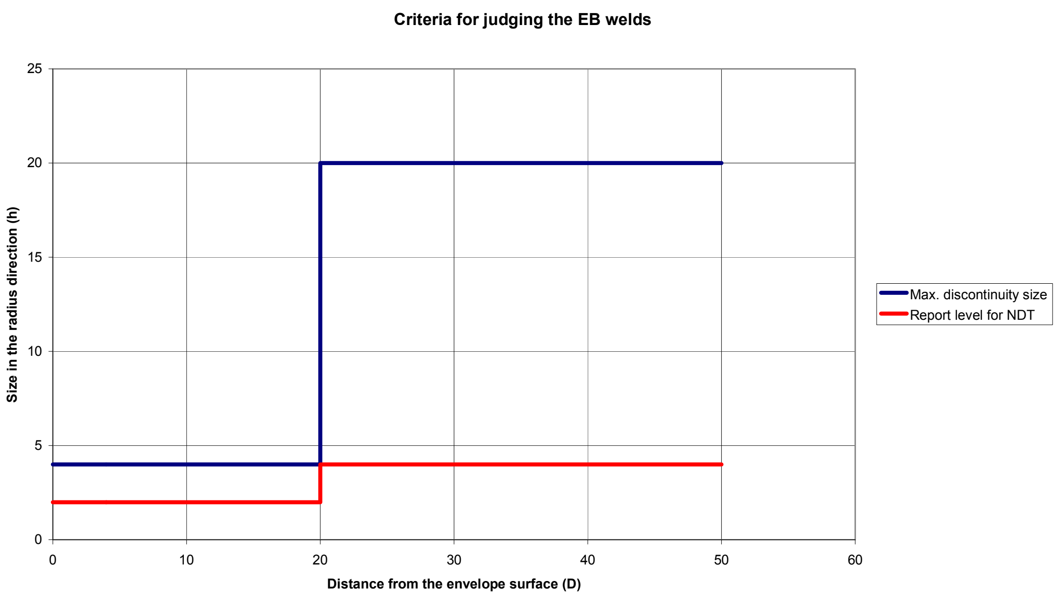
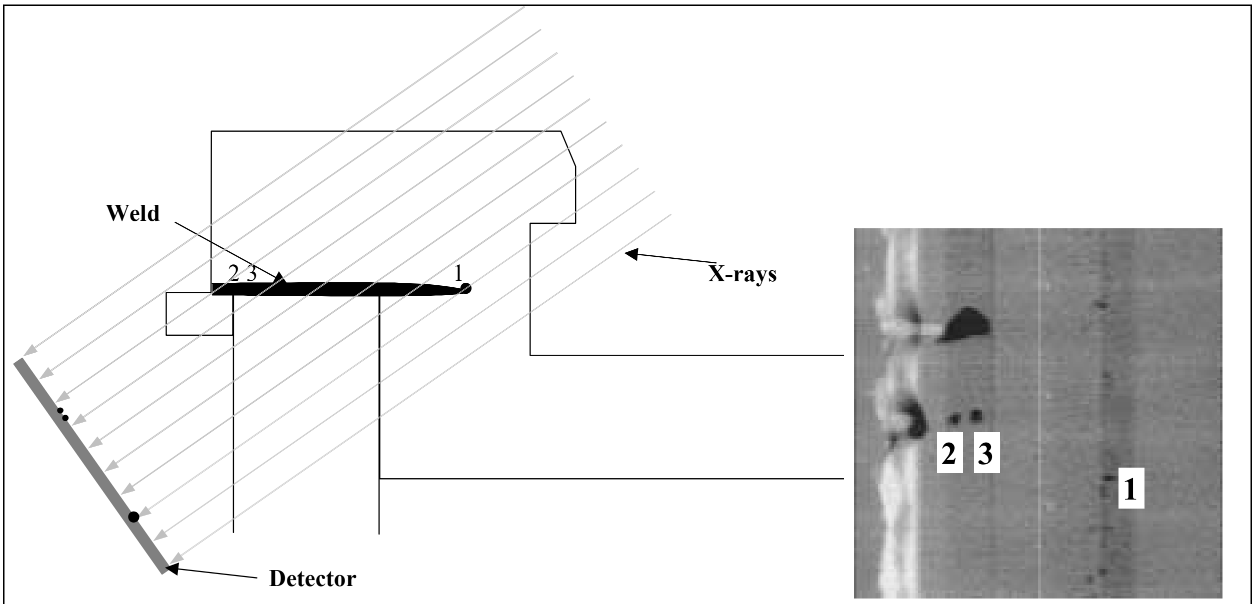


Figure 2: *Criteria for the development process regarding welding and NDT at the Canister Laboratory*

2.7.2 Radiographic inspection method (RT)

The RT is mainly performed according to SKB routine SDKL-009 [47], Radiographic Inspection. The main principles of this are that the object rotates while the 9 MeV Linear Accelerator pulses X-rays through the weld at an incident angle of 35° (see figure 3). The transmitted X-rays are detected by a linear array detector with 0,4 x 0,4 mm resolution. The linear detector is placed perpendicular to the beam angle and the X-ray images are built up of several of these collected lines (see figure 4). These digital X-ray images have been evaluated according to SKB preliminary acceptance criteria.

Figure 3: *X-ray equipment for inspection of the electron beam welded lid.*



The numbers above shows where the indications in the X-ray image to the right are located in the weld. The white pattern to the left of the X-ray image is an effect of the weld surface and the vertical axis represents the welding direction with start at the top.

Figure 4: *Sketch of the radiographic inspection with a corresponding X-ray image.*

2.7.3 Ultrasonic inspection method (UT)

The UT is mainly performed according to SKB routine SDKL-010 [49], Ultrasonic Inspection. The main principles are that the object rotates while the 80 elements phased array electronically scanning in the radial direction with a coupling of a thin water path made by a probe head (see figure 5 and 6). The array configuration consists of a sequence of angled steered ultrasound towards the outer surface, focused ultrasound in the centre and reversed angled steered ultrasound towards the inner surface. For steering an aperture of 16 elements has been used and for focusing has apertures with up to 32 elements been used to optimise the ultrasonic inspection of the whole weld. The maximum amplitude value has been collected to form the C-scans. These C-scans images have been evaluated according to SKB preliminary acceptance criteria.

The C-scan image in figure 6 shows the weld surface to the left, the brighter area to the right is an effect from the area inside the weld (the parent material scatters less than the welded material, which can be used to decide the weld depth). The vertical axis represents the welding direction with start at the top.

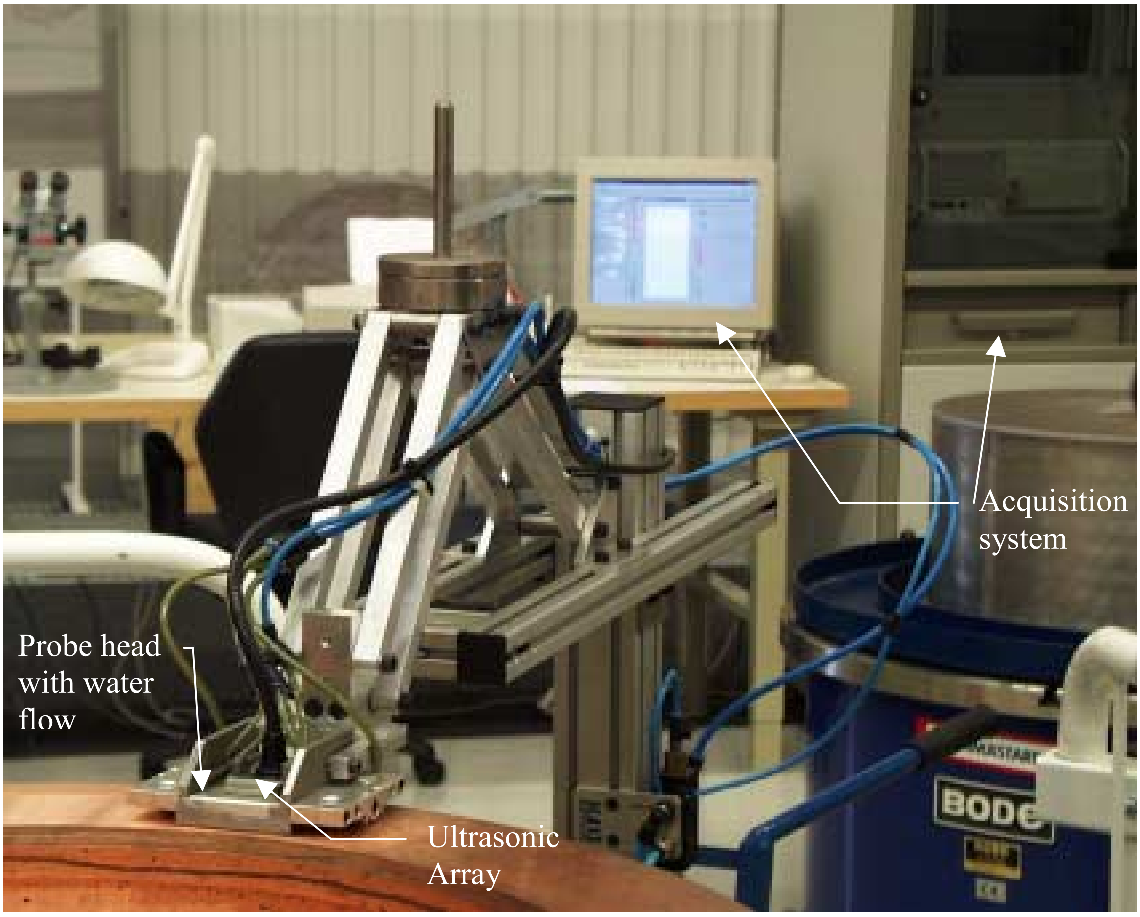


Figure 5: Ultrasonic equipment for inspection of the electron beam welded lid.

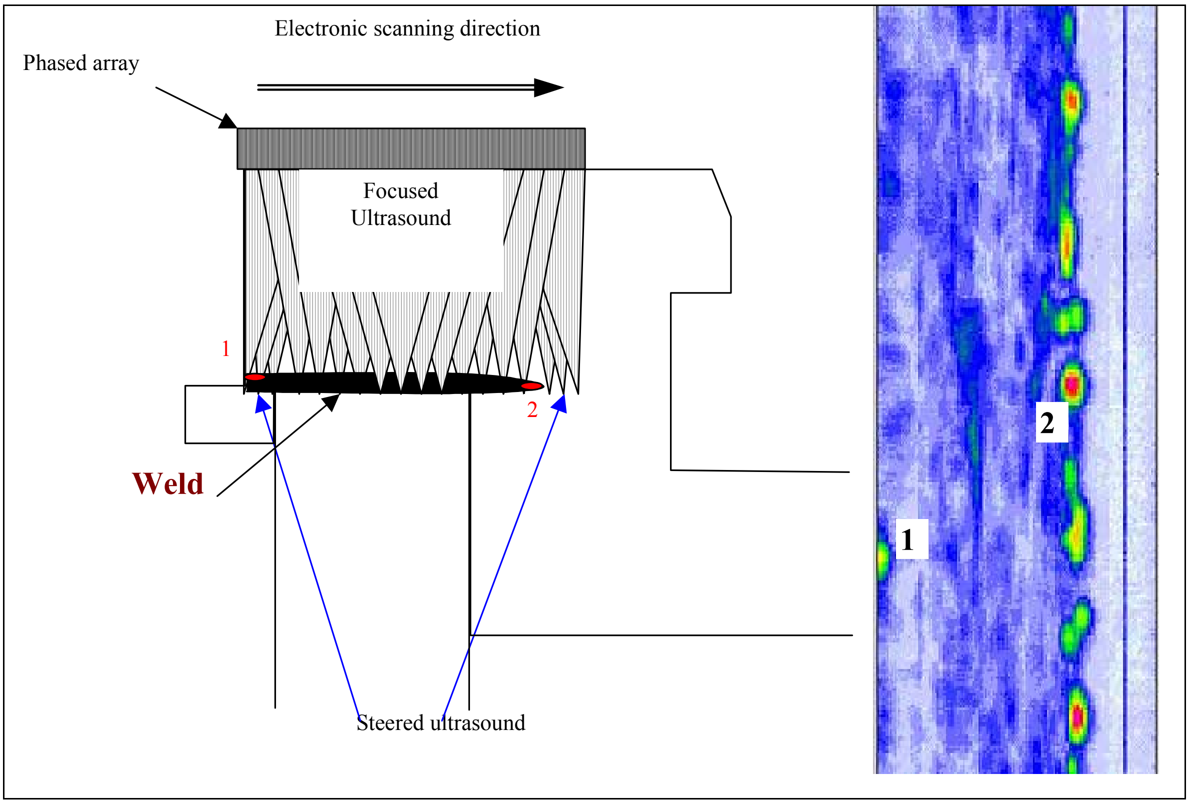


Figure 6: Sketch of the ultrasonic inspection with a corresponding C-scan image.

2.7.4 Welding parameters

Different welding parameter settings have been tested. There are about 30 different parameters, which have been investigated.
The main parameters, test range and their influence on the weld profile as follows:

Parameter	**Test range**	**Influence on the beam/weld**
Acceleration voltage	190–200 kV	Kinetic energy of electrons / Weld profile and weld depth.
Beam current	100–440 mA	Electron flow / Weld profile and weld depth.
Travel speed	210–300 mm/min	Melting and solidification behaviour of the weld metal, affecting the weld profile and the weld quality.
Focus lens Q1	1,150–1,260 A	Beam profile and size of beam through nozzles / Weld profile.
Focus lens Q2	1,375–1,550 A	Size of beam diameter at the work piece / Weld profile and weld width.
Chamber pressure	0,15–0,32 mbar	Beam stability / Weld quality.
Working distance	100–125 mm	Heat input and size of the weld.
Gun tilt angle	–0,9 → –3,6°	Joint melting and direction of weld profile.
Slope in distance	2–50°	Weld quality at weld slope in area.
Slope out distance	10–130°	Weld quality at weld slope out area.
Helium flow	1–3 l/min	Helium is added in the gun to reduce the beam scattering.

2.7.5 Weld trials in copper blocks

The welding in copper blocks is carried out as a pre test of the parameter settings before a weld is performed in a real lid. Another reason for welding in a copper block is to test the stability of the machine parameter settings. The standard parameter setting given below has therefore been used as follows:

Acceleration Voltage	190 kV	Beam Current	350 mA
Welding Speed	236 mm/min	Beam Focus Q2	1,400–1,500 A
Working Distance	125 mm	Helium Flow	1 l/min
Weld Tilt position downwards	3,5°	Beam Positioning	3,5 mm above front bar
Chamber pressure	≤ 0,20 mbar		

Note 1: Recent experiments show, that the Coil Q1 setting (internal focus) also affects the beam profile. No standard setting of Q1 has been decided yet.

Note 2: The beam profile is also affected by the cathode design. Development of the cathode design remains ongoing.

Note 3: Big variations have occurred in weld profile in copper block welding. Weld profile average values using the standard parameter settings has been: depth 70 mm, width 9,5 mm and a tip radius of 1,5 mm. The weld profile in lid welding is much more stable.

A promising test has recently been performed with surface focus, working distance < 100 mm and the biggest possible Q1 setting. Further weld trials are needed before evaluation of the results from these settings.

2.7.6 Weld trials in lids/cylinders

The initial strategy was to start with the best parameter settings from the TWI trials and in a few trials optimise the parameter settings. Thereafter determine the allowed parameter box in a couple of weld trials. Finally establish a welding procedure specification (WPS) document.

Initially it was sound that the weld quality was improved compared to TWI trials, but root cavities caused by a too small root radius were a problem. This problem could not be corrected using parameter settings and hence connected to the design of the components creating and forming the beam.

After lid weld no 4 it was decided to develop the cathode design to create a weld profile with a tip radius ≥ 2,5 mm.

Beginning with lid weld no 5 the new type of cathode called HCC1 was used which increased the weld tip radius. Lid welds no 5–9 were performed with 1 revolution and some internal cavities were a problem. The internal cavities could possible be created from entrapped metal gases in the weld body. The common way to get rid of such gases is to stir in the weld melt by the beam. However the gun is not equipped with that facility so another approach to get rid of the cavities by re-melting was chosen.

Lid welds no 10–14 were performed with 2 revolutions, which resulted in improvement of the weld internal. The improved quality resulted in lid weld no 11 and 13 fulfilling the preliminary requirements and only local defects in lid welds no 10, 12 and 14 occurred.

Lid welds no 15–18 were performed with 4 revolutions and in lid weld no 16 and 17 a special slope out ramp also was tested. Lid weld no 15 and 18 fulfilled the requirements and apart from defects in the test ramp so did lid weld no 16 and 17.

Lid weld no 19–21 were performed with a new cathode of the same type, HCC1. The cathode has a limited lifetime and was exchanged prior to the lid weld no 19, but the weld profile was different, the tip radius was more pointed again. To compensate for the pointed beam profile the Q2 setting was increased and because of that, the width of the weld was increased. The numbers of weld rotations were as follows:

Lid weld no	Revolutions
19	4 (1440° rotation)
20	5 (1800° rotation)
21	3 (1080° rotation)

The weld internal was good but the weld surface was overheated by the increased heat input and the increased width of the beam/weld and a lot of surface cavities were created. TWI has recently made adjustments of the gun and is considering improved design, especially for the cathode.

2.7.7 Beam slope in and slope out

Beam slope in

At lid weld no 1 to 8 TWI recommended beam slope in procedure was used. The beam current slope in speed was 3,52–14,18 mA/sec, at canister rotation of 30°–12°. In the area where the beam/weld overlaps, the slope in area had problems with eruptions from the weld melt. The eruptions can be caused by overheating of the weld melt or maybe by entrapped gases from the weld root that will expand by melting and blowing out some weld melt. (That problem was serious as it caused internal or surface braking cavities and it had to be solved.)

Examples of how these cavities are indicated by UT and RT are shown in figure 7 and 8 below. The two lower defects (1) have a size of 6–7 mm and can represent the slope in defects of weld 1–8. Defects like the larger (2) one, with 27 mm propagation, arise more sporadic.

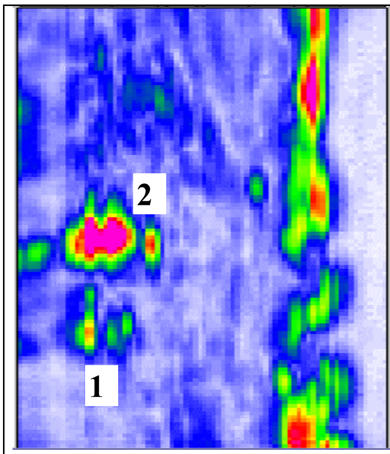


Figure 7: *Ultrasonic C-scan of slope in region 0–12 ° of weld 3.*

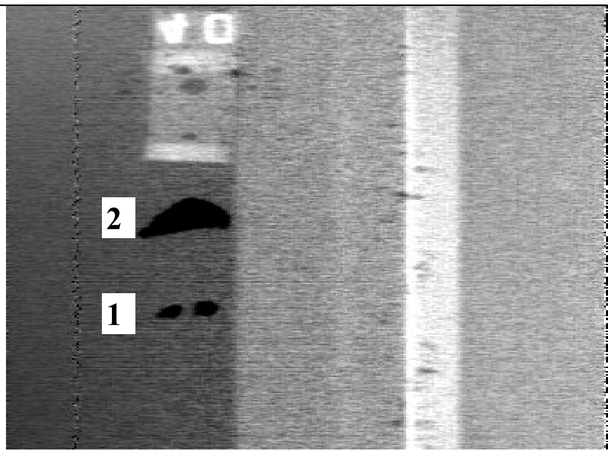


Figure 8: *X-ray image of slope in region 0–12 ° of weld 3.*

At lid weld no 9 to 12 a very slow beam slope in speed 3,13 mA/sec was tried, at canister rotation 50°, after recommendations from TWI. But no improvement was achieved.

Examples of how these cavities are indicated by ultrasonic and X-rays are shown in figure 9 and 10 below. The defects around 35° (3) have a size of 4 and 12 mm and can represent the slope in defects of weld 9–12. Defects like the larger one (4), with 19 mm propagation, arise more sporadically. In some cases the defects caused by eruptions were shallow enough to disappear in the machining.

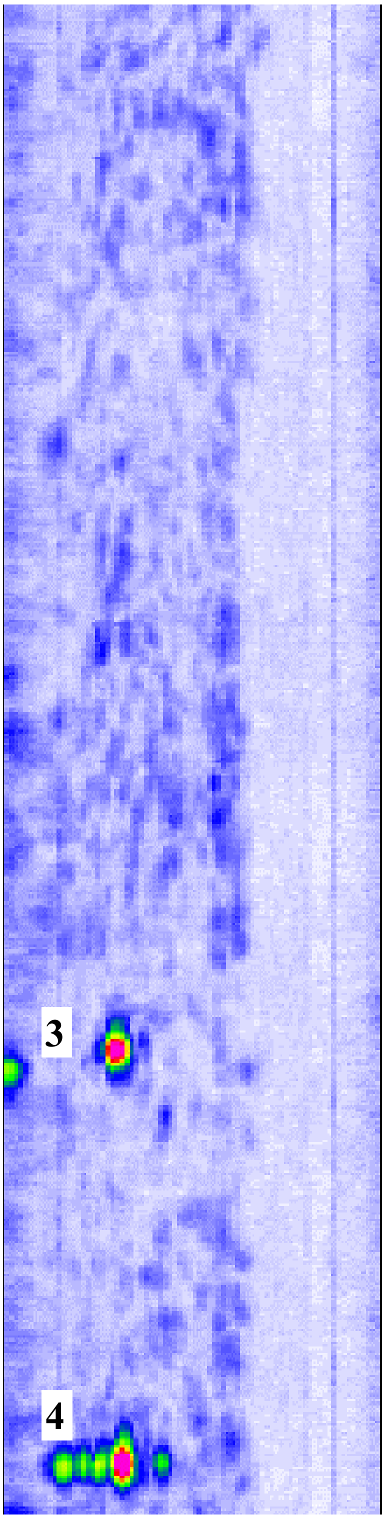


Figure 9: *Ultrasonic C-scan of slope in region 0–50° of weld 10.*

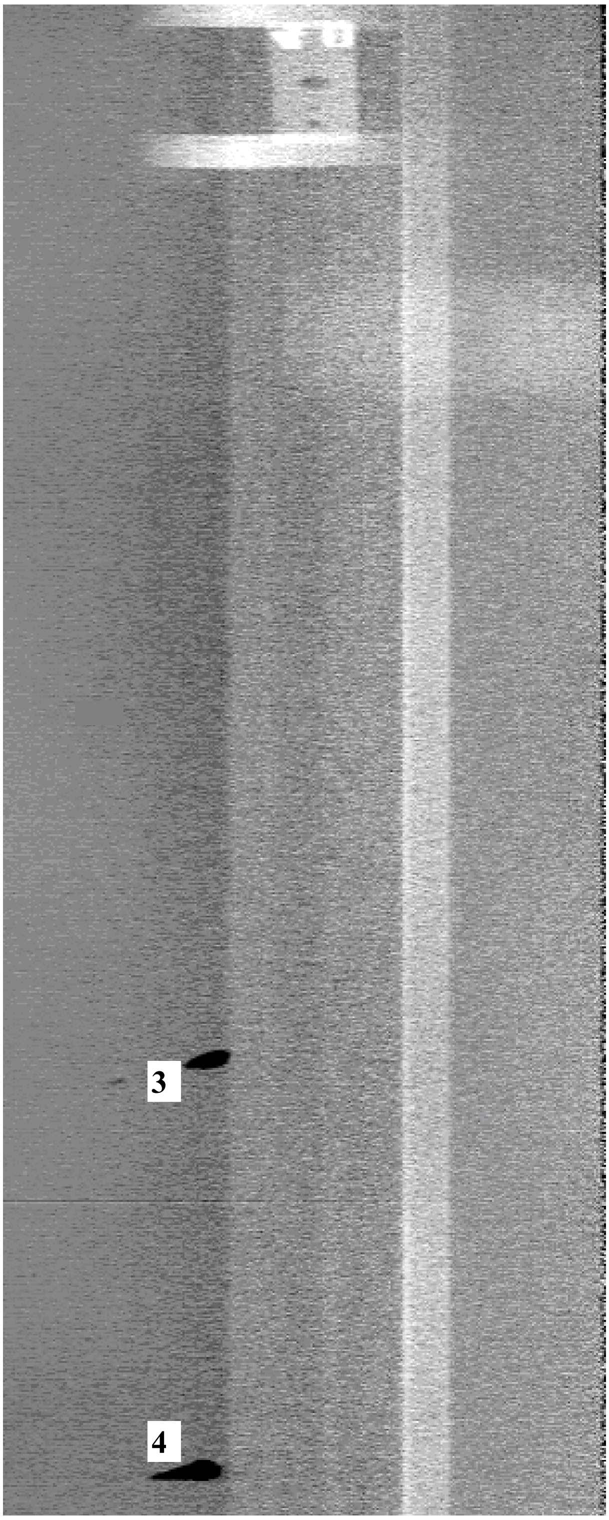


Figure 10: *X-ray image of slope in region 0–50° of weld 10.*

After several failures with the slow slope in procedure it was decided to try a different approach. Instead of a slow beam slope in a very steep one was used, to get the smallest possible overlap area. At lid weld no 13 the fastest possible beam slope in procedure 85,8 mA/sec, at canister rotation of 2° was tried. That led to a significant improvement so the decision was to continue with the fast beam slope in procedure. The standard procedure for beam slope in is now 66,7mA/sec at canister rotation of 2,3°. The lid welds no 14 to 21 were welded without any quality problem in the slope in overlapping region.

The result from the ultrasonic and radiographic inspection verifies the absence of defects in the slope in region. See figure 11 and 12 for example of results from the NDT.

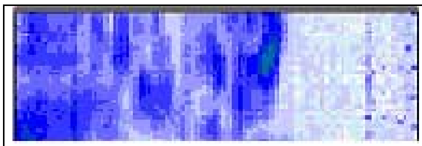


Figure 11: *Ultrasonic C-scan of slope in region 0–2,3 ° of weld 14.*

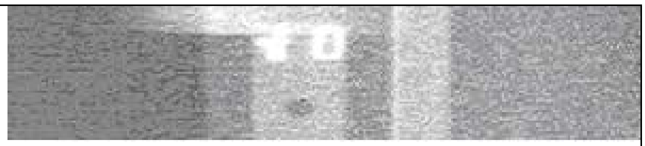


Figure 12: *X-ray image of slope in region 0–2,3 ° of weld 14.*

<u>Beam slope out</u>

A critical part of the weld process is the beam slope out, while the beam current is decreasing, the weld pool is less stable than during periods of steady beam current and the beam focus position will alter as the beam current is changed. That can lead to collapse of the weld pool and cavity formation in the weld metal.

The recommended beam slope out procedure from TWI was a two step procedure during increasing the coil Q2 setting from 1,375 to 1,523 A. The beam slope out speed was 3,53 and 3,83 mA/sec, at canister rotation of 16,5° and 33,1°.

Tests at a range of beam slope out speed of 0,95–6,58 mA/sec, at canister rotation of 10°–130° and Q2 setting from 1,375 to 1,523 A have been tested. Slope out procedure in both one and two steps have also been tested. Problems with cavity formation in the weld metal have occurred in 4 of 21 lid-welds.

