

Investigation of defects in manufacturing of copper tubes

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Abstract

This investigation was originated by SKB (Swedish Nuclear Fuel and Waste Management Co) in the context of clarifying the background of certain defects that can be found in cast copper ingots and in extruded pipes for nuclear waste disposal. It is the purpose of this investigation to bring forward more facts about the actual defects. Studies of literature from open sources and of SKB reports have been performed. A visit has been carried out to the production unit for copper ingots at Luvata Pori Oy in Pori.

According to the most common definition in the literature Hot Tearing is a separation either internally or externally in a casting due to loadings or internal stresses or both; it results from improper solidification, and shrinkage near the temperature at which the casting is completely solid". Within the literature a number of types of discontinuities are defined for different alloys but these may not be relevant for casting and extrusion of almost pure copper ingots. The term Hot Tearing is not unambiguous as it is found mainly in connection with casting and solidification of metals but was also used by Bowyer (1999) for extrusion defects in this case with a different definition.

The term "Speed cracking" which was used by Bowyer (1999) refers to a defect which is formed during extrusion due to local melting. No relevant information about Speed Cracking during extrusion of copper pipes was found in the literature in this investigation. FE simulations by Swerea MEFOS indicate that the relatively low extrusion temperature combined with the limited friction and the high conduction of heat in copper will not result in sufficient temperature increase to provide local melting.

Discontinuities which normally can be found on the periphery of ingots produced by Luvata are longitudinal cracks, cold laps, oscillation marks and uneven colour on the surfaces.

Referring to Luvata the ingots also may contain discontinuities in the centre, located in the starting end and in the top end of the cast ingot. These discontinuities are referred to as Spider Cracks.

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1 Introduction

This investigation was originated by SKB (Swedish Nuclear Fuel and Waste Management Co) in the context of clarifying the background of certain defects that can be found in cast copper ingots and in extruded pipes for nuclear waste disposal. The existence of these defects, Hot Tearing and Speed Cracking were mentioned in a previous revision of a document from SKB "Tillverkning av kapselkomponenter" (SKBdoc 1175208) and then later removed without full explanation which prompted SSM (Swedish Radiation Safety Authority) to ask for additional information. It is the purpose of this investigation to bring forward more facts about the actual defects. This investigation contains a summary of the process for copper ingot casting and the major steps of development that has influenced the improvement on the quality of the ingots. The acceptance levels for surface defects are discussed and also how the requirements are handled by the quality management system.

1.1 The order

SSM has asked SKB for technical motivation that surface breaking cracks cannot appear on the inner and outer surfaces of the copper tube. Swerea MEFOS has received an order from SKB to investigate and document the definition, physical background and other important information regarding discontinuities designated as "Hot Tearing" and "Speed Cracking".

1.2 Aim

The aim of this investigation is to find as much information as possible regarding the discontinuities designated as Hot Tearing and Speed Cracking. The task is to determine whether or not these defects are a potential risk for the quality of the final extruded copper pipe.

1.3 Limitations

This investigation is limited to information from SKB reports and information from Luvata engineers on a visit at the production unit at Luvata Pori Oy in Pori. Information is also collected from a literature survey in open sources like Scopus, Science direct and ASM handbook. No experimental or laboratory work has been performed within this investigation but information is compiled from previous work by Luvata, SKB and Posiva.

1.4 Methodology

Studies of literature from open sources and of SKB reports have been performed. A visit has been carried out to the production unit for copper ingots at Luvata Pori Oy in Pori. A list of questions has been prepared and sent in advance to Luvata.

2 Development work with copper ingot casting

2.1 General

The casting process for copper billets with a diameter of 850 mm is carried out on a semi-continuous casting line and the process was introduced in the early 1990s as reported by Nolvi (2009). The first casts for the diameter 850 mm billets were produced in 1995 and after preliminary trials some modifications were made. Results from several campaigns are reported in "Tillverkning av kapselkomponenter" (SKBdoc 1175208) and Nolvi (2009). At the early stages of the development there was probably limited experience regarding casting of large ingots of almost pure copper. During the period to date- both the casting technique and the quality control system have been developed. During the last 10 years about 40 copper ingots have been cast and from these cast ingots 27 tubes have been extruded. The development has later been focused of improvement of phosphorous control, lowering of the oxygen content, improved cooling control, surface quality improvements and reduction of centre discontinuities. Methods for non-destructive testing like dye penetrant testing and eddy current testing has been introduced. As a result of the development, during 2004 the capacity for each cast was increased to 16 tonnes. One consequence of this is that the start (bottom) and top part of the ingot which is expected to have discontinuities can be removed, keeping the necessary weight for extrusion. By turning the periphery and cutting the end surfaces before using penetrant testing the possibility to find and delete surface defects has been improved.

2.2 Casting of large copper ingots, description of the production process at Luvata works

This part of the report describes the manufacture