The conclusions of the experiments are:

1) Cavities in the slope out region, occurs randomly and no weld condition has yet been found to control it completely.
2) The coil Q2 setting should not be less than 1,450 A, depending on the risk of porosity in the weld root. According to weld trials with the cathode HCC1/SKB3(1).
3) Beam slope out procedure can be further developed.

2.7.8 Parameter studies based on weld trials

Weld trials with different settings of the weld parameters have been performed.
The standard parameter settings used after initial weld trials are as follows:

Acceleration Voltage	190 kV	Beam Current	340–350 mA
Welding Speed	250 mm/min	Beam Focus Q2	1,400–1,500 A
Working Distance	125 mm	Beam Focus Q1	1,200 A
Weld Tilt position downwards	3,5°	Helium Flow	1 l/min
Chamber pressure	≤ 0,20 mbar	Beam Positioning	2,5 mm above fronting bar

Acceleration Voltage is normally not altered, because it affects many of the other welding parameters, which then have to be adjusted.

Beam Current is altered to change the weld penetration, 10 mA variation in the region of 200–400 mA has given the following average variations in weld penetration:

Cathode Standard	2,4 mm	(Min 2,0 – max 2,7)
Cathode HCC1	1,8 mm	(Min 1,3 – max 2,4)

Beam Focus Q2 is altered to change penetration, width and tip radius of the weld profile.

Cathode Standard Test Lid Weld No 2: 350 mA/190 kV/250 mm/min			
Q1	**Penetration (mm)**	**Width (mm)**	**Tip radius (mm)**
1,375 A	73	7,2	0,4
1,400 A	72	7,9	0,5
1,425 A	69,5	8,3	0,6
1,450 A	67	8,4	0,7
1,475 A	66	8,7	0,9
1,500 A	64	9,3	1,4

Cathode HCC1 Test Lid Welds: 350 mA/190 kV/250 mm/min						
Q1	**Penetration (mm)**		**Width (mm)**		**Tip radius (mm)**	
	SKB3(1)	**SKB3(2)**	**SKB3(1)**	**SKB3(2)**	**SKB3(1)**	**SKB3(2)**
1,400 A	70	--------	7	--------	1,3	--------
1,425 A	66	--------	8,2	--------	1,8	--------
1,450 A	66	--------	8,2	--------	1,6	--------
1,475 A	--------	65	--------	8,2	--------	1,2
1,500 A	70	--------	9,2	--------	1,5	--------

Helium Flow is not normally altered. A trial with He-flow between 1 and 3 l/min gave no measurable change of weld profile or nozzle temperature.

When raising the He-flow from 1 to 3 l/min the following increase in pressure (mbar) was measured.

He-flow	**G1 (gun)**	**G2 (gun)**	**G3 (gun)**	**G4 (gun)**	**G5 (gun)**	**G6 (chamber)**
1 l/min	$2,8 \times 10^{-3}$	$4,5 \times 10^{-6}$	$4,5 \times 10^{-5}$	$1,5 \times 10^{-3}$	$2,9 \times 10^{-2}$	0,24
3 l/min	$3,3 \times 10^{-3}$	$7,5 \times 10^{-6}$	$4,8 \times 10^{-5}$	$2,2 \times 10^{-3}$	$3,5 \times 10^{-2}$	0,27

Welding speed is not normally altered but two trials have been made with 20 % increase and 20 % decrease in speed. At 20 % increase in speed (300 mm/min) there was a big increase of internal cavities, the tip radius was < 0,5 mm and the penetration was surprisingly the same as at normal speed. The conclusion is that welding speed of 300 mm/min is not useful for welding. At 20 % decrease in speed (210 mm/min) the weld penetration increased with 8 % (Min 4 – max 12 %) with cathode HCC1.

Working distance is also normally kept constant, but trials with shorter working distance, for welding the copper blocks is in progress.

Comparison between SKB trials at the Canister Laboratory and TWI trials regarding penetration according to variations in different parameters are presented below:

Parameter	TWI	SKB	Penetration
Beam Current	+ 4 mA	+ 5 mA	+ 1 mm
Welding Speed	+ 9 mm/min at range 200–350	+ 8 mm/min at range 210–250	– 1 mm
Beam Focus Q2	+ 0,01 A	+ 0,014 A	– 1 mm
Working Distance	+ 5 mm	Not measured	– 1 mm
Acceleration Voltage	+ 1 kV	Not measured	+ 1 mm

2.7.9 Deformation measurements after weld trials

Shrinkage: The deformation depending on shrinkage of the weld metal has been measured.

The specified values are the average value from the lid welds as follows:

Reduction of lid outer diameter	1,12 mm	(min 0,93 – max 1,50)
Reduction of lid inner diameter	0,20 mm	(min 0,00 – max 0,50)
Reduction of lid height	0,77 mm	(min 0,60 – max 0,90)

The run out: on the canister and the lid have also been measured before and after welding with a dial test. No change after welding has been measured:

Radial run out of lid outer surface	0,90 mm	(min 0,50 – max 2,34)
Axial run out of lid upper surface	0,28 mm	(min 0,05 – max 0,70)

Chronological description of lid weld trials

2.7.10 Lid welds 1–4

Cathode Standard

Lid weld no 1, 1999-02-12 [1], [50], [51]

The first lid weld performed at the Canister Laboratory with the SKB EB-machine. It was decided as a first trial to use the recommended parameters from the earlier test weldings performed at TWI, Cambridge UK.

Welding parameter:

Run	Acceleration voltage	Beam current	Focus Q1	Focus Q2	Travel speed	Working distance
1	190 kV	420 mA	1,240 A	1,375 A	250 mm/min	125 mm

The weld profile was very pointed at the weld tip with circumferential large root cavities. The tip radius was ≈ 0,5 mm. Weld depth was 98 mm. Internal cavities in the weld were a problem, especially in the overlap zone. The weld surface was rather rough.

Lid weld no 2, 1999-04-23 [2[, [52], [53]

Welding parameter:

Run	Acceleration voltage	Beam current	Focus Q1	Focus Q2	Travel speed	Working distance
1	190 kV	350 mA	1,250 A	1,375–1,500 A	250 mm/min	125 mm

Tip radius was ≈ 0,35–1,4 mm. Large root cavities in 10 % of the circumference and smaller ones sporadically in rest of the weld as a result of a bigger tip radius was found. In the overlap zone large cavities were detected and the surface was rough over the whole circumference. The helium flow to the gun 1–3 l/min was also tested. The helium flow had no measurable influence on the weld shape or the weld quality.

(This lid weld is now used as a tool for supporting the copper block at test welding. Eight bars of steel were screwed to the lid as supporting pins.)

Lid weld no 3, 1999-09-10 [3], [54], [55]

The best parameters from lid weld no 2 were tested around the whole circumference and a re-melting pass at 100 mA was included.

Welding parameter:

Run	Acceleration voltage	Beam current	Focus Q1	Focus Q2	Travel speed	Working distance
1	190 kV	380 mA	1,260 A	1,475 A	250 mm/min	125 mm
2	190 kV	100 mA	1,260 A	1,500 A	250 mm/min	125 mm

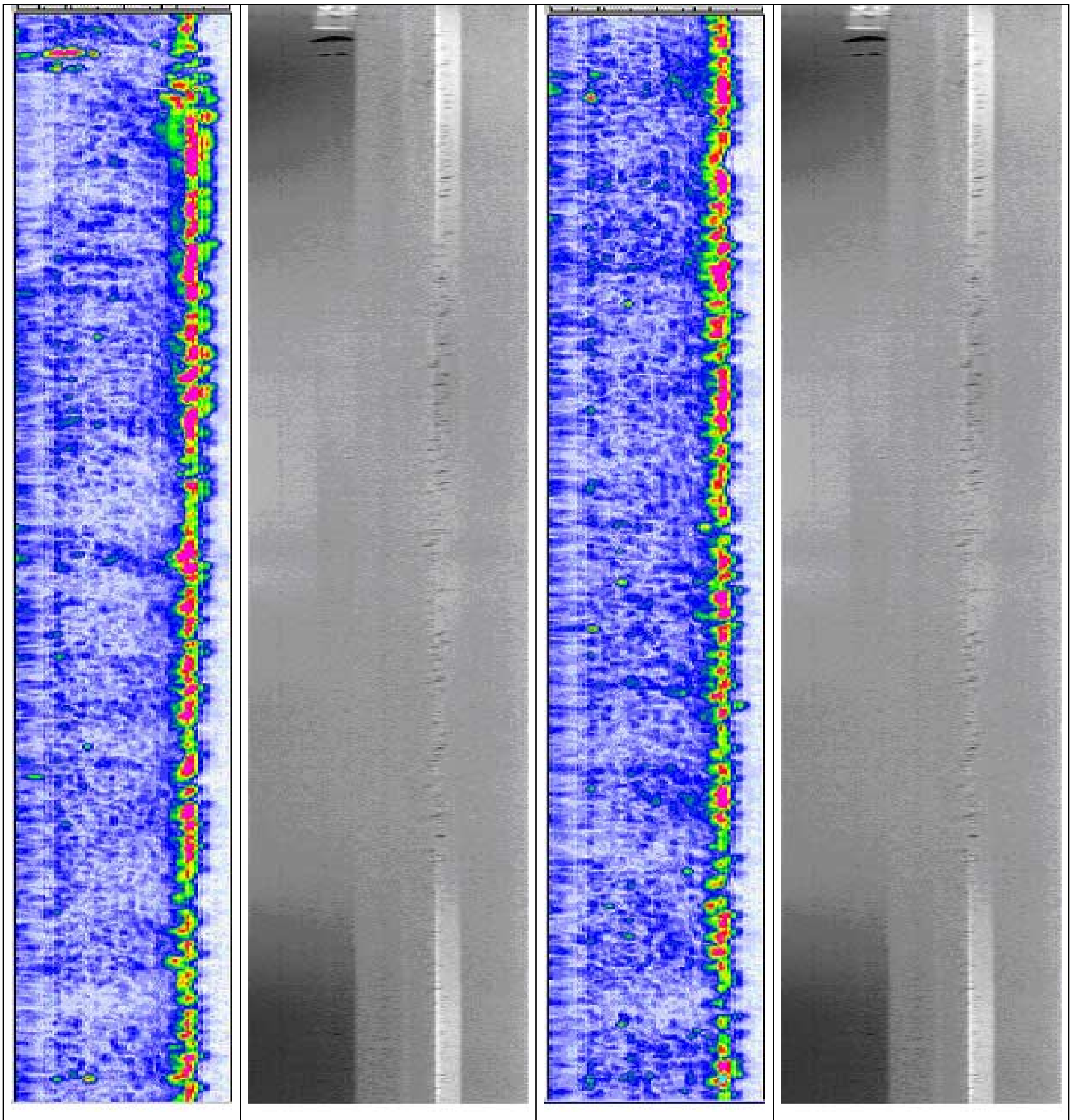
Large root cavities were indicated around the whole circumference and as in weld no 2 large defects in the overlap area. Surface improved after the re-melting pass. This lid has a typical result for weld no 1, 2, 3 and 5 from NDT point of view, see figure 13 below.

Lid weld no 4, 1999-10-06 [4], [56]

The aim of this weld was to try out beam slope in and beam slope out parameters. Four slope in/out sequences was performed at a chamber pressure of 0,26 mbar.

Run	Acceleration voltage	Beam current	Focus Q1	Focus Q2	Travel speed	Working distance
1	190 kV	380 mA	1,260 A	1,475–1,500 A	250 mm/min	125 mm

Beam stability was a problem. The beam was pulsing and the weld quality was really bad both internal and at surface. In a way to try to improve the quality, the weld was re-melted (1999-10-28) without any improvement.



UT 0–180°	RT 0–180°	UT 180–360°	RT 180–360°

Figure 13: *NDT of Lid weld 03.*

In order to find out the reason for the bad result an extra weld was made (1999-11-02). The welding was performed with the beam directed to the lid above the joint and to the cylinder beneath the joint. The result was the same, beam pulsing with big surface defects in a wavy form. The Acceleration voltage, Beam current, Focus Q1, Q2 and Rotation speed was measured with an extra testing device during the melt welding. No instability was measured.

2.7.11 Lid welds 5–18

Cathode HCC1/SKB3(1)

Lid weld no 5, 2000-05-18 [5], [57], [58]

Test weld with a new type of cathode.

Run	Acceleration voltage	Beam current	Focus Q1	Focus Q2	Travel speed	Working distance
1	190 kV	350 mA	1,200 A	1,400 A	250 mm/min	125 mm

Tip radius ≥1,0 mm, improved root quality but still some porosity. Several surface breaking or near surface defects detected.

The weld was re-melted (2000-06-08) with lower power (≈70 % and ≈50 %).

Run	Acceleration voltage	Beam current	Focus Q1	Focus Q2	Travel speed	Working distance
2	190 kV	240 mA	1,200 A	1,500 A	250 mm/min	125 mm
3	190 kV	180 mA	1,200 A	1,500 A	250 mm/min	125 mm

Some of the internal cavities disappeared and some of them had moved towards the surface, which still was rough.

Lid weld no 6, 2000-08-23 [6], [59]

Test weld with 20 % lower travel speed (210 mm/min) than normal.

Run	Acceleration voltage	Beam current	Focus Q1	Focus Q2	Travel speed	Working distance
1	190 kV	280–320 mA	1,200 A	1,400–1,500 A	210 mm/min	125 mm

Tip radius 0,9–2,2 mm. Root quality as lid weld no 5. Internal cavities and rough surface still a problem. The weld tip was in some areas above the joint line with the consequence that 5–10 mm of the joint for 65 % of the circumference in the inner part of the joint was not welded. This was explained by tilting the position of the gun downwards only 0,9° instead of the normal 2,0°.

Lid weld no 7, 2000-09-06 [7], [60]

Test weld with 20 % higher travel speed (300 mm/min) than normal.

Run	Acceleration voltage	Beam current	Focus Q1	Focus Q2	Travel speed	Working distance
1	190 kV	420–440 mA	1,200 A	1,450–1,550 A	300 mm/min	125 mm

Large root defects of the whole welded circumference with a tip radius < 0,5 mm. The weld has missed up to 15 mm of the joint around the whole welded circumference. After re-melting over the area where the weld was missed the joint decreased to 5 mm. This was explained by the fact that tilting the position of the gun downwards only was 0,9° instead of the normal 2,0°and part of the weld was made above the joint line. The amount of internal cavities was increased but the surface quality was better.

The weld was re-melted (2000-09-15) with full beam power at normal travel speed (250 mm/min).

Run	Acceleration voltage	Beam current	Focus Q1	Focus Q2	Travel speed	Working distance
1	190 kV	360 mA	1,200 A	1,500 A	250 mm/min	125 mm

Internal cavities close to the surface disappeared, but deep internal cavities were still left. The surface was further improved and the tip radius increased to 1,5 mm.

A slice of 45° of the welded lid was cut out for demonstration with the following layout:

Part 1) 15° joint before welding. Part 2) 15° as welded. Part 3) 15° as welded and machined.

<u>Lid weld no 8, 2000-09-22 [8], [61]</u>

Test weld with insert according to Test Disposal Canister drawing LAB-00003.

Run	Acceleration voltage	Beam current	Focus Q1	Focus Q2	Travel speed	Working distance
1	190 kV	370 mA	1,200 A	1,500 A	250 mm/min	125 mm

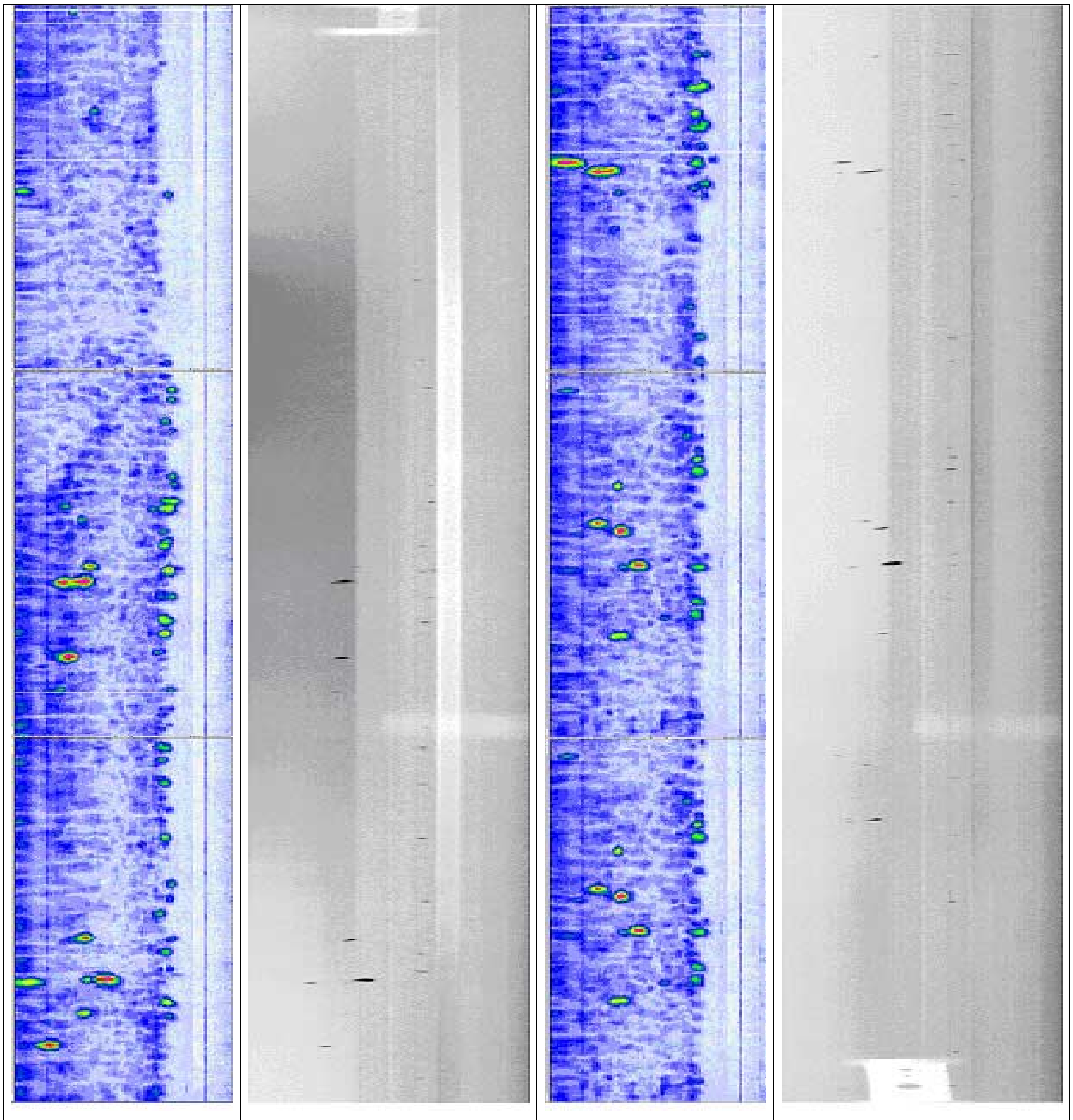
The weld was largely undercut depending on a big gap (1–1,5 mm) in the joint between the copper lid and the cylinder. The insert was not correctly machined and too long, so the lid was hanging on the insert. Maximum allowed gap in the joint is not tested but estimated to 0,1–0,2 mm. The consequence of this big gap was a lot of large defects of the whole weld volume, specially concentrated to the weld surface.

<u>Lid weld no 9, 2000-10-06 [9], [62], [63]</u>

Test weld with increased tilting of the gun downward to 3°.

Run	Acceleration voltage	Beam current	Focus Q1	Focus Q2	Travel speed	Working distance
1	190 kV	350 mA	1,200 A	1,450–1,500 A	250 mm/min	125 mm

The whole joint was melted. The root had a tip radius of 1,8 mm and smaller defects indicated sporadically around the whole circumference of the weld, some of them in the critical area close to the surface, figure 14 below shows the better root and the internal cavities.



UT 0–180°	RT 0–180°	UT 180–360°	RT 180–360°

Figure 14: *NDT of Lid weld 09.*

Lid weld no 10, 2000-10-16 [10], [64], [65]

Test weld with one additional re-melt pass trying to eliminate internal cavities and to improve the weld surface.

Run	Acceleration voltage	Beam current	Focus Q1	Focus Q2	Travel speed	Working distance
1	190 kV	350 mA	1,200 A	1,450 A	250 mm/min	125 mm
2	190 kV	300 mA	1,200 A	1,450 A	250 mm/min	125 mm

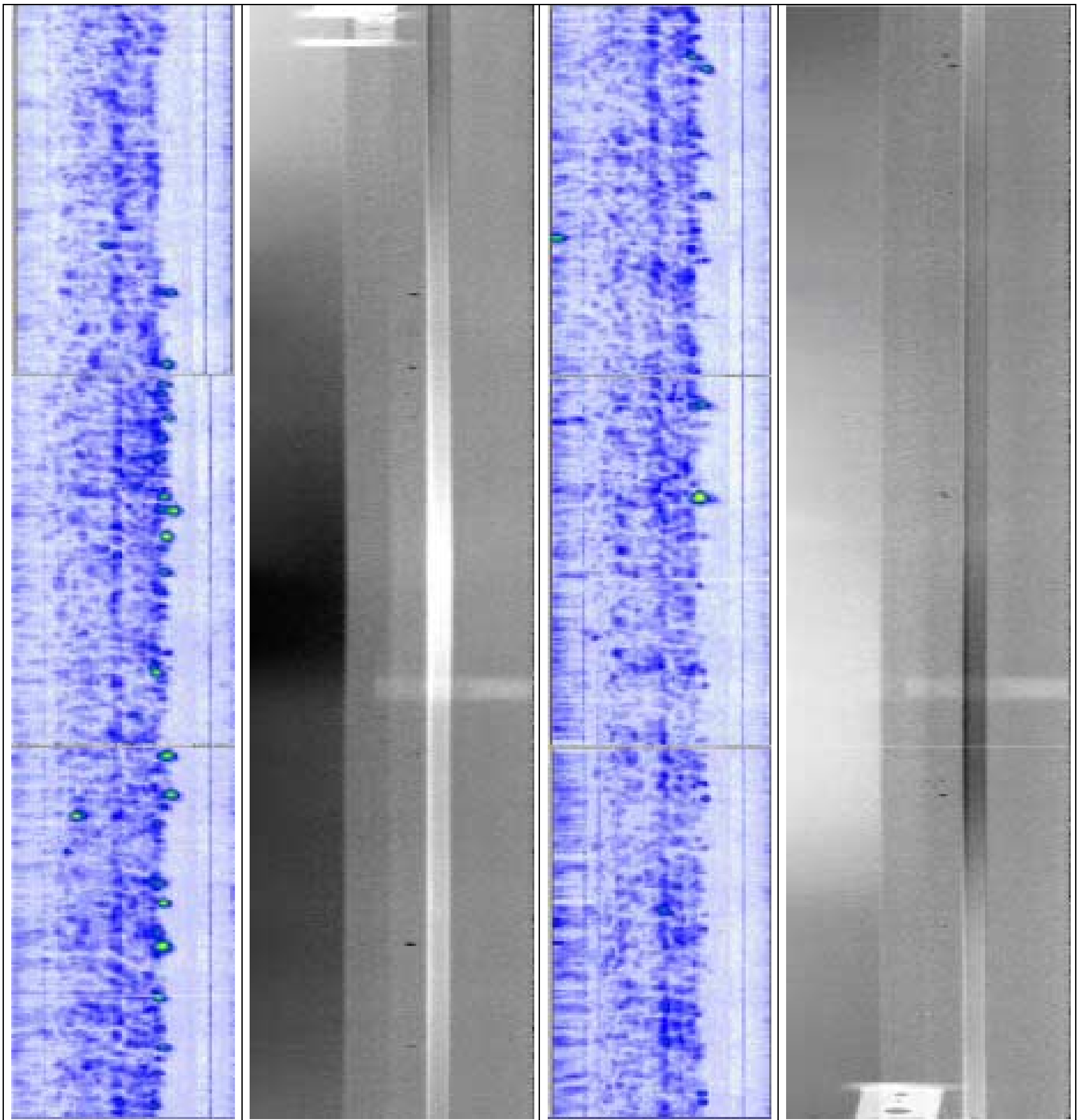
The weld internal and the weld surface were improved but some eruptions resulted in large defects in the overlap area. The tip radius was 1,8 mm at the main pass and 2,0 mm at the re-melt pass.

Lid weld no 11, 2000-10-27 [11], [66], [67]

Test weld to improve weld quality in the overlap area.

Run	Acceleration voltage	Beam current	Focus Q1	Focus Q2	Travel speed	Working distance
1	190 kV	350 mA	1,200 A	1,450 A	250 mm/min	125 mm
2	190 kV	275 mA	1,200 A	1,450 A	250 mm/min	125 mm

The weld internal was very good and there was only some sporadically defects in the root. The weld surface was rather rough with three eruptions, two at the passage of slope in and one just before start of slope out. The eruptions caused local roughness at the surface but no internal cavities. After machining the surface was free from defects and the lid weld fulfilled the preliminary acceptance criteria, see the NDT in figure 15. Tip radius was 1,8 mm at main pass and 1,7 mm at re-melt pass.



UT 0–180°	RT 0–180°	UT 180–360°	RT 180–360°

Figure 15: *NDT of Lid weld 11 (weld 13 and 15 had a similar look).*

<u>Lid weld no 12, 2000-11-13 [12], [68], [69]</u>

Test weld to improve the weld quality at the surface.

Run	Acceleration voltage	Beam current	Focus Q1	Focus Q2	Travel speed	Working distance
1	190 kV	350 mA	1,200 A	1,425 A	250 mm/min	125 mm
2	190 kV	275 mA	1,200 A	1,425 A	250 mm/min	125 mm

The weld internal was good and the weld surface was rather rough but improved compared with lid weld no 11. Two eruptions arose; one at the passage of slope in and one at slope out. The eruptions caused locally roughness at the surface and internal cavities. After machining there was still one surface braking defect at the slope out area, size 7 x 3 mm and one internal cavity at the slope in area, size 3 x 2 mm at 3 mm beneath surface. Tip radius 1,8 mm at main pass and re-melt pass.

<u>Lid weld no 13, 2000-11-29 [13], [70], [71]</u>

Test weld to improve the weld quality at the surface and to reduce the risk for eruptions of the weld melt in the slope in and out area.

Run	Acceleration voltage	Beam current	Focus Q1	Focus Q2	Travel speed	Working distance
1	190 kV	350 mA	1,195 A	1,415 A	250 mm/min	125 mm
2	190 kV	275 mA	1,195 A	1,415 A	250 mm/min	125 mm

Slope in distance was decreased from 50° to 2° to try the fastest possible slope in procedure. Slope out distance was increased from 50° to 130° to get a slow slope out procedure.

This resulted in a very good weld internal, a good root and a rather good weld surface. The weld erupted twice, one at the passage of slope in and one at slope out. The eruption at the slope in caused no internal or surface braking defect. The eruption at the slope out caused a local roughness at the surface. After machining the surface was free from defects and the lid weld fulfilled the requirements. Tip radius 1,8 mm at main pass and re-melt pass.

The new and short slope in distance was now set as a standard procedure.

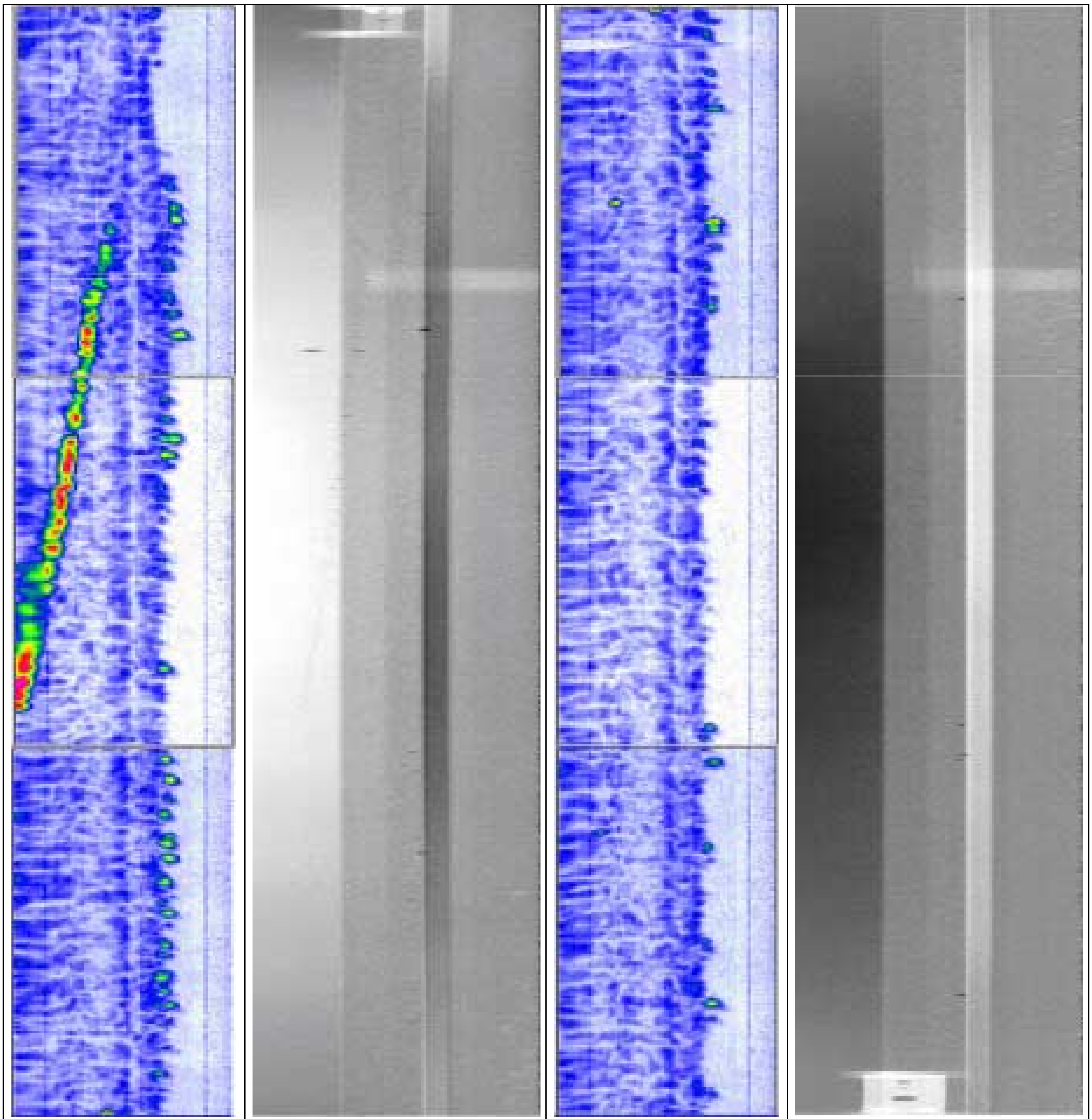
<u>Lid weld no 14, 2000-12-18 [14], [72], [73]</u>

Test weld to improve the weld quality at the surface and to reduce the risk for eruptions of the weld melt in the slope out area.

Run	Acceleration voltage	Beam current	Focus Q1	Focus Q2	Travel speed	Working distance
1	190 kV	350 mA	1,195 A	1,410 A	250 mm/min	125 mm
2	190 kV	275 mA	1,195 A	1,410 A	250 mm/min	125 mm

Slope out distance 130° with Q2 varying from 1,410 to 1,200 A. The weld internal and the weld root area were good. The weld surface was rather good. One eruption arose at the slope out. The eruption caused a locally internal cavity with the size of 8 x 3 mm at 15 mm beneath the surface. There was also a continuous root defect at the slope out area when Q2 was less than 1,361 A, see figure 16. Tip radius 2,0 mm at main pass and 1,2 mm at re-melt pass.

After machining the surface was free from defects.



UT 0–180°	RT 0–180°	UT 180–360°	RT 180–360°

Figure 16: *NDT of Lid weld 14.*

Lid weld no 15, 2001-01-26 [15], [74], [75]

Test weld to improve the weld quality at the surface and to reduce the risk for eruptions of the weld melt and root defects at slope out. The weld is performed in four passes, for gradual elimination of internal cavities and to minimise the slope out distance.

Pass	Acceleration voltage	Beam current	Focus Q1	Focus Q2	Travel speed	Working distance
1	190 kV	340 mA	1,195 A	1,410 A	250 mm/min	125 mm
2	190 kV	275 mA	1,195 A	1,410 A	250 mm/min	125 mm
3	190 kV	210 mA	1,185 A	1,390 A	250 mm/min	125 mm
4	190 kV	160 mA	1,180 A	1,380 A	250 mm/min	125 mm

Slope out distance 15° and Q2 during slope out was set to 1,380 A. The weld internal was very good and the weld surface was also very good. No eruption arose during welding. There was small linear root defect at 30 % of pass IV.

The tip radius for the different weld runs was:

Pass 1≈1,8 mm Pass 2≈1,4 mm Pass 3≈1,1 mm Pass 4≈1,1 mm

After machining the surface was free from defects and the lid weld fulfilled the requirements.

Lid weld no 16, 2001-02-02 [16], [76]

Test weld to reduce the risk for root defects at slope out.

Pass	Acceleration voltage	Beam current	Focus Q1	Focus Q2	Travel speed	Working distance
1	190 kV	340 mA	1,195 A	1,410 A	250 mm/min	125 mm
2	190 kV	275 mA	1,195 A	1,410 A	250 mm/min	125 mm
3	190 kV	210 mA	1,185 A	1,400 A	250 mm/min	125 mm
4	190 kV	160 mA	1,180 A	1,400 A	250 mm/min	125 mm

Slope out distance 15° and Q2 during slope out was set to 1,400 A.

The weld internal was good and the weld surface was good as well. No eruption arose during welding. There were small linear root defects at 30 % of pass IV. No macro section has been taken out from the weld. The lid weld is special machined for an NDT test. Only 180° of the outer surface were machined. The machined area was free from defects and the examined part of the lid weld fulfilled the requirements.

Lid weld no 17, 2001-02-09 [17], [77], [78]

Test weld to reduce the risk for root defects at pass IV.

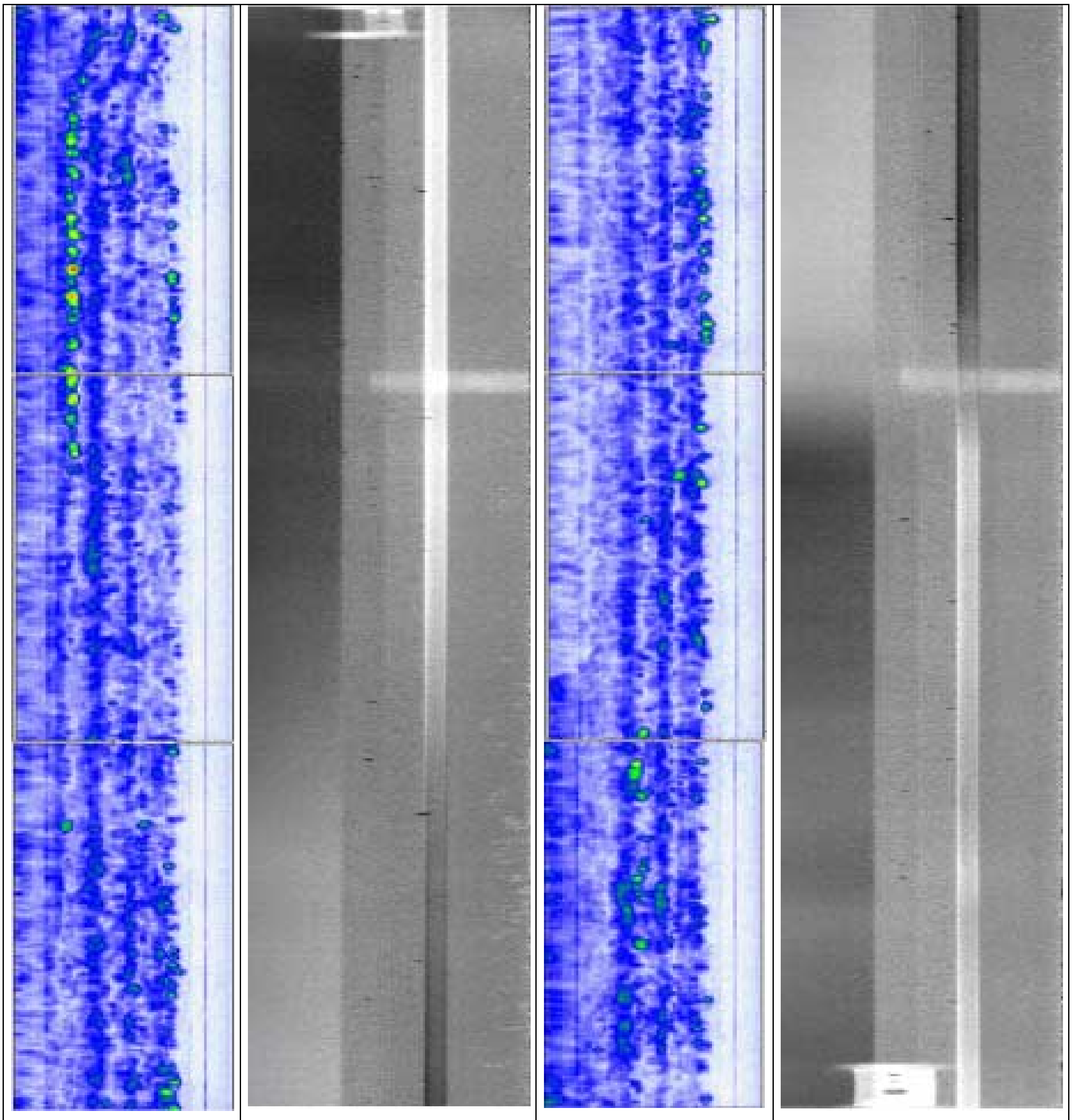
Pass	Acceleration voltage	Beam current	Focus Q1	Focus Q2	Travel speed	Working distance
1	190 kV	340 mA	1,195 A	1,410 A	250 mm/min	125 mm
2	190 kV	270 mA	1,195 A	1,410 A	250 mm/min	125 mm
3	190 kV	210 mA	1,185 A	1,400 A	250 mm/min	125 mm
4	190 kV	160 mA	1,180 A	1,425–1,500 A	250 mm/min	125 mm

Slope out distance 15° and Q2 during slope out was set to 1,500 A.

The weld internal was good and the weld surface was good as well. Two eruptions arose during pass IV. There were small linear root defects at pass IV and Q2 1,425 A and some local root defects at 1,450 A. The ultrasonic C-scan pictures visualise the penetration of the four weld passes, which can bee seen in figure 17. After machining there was still some small local defects on the surface. The tip radius for the different weld passes was:

Pass 1≈1,2 mm Pass 2≈1,1 mm Pass 3≈0,8 mm Pass 4≈0,8–1,5 mm

Comments: Q2 ought not to be less than 1,450 A depending on risk for root defects. Re-melting of the weld at beam current 160 mA and Q2 1,425–1,500 A improves the weld surface. At Q2 > 1,475 A increases the risk for eruptions.



UT 0–180°	RT 0–180°	UT 180–360°	RT 180–360°

Figure 17: *NDT of Lid weld 17.*

<u>Lid weld no 18, 2001-03-13 [18], [79], [80]</u>

Test weld to reduce the risk for root defects or eruptions at pass IV and slope out. Slope out distance 15° and Q2 during slope out was set to 1,460 A.

Pass	Acceleration voltage	Beam current	Focus Q1	Focus Q2	Travel speed	Working distance
1	190 kV	340 mA	1,195 A	1,410 A	250 mm/min	125 mm
2	190 kV	270 mA	1,195 A	1,410 A	250 mm/min	125 mm
3	190 kV	210 mA	1,185 A	1,420 A	250 mm/min	125 mm
4	190 kV	160 mA	1,180 A	1,460 A	250 mm/min	125 mm

At rotation position 23° and time 1,09 min the temperature on the nozzle N2 rose to 101°C and the weld machine tripped off. After 10 min the welding program was restarted from the zero point again without any visible problem.

The weld internal was good except from some small cavities at the trip area and at the root of the first weld. The weld surface was good apart from a local defect at the trip area and two other small defects. These defects did not remain after machining and the weld fulfilled the requirements, see figure 18. The rewelding after the trip was better than expected and it is obvious that it is possible to effect a repair after an interrupted weld program.

The tip radius for the different weld passes were:

Pass 1≈1,4 mm Pass 2≈1,0 mm Pass 3≈1,2 mm Pass 4≈1,6 mm

After welding, the filament and the cathode were changed after 596 kWh in service.

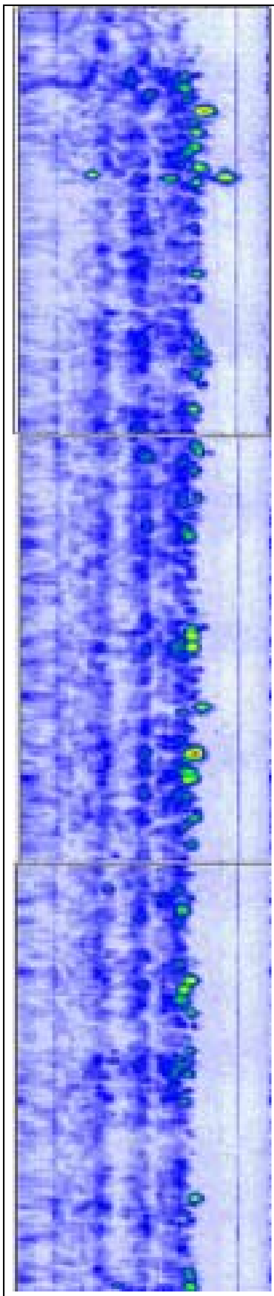
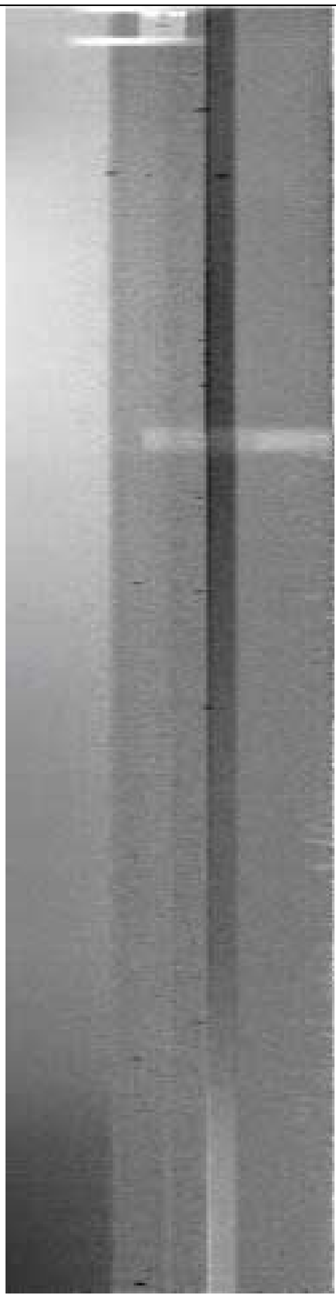
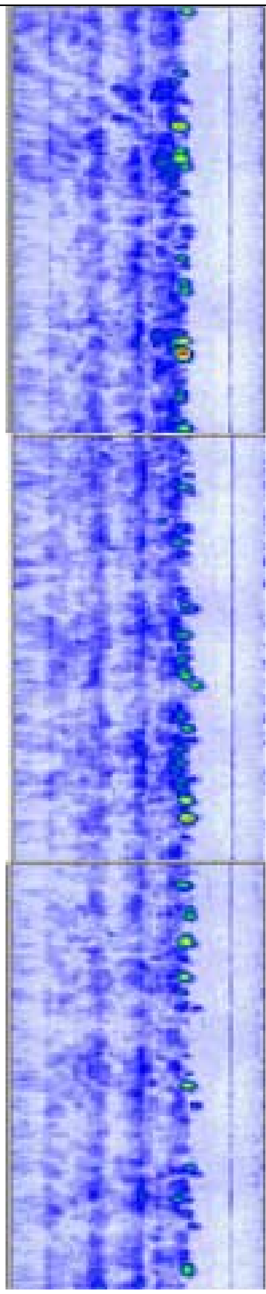
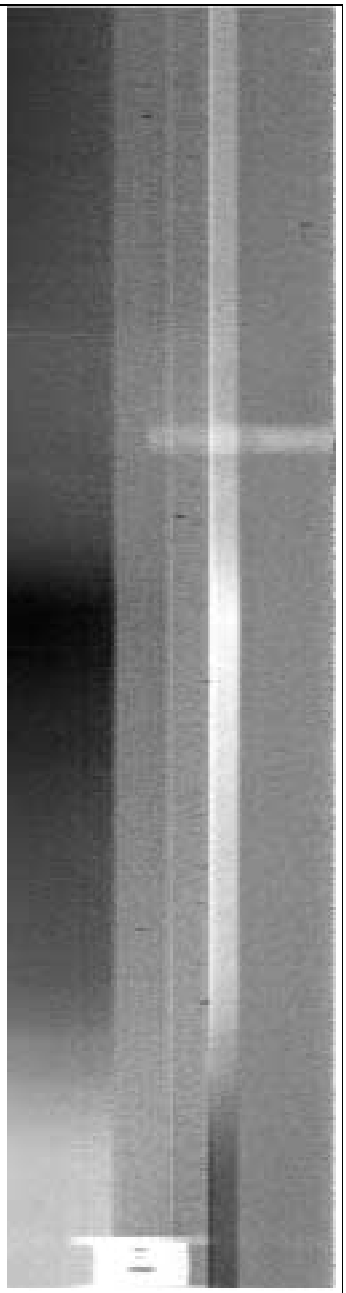
			
UT 0–180°	RT 0–180°	UT 180–360°	RT 180–360°

Figure 18: *NDT of Lid weld 18.*

2.7.12 Lid welds 19–21

Cathode HCC1/SKB3(2)

Lid weld no 19, 2001-05-18 [19], [81], [82]

Test weld to examine the repeatability of the parameter settings of the machine after new filament, cathode, HV-cable and RF-amplifier.

Test weld in copper block showed that the weld profile was more pointed with the same parameter setting compared with the weld profile before changing the above mentioned parts. The parameter Q2 was therefore increased with 3,5 % to compensate for the pointed weld profile.

Pass	Acceleration voltage	Beam current	Focus Q1	Focus Q2	Travel speed	Working distance
1	190 kV	340 mA	1,195 A	1,460 A	250 mm/min	125 mm
2	190 kV	270 mA	1,195 A	1,460 A	250 mm/min	125 mm
3	190 kV	210 mA	1,185 A	1,470 A	250 mm/min	125 mm
4	190 kV	160 mA	1,180 A	1,490 A	250 mm/min	125 mm

Slope out distance 15° and Q2 during slope out was set to 1,490 A.

During welding of the forth pass about 10 eruptions in the weld melt was observed. The weld internal was disappointing with severe root defects visible in the first pass. Apart from the root the weld internal was free from visible defects, see figure 19. The weld surface had ten big cavities; one of them (size 2–3 mm) remained after the machining.

The weld profile was different than before the change of cathode, the width had increased about 20 % and the root radius in the first run was irregular and had decreased about 30 %. The increase in width can be explained by the increased setting of the parameter Q2 (bigger beam spot). But the decrease of the root radius is difficult to explain. It seems that the beam profile had changed for an unknown reason.

The tip radius for the different weld passes was:

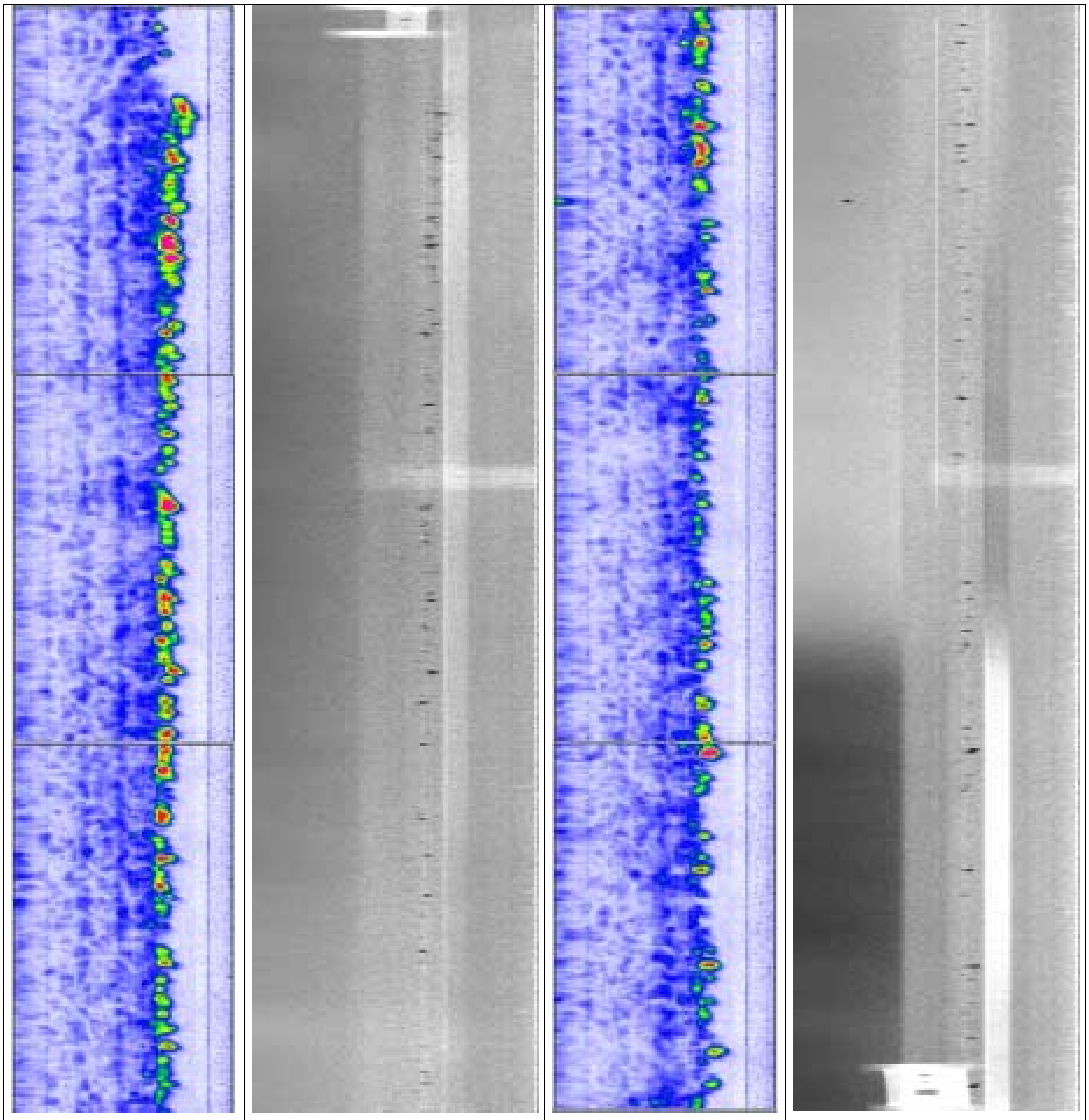
Pass 1≈1,0 mm   Pass 2≈1,2 mm   Pass 3≈1,4 mm   Pass 4≈1,7 mm

Comments: The new cathode or the position of the cathode is the most likely reason for the change in the weld profile.

Lid weld no 20, 2001-06-19 [20], [83], [84]

Test weld to reduce the risk for surface eruptions and to improve the root quality. One additional weld pass was added to reduce the weld depth from full depth to zero very slowly.

Pass	Acceleration voltage	Beam current	Focus Q1	Focus Q2	Travel speed	Working distance
1	190 kV	345 mA	1,195 A	1,470 A	250 mm/min	125 mm
2	190 kV	270 mA	1,195 A	1,470 A	250 mm/min	125 mm
3	190 kV	210 mA	1,185 A	1,470 A	250 mm/min	125 mm
4	190 kV	170 mA	1,180 A	1,470 A	250 mm/min	125 mm
5	190 kV	125 mA	1,180 A	1,470 A	250 mm/min	125 mm



UT 0–180°	RT 0–180°	UT 180–360°	RT 180–360°

Figure 19: *NDT of Lid weld 19.*

Slope out distance 10° and Q2 during slope out was set to 1,470 A.

During welding of the forth pass about 12 eruptions in the weld melt were observed and during the fifth pass about 100 eruptions were observed. The weld internal was about the same as lid weld no 19, with severe root defects in the first pass. The weld surface had a lot of cavities eight of them were very big. After machining two surface-breaking defects and one defect close to the surface remained. The weld profile was about the same as for lid weld no 19.

The tip radius for the different weld passes were:

Pass 1≈1,0 mm   Pass 2≈1,2 mm   Pass 3≈1,3 mm   Pass 4≈1,4 mm   Pass 5≈2,3 mm

The high heat input caused by the five passes caused overheating in the weld melt and many eruptions in the weld surface.

Comments: The heat input must be reduced.

One additional odd observation was that the zero marking was Z-shaped instead of straight, see figure 20. TWI has checked the equipment without finding any reason for the behaviour. The phenomenon has not been possible to repeat.

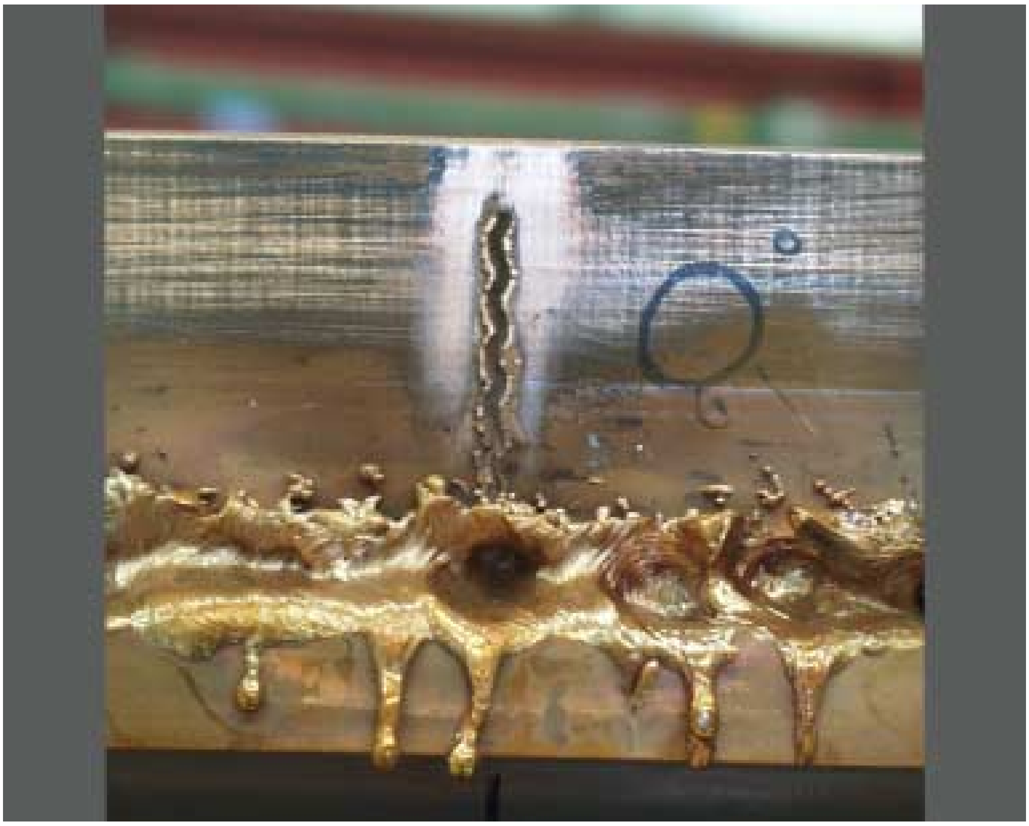


Figure 20: *Lid weld no 20, view of the weld surface and the zero marking.*

Lid weld no 21, 2001-08-22 [21], [85], [86], [87]

Test weld to reduce the risk for surface eruptions and to minimise the risk for overheating of the nozzles. During run 3 the gun was raised 2 mm to add more melt copper to the weld melt in a trial to improve the weld surface.

Pass	Acceleration voltage	Beam current	Focus Q1	Focus Q2	Travel speed	Working distance
1	190 kV	345 mA	1,165 A	1,470 A	250 mm/min	125 mm
2	190 kV	270 mA	1,150 A	1,470 A	250 mm/min	125 mm
3	190 kV	150 mA	1,150 A	1,490 A	250 mm/min	125 mm

Slope out distance 10° and Q2 during slope out was set to 1,490 A.

During welding of the third pass 4 eruptions in the weld melt were observed. The weld internal was a little worse than lid weld no 20 with severe root defects in the first run. The weld surface was rather good apart from four cavities, see figure 21. Two of these surface-breaking defects did remain after the machining. The weld profile was very pointed at the weld root.

The tip radius for the different weld passes was:

Pass 1≈0,7 mm Pass 2≈1,7 mm Pass 3≈2,1 mm

The zero marking was a straight line again. Because of the problem with the root defects it was decided to start to make weld trials in copper block with different parameter settings.

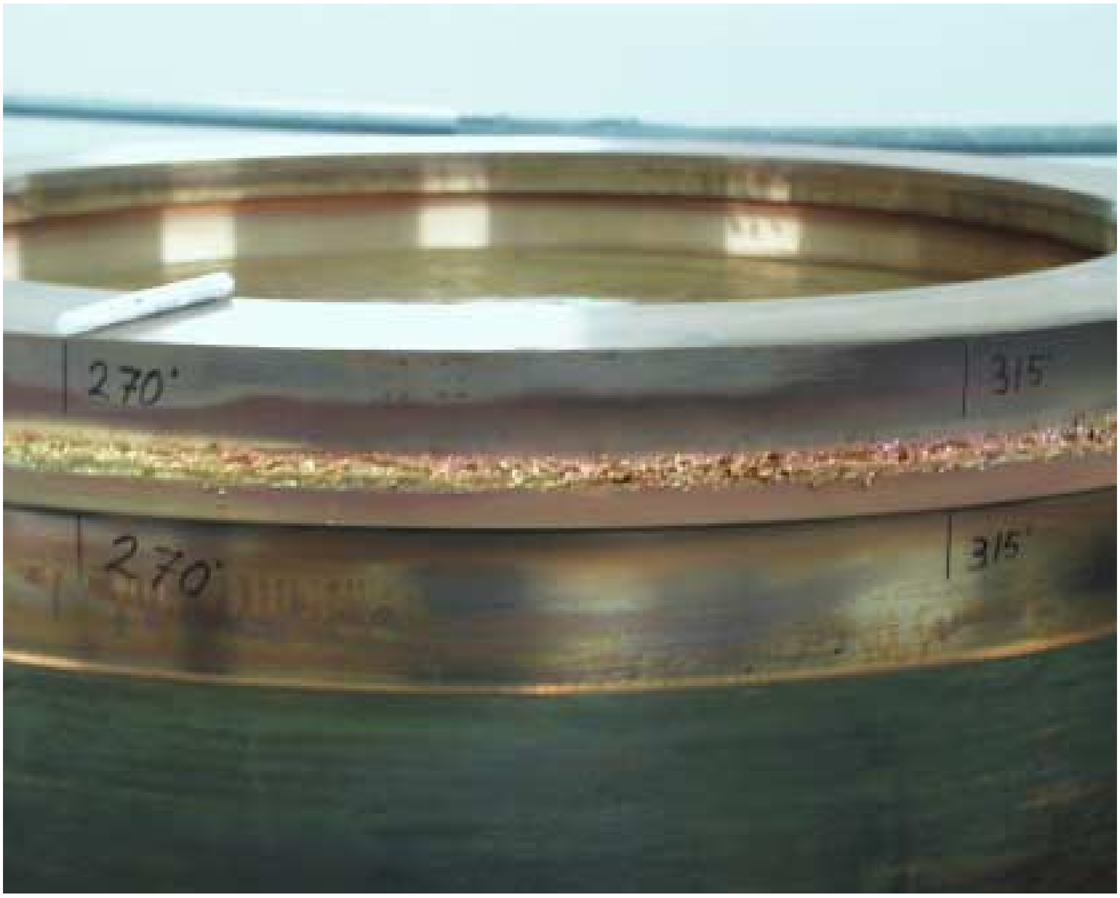


Figure 21: *Lid weld no 21, view of the weld surface.*

3 Welding system

The items supplied by TWI for the EBW equipment are as follows:

- EB Gun and pumps
- 100 kW, 220 kV power supply
- Control Console
- Gun Control Cabinet
- Pump Control Cabinet
- Beam Current Control Cabinet
- HV cables, RF, Siemens and Drag chain

The equipment works in association with the following items, not supplied by TWI:

- Welding Chamber
- Chamber pumps
- Sliding Seal and motor drive Cabinet
- Jacking Frame rotary table and motor drive Cabinet
- Lid grab and motor drive Cabinet
- Canister Laboratory Main Computer
- Emergency stop Cabinet and System interlocks

The EBW Control Console can be operated independently of the Main Computer for the Canister Lab, and under these conditions the operator can adjust parameters or select and run a part program to carry out a weld.

Alternatively, the EBW Control Console can act as a client to the main Computer and receive all commands from the Main Computer. Under these conditions, the CNC is sequenced to run a number of pre-written programs that carry out the Lid welding.

3.1 Welding equipment

Developed by	TWI
Delivered to SKB	1997
Commissioned	1998
Beam Power	100 kW
Acceleration Voltage	200 kV
Beam Current	500 mA
Cathode Heating by	RF 84 MHz, 250 W
Cathode Material	Ceramic LaB_6
Filament Material	Tungsten alloy
Chamber Size	180 m^3
Chamber Pressure	0,20 mbar
CNC System	Siemens 840C
Control System	TWI
Monitoring System	NI Labview 4.0/TWI

3.1.1 Gun design

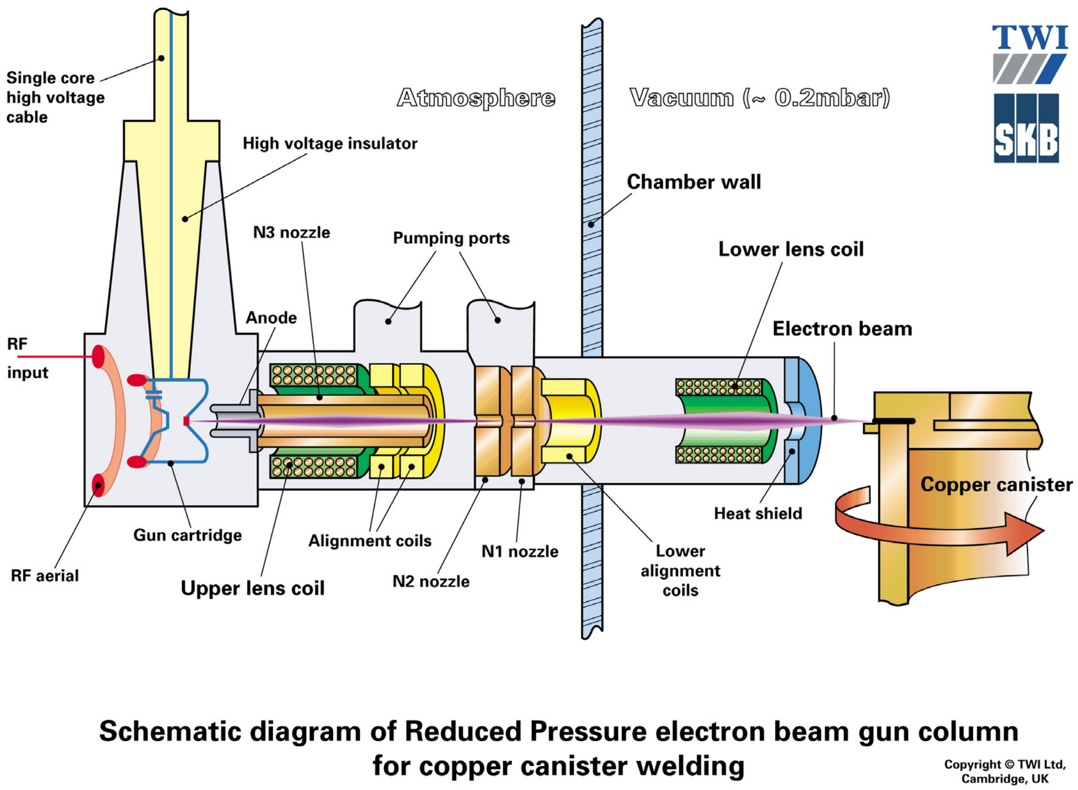


***Figure 22:** Schematic sketch of the gun.*

3.1.2 Gun system description

The gun is developed by TWI and designed for use in reduced pressure. The design is unique with an indirectly heated diode gun and switch mode power source requiring no conventional auxiliary power supplies.

RF power at a frequency of 84 MHz is beamed at the gun cartridge by an aerial enclosed within the gun housing. A secondary winding consisting of a single turn cylinder, housed within the gun cartridge, collects the RF power. This winding, in combination with a small ceramic capacitor is held in resonance at 84 MHz, producing a high current circulating through a ribbon filament. As the RF power level is raised the filament is brought to electron emission temperature. Since a high alternating voltage then exists between the filament and the cathode element, electrons are drawn from the filament every half cycle producing a primary electron beam, which heats the main cathode. Further increase in RF drive power is transformed into primary beam power, raising the cathode to electron emission temperature.

The emitted electrons are then accelerated up to two thirds the speed of light by the high acceleration voltage and passing through the anode. The beam of electrons is then focused by the upper lens coil (Q1) and transmitted through fine bore nozzles in the gun to achieve efficient differential pumping. The divergent beam is then focused at the work piece by the lower lens coil (Q2).

The upper alignment coils (X1, Z1) and the lower alignment coils (X3, Z3) centralise the beam in the gun to place it precisely down the column axis and through the exact centre of the long small bore nozzle pack constituting nozzles N2 and N1.

Thermocouples are monitoring the temperature of nozzles (N1, N2, N1 and N0).

There are two temperature levels associated with each thermocouple.

- If the first one is exceeded a warning message is displayed on the CNC screen and an alarm sounds.
- If the second one is exceeded, the system will trip.

Gun pumping system consists of two rotary vane pumps and three turbo molecular pumps. The required vacuum in the upper gun column is < 1 x 10^{-5} mbar.

Following components are water cooled in the EB gun column:

- Heat shield at the end of the transfer column.
- Nozzle N2.
- High voltage insulant (Flutec) heat exchanger.
- Upper column turbo molecular pump T1.
- Inner cavity turbo molecular pump T2.
- Outer cavity hybrid turbo molecular pump T3.

A flow meter checks that the flow is above a present minimum.

A small flow of helium is introduced to the bottom of the transfer column, just above the heat shield. The helium is designed to reduce electron/gas collisions, as the residual gas molecules from helium are smaller and lighter than from oxygen, nitrogen and water vapour.

In order to stabilise the main beam current, a DC current transformer (DCCT) is employed which monitors the electron flow. A feedback loop then compares the beam current obtained with the demand level making dynamic changes to the RF power level to achieve the desired beam current level.

The power supply consists of an inverter and a transformer tank. The function of the power supply is to convert the 3 phase mains at 400V, 50Hz into a regulated voltage of about 200kV. The inverter converts the mains to a 5kHz output. The transformer tank consists of a transformer, rectifier, smoothing capacitor, surge arrest resistor and monitoring components for the high voltage and the beam current. To provide insulation, the components are submerged in oil.

When the HV is first switched on there is a special mode of operation of the power supply called conditioning. In this mode the inverter produces a maximum of 10 pulses per second with duration of up to 60 µsec each. This limits the maximum output power to just a few 100 Watts. If a flashover occurs at this time the voltage collapses to 0kv, the flashover quenches and the volts are progressively increased to the working level over the next few seconds.

4 Calibration [38], [40], [41]

The electron beam machine is calibrated once a year. The Supplier TWI, does this at the Canister Laboratory. So far the machine has been calibrated twice in August 2000 and in August 2001.

Following items are calibrated.

1) High Voltage
2) Beam Current
3) Lenses
4) Alignment Currents
5) Thermocouples
6) Beam pick-ups
7) RF metering
8) Vacuum gauges

The machine was found to meet the specifications at both calibrations, only insignificant deviations were measured.

5 Operation experiences and problems to consider

5.1 Gun components [27]

5.1.1 Nozzles

The beam has to pass 4 nozzles on its way out from the gun column.

1) N3 nozzle with diameter ∅ 7 mm.
2) N2 nozzle with diameter ∅ 3,5 mm.
3) N1 nozzle with diameter ∅ 3 mm.
4) N0 nozzle with diameter ∅ 8–40 mm.

The N3 nozzle is the first nozzle in the beam path. Problem with overheating has sometimes occurred. The cathode stand off position, the mechanical and electrical alignment can influence the nozzle heating.

The main problem with overheating at N3 nozzle occurs at low beam power < 50 mA with a maximum at about 20 mA. A short study of the effect of upper lens Q1 setting was made to see if it altered the anode pick-up current and the N3 temperature at a beam current level of 20 mA at 190 kV. Over the range of Q1 current settings of 1,15A to 1,21A there was no significant effect although, as would be expected, N1 rose from 21°C to 39°C for the highest Q1 setting.

TWI Visit Report V6758 [33]: Date 01-04-25.

The N2 and N1 nozzles are the smallest and most critical one′s. The beam is focussed between N2 nozzle and N1 nozzle in the gun column. The holes in those nozzles need to be as small as possible as the nozzles work as pressure stage. But the holes have to be big enough to let the beam pass through the holes without heating the nozzles. The Coil Q1 setting adjusts the internal beam focus point. The focus point changes position in the gun when the beam power or the acceleration voltage is changed. Therefore the Q1 setting has to be programmed in a lid weld with different beam power. One critical moment is the fast weld start. Very often the temperature rises at N1 nozzle or N2 nozzle directly after weld start and then the temperature decreases to normal again. Twice the temperature has gone up to trip level of 100°C, both times at N2 and with cathode HCC1/SKB3(1) at lid weld no 8 and 18. TWI performed a modification of the safety interlock system that allows the nozzle temperature to exceed a threshold for a pre-set time.

TWI Visit Report V6802 [37]: Date 01-06-14.

Good mechanical and electrical alignment is also vital to avoid overheating.

The Coil Q1 setting also affects the beam profile. The best beam profile with the cathode type HCC1 is with high setting of Coil Q1 ≥ 1,225 A. At normal weld power, 350 mA and Q1 above 1,225 A the nozzle N1 starts to be overheat.

Comments: It had been desired to develop the gun for higher Coil Q1 setting to get improved beam profile and avoid over heating of the nozzles.

The N0 nozzle is the last nozzle in the beam path. No problem with overheating has occurred, since the water-cooling system was installed.

5.1.2 Weld spatter in nozzles

Another problem is weld spatter in the nozzles. When TWI changed the N1, N2 and N3 nozzles (00-05-09) to nozzles with bigger holes it was observed that a lot of copper spatter was sitting at N1 nozzle and a big piece of copper spatter was sitting in the hole of N2 nozzle. Long drills and reamers have been manufactured to make it possible to clean the holes in the N1 and N2 nozzles from the chamber side. During welding some spatter gets into the gun. Normally that spatter will been burnt up by the electron beam. But there is a risk that the spatter will be fastened in the nozzle holes. If that happens, it will lead to a sudden over heating leading to a machine shutdown. The weld process has then to be restarted with increased risk for weld cavities at the shut down area.

Comments: If possible a protection device against weld spatter should be developed.

5.1.3 Valve for cleaning the gun

A manual operated valve for cleaning the gun from internal moveable weld spatter, has been installed at the outlet channel from the inner cavity. The valve is in line with the Pirini gauge G3 and the Turbo pump T2 and should be opened for a short moment just before welding, when the chamber pressure is reduced.

5.1.4 Cathodes [32], [45]

The weld profile with the standard cathode was rather pointed and caused severe root defects. High Coil Q2 setting improved the weld root but the weld profile became very wide and the weld surface was rough with big cavities caused from metal pour out. The Lid welds no 1–4 were welded with the standard cathode and the weld quality was disappointing. In 1999 it was decided that TWI should develop the equipment to fulfil the requirements concerning the specified weld profile. Reference BNFL E0807 6-12-99 [88].

TWI developed a new type of cathode called HCC1. The aim of that cathode was to get a weld profile with the tip radius ≥ 2,5 mm and a weld surface and weld internal within the weld requirements.

The work at TWI is described in TWI visit reports V6259 Date 00-03-03 [28], V6345 Date 00-04-12 [29] and V6379 Date 00-06-06 [31].

TWI succeeded to develop a cathode with improved weld profile and the experimental welding at TWI showed that it was possible to get a weld profile good enough to fulfil the requirement. But more work had to be done with development of the weld process and the parameter settings.

Lid welds no 5–18 were welded with the cathode HCC1/SKB3(1). The weld profile was improved but the weld had to be remelted once or twice, to get rid off the internal cavities. A final remelting pass to improve the surface quality was also found necessary.

The primary filament and the main cathode were inspected after 596 kWh in service. The filament had a slot almost across it, and yet it had been working well the day before. The cathode had a pitting spot, which was almost certainly due to ion bombardment damage. Both the filament and the cathode were replaced. The spare cathode HCC1/SKB1(RG) was installed but caused problem with N3 nozzle overheating and anode pick-up plate current indications. Electrical alignment procedure was performed but with no significant effect. TWI Visit Report V6742: Date 01-04-26 [35].

New cathode stand off position was tried but it had little effect on the N3 nozzle overheating and the Anode pick-up plate current indications.

TWI Visit Report V6801: Date 01-06-13 [36].

The cathode HCC1/SKB1(RG) was replaced with the cathode HCC1/SKB3(2) and the gun was mechanical and electrical aligned. The Anode, HV cable and the RF amplifier were replaced. A leak detection of the gun column and the gun housing was performed, only a very small leakage was found. The N3 nozzle overheat problem was reduced and occured only at low beam current below 50 mA. The most important action was probably to achieve good mechanical alignment.

After replacement of the cathode and alignment of the gun, test welds were performed in copper blocks to compare the parameter settings.

Disappointingly the weld profile became more pointed again and the Q2 setting had to be increased with 5 % to get back to about the same tip radius.

Lid welds no 19–21 were welded with the cathode HCC1/SKB3(2). The Q2 setting was increased from 1,410 to 1,460 A to compensate for the more pointed weld profile. The result was that the weld root became pointed with severe cavities and the weld width was increased.

TWI Visit Report V6758: Date 01-04-25 [33].

<u>Table of welds in Test block (TB) and Lids (Lid) before and after replacement of the cathode HCC1/SKB3(1):</u>

Figure within bracketing is the number of welds and the value is the average

Weld TB/Lid	Cathode Type	Acc voltage kV	Beam Current mA	Travel Speed mm/min	Work Distance mm	Focus Q2 A	Weld Depth mm	Top Width mm	Max Width mm	Tip Radius mm
TB Before	Stand	190	350	236	125	1,400	76	9,3	9,1	0,9
TB (5) Before	HCC1 SKB-3(1)	190	350	236	125	1,400	73,2	8,4	9,6	2,2
TB (2) After	HCC1 SKB-3(2)	190	340	236	125	1,410	79,5	7,7	8,2	0,6
TB After	HCC1 SKB-3(2)	190	340	236	125	1,450	74	8,2	8,8	0,8
TB After	HCC1 SKB-3(2)	190	340	236	125	1,470	68	8,1	10,0	2,1
Lid (4) Before	HCC1 SKB-3(1)	190	340	250	125	1,410	67,2	7,1	7,5	1,8
Lid After	HCC1 SKB-3(2)	190	340	250	125	1,460	65	8,3	8,6	1,0

The Cathodes HCC1 SKB3(2), HCC1 SKB4(1), HCC1 SKB5(1) and HCC1 SKB1(RG) were tested. The beam shape was about the same for all cathodes, maybe the cathode HCC1/SKB1(RG) was slightly better. That Cathode was the SKB spare and is now in service.
TWI Visit Report V6889: Date 01-12-19 [39].

5.1.5 List of Cathodes EBW Machine SKB P257

Type	No	Install date	Removal date	Filament change	kWh	Remark
Standard	221022/001	97-08-15	99-02-10	97-08-15	656	
				97-10-30	(36)	Only Filament
Standard	221022/003	99-02-10	99-09-03	99-02-10	300	
				99-06-23	(219)	Only Filament
Standard	221022/002	99-09-03	99-09-07	----------	36	
Special	???	99-09-07	99-09-09	----------	< 10	TWI, Allan Sanderson
Standard	221022/002	99-09-09	00-05-11	----------	398	
HCC1	SKB1(1)	00-05-11	00-05-11	----------	< 10	
HCC1	SKB3(1)	00-05-15	01-03-20	00-05-15	590	Good weld profile
HCC1	SKB1(RG)	01-03-20	01-04-04		< 10	
HCC1	SKB3(2)	01-04-04	01-10-10	01-03-14	250	
HCC1	SKB5(1)	01-10-10	01-10-15	01-10-10	230	
HCC1	SKB4(1)	01-10-16	01-10-18	----------	25	
HCC1	SKB1(RG)	01-10-18		----------		Machined 0,05 mm
HCC1	SKB6(1)					Spare Cathode Improved design

5.1.6 Cathode replacement procedure

Cathode replacement procedure is well described in the servicing and maintenance manual but there is no information about the procedure to run in a new cathode. That procedure is tricky and different cathode stand-off positions and electrical alignments have to be tried. It would be very useful to simplify the procedure with a replacement system of complete gun cartridges.

The practise to run in a new cathode is to heat up the cathode slowly by using the manual RF control until approximately 3 mA of beam current, to avoid sudden out gassing from the new cathode which can cause gun discharges. The beam current control should then be switched back to feedback control and beams up to 300 mA at 190kV. Beam transmissions should then be tested and if necessary electrical alignment should be performed.

5.1.7 Beam profile

Depending on the problem with the weld profile it was decided to try to measure the beam profile. TWI has developed equipment for measuring, called Beam Probing working from low up to full beam power. When measured the SKB EB-machine beam profile, the required profile at low beam power < 200 mA was achieved, but with increased beam power a core in the middle of the beam started to be formed. At normal welding power (340 mA), the core in the middle became very intensive. Four different cathodes and different cathode stand-off positions were tried, but had little effect on the beam profile. The influences from Q1 and Q2 settings were examined. High setting of Q1 > 1,225 A increased the beam current level where the core occurred to 250 mA, that was a useful experience for future development of the beam parameter setting. High setting of Q2 increased as expected the width of the beam, but the core in the beam was not visibly affected. TWI Report L6910: Date 01-11-09 [42].

A good estimation of the beam profile can be done in a simple way. The beam is aimed to the heat sink at a distance of about 2,4 m. Two cameras are pointed to the beam, one against the gun side and the other against the heat sink side. The cameras are connected to two TV sets in front of the Control console. The EB-machine is started with low beam current and when the beam current then increases, the beam profile can be seen on the TV screens. Then the appearance of the core in the middle of the beam can be studied and also the intensity of the core at the weld power of 340–350 mA.

5.1.8 Beam positioning

As the joint is hidden behind the lid wall it is not possible to use a joint tracer. Today the positioning is manual. The position of the upper edge of the fronting bar is located with a low power beam focused at surface and a reading of the Z-position of the gun is recorded. The gun is then moved upwards to a calculated value. The procedure is time consuming and requires the full concentration of the operator. The tolerance is approximately ± 1 mm.

Comments: A more simple and reliable procedure needs to be developed for production.

5.2 HV-cable [33]

High voltage discharging has occurred inside the gun termination several times since the equipment was commissioned in 1998. According to TWI this generally can be attributed to overheating of the termination or gas bubbles in the silicone grease.

During 0-marking of the lid weld no 19 date 01-03-16 when the beam was reduced from 20 mA to 5 mA the high voltage cable termination shorted to earth causing damage to the cable end. The termination insulator was cleaned, and the HV tracking marks from the rubber cable end were removed. At beam trials after repair there was a problem with beam and HV instability. The HV-cable was found to be broken at 01-04-06. The HV-cable (TWI no C22 and serial no: 019071) was therefore removed from the system and the spare HV-cable (TWI no C23 and serial no: 031428) was inserted. A new spare HV-cable was ordered from TWI and it was delivered to SKB 01-12-02, with the Cable Part no A91028 and serial no: 025190.

So far with the new HV-cable C23 installed no discharging has occurred.

5.3 HF-amplifier [26], [33]

The BNOS HF-amplifier was found to be broken at 01-03-30. On a bench test the amplifier was found to only delivering some 70 watts maximum. The supposed problem was partial failure of the power amplifier output stage. The amplifier, serial no 522627, was therefore replaced by the spare held by SKB serial no 522365 .The broken amplifier was sent to TWI for repair.

5.4 Water supply

Re-occurrence of the kV tripping fault 01-04-09 led to an investigation of the state of the column water supply filter, which was found to be heavily contaminated with a slimy thick brown substance. This filter was therefore removed and thoroughly cleaned. Upon replacement it was found that a flow rate of 6 l/min was readily possible, this was limited to 4 l/min by manual adjustment of the flow regulator. The trip switch level was raised to 2 l/min. Replacement of the water filter every 12 months is added in the Maintenance list.

5.5 Welding chamber

The weld chamber generally works well, but some problem with high pressure, leaking sealing and unhealthy environmental issues has occurred.

5.5.1 Pressure

The recommended pressure in the welding chamber is ≤ 0,5 mbar. That level is too high according to weld experiences. To achieve a stable welding process the pressure in the chamber should be < 0,2 mbar. At level > 0,25 mbar at full weld power there is a risk for severe plasma creation around the beam. At severe plasma the beam became unstable and fluttered. The weld quality will also be poor.

At remelting of lid weld no 5 (2000-06-08) the pressure was only 0,32 mbar and the weld quality became poor. The reason for the high pressure was many loose bolts (M16) in the chamber flanges. Some of them was possible to turn by hand. After tightening all the bolts with a torque spanner at 160 Nm it was possible to get 0,23 mbar after two hours pumping time.

To achieve pressure ≤ 0,2 mbar in the chamber the pumping time has to be extended up to four hours.

To further improve the pressure situation in the chamber an additional booster pump, Edwards EH2600, recently has been installed. The goal is to achieve pressure level ≤ 0,1 mbar.

5.5.2 Seals

The inflatable rubber seals in the door, hatch, docking module and Jacking Frame have caused many problems. The seals leak air and the operator has to supervise and refill many times during the process of a lid weld.
Four of ten seals were flat after 2 years of operation. Fortunately the seals are doubled in case of a damaged seal.

A set of new seals was ordered from the manufacturer Dunlop, England at 2000-12-19. The delivery time was about 10 months. The seals were replaced at 2001-11-22 to 2001-11-29. Another Supplier has been contacted as an alternative to provide seals with a higher quality and shorter delivery times.

To achieve a good vacuum with the weld hatch connected the tube connections through the docking module side wall and bottom flange were sealed with silicon. A simple instruction for replacement of seals has been produced.

The achieved pressure levels in the weld chamber with the new sealing were:

1) Jacking Frame connected 0,18 mbar
2) Weld hatch connected 0,21 mbar

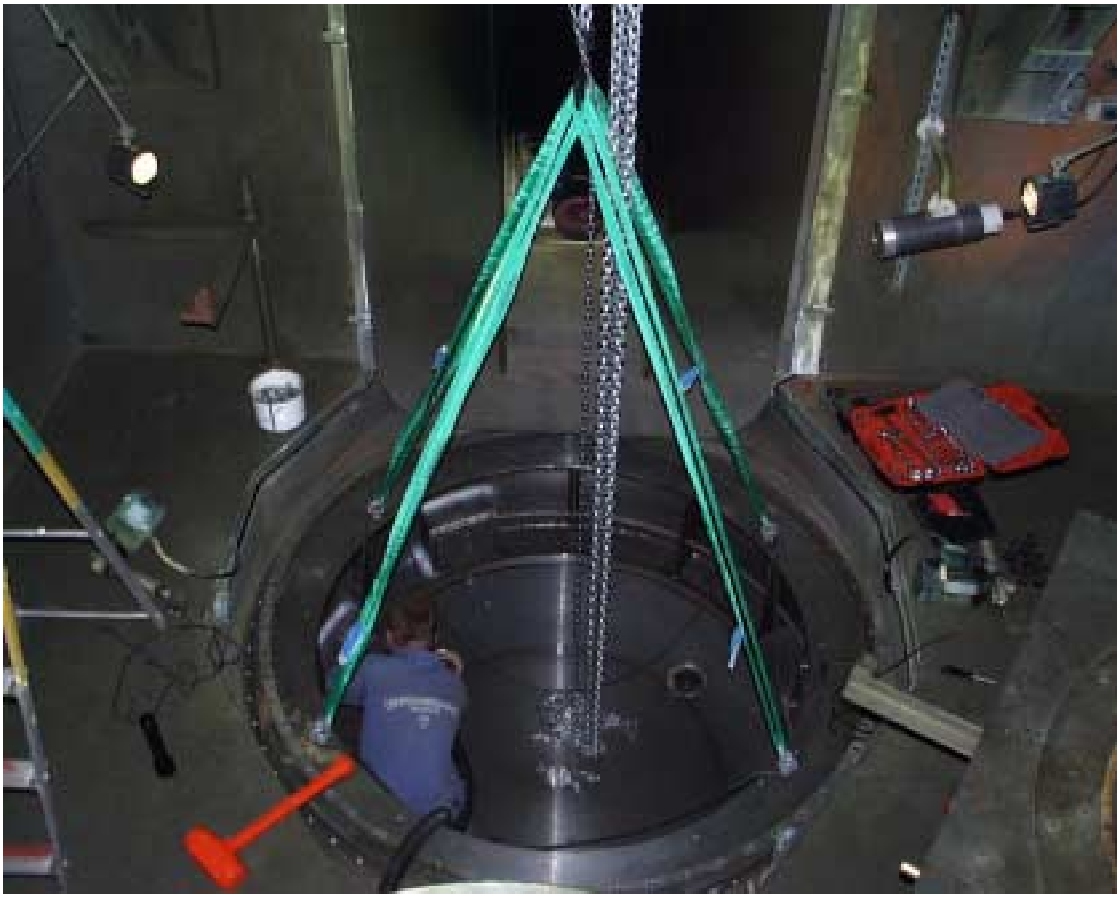


Figure 23: *View inside the chamber at work with replacing the sealing in the docking module.*

5.5.3 Cleaning/Environmental considerations

A serious problem has been bad contamination in the chamber after welding and during cleaning of the chamber. After a few minutes of work in the chamber directly after welding or at activities which agitates the copper dust in the air gives problems with the health due to inhalation of copper particles. The symptoms are irritation in the respiratory system, sore throat, headache and illness. After a couple of hours in fresh air people have recovered.

The environmental aspect is well examined and described in following reports:

CSM Materialteknik T90793MP.091 Date 99-11-25 [23].

CSM Materialteknik TEK00-0434 Date 00-10-25 [24].

CSM Materialteknik TEK01-0613 Date 01-11-05 [25].

Following actions have been taken to improve the environmental issues:

- Installation of an air circulation unit Maxi Floor Freshman model FM 1600-10.
- Installation of a central vacuum cleaner equipment Tedack, type E-pack 500.
- Purchase of fresh air masks to be used when cleaning the weld chamber.
- Filter replacement according to the Suppliers instructions is included in the maintenance schedule.
- Instructions for use of the new equipment have been added in the SKB procedure for electron beam welding SDKL-008 version 3.0.

5.6 Component failure

Some Electrical Components have showed intermittent failure. That has caused us much trouble. The components are now replaced or repaired.

List of failed components	Location
Flow meter for cooling water	Behind Inverter Cabinet
Circuit board	Beam Control Cabinet
Thermocouple Module ADAM-3011	Gun Control Cabinet
Water cooling system	Inverter Cabinet
Terminal Block MC001A [27]	Pumping Control Cabinet Beam Control Cabinet Control Console
Temperature gauge Nozzle1 (T2)	Cabinet PAP 006

6 Conclusions

- Welding of Copper Canister with Electron Beam is a good choice of method.
- Good quality welds have been achieved in copper canisters.
- The SKB/TWI machine concept is a good engineering art but the system need to be further developed and more robust to work reliably in production.
- RF heating system works well but it is sensitive to adjust the signal to the right frequency.
- The Inverter system works well and gun discharges are very rare.
- The conditioning mode for approaching the demand voltage level works well.
- The cathode life is least 10 lid welds.
- The primary filament life is about 10 lid welds.
- The electron beam needs to be tilted down by 3,5° from the horizontal to maintain good beam to joint alignment
- The beam profile depends on Cathode design, Cathode position, Acceleration voltage, Beam current, Focus Q1, Focus Q2, Alignments coils and Chamber pressure.
- The weld profile depends on Cathode design, Cathode position, Acceleration voltage, Beam current, Focus Q1, Focus Q2, Alignments coils, Chamber pressure, Working distance and Travel speed.
- He-flow in the range of 1–3 l/min has no measurable influence on the weld profile.
- Nozzle heating is a problem.
- Mechanical and electrical alignment is of vital importance and it requires very accurate positioning to ensure beam transmission through the nozzles.
- Spatter from the weld pool is prone to fly in the gun and cause disturbance on the beam and cause problems with nozzle heating.
- A Tack welding program is developed and works satisfactory.
- The Main weld program is developed, but not optimised.
- All welding parameters have been tested but parameter limits are not determined.
- A Beam slope in procedure is developed and works satisfactory.
- A Beam slope out procedure is not optimised.
- Internal and surface cavities are a problem.
- Internal cavities can be removed by re-melting the weld.
- Surface roughness can be improved by re-melting the weld.
- Following shrinkage of the weld metal has been measured:
  Outer diameter 1,12 mm.
  Inner diameter 0,20 mm
  Height across the weld 0,77 mm
- The preliminary inspection methods of the weld quality work satisfactory to give feedback to further weld process development.

6.1 Actions to improve welding equipment for process development

1) Cathode and Cartridge design development, to improve beam profile.
2) Improved Parameter stability after Cathode replacement, to get good reproducibility.
3) Replacement of unreliable Electrical Components, to get improved machine reliability.
4) Improved Beam stability, to get regular melting of the cooper material by minimising disturbance from plasma in the welding chamber.
5) A beam oscillation device in the gun could reduce internal cavities
6) Chamber Pressure ≤ 0,1 mbar, to minimise the amount of plasma in the welding chamber.

6.2 Remaining process development to achieve a qualified weld process

1) Optimisation of the parameter settings for canister welding according to Beam Current, Coil setting Q1 and Q2, Working distance, Travel speed, Chamber pressure level and number of weld runs.
2) Development of a beam slope out procedure.
3) Determination of parameter setting limits for a Welding Procedure Specification (WPS).

6.3 Actions to improve welding equipment for production

1) Development of a Spatter Trap in the Gun, to avoid beam disturbance and annoying trip of the welding machine during welding.
2) Improved Beam Positioning equipment, to avoid misaligned beam at the weld joint.
3) Installation of Beam Probe equipment, to read and adjust the beam profile.
4) Improved Nozzle design, to avoid overheating.
5) Improved High voltage cable termination design, to avoid breakdown in the welding equipment.
6) Improved mechanical alignment procedure, to improve the centring of the beam and gun components and to simplify the procedure.
7) Improved electrical alignment procedure, to improve the centring of the beam and gun components and to simplify the procedure.
8) Install a beam oscillation device in the gun, to increase the weld quality by allowing gas porosity to rise and escape from the weld pool.
9) Improved Chamber sealing design, to improve the vacuum and to avoid annoying stoppages caused by leaking of the seals.

7 Reference list

1) Utvärdering och analys av Locksvets nr: 01- Pr1E.010629 by Sören Claesson, SKB.
2) Utvärdering och analys av Locksvets nr: 02- Pr1E.010629-2 by Sören Claesson, SKB.
3) Utvärdering och analys av Locksvets nr: 03- Pr1E.010629-3 by Sören Claesson, SKB.
4) Utvärdering och analys av Locksvets nr: 04- Pr1E.010629-4 by Sören Claesson, SKB.
5) Utvärdering och analys av Locksvets nr: 05- Pr1E.010629-5 by Sören Claesson, SKB.
6) Utvärdering och analys av Locksvets nr: 06- Pr1E.010629-6 by Sören Claesson, SKB.
7) Utvärdering och analys av Locksvets nr: 07- Pr1E.010629-7 by Sören Claesson, SKB.
8) Utvärdering och analys av Locksvets nr: 08- Pr1E.010629-8 by Sören Claesson, SKB.
9) Utvärdering och analys av Locksvets nr: 09- Pr1E.010629-9 by Sören Claesson, SKB.
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11) Utvärdering och analys av Locksvets nr: 11- Pr1E.010629-11 by Sören Claesson, SKB.
12) Utvärdering och analys av Locksvets nr: 12- Pr1E.010629-12 by Sören Claesson, SKB.
13) Utvärdering och analys av Locksvets nr: 13- Pr1E.010629-13 by Sören Claesson, SKB.
14) Utvärdering och analys av Locksvets nr: 14- Pr1E.010629-14 by Sören Claesson, SKB.
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Appendix 1

Weld record list, Lid welds no L01-021

All main weld parameter settings and the result from NDT inspection and macro section examination are presented in a perspicuous way.

Weld record list: Lid weld 001-004   Chatode: Standard

Macro sections: L001: 180°, L003: 7°/25°/50°/65°/210°/309,2°, L004: --

Weld No Date	Acc Voltage kV	Beam Current mA	Travel Speed mm/min	Work dist mm	Focus Q1 A	Focus Q2 A	Beam Power kW	Heat input KJ/mm	Chamber Pressure mbar	Weld Depth mm	Weld Width mm	Tip Radius mm	Comments
Lid 001 99-02-12	190	420	250	125	1,240	1,375	79,8	19,2	0,14	98	7	0,55	180° Root defect
Goal										*70 - 75*	*8 - 9*	*≥ 2,5*	
Lid 003 99-09-10	190	380	250	125	1,260	1,475	72,2	17,3	0,24				7,0° Subsurface cavities Reference piece, not cutted
		380			1,260	1,475				83,5	8,8	0,5	25° Root defect
		300			1,260	1,500				48,5	8,8	2,1	25° Slope out
		380			1,260	1,475				81,5	8,4	0,6	50° Root defect
		100			1,260	1,500				------	------	------	50° Cosmetic weld
		380			1,260	1,475				83,5	8,0	0,5	65° Root defect
		100			1,260	1,500				------	------	------	65° Cosmetic weld
		380			1,260	1,475				78,5	8,8	0,6	210°
		100			1,260	1,500				------	------	------	210° Cosmetic weld
		380			1,260	1,475				76,5	8,8	0,6	309,2°
		100			1,260	1,500				------	------	------	309,2° Cosmetic weld
Lid 004-1 99-10-06	190	380	250	125	1,260	1,475	72,2	17,3	0,26				1 run. Beam pulsation Very rough surface and internal
Lid 004-2 99-10-28	190	100→250	250	125	1,260	1,500	47,5	11,4	0,25				1 Remelting run Very rough surface and internal
Lid 004-3 99-11-02	190	100→380	250	125	1,260	1,400 1,475	72,2	17,3	0,21				Testrun 30 mm above the joint. Not cutted
Lid 004-4 99-11-02	190	100 200	250 350	125	1,260	1,475	38	9,1	0,21				Testrun in the tube 150 mm below frontong bar. Not cutted
Lid 004-5 99-11-02	190	100→380	250 350	125	1,260	1,525	72,2	17,3	0,21				2 Remelt run. Not cutted Very rough surface and internal

Macro sections: L002: 1,5°/18,5°/33°/48°/63°/83,5°/100,5°/117,5°/134,5°/ 151,5°/168,5°/188,5°/205,5°/222,5°/239,5°/256,5°/273,5°/293,5°/310,5°/327,5°/344,5°

Weld no	Acc Voltage kV	Beam Current mA	Travel Speed mm/min	Work dist mm	Focus Q1 A	Focus Q2 A	Beam Power kW	Heat input KJ/mm	Chamber Pressure Mbar G6/ G4 / He lit	Weld Depth mm	Weld Width mm	Tip Radius mm	Comments
Lid 02 99-04-23	190	350	250	125	1,250	1,375	66,5	15,7	0,24/ 0,13/ 1	83	6,3	0,25	33° Root defect
					1,250	1,375			0,24/ 0,14	81	6,5	0,3	48° Root defect, porosity
					1,250	1,375			0,24/ 0,14	78	7	0,5	63° Root defect
					1,250	1,375			0,24/ 0,20/ 3	74,5	6,8	0,5	83,5°
					1,250	1,400			0,25/ 0,21	73	7,5	0,8	100,5° Crack 7,5 mm/ weldnose
					1,250	1,425			0,25/ 0,22	68	8,3	0,5	117,5° Porosity
					1,250	1,450			0,26/ 0,23	68	8,3	0,6	134,5° Root defect
					1,250	1,475			0,26/ 0,24	65,5	8,7	0,6	151,5°
					1,250	1,500			0,26/ 0,24	66	9	1,3	168,5° Crack 1,6 mm/ weldnose
					1,250	1,375			0,27/ 0,22/ 2	72	7,8	0,3	188,5°
					1,250	1,400			0,27/ 0,22	72	8	0,5	205,5° Root defect
					1,250	1,425			0,27/ 0,22	69,5	8	0,6	222,5°
					1,250	1,450			0,27/ 0,22	65	8,2	0,8	239,5°
					1,250	1,475			0,27/ 0,22	66	8,5	1,0	256,5°
					1,250	1,500			0,27/ 0,22	62,5	8,9	1,5	273,5°
					1,250	1,375			0,26/ 0,19/ 1	73	6,9	0,3	293,5°
					1,250	1,400			0,26/ 0,19	72	8,2	0,4	310,5°
					1,250	1,425			0,26/ 0,18	71	9	0,4	327,5° Root defect
					1,250	1,450			0,26/ 0,18	68	8,7	0,7	344,5°
					1,250	1,475			0,26/ 0,18	66,5	9	1,2	361,5° (1,5°) Porosity
					1,250	1,500			0,25/ 0,18	64,5	10	1,3	378,5° (18,5°) Porosity
		295			1,250	1,500	56	13,2	0,25/ 0,18	51	10	1,6	393° (33°) Slope out, porosity
		191			1,250	1,500	36	8,5	0,25/ 0,18	30	9	2,5	408° (48°) Slope out, porosity
		88			1,250	1,500	16,7	3,9	0,25/ 0,17	------	------	------	423° (63°) Slope out

Weld record list: Lid weld 005-006 Chatode: HCC1 SKB3(1)
Macro sections: L005: 180°, L006: 10°/50°/90°/130°/170°/210°/250°/290°/330°

Weld No Date	Acc Voltage kV	Beam Current mA	Travel Speed mm/min	Work dist mm	Focus Q1/Q2 A	Beam Power kW	Heat input KJ/mm	Chamber Pressure Mbar G6	Weld Depth mm	Weld Width mm Top/max	Tip Radius mm	Macro section position	Comments
L005-1 00-05-18	190	350	250	125	1,20/1,40	66,5	16	0,24	72	6,3	1	180°	Surface rough, 3 subsurface defects and 40 root defects
													Open the chamber and x-ray the weld
L005-2 00-06-08	190	240	250	125	1,20/1,50	45,6	10,9	0,28	40	8	2,2	180°	Remelt run, rough surface, 5 subsurface defects and 40 root defects
													Open the chamber and x-ray the weld
L005-3 00-06-08	190	180	250	125	1,20/1,50	34,2	8,2	0,32	24	9	3	180°	Remelt run, rough surface, 3 subsurface defects and 40 root defects
L006-1 00-08-23	190	280	210	125	1,20/1,40	53,2	15,2	0,24	63	---/6,6	1,1	50°	Joint tip unmelt 5,6 mm. Alignment, gun angle –0,9°
					1,20/1,45	”	”	”	61	6,5/8,0	0,9	90°	Joint tip unmelt 5,5 mm
					1,20/1,50	”	”	”	55	8,0/8,5	1,5	130°	Joint tip unmelt 12,5 mm
L006-2 00-08-23	190	300	210	125	1,20/1,40	57	16,3	”	65	7,0/7,8	1,0	170°	Joint tip unmelt 1,5 mm
					1,20/1,45	”	”	”	62	7,8/8,3	1,5	210°	Joint tip unmelt 2,7 mm
					1,20/1,50	”	”	”	58	7,5/8,3	1,7	250°	Joint tip unmelt 9,6 mm
L006-3 00-08-23	190	320	210	125	1,20/1,40	60,8	17,4	”	69	7,0/7,8	1,0	290°	Joint tip melt
					1,20/1,45	”	”	”	63	7,8/8,8	1,5	330°	Joint tip melt
					1,20/1,50	”	”	”	60,5	8,5/10	2,2	370° (10°)	Joint tip unmelt 3,1 mm
													Surface rough, 10 subsurface defects and 25 root defects

Weld record list: Lid weld 007 Chatode: HCC1 SKB3(1)
Macro sections: L007: 60°/80°/115°/150°/185°/220°/255°/290°/310°/320°

Weld No Date	Acc Voltage kV	Beam Current mA	Travel Speed mm/min	Work dist mm	Focus Q1/Q2 A	Beam Power kW	Heat input KJ/mm	Chamber Pressure Mbar G6	Weld Depth mm	Weld Width Mm Top/max	Tip Radius mm	Macro section position	Comments
L007-1 00-09-06	190	420	300	125	1,20/1,50	79,8	16	0,23	87		< 0,5	60°	Alignment, gun angle –0,9° Joint tip unmelt
					1,20/1,45	”	”	”	85		< 0,5	80°	Joint tip unmelt
					1,20/1,50	”	”	”	81		< 0,5	115°	Joint tip unmelt
					1,20/1,525	”	”	”	81		< 0,5	150°	Joint tip unmelt
					1,20/1,550	”	”	”	78		< 0,5	185°	Joint tip unmelt
L007-2 00-09-06	190	440	300	125	1,20/1,50	83,6	16,7	”	85		< 0,5	220°	Joint tip unmelt
					1,20/1,525	”	”	”	84		< 0,5	255°	Joint tip unmelt
					1,20/1,550	”	”	”	75		1,1	290°	Joint tip unmelt
													Open the chamber and x-ray the weld Surface good, 5 subsurface defects, 40 root defects some very big
L007-3 00-09-16	190	360	250	125	1,20/1,500	68,4	16,4	0,22	74	8,0/9,1	1,3	60°	Remelt run, alignment, gun angle –2,1° Joint tip unmelt 2 mm
		”	”	”	”	”	”	”	76	7,8/8,6	1,4	80°	Joint tip unmelt 1 mm
		”	”	”	”	”	”	”	73	8,3/8,9	1,2	115°	Joint tip unmelt 1 mm
		”	”	”	”	”	”	”	72	8,1/8,5	1,3	150°	Joint tip unmelt 8,6 mm
		”	”	”	”	”	”	”	70	8,7/10	1,6	185°	Joint tip unmelt 2 mm
		”	”	”	”	”	”	”	73	8,7/9,2	1,5	220°	Joint tip unmelt 2 mm
		”	”	”	”	”	”	”	73	8,2/9,6	1,1	255°	Joint tip unmelt 8 mm
		”	”	”	”	”	”	”	74	8,7/9,2	1,4	290°	Joint tip unmelt 5 mm
		285	”	”	”	53,2	12,7	”	55	7,8/9,2	2,2	310°	Joint tip unmelt 13 mm
		203	”	”	”	38	9,1	”	38	8,0/8,0	2,3	320°	Joint tip unmelt 38 mm
													Surface good, no subsurface defects 40 root defects some very big

Weld record list: Lid weld 008-012 Chatode: HCC1 SKB3(1)
Macro sections: L008:--, L009: 180°, L010: 180°, L011: 180°, L012: 180°

Weld No Date	Acc Voltage kV	Beam Current mA	Travel Speed mm/min	Work dist mm	Focus Q1/Q2 A	Beam Power kW	Heat input KJ/mm	Chamber Pressure Mbar G6	Weld Depth mm	Weld Width mm Top/max	Tip Radius mm	Macro section position	Comments
L008-1 00-09-22	190	370	250	125	1,200 1,500	70,3	16,9	0,24					Bad joint fit, gap ≈ 2 mm. Surface undercut ≈ 20 mm. Not cutted
L008-2 00-09-29	190	370	250	125	1,200 1,500	70,3	16,9	0,24					Test run 30 mm above the joint. Not cutted
L009 00-10-06	190	350	250	125	1,200 1,450	66,5	16,0	0,23	68	7,3/8,0	1,8	180°	1 run, alignment gun angle –3,1° Surface rough, 15 subsurface defects and 20 root defects
L010 00-10-16	190	350	250	125	1,200 1,450	66,5	16,0	0,23	68	----------	1,8	180°	1 run. Alignment gun angle –3,1°
	190	300	250	125	1,200 1,450	57	13,7	0,23	57	7,2/9,2	2,0	180°	Remelt run 360-770° Surface rough, 3 subsurface defects and 5 root defects
L011 00-10-27	190	350	250	125	1,200 1,450	66,5	16,0	0,23	65	----------	1,8	180°	1 run. Alignment gun angle –3,1°
	190	275	250	125	1,200 1,450	52,3	12,5	0,23	53	7,6/8,8	1,7	180°	Remelt run 360-820° Surface rough, no subsurface defects and 10 root defects
L012 00-11-13	190	350	250	125	1,200 1,425	66,5	16,0	0,22	65	----------	1,8	180°	1 run. Alignment gun angle –3,1°
	190	275	250	125	1,200 1,425	52,3	12,5	0,22	53	7,5/8,6	1,8	180°	Remelt run 360-820° Surface rough 40-200° remain good 1 big defect at slope out 788° (68°) No subsurface defects and 10 root defects

Weld record list: Lid weld 013-014 Chatode: HCC1 SKB3(1)
Macro sections: L013: 180°, L014: 42,5°/67,5°/92,5°/180°

Weld No Date	Acc Voltage kV	Beam Current mA	Travel Speed mm/min	Work dist mm	Focus Q1/Q2 A	Beam Power kW	Heat input KJ/mm	Chamber Pressure Mbar G6	Weld Depth mm	Weld Width mm Top/max	Tip Radius mm	Macro section position	Comments
L013 00-11-29	190	350	250	125	1,195/1,415	66,5	16,0	0,24	67	--------	1,8	180°	1 run. Alignment gun angle –3,1°
	190	275	250	125	1,195/1,415	52,3	12,5	0,24	54	7,4/8,5	1,8	180°	Remelt run 360-855° Surface good 1 defect at slope out 776° (56°) No subsurface defects and 10 small root defects
L014 00-12-18	190	340	250	125	1,195/1,410	64,6	15,5	0,23	66	--------	2,0	180°	1 run. Alignment gun angle –3,1°
	190	275	250	125	1,195/1,410	52,3	12,5	0,23	57	7,0/7,4	1,2	180°	Remelt run 360-855° Surface good 1 subsurface defect at slope out 775° (55°), 1 small at 180° Linear root defects at slope out 754→843° (34→123°) Q2 = 1,361→1,218 A
	190	340	250	125	1,195/1,410	64,6	15,5	0,23	69	--------	2,0	42,5°	1 run full weld
	190	275	250	125	1,195/1,410	52,3	12,5	0,23	55	7,0/7,5	1,3	42,5°	2 run remelt run
	190	197	250	125	1,195/1,348	37,4	9,0	0,23	42	----/5,5	1,0	42,5°	Slope out 762,5° root defect at UT
	190	340	250	125	1,195/1,410	64,6	15,5	0,23	67	--------	2,0	67,5°	1 run full weld
	190	275	250	125	1,195/1,410	52,3	12,5	0,23	55	7,0/7,5	1,3	67,5°	2 run remelt run
	190	145	250	125	1,195/1,307	27,6	6,6	0,23	32	4,1/4,1 cent 2,9	0,7	67,5°	Slope out 787,5° root defect at UT
	190	340	250	125	1,195/1,410	64,6	15,5	0,23	68	--------	1,3	92,5°	1 run full weld
	190	275	250	125	1,195/1,410	52,3	12,5	0,23	55	6,8/7,4	1,2	92,5°	2 run remelt run
	190	93	250	125	1,195/1,268	17,7	4,2	0,23	22	2,5/2,5 cent 1,9	0,5	92,5°	Slope out 812,5° root defect at UT

Weld record list: Lid weld 015-016 Chatode: HCC1 SKB3(1)
Macro sections: Lid 015: 180°, L016: --

Weld No Date	Acc Voltage kV	Beam Current mA	Travel Speed mm/min	Work dist mm	Focus Q1/Q2 A	Beam Power kW	Heat input KJ/mm	Chamber Pressure Mbar G6	Weld Depth mm	Weld Width mm Top/max	Tip Radius mm	Macro section position	Comments
L015-1 01-01-26	190	340	250	125	1,410/1,195	64,6	15,5	0,23	66	--------	1,8	180°	1 run Main weld No subsurface defects
L015-2 01-01-26	190	270	250	125	1,410/1,195	51,3	12,3	0,23	57	7,5/7,7	1,4	180°	2 run Remelt 360-720° No subsurface defects
L015-3 01-01-26	190	210	250	125	1,390/1,185	39,9	9,6	0,23	46		1,1	180°	3 run Remelt 720-1080° Some subsurface defects
L015-4 01-01-26	190	160	250	125	1,380/1,180	30,4	7,3	0,23	32		1,1	180°	4 run Remelt 1080-1460° Linear root defects/not continuous Visible at UT, not visible at RT Surface good
L016-1 01-02-02	190	340	250	125	1,410/1,195	64,6	15,5	0,23					1 run Main weld Some subsurface defects
L016-2 01-02-02	190	270	250	125	1,410/1,195	51,3	12,3	0,23					2 run Remelt 360-720° No subsurface defects
L016-3 01-02-02	190	210	250	125	1,400/1,185	39,9	9,6	0,23					3 run Remelt 720-1080° No subsurface defects
L016-4 01-02-02	190	160	250	125	1,400/1,180	30,4	7,3	0,23					4 run Remelt 1080-1460° Subsurface defects Surface good

Weld record list: Lid weld 017 Chatode: HCC1 SKB3(1)

Macro sections: L017: 43°/180°

Weld No Date	Acc Voltage kV	Beam Current mA	Travel Speed mm/min	Work dist mm	Focus Q1/Q2 A	Beam Power kW	Heat input KJ/mm	Chamber Pressure Mbar G6	Weld Depth mm	Weld Width mm Top/max	Tip Radius mm	Macro section position	Comments
L017-1 01-02-09	190	340	250	125	1,195/ 1,410	64,6	15,5	0,22	73	--------	1,2	180°	1 run Main weld Some subsurface defects
L017-2 01-02-09	190	270	250	125	1,410/ 1,195	51,3	12,3	0,22	59	----/6,9	1,1	180° (540°)	2 run Remelt 360-720° No subsurface defects
L017-3 01-02-09	190	210	250	125	1,410/ 1,185	39,9	9,6	0,22	42	----/6,9	0,8	180° (900°)	3 run Remelt 720-1080° Some subsurface defects
L017-41 01-02-09	190	160	250	125	1,425/ 1,180	30,4	7,3	0,22	32	7,5/7,5	0,8	43° (403°)	4 run Remelt 1095-1155° Surface good
L017-42 01-02-09	190	160	250	125	1,450/ 1,180	30,4	7,3	0,22					4 run Remelt 1165-1225° Surface good
L017-43 01-02-09	190	160	250	125	1,475/ 1,180	30,4	7,3	0,22	26	6,8/6,8	1,5	180° (1260°)	4 run Remelt 1235-1295° Surface good
L017-44 01-02-09	190	160	250	125	1,500/ 1,180	30,4	7,3	0,22					4 run Remelt 1305-1365° Surface breaking defect at 270°
L017- Slope out	190	160→5	250	125	1,5007 1,180								4 run Slope out 1365-1380° Surface good

Weld record list: Lid weld 018 Chatode: HCC1 SKB3(1)

Macro sections: L018: 23°/180°

Weld No Date	Acc Voltage kV	Beam Current mA	Travel Speed mm/min	Work dist mm	Focus Q1/Q2 A	Beam Power kW	Heat input KJ/mm	Chamber Pressure Mbar G6	Weld Depth mm	Weld Width mm Top/max	Tip Radius mm	Macro section position	Comments
L0018-1 01-03-13	190	340	250	125	1,195/ 1,410	64,6	15,5	0,22	68	--------	1,4	180°	1 run Main weld Some subsurface defects
L0018-2 01-03-13	190	270	250	125	1,195/ 1,410	51,3	12,3	0,22	56	----/6,8	1,0	180° (540°)	2 run Remelt 360-720° No subsurface defects
L0018-3 01-03-13	190	210	250	125	1,185/ 1,420	39,9	9,6	0,22	42	----/6,8	1,2	180° (900°)	3 run Remelt 720-1080° No subsurface defects
L0018-4 01-03-13	190	160	250	125	1,180/ 1,460	30,4	7,3	0,22	24	7,7/7,7	1,6	180° (1260°)	4 run Remelt 1095-1445° Surface good
L0018-1 01-03-13	190	340	250	125	1,195/ 1,410	64,6	15,5	0,22	82	--------	1,3	23°	Remelting of trip area Some subsurface defects
L0018-2 01-03-13	190	270	250	125	1,195/ 1,410	51,3	12,3	0,22	67	----/6,8	1,2	23° (383°)	Remelting of trip area Some subsurface defects
L0018-3 01-03-13	190	210	250	125	1,185/ 1,420	39,9	9,6	0,22	51	----/6,8	0,9	23° (743°)	Remelting of trip area Some subsurface defects
L0018-4 01-03-13	190	160	250	125	1,180/ 1,460	30,4	7,3	0,22	30	7,8/7,8	1,4	23° (1103°)	Remelting of trip area Some subsurface defects Surface good

Weld record list: Lid weld 019-021 Chatode: HCC1 SKB3(2)
Macro sections: L019: 180°, L020: 180° and L021: 180°

Weld No Date	Acc Voltage kV	Beam Current mA	Travel Speed mm/min	Work dist mm	Focus Q1/Q2 A	Beam Power kW	Heat input KJ/mm	Chamber Pressure Mbar G6	Weld Depth mm	Weld Width mm Top/max	Tip Radius mm	Macro section position	Comments
L019-1 01-05-18	190	340	250	125	1,195/ 1,460	64,6	15,5	0,17	65	--------	1,2	180°	1 run Main weld Subsurface defects
L019-2 01-05-18	190	270	250	125	1,195/ 1,460	51,3	12,3	0,17	53	----/8,0	1,25	180° (540°)	2 run Remelt 360-720° No subsurface defects
L019-3 01-05-18	190	210	250	125	1,185/ 1,470	39,9	9,6	0,17	40	----/8,1	1,5	180° (900°)	3 run Remelt 720-1080° No subsurface defects
L019-4 01-05-18	190	160	250	125	1,180/ 1,490	30,4	7,3	0,17	28	8,6/8,6	1,8	180° (1260°)	4 run Remelt 1095-1445° 10 surface defcts
L020-1 01-06-19	190	345	250	125	1,195/ 1,470	65,6	15,7	0,18	64	--------	1,0	180°	1 run Main weld Subsurface defects
L020-2 01-06-19	190	270	250	125	1,195/ 1,470	51,3	12,3	0,18	52	----/8,5	1,2	180° (540°)	2 run Remelt 360-720° No subsurface defects
L020-3 01-06-19	190	210	250	125	1,185/ 1,470	39,9	9,6	0,18	39	----/8,5	1,3	180° (900°)	3 run Remelt 720-1080° No subsurface defects
L020-4 01-06-19	190	170	250	125	1,180/ 1,470	32,3	7,8	0,18	31	----/8,3	1,4	180° (1260°)	4 run Remelt 1095-1445° 12 surface defcts
L020-5 01-06-19	190	125	250	125	1,180/ 1,470	23,8	5,7	0,18	14	8,4/8,4	2,3	180° (1620°)	5 run Remelt 1455-1805° 100 surface defcts
L0021-1 01-08-22	190	345	250	125	1,165/ 1,470	65,6	15,7	0,15	68	--------	1,2	180°	1 run Main weld Subsurface defects
L0021-2 01-08-22	190	270	250	125	1,150/ 1,470	51,3	12,3	0,15	50	----/8,0	1,25	180° (540°)	2 run Remelt 360-720° No subsurface defects
L0021-3 01-08-22	190	150	250	125	1,150/ 1,490	28,5	6,8	0,15	22	----/8,1	1,5	180° (900°)	3 run Remelt 720-1080° No subsurface defects

Appendix 2

Weld record list, Test block no TB01-054

All main weld parameter settings and the result from NDT inspection and macro section examination are presented in a perspicuous way.

Weld record list Testblock I Cathode Type: Standard

Weld no	Acc Voltage kV	Beam Current mA	Travel Speed mm/min	Work dist mm	Focus Q2 A	Beam spot ∅ mm	Beam Power kW	Heat input KJ/mm	Chamber Pressure mbar	Weld Depth mm	Weld Width mm	Tip Radius mm	Comments
TB001	190	394	248	150	1,180	3,2	74,9	18,1	0,68	89	7	0,9	Date: 98-12-11
TB002	190	394	248	150	1,271	5,9	74,9	18,1	0,68	67	11	1,9	Date: 98-12-11
TB003	190	400	236	125	1,270	3,7	76	19,3	0,27	94	8	0,4	Date: 99-02-09
TB004	190	400	236	127	1,325	5,4	76	19,3	0,27	85	9	1,4	Date: 99-02-09
TB005	190	400	236	127	1,300	4,6	76	19,3	0,27	87	8,5	1,1	Date: 99-02-09
TB006:1	190	420	250	125	1,375	6,8	79,8	19,2	0,27	97	8,5	0,9	Date: 99-02-11
TB006:21	190	332	250	125	1,464	8,5	63,1	15,1	0,27	72	9,5	1,8	Slope out
TB006:22	190	220	250	125	1,510	9,4	41,8	10	0,27	46	10,5	3,5	Slope out
TB006:23	190	104	250	125	1,518	9,5	19,8	4,7	0,27	15	10,5	4,0	Slope out
TB007:1	190	380	238	100	1,350	3,6	72,2	18,2	0,3	81	8	0,6	Date: 99-04-20
TB007:2	190	380	238	100	1,400	5,0	72,2	18,2	0,3	82	8,2	0,6	
TB007:3	190	380	238	100	1,450	6,3	72,2	18,2	0,3	80	10,2	1	Rough surface
TB007:4	190	380	238	100	1,500	7,4	72,2	18,2	0,3	76	10,2	2,3	Surface pore ∅ 10/ depth 15 mm
TB007:5	190	380	238	100	1,550	8,6	72,2	18,2	0,3	74	12	2,2	Surface pore ∅ 8/ depth 15 mm
TB008:1	200	335	238	100	1,400	3,7	67	16,9	0,3	85	5,9	0,4	Date: 99-04-21
TB008:2	200	335	238	100	1,450	5,3	67	16,9	0,3	83	7	0,6	
TB008:3	200	335	238	100	1,500	6,5	67	16,9	0,3	80	8	0,7	
TB008:4	200	335	238	100	1,550	7,6	67	16,9	0,3	79	8,5	0,8	Rough surface
TB008:5	200	335	238	100	1,600	8,6	67	16,9	0,3	72	10,4	0,9	Rough surface
TB009:1	190	350	276	125	1,450	8,3	66,5	14,5	0,3	80,5	6,5	0,4	Date: 99-09-03 New cathode standard type
TB009:2	190	330	276	125	1,450	8,3	62,7	13,6	0,3	56	7,5	1,4	Date: 99-09-07 New cathode type, test by AS
TB010-N	190	420	300	125	1,450	8,3	79,8	16	0,3	86	7,9	0,3	Date: 99-06-16
TB010-Ö	190	420	300	125	1,450	8,3	79,8	16	0,3	83	7	0,8	Rough surface HS no bulgeshape

Weld record list Testblock II Cathode Type: Standard and HCC1

Weld TB no	Acc voltage kV	Beam Current mA	Travel Speed mm/min	Work Distance mm	Focus Q2 A	Cathode Type	Weld Depth mm	Top Width mm	Max Width mm	Tip Radius mm	Surface condition	Comments
011:1/1	190	350	236	125	1,400	Stand	68		10	2	?	Date: 00-04-20
011:1/2	190	150	236	125	1,500	Stand	18	9,2	10	2,5	Undercut 20 mm	Cosmetic run in hot testblock
012:1	190	50	236	125	1,180	Stand	14,5	2	2	0,1	NR	Date: 00-04-20
012:2	190	65	236	125	1,180	Stand	18	2,2	2,2	0,1	NR	
012:3	190	80	236	125	1,180	Stand	23	2,3	2,3	0,1	NR	
013:1	190	100	236	125	1,500	Stand	5	8	8	3	Undercut 3 mm	Date: 00-04-20
013:2	190	125	236	125	1,500	Stand	8	10,5	10,5	3	Undercut 3 mm	
013:3	190	150	236	125	1,500	Stand	13	11	11	2,5	Undercut 3 mm	
014:1	190	175	236	125	1,500	Stand	22	9,7	11	3	Minor roughness	Date: 00-04-20
014:2	190	200	236	125	1,500	Stand	31	8	10	2	Rough	
014:3	190	225	236	125	1,500	Stand	35	8,8	11	2	Rough	
015	190	350	236	125	1,400	Stand	76	9,3	9,1	0,9	NR	Date: 00-05-10
016:A	190	350	236	125	1,350	SKB 1(1)	77	9,5	7,2	1	NR	Date: 00-05-12
016:B	190	350	236	125	1,400	SKB 1(1)	76	9,3	9,3	2	Minor roughness	New cathode set back = 0 in the holder
016:C	190	350	236	125	1,450	SKB 1(1)	72	10,3	9,5	2	Rough	
017:A	190	350	236	125	1,350	SKB 3(1)	67	9,7	10	2,4	NR	Date: 00-05-16
017:B	190	350	236	125	1,400	SKB 3(1)	65	8,5	11	3,2	Minor roughness	New cathode set back = 0,04
017:C	190	350	236	125	1,450	SKB 3(1)	65	8,5	10,7	4,1	Minor roughness	
018:A	190	250	143	125	1,350	SKB 3(1)	72	6,7	7,4	2	Rough	Date: 00-05-16
018:B	190	250	143	125	1,400	SKB 3(1)	64	8,1	9,6	4,7	Rough	
018:C	190	250	143	125	1,450	SKB 3(1)	59,5	10,4	12,1	5,1	Rough	
019	190	350	236	125	1,400	SKB 3(1)	75	7,8	8,5	2	NR	Date: 00-05-17
020	190	350	278	125	1,400	SKB 3(1)	62	7,3	8,3	2	NR	Date: 00-05-17
021:1	190	175	236	125	1,450	SKB 3(1)	17,3	11,5	10,3	3,6	Undercut 3 mm	Date: 00-05-30
021:2	190	175	236	125	1,500	SKB 3(1)	18,3	11,9	10,9	3,8	NR	The beam has hit the fronting bar
022:1	190	200	236	125	1,450	SKB 3(1)	24,8	10	10	2,7	NR	Date: 00-05-30
022:2	190	200	236	125	1,500	SKB 3(1)	21,5	10,4	10,4	3,4	NR	The beam has hit the fronting bar
023:1	190	225	236	125	1,450	SKB 3(1)	42	8,2	8,2	1,7	Minor roughness	Date: 00-08-14
023:2	190	225	236	125	1,500	SKB 3(1)	36,5	9,0	8,5	3		RT-internal no defects / 0,18 mbar

Weld TB no	Acc voltage kV	Beam Current mA	Travel Speed mm/min	Work Distance mm	Focus Q2 A	Chatode Type HCC1	Weld Depth mm	Top Width mm	Mid Depth Width mm	Tip Radius mm	Surface condition	Comments
024:1	190	250	236	125	1,450	SKB 3(1)					NR	Date: 00-08-17
024:2	190	250	236	125	1,500	SKB 3(1)					NR	RT-internal no defects *Block l=400*
025	190	350	236	125	1,400	SKB 3(1)	89	7,3	8,0	1	Rough	RT-internal cavities / 0,18 mbar
												Date: 00-08-14
026:1	190	300	236	125	1,400	SKB 3(1)					Rough	RT-internal defects *Block l =500*
026:2	190	300	236	125	1,450	SKB 3(1)					Rough	RT-internal defects *Block l =500*
026:3	190	300	236	125	1,500	SKB 3(1)					Rough	RT-internal defects *Block l =500*
												Date: 00-08-17
027:1	190	325	236	125	1,400	SKB 3(1)					Rough	RT-some internal defects *Block l =500*
027:2	190	325	236	125	1,450	SKB 3(1)					Rough	RT-some internal defects *Block l =500*
027:3	190	325	236	125	1,500	SKB 3(1)					Rough	RT-some internal defects *Block l =500*
												Date: 00-08-17
028	185	350	236	125	1,400	SKB 3(1)					Rough	RT-severe internal defects *Block l=400*
029:1	190	350	236	125	1,400	SKB 3(1)	74	6,9	9,9	1,7	Minor roughness	Date: 00-09-14
029:2	190	350	236	125	1,450	SKB 3(1)	70	8,0	10,0	1,8	Minor roughness	
030:1	190	350	342	125	1,400	SKB 3(1)	64	6,4	8,3	1,1	Minor roughness	Date: 00-09-14
030:2	190	350	342	125	1,450	SKB 3(1)	61	7,3	8,9	1,5	Rough	
031:1	190	360	236	125	1,500	SKB 3(1)	66	10,0	9,7	2,0	Rough	Date: 00-09-14
031:2	190	360	236	125	1,550	SKB 3(1)	68	9,0	11,0	2,6	NR	Beautiful straight weld shape
032	190	350	236	125	1,500	SKB 3(1)	52	12	10	2,7	Keyhole: 20 x 8,5 depth 43 mm	Date: 00-11-30 Test of trip effect on weld

Weld record list Testblock III Cathode Type:HCC1

Weld TB no Date	Acc voltage kV	Beam Current mA	Travel Speed mm/min	Work Distance mm	Focus Q1 Q2 A	Cathode	Weld Depth mm	Top Width mm	Mid Depth Width mm	Tip Radius mm	Surface condition	Comments
033 01-04-18	190	340	236	125	1,195 1,410	HCC1 SKB 3(2)	76	7,7	8,1	0,6	Minor roughness	New Cathode, Filament, Amplifier and HV-cable.JF not connected 0,31mbar No root defect
034:1 01-05-03	190	340	236	125	1,195 1,410	HCC1 SKB 3(2)	83	7,7	8,4	0,6	Minor roughness	New Cathode, Filament, Amplifier and HV-cable. JF connected 0,20 mbar. Root defects
034:2 01-05-03	190	340	236	125	1,195 1,430	HCC1 SKB 3(2)	80	8,7	9,8	0,8	Minor roughness	Root defects
035:1 01-05-03	190	340	236	125	1,195 1,450	HCC1 SKB 3(2)	74	8,2	8,8	0,8	Minor roughness	New Cathode, Filament, Amplifier and HV-cable. JF connected 0,20 mbar. Root defects
035:2	190	340	236	125	1,195 1,470	HCC1 SKB 3(2)	68	8,1	10,0	2,1	Minor roughness	No root defect
036 01-06-15	190	340	236	125	1,185 1,470	HCC1 SKB 3(2)	66 70	9,6 8,2	9,8 9,9	1,4 1,5	Minor roughness	Before installation of additional vaccumpump and calibration JF connected 0,60 mbar!!! RT-only a few root defects
037 01-08-13	190	340	236	125	1,185 1,470	HCC1 SKB 3(2)	60 62	10 9,2	10,6 9,9	2,1 1,8	Minor roughness	After installation of additional vaccumpump and calibration JF connected 0,21 mbar. RT-some root defects and one big internal defect
038 01-09-20	190	350	236	125	1,165 1,500	HCC1 SKB 3(2)	72	8,9	8,8	1,5	Minor roughness	New Cathode Trip test, comparison to TB 032. JF connected 0,15 mbar Root defect in the section and at RT
							71	8,3	8,0	0,6	Keyhole: 10 x 6,3 depth 46 mm	Trip area Root defect in the section 9 x 4,6 mm

Weld TB no Date	Acc voltage kV	Beam Current mA	Travel Speed mm/min	Work Distance mm	Focus Q1 Q2 A	Cathode Type and No	Weld Depth mm	Top Width mm	Mid Depth Width mm	Tip Radius mm	Surface condition	Comments
039 01-09-20	190	350	236	125	1,165 1,500	HCC1 SKB 3(2)	66	9,8	9,4	1,3	Minor roughness	New Cathode. Trip test, comparison to TB 032. JF connected 0,15 mbar Root defect in the section and at RT
							67	9,3	9,5	2,5	Keyhole: 13 x 6,7 depth 45 mm	Trip area No root defect in the section
040 01-10-04	190	350	236	125	1,165 1,600	HCC1 SKB 3(2)	58	10,9	11	3,3	Minor roughness	New Cathode. Trip test, comparison to TB 032. JF connected 0,16 mbar No root defect at RT
							60	9,2	10,7	3,0	Keyhole: 16 x 8 depth 51 mm	Trip area No root defect in the section
041 01-10-24	190	200	236	125	1,150 1,500	HCC1 SKB1 (RG)	31	8,9	9,2	1,9	Minor roughness	New Cathode. JF connected 0,13 mbar No root defect in the section and at RT
							30	8,9	9,0	1,6	Keyhole: 10 x 7,5 depth 18 mm	Trip area No root defect in the section and RT
042 01-10-24	190	250	236	125	1,150 1,500	HCC1 SKB1 (RG)	43	9,1	9,0	1,6	Minor roughness	New Cathode. JF connected 0,13 mbar No root defect in the section and at RT
							42	9,5	9,3	2,1	Keyhole: 9 x 7 depth 31 mm	Trip area No root defect in the section and at RT
043 01-10-24	190	300	236	125	1,150 1,500	HCC1 SKB1 (RG)	56	8,9	8,9	1,1	Minor roughness	New Cathode. JF connected 0,13 mbar No root defect in the section and at RT
							58	8,0	8,6	1,2	Keyhole: 8,5 x 6,5 depth 41 mm	Trip area No root defect in the section and at RT
044 01-10-24	190	350	236	125	1,150 1,500	HCC1 SKB1 (RG)	70	8,8	9,0	0,8	Minor roughness	New Cathode. JF connected 0,13 mbar Root defects at RT
							69	8,8	8,8	1,0	Keyhole: 8,4 x 6,8 depth 53 mm	Trip area Root defect in the section 6 x 3,5 mm

Weld record list Testblock IV   New Q1 setting

Weld TB no Date	Acc voltage kV	Beam Current mA	Travel Speed mm/min	Work Distance mm	Focus Q1 Q2 A	Cathode	Weld Depth mm	Top Width mm	Mid Depth Width mm	Tip Radius mm	Surface condition	Comments
045 01-11-01	190	350	236	125	1,225 1,500	HCC1 SKB1(RG)	57	11,3	11,3	2,7	Minor roughness	Chamber pressure 0,20 mbar No root defect in the section and at RT
							57	10,6	11,4	2,4	Keyhole	19 x 8 mm, depth 50 mm
046 01-11-01	190	350	236	125	1,225 1,425	HCC1 SKB1(RG)	60	10,0	11	1,8	Minor roughness	Chamber pressure 0,20 mbar No root defect in the section and at RT
							62	9,2	10,6	2,2	Keyhole	16 x 7,7 mm, depth 49 mm
051 01-11-16	190	350	236	125	1,230 1,400	HCC1 SKB1(RG)	66	8,5	9,7	1,2	Minor roughness	Chamber pressure 0,15 mbar No root defect in the section and at RT
							67	8,0	10,0	1,2	Keyhole	10 x 7,4 mm, depth 57 mm
052 01-11-16	190	350	236	125	1,230 1,375	HCC1 SKB1(RG)	68	8,3	8,7	1,1	Minor roughness	Chamber pressure 0,15 mbar No root defect in the section and at RT
							68	8,7	9,1	0,8	Keyhole	9 x 7,2 mm, depth 57 mm
053 01-11-16	190	375	236	125	1,230 1,450	HCC1 SKB1(RG)	63	10,5	10,8	1,3	Minor roughness	Chamber pressure 0,15 mbar No root defect in the section and at RT
							66	9,5	11,0	1,4	Keyhole	16 x 8,1 mm, depth 57 mm
054 01-11-16	190	375	236	125	1,230 1,400	HCC1 SKB1(RG)	74	8,4	10,2	0,7	Minor roughness	Chamber pressure 0,15 mbar No root defect in the section and at RT
							73	7,8	10,4	1,2	Keyhole	10 x 7,1 mm, depth 62 mm

Appendix 3

Pressure recording in gun and chamber during welding of Lid welds no L01-021

Pressure recording in gun and chamber during lid welding

Lidweld no	**Weld date**	**Gauge G1** (AM) Gun Valve V1 mbar	**Gauge G2** (AO) Gun Upper column mbar	**Gauge G3** (AQ) Gun Inner cavity mbar	**Gauge G4** (AS) Gun Outer cavity mbar	**Gauge G5** (AU) Gun ValveV3 mbar	**Gauge G6** (AW) Chamber mbar
L001	99-02-12	3,2 x 10^{-3}	7,5 x 10^{-6}	4,8 x 10^{-5}	9,5 x 10^{-4}	2,2 x 10^{-2}	no reading
L002	99-04-23	3,2 x 10^{-3}	7,3 x 10^{-6}	4,8 x 10^{-5}	2,1 x 10^{-3}	3,4 x 10^{-2}	2,4 x 10^{-1}
L003	99-09-10	3,6 x 10^{-3}	7,2 x 10^{-6}	5,0 x 10^{-5}	1,6 x 10^{-3}	2,4 x 10^{-2}	2,4 x 10^{-1}
L004-1	99-10-06	3,5 x 10^{-3}	1,0 x 10^{-5}	5,0 x 10^{-5}	1,4 x 10^{-3}	1,9 x 10^{-2}	2,6 x 10^{-1}
L004-2	99-10-28	3,4 x 10^{-3}	8,8 x 10^{-6}	5,0 x 10^{-5}	1,3 x 10^{-3}	1,8 x 10^{-2}	2,5 x 10^{-1}
L004-3	99-11-02	3,5 x 10^{-3}	1,0 x 10^{-5}	4,9 x 10^{-5}	1,2 x 10^{-3}	1,6 x 10^{-2}	2,1 x 10^{-1}
L004-4	99-11-02	3,4 x 10^{-3}	9,1 x 10^{-6}	4,9 x 10^{-5}	1,2 x 10^{-3}	1,6 x 10^{-2}	2,1 x 10^{-1}
L004-5	99-11-02	3,4 x 10^{-3}	9,6 x 10^{-6}	4,9 x 10^{-5}	1,2 x 10^{-3}	1,6 x 10^{-2}	2,1 x 10^{-1}
L005-1	00-05-18	3,0 x 10^{-3}	7,0 x 10^{-6}	5,0 x 10^{-5}	2,0 x 10^{-3}	2,6 x 10^{-2}	2,4 x 10^{-1}
L005-2	00-06-08	4,0 x 10^{-3}	1,8 x 10^{-5}	5,1 x 10^{-5}	2,2 x 10^{-3}	2,8 x 10^{-2}	2,8 x 10^{-1}
L005-3	00-06-08	3,5 x 10^{-3}	1,1 x 10^{-5}	5,2 x 10^{-5}	2,2 x 10^{-3}	2,8 x 10^{-2}	3,2 x 10^{-1}
L006	00-08-23	3,5 x 10^{-3}	1,7 x 10^{-5}	4,3 x 10^{-5}	1,1 x 10^{-3}	1,7 x 10^{-2}	2,4 x 10^{-1}
L007-1	00-09-06	3,5 x 10^{-3}	1,6 x 10^{-5}	4,3 x 10^{-5}	1,1 x 10^{-3}	1,7 x 10^{-2}	2,3 x 10^{-1}
L007-2	00-09-15	3,5 x 10^{-3}	1,6 x 10^{-5}	4,3 x 10^{-5}	9,6 x 10^{-4}	1,4 x 10^{-2}	2,2 x 10^{-1}
L008-1	00-09-22	3,4 x 10^{-3}	1,8 x 10^{-5}	4,3 x 10^{-5}	1,0 x 10^{-3}	1,6 x 10^{-2}	2,3 x 10^{-1}
L008-2	00-09-29	3,8 x 10^{-3}	2,0 x 10^{-5}	4,3 x 10^{-5}	1,1 x 10^{-3}	1,5 x 10^{-2}	2,4 x 10^{-1}
L009	00-10-06	3,4 x 10^{-3}	1,8 x 10^{-5}	4,3 x 10^{-5}	9,8 x 10^{-4}	1,6 x 10^{-2}	2,3 x 10^{-1}
L010	00-10-16	3,4 x 10^{-3}	1,8 x 10^{-5}	4,3 x 10^{-5}	9,8 x 10^{-4}	1,6 x 10^{-2}	2,3 x 10^{-1}
L011	00-10-27	3,3 x 10^{-3}	1,5 x 10^{-5}	4,3 x 10^{-5}	8,9 x 10^{-4}	1,4 x 10^{-2}	2,3 x 10^{-1}
L012	00-11-13	3,4 x 10^{-3}	1,7 x 10^{-5}	4,3 x 10^{-5}	8,8 x 10^{-4}	1,5 x 10^{-2}	2,2 x 10^{-1}
L013	00-11-29	3,3 x 10^{-3}	1,7 x 10^{-5}	4,3 x 10^{-5}	1,3 x 10^{-3}	1,9 x 10^{-2}	2,4 x 10^{-1}
L014	00-12-18	5,7 x 10^{-3}	1,5 x 10^{-5}	4,3 x 10^{-5}	1,0 x 10^{-3}	1,7 x 10^{-2}	2,3 x 10^{-1}
L015	01-01-26	6,5 x 10^{-3}	1,5 x 10^{-5}	4,4 x 10^{-5}	1,0 x 10^{-3}	1,7 x 10^{-2}	2,3 x 10^{-1}
L016	01-02-02	6,0 x 10^{-3}	1,5 x 10^{-5}	4,3 x 10^{-5}	1,0 x 10^{-3}	1,8 x 10^{-2}	2,3 x 10^{-1}
L017	01-02-09	6,0 x 10^{-3}	1,7 x 10^{-5}	4,4 x 10^{-5}	1,0 x 10^{-3}	1,6 x 10^{-2}	2,2 x 10^{-1}
L018	01-03-13	6,0 x 10^{-3}	1,5 x 10^{-5}	4,3 x 10^{-5}	9,6 x 10^{-4}	1,5 x 10^{-2}	2,2 x 10^{-1}
L019	01-05-18	5,5 x 10^{-3}	1,4 x 10^{-5}	4,3 x 10^{-5}	5,9 x 10^{-4}	1,2 x 10^{-2}	1,7 x 10^{-1}
L020	01-06-19	5,0 x 10^{-3}	1,1 x 10^{-5}	4,3 x 10^{-5}	5,4 x 10^{-4}	1,1 x 10^{-2}	1,8 x 10^{-1}
L021	01-08-22	4,5 x 10^{-3}	1,2 x 10^{-5}	4,4 x 10^{-5}	1,0 x 10^{-4}	1,0 x 10^{-2}	1,5 x 10^{-1}

Notes:
1) Gauge G6 before welding (no He) is ≈ 0,2 - 0,3 mbar less
2) Siemens Computer reading is ≈ 0,4 - 0,6 mbar less than G6
3) Central Computer reading correspond well to G6

Appendix 4

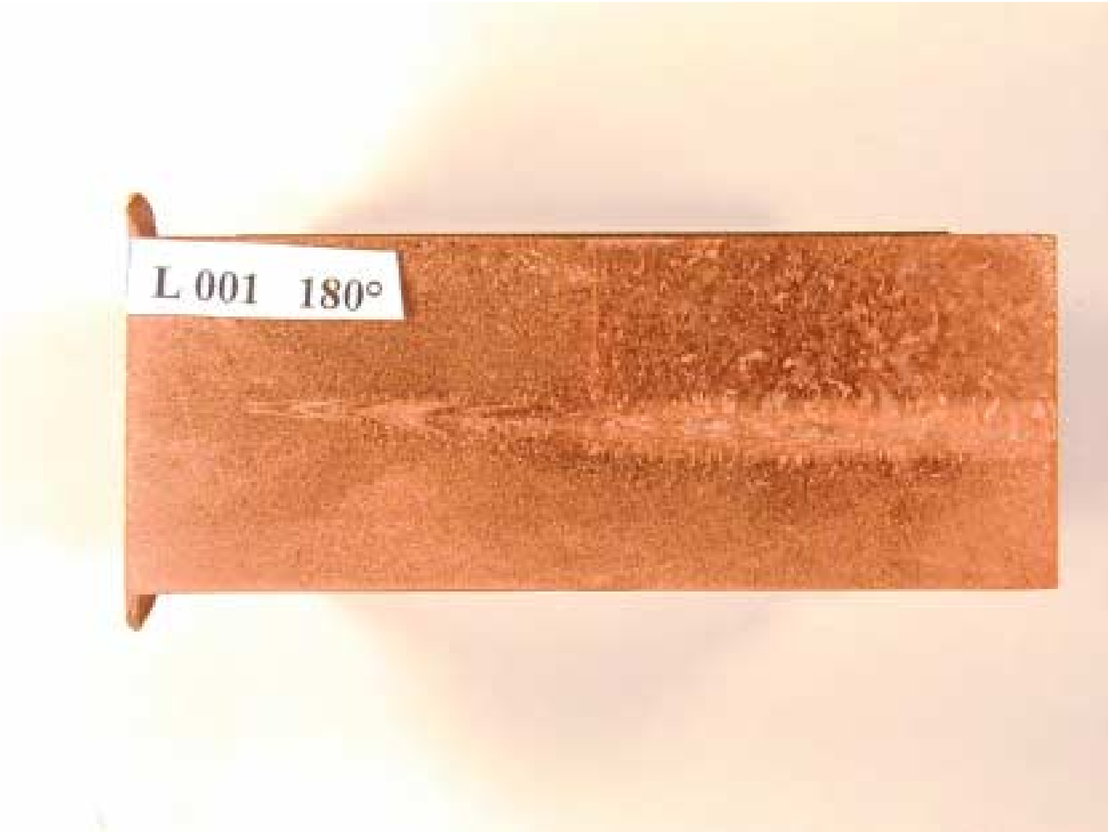
Beam slope in and out parameters during welding of Lid welds no L01-021

Beam slope in and out parameters during lid welding

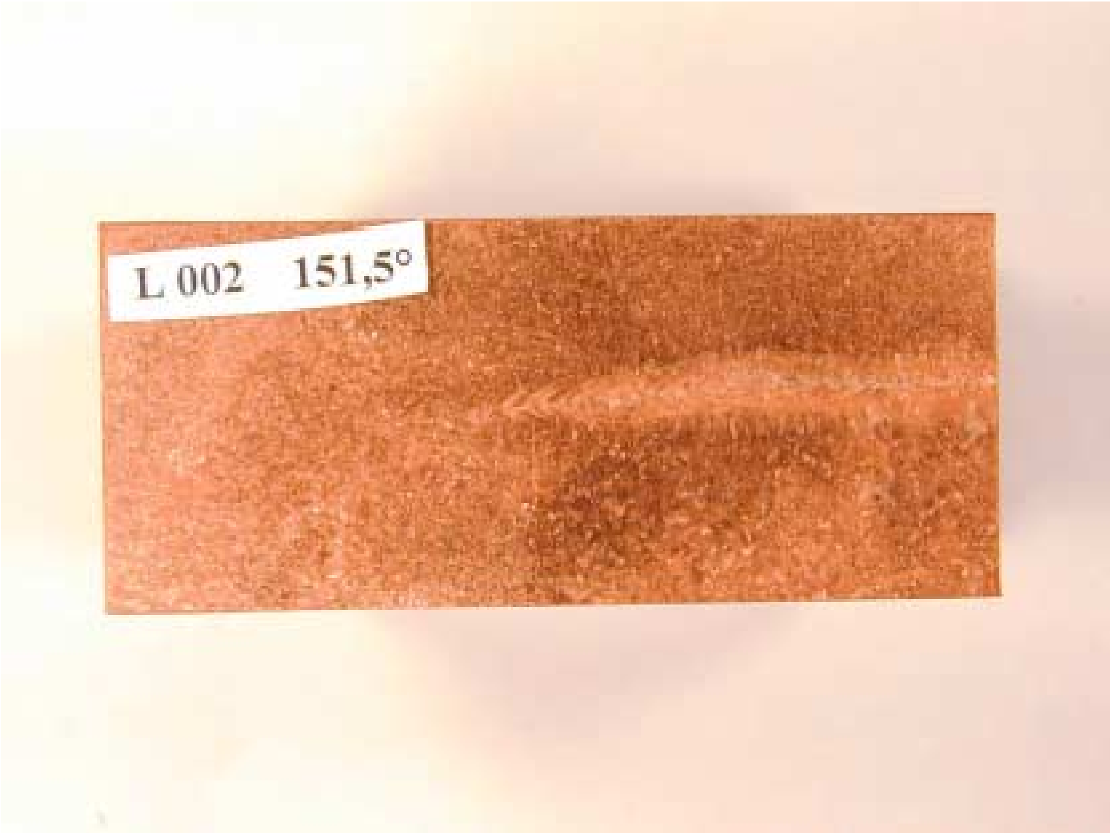
Object	Slope in Distance	Q2 A	Slope out Distance	Q2 A	Comments
Lid 001 99-02-12	24,6° (5→420 mA)	1,375	16,5 → 33,1° (420→5 mA)	1,375→1,503 1,503→1,523	Internal defects at slope in area
Lid 002 99-04-23	24,6° (5→350 mA)	1,375	50° (350→5 mA)	1,500	Surface and internal defects at slope in area
Lid 003 99-09-10	12° (5→380 mA)	1,475	35 → 15° (100→5 mA)	1,500	Surface and internal defects at slope in area
Lid 004 99-10-28	12° (5→380 mA)	1,475	30° (250→5 mA)	1,500	Surface and internal defects at slope in area
Lid 005 00-05-18	30° (5→350 mA)	1,40	50° (350→5 mA)	1,400→1,500	
Lid 006 00-08-23	30° (5→280 mA)	1,40	50° (320→5 mA)	1,500	Surface and internal defects at slope in area
Lid 007 00-09-06	30° (5→420 mA)	1,50	45° (440→5 mA)	1,550	Internal defects at slope out area
Lid 008 00-09-22	30° (5→370 mA)	1,50	50° (370→5 mA)	1,500	*(Incorrect joint gap)*
Lid 009 00-10-06	50° (5→350 mA)	1,50	50° (350→5 mA)	1,450→1,500	Surface defects at slope out area
Lid 010 00-10-16	50° (5→350 mA)	1,50	50° (300→5 mA)	1,450→1,500	Surface and internal defects at slope in area
Lid 011 00-10-27	50° (5→350 mA)	1,50→1,45	50° (275→5 mA)	1,450→1,500	
Lid 012 00-11-13	50° (5→350 mA)	1,50→1,425	50° (275→5 mA)	1,425→1,500	Surface defects at slope out area
Lid 013 00-11-29	2° (5→350 mA)	1,415	130° (275→5 mA)	1,415	Surface defects at slope out area
Lid 014 00-12-18	2° (5→340 mA)	1,410	130° (275→5 mA)	1,410→1,200	1 internal cavity and linear root defects at slope out
Lid 015 01-01-26	2° (5→340 mA)	1,410	15° (160→5 mA)	1,380	*(Linear root defects in the weld run before slope out)*
Lid 016 01-02-02	2° (5→340 mA)	1,410	15° (160→5 mA)	1,400	*(Linear root defects in the weld run before slope out)*
Lid 017 01-02-09	2° (5→340 mA)	1,410	15° (160→5 mA)	1,500	*(Surface defects in the weld run before slope out)*
Lid 018 01-03-13	2° (5→340 mA)	1,410	15° (160→5 mA)	1,460	
Lid 019 01-05-18	2,3° (5→340 mA)	1,460	15° (160→5 mA)	1,490	
Lid 020 01-06-19	2,3° (5→345 mA)	1,470	10° (125→5 mA)	1,490	
Lid 021 01-08-22	2,3° (5→345 mA)	1,470	15° (150→5 mA)	1,490	

Appendix 5

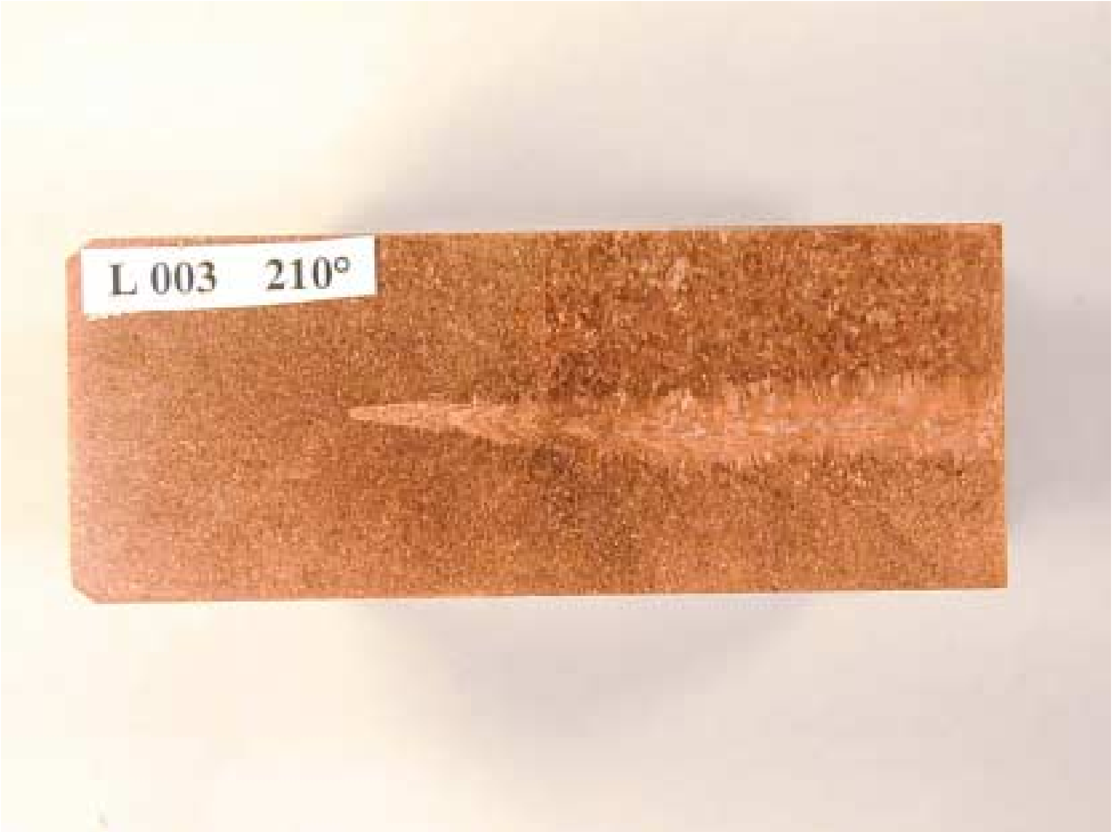
Photographs of macro sections of weld profile from Lid welds L01-021



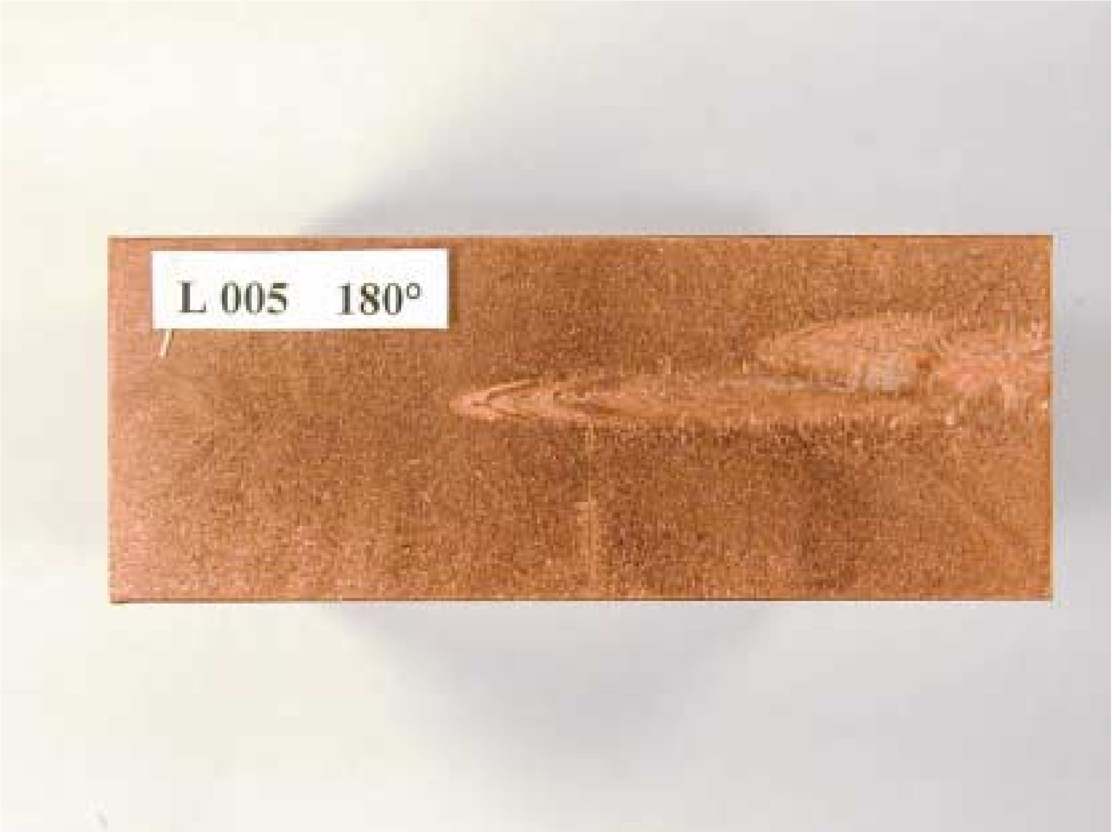
Lid weld no 1: Tip radius 0,25 mm
Cathode: Standard Q1=1,240A/ Q2=1,375A



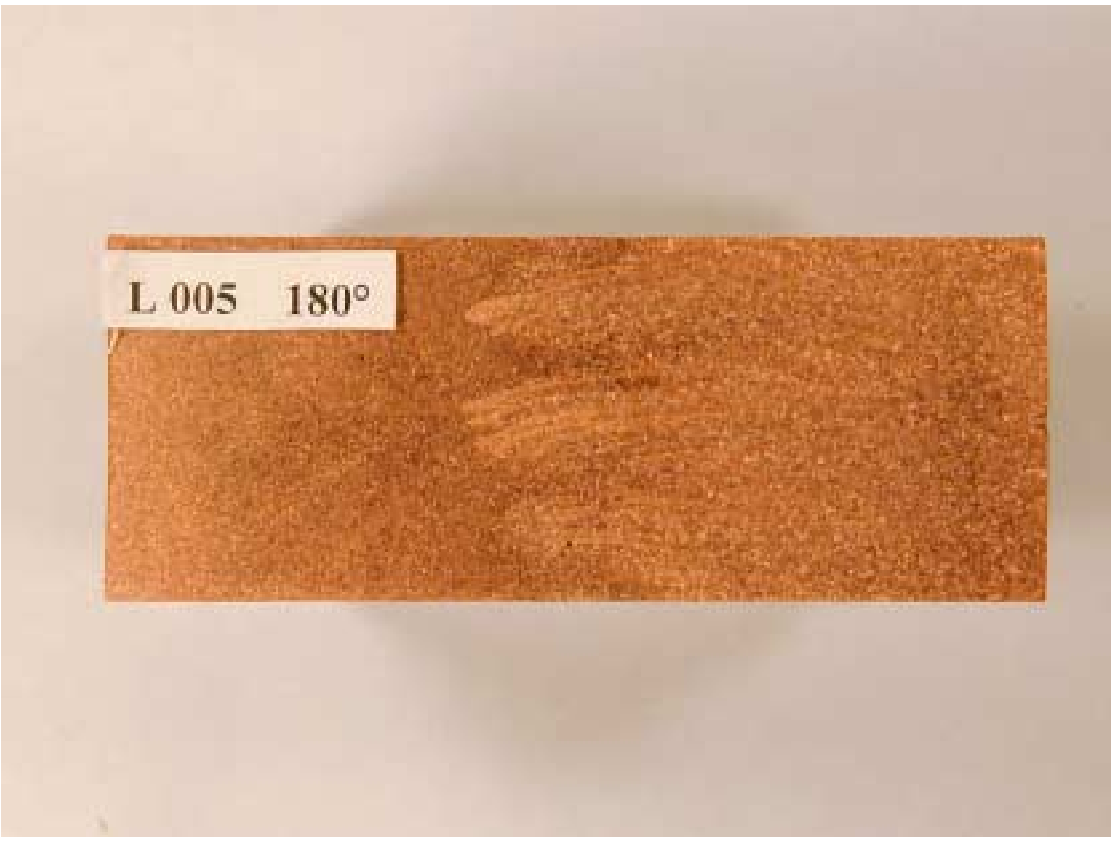
Lid weld no 2: Tip radius 0,6 mm
Cathode: Standard Q1=1,250A/ Q2=1,475A



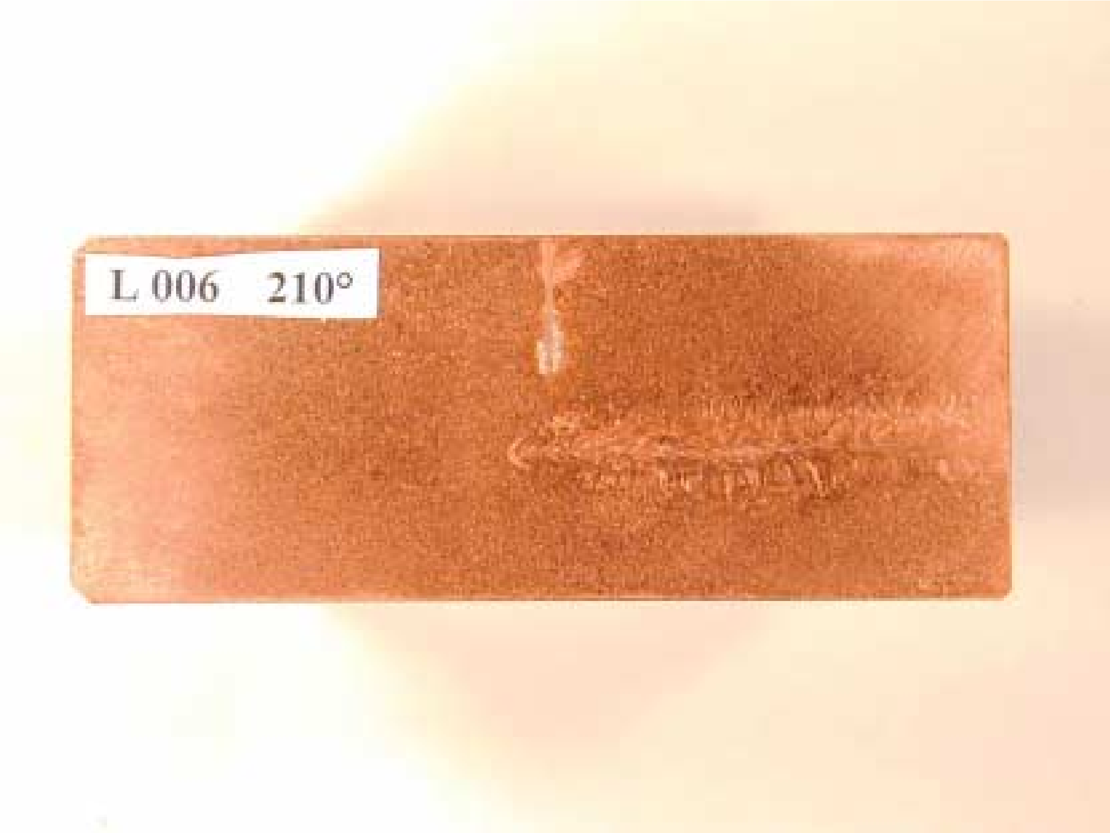
Lid weld no 3: Tip radius 0,6 mm
Cathode: Standard Q1=1,260A/ Q2=1,475A



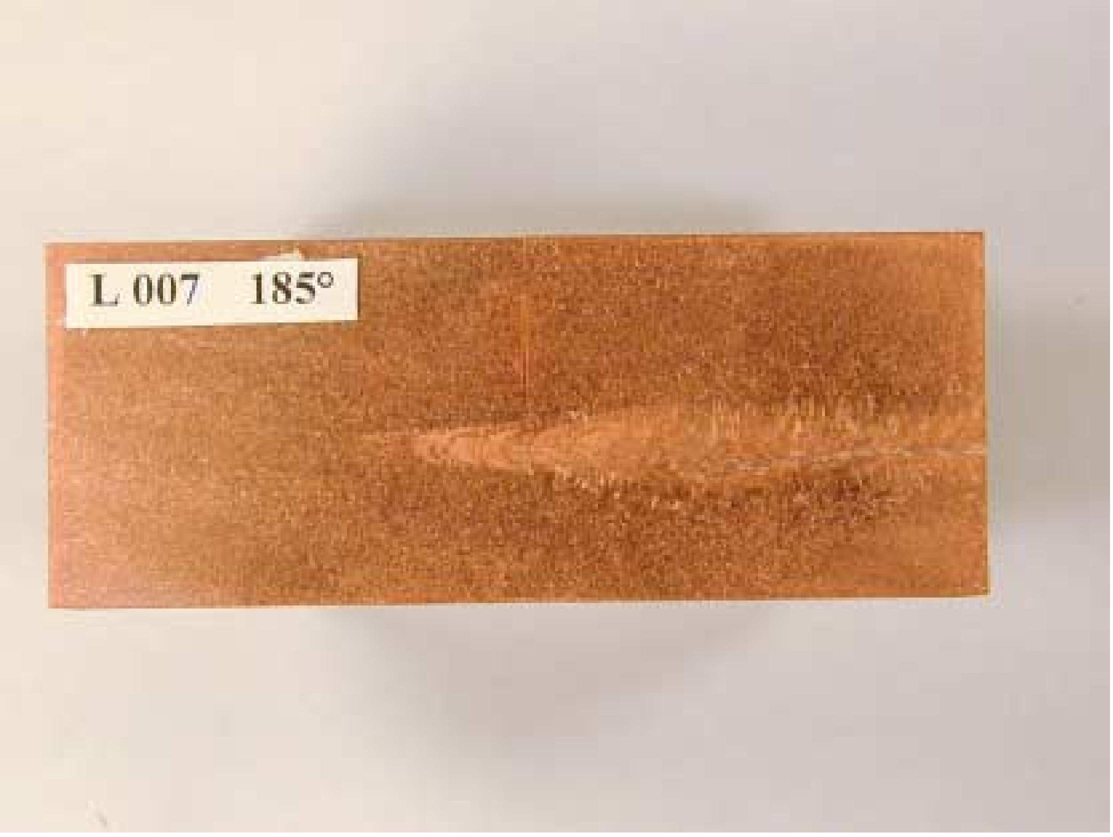
Lid weld no 5: Tip radius 1 mm
Cathode: HCC1 Q1=1,200A/ Q2=1,400A



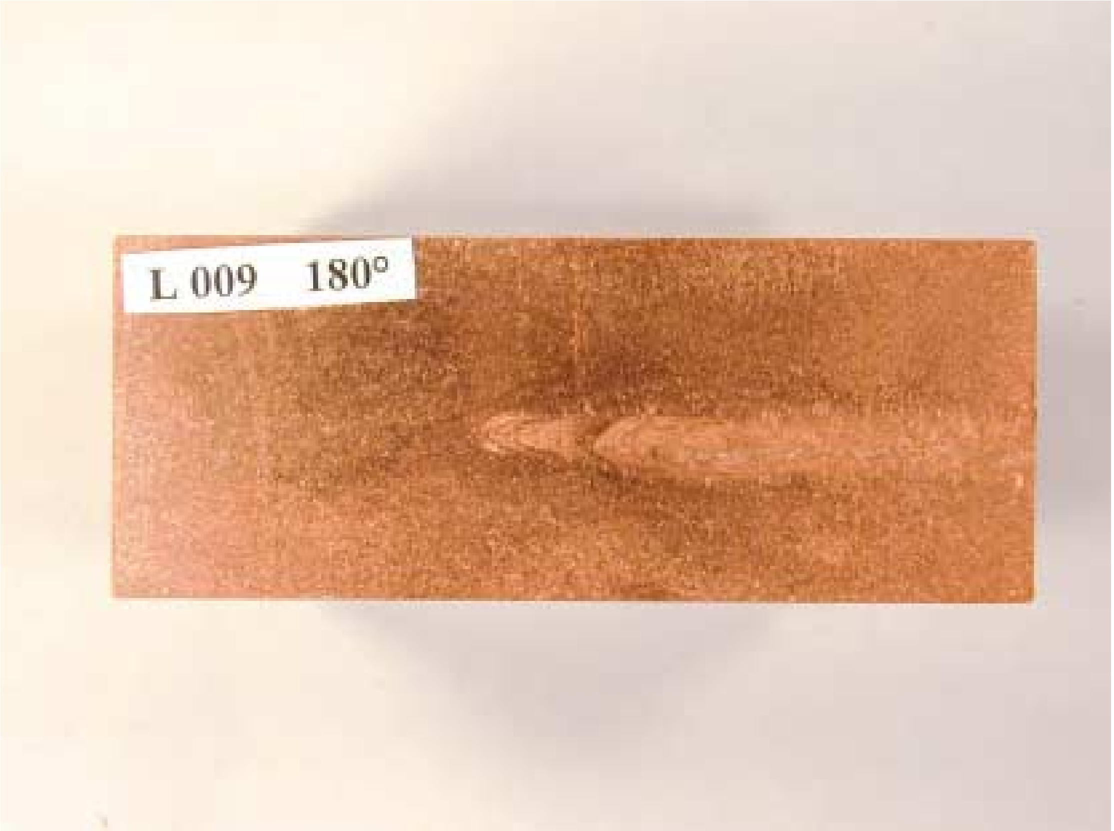
Lid weld no 5: longitudinal section



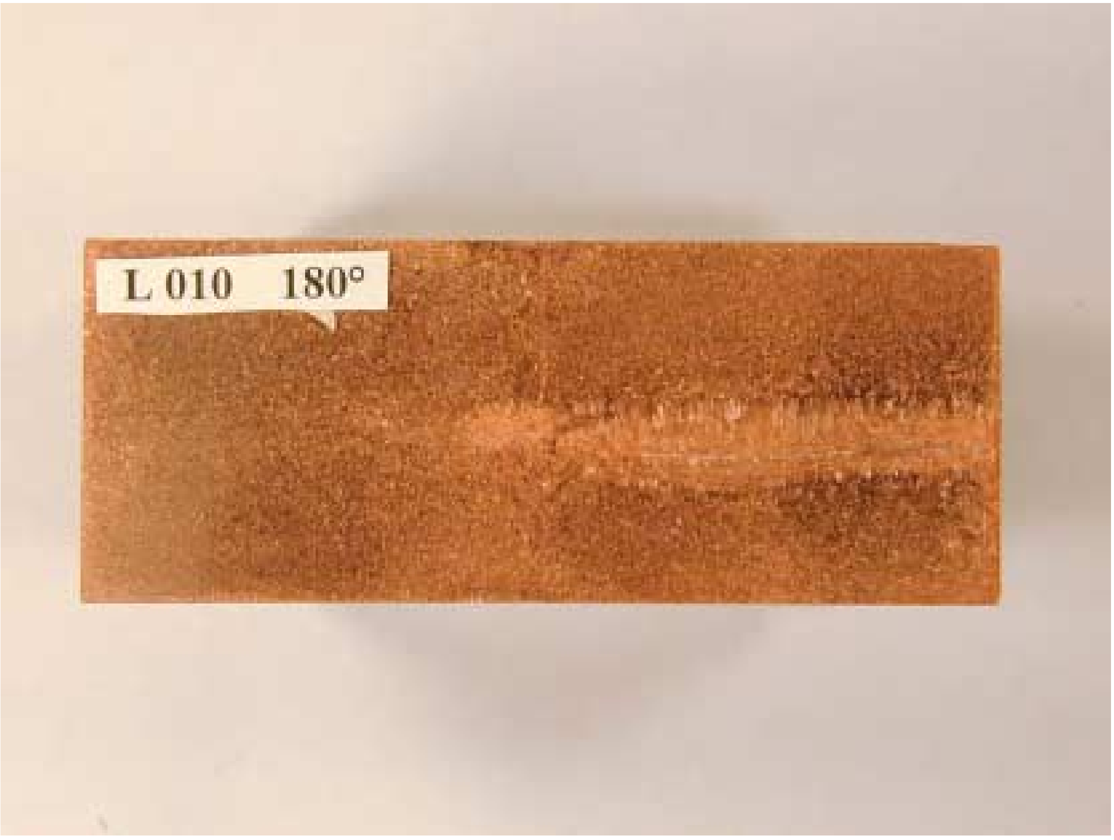
Lid weld no 6: Tip radius 1,5 mm
Cathode: HCC1 Q1=1,200A/ Q2=1,450A



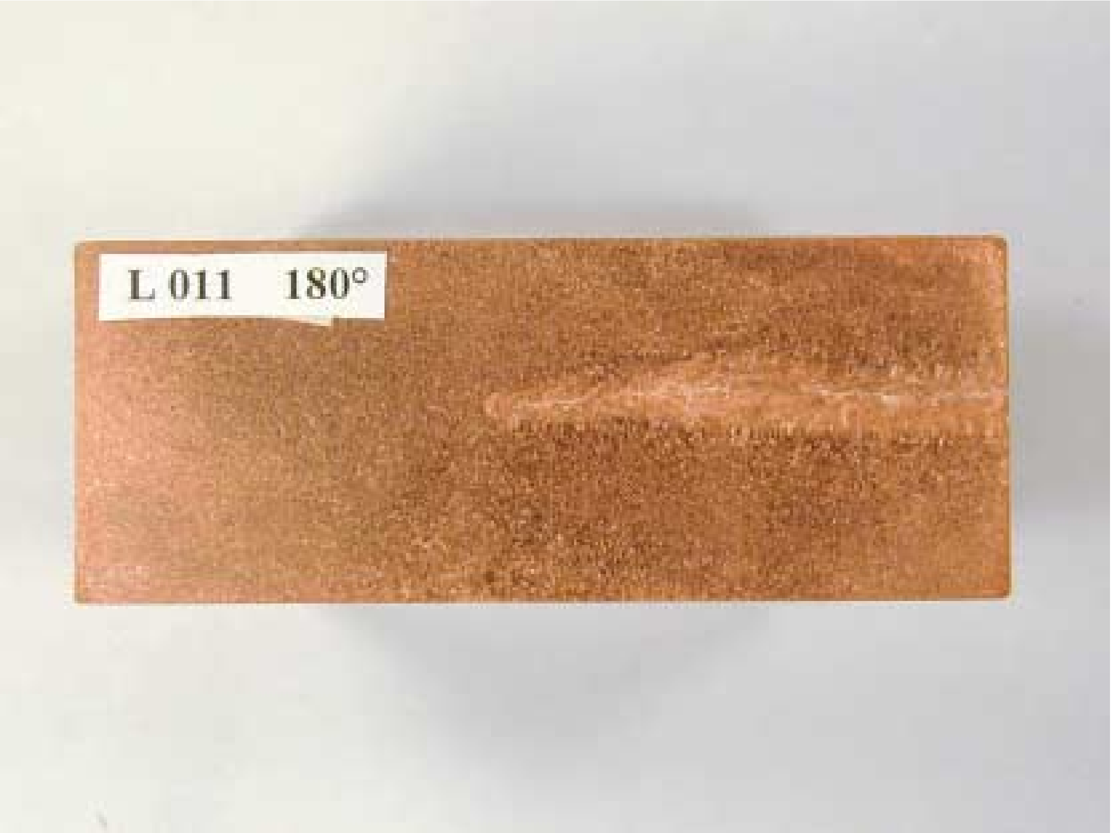
Lid weld no 7: Tip radius 1,6 mm
Cathode: HCC1 Q1=1,200A/ Q2=1,500A



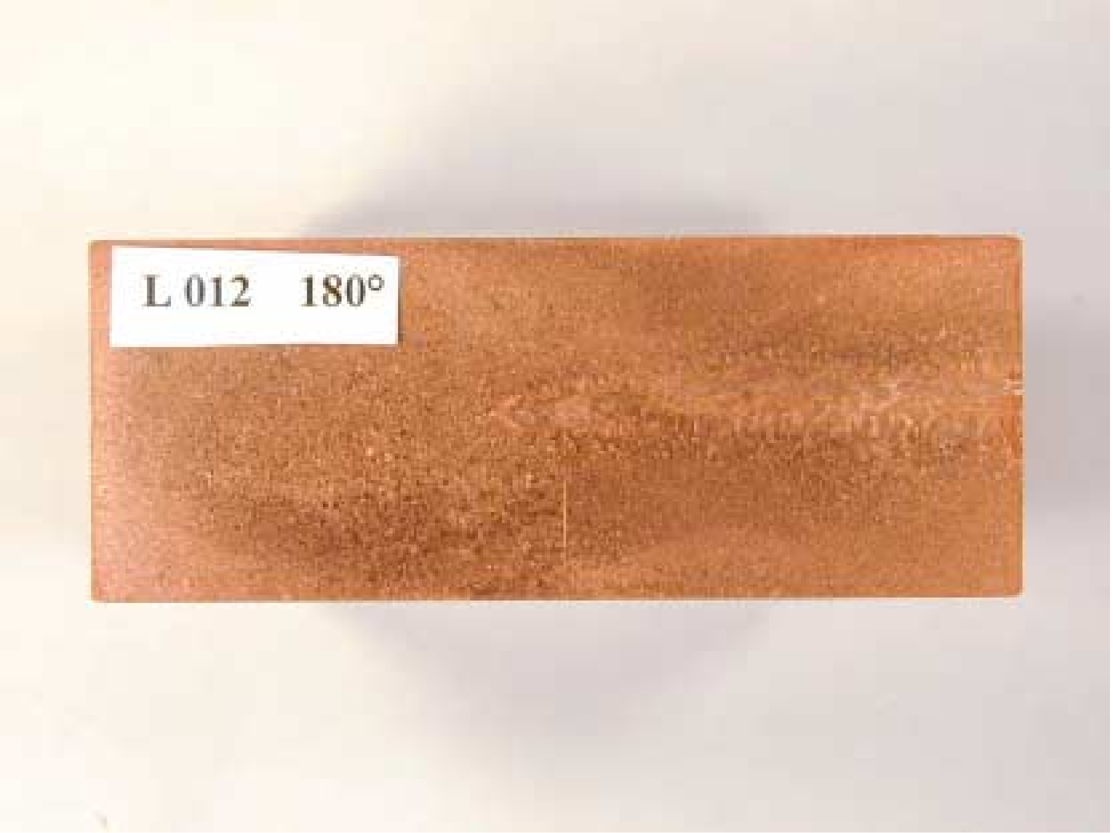
Lid weld no 9: Tip radius 1,8 mm
Cathode: HCC1 Q1=1,200A/ Q2=1,450A



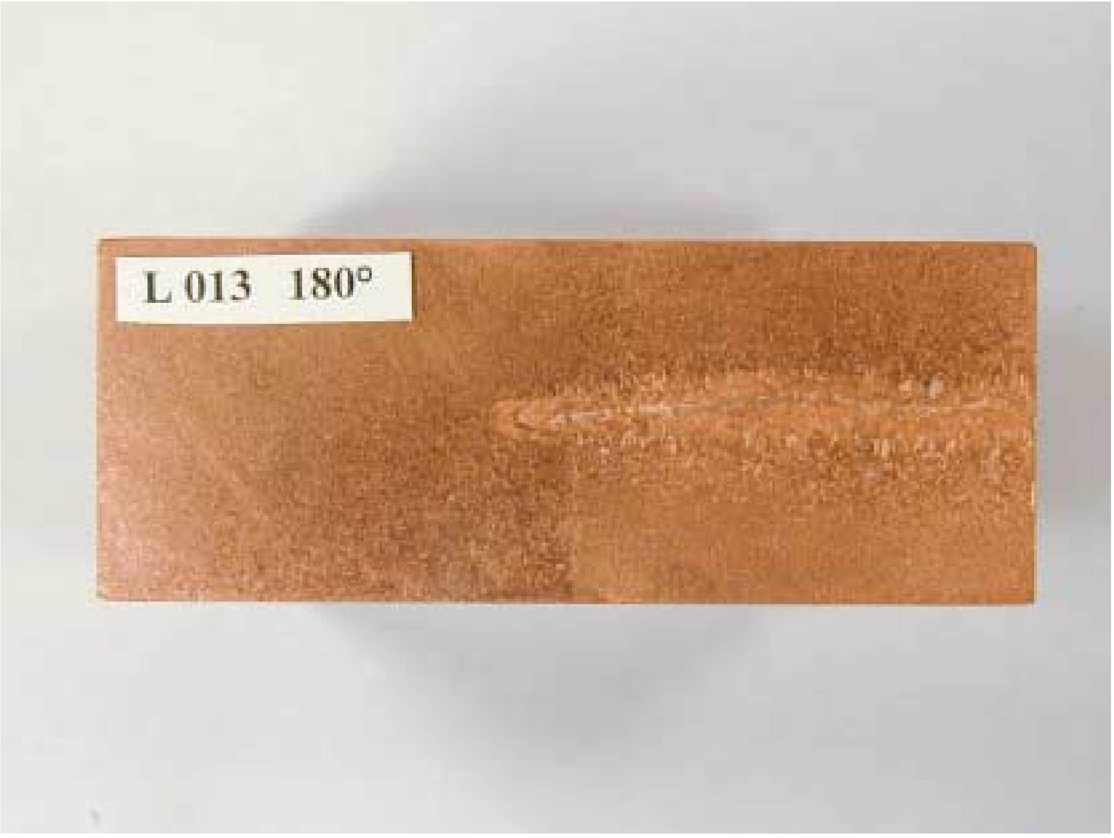
Lid weld no 10: Tip radius 1,8 mm
Cathode: HCC1 Q1=1,200A/ Q2=1,450A



Lid weld no 11: Tip radius 1,8 mm
Cathode: HCC1 Q1=1,200A/ Q2=1,450A

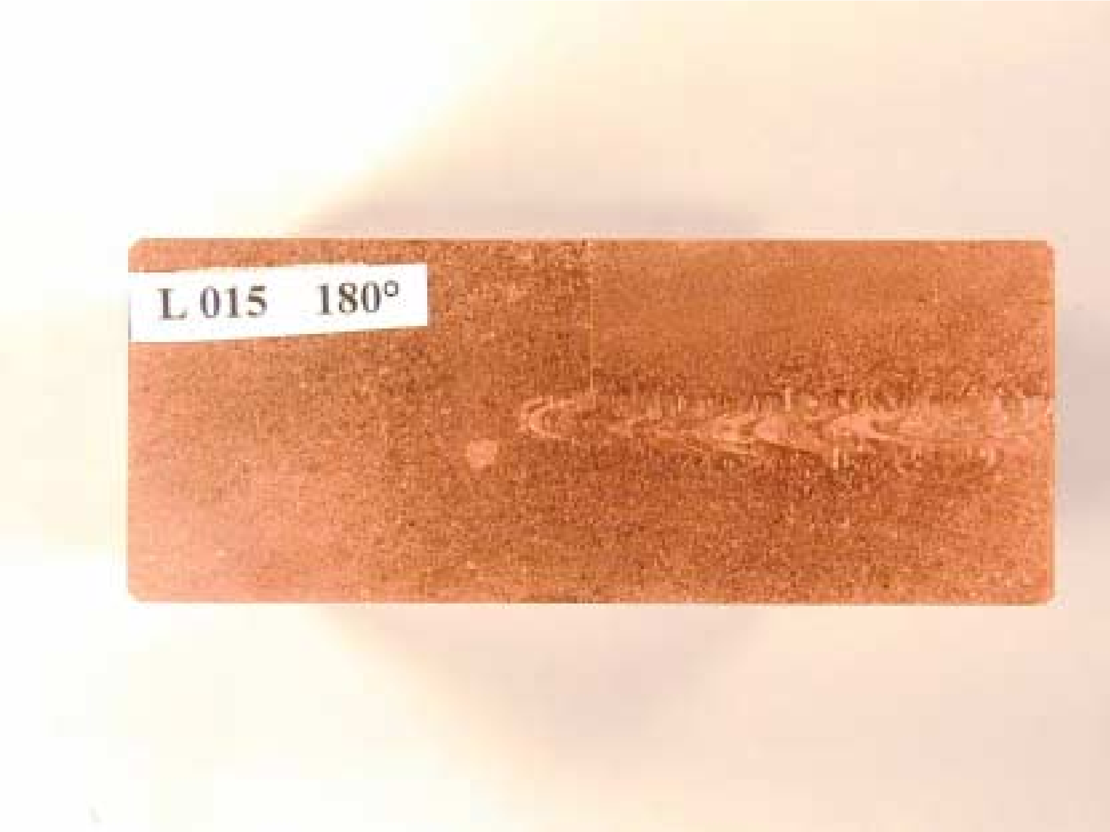


Lid weld no 12: Tip radius 1,8 mm
Cathode: HCC1 Q1=1, 200A/ Q2=1,425A

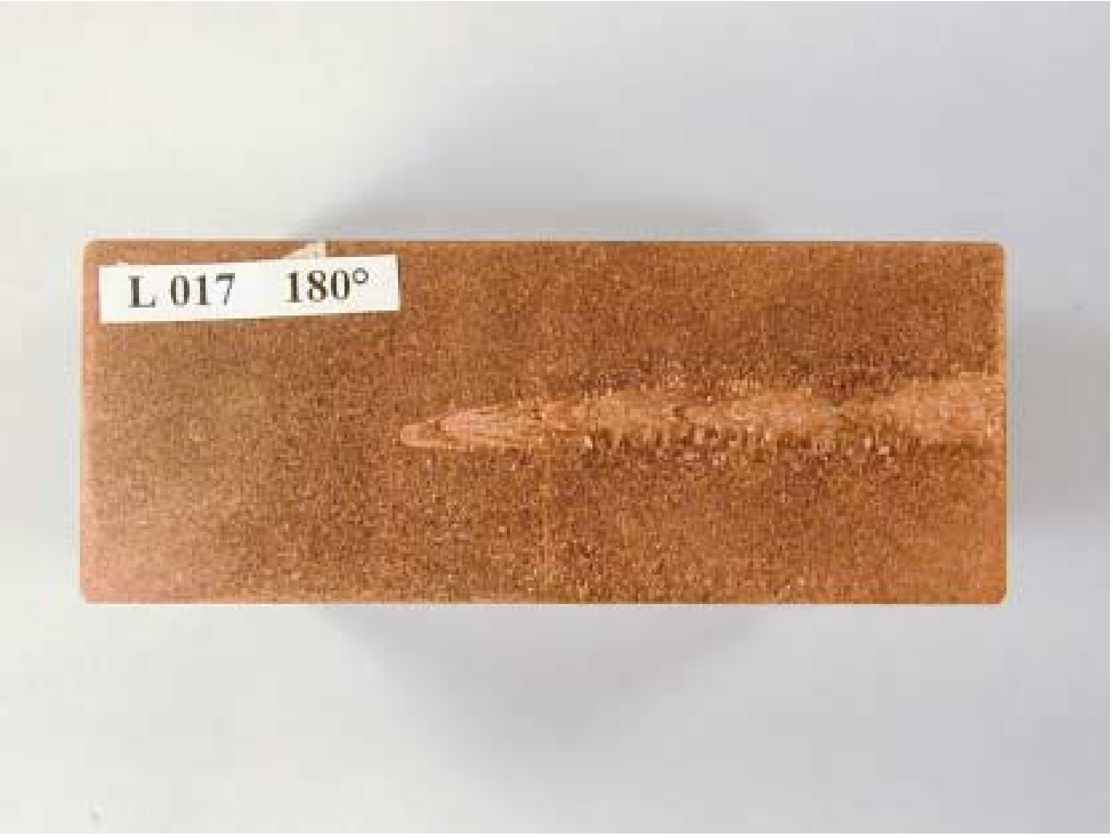


Lid weld no 13: Tip radius 1,8 mm
Cathode: HCC1 Q1=1,195A/ Q2=1,415A

Lid weld no 14: Tip radius 2,0 mm
Cathode: HCC1 Q1=1,195A/ Q2=1,410A

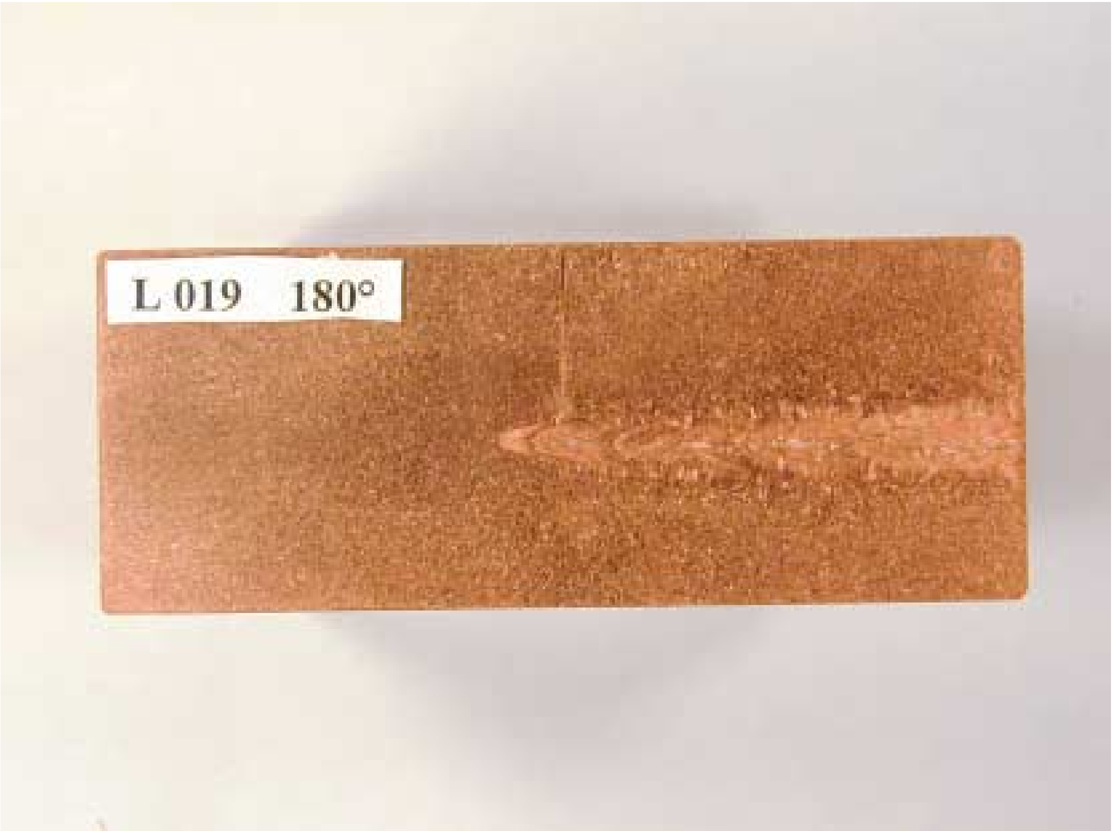


Lid weld no 15: Tip radius 1,8 mm
Cathode: HCC1 Q1=1,195A/ Q2=1,410A



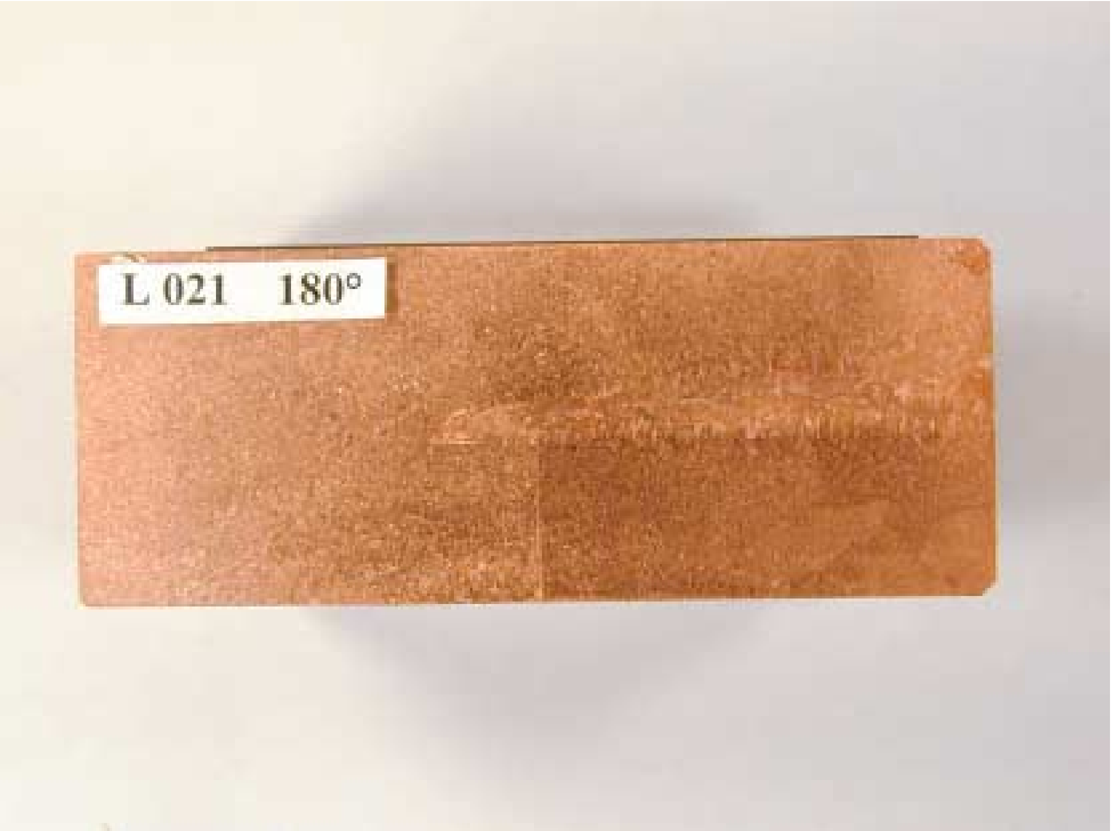
Lid weld no 17: Tip radius 1,2 mm
Cathode: HCC1 Q1=1,195A/ Q2=1,410A

Lid weld no 18: Tip radius 1,4 mm
Cathode: HCC1 Q1=1,195A/ Q2=1,410A



Lid weld no 19: Tip radius 1,2 mm
Cathode: HCC1 Q1=1,195A/ Q2=1,460A

Lid weld no 20: Tip radius 1,0 mm
Cathode: HCC1 Q1=1,195A/ Q2=1,470A



Lid weld no 21: Tip radius 1,2 mm
Cathode: HCC1 Q1=1,165A/ Q2=1,470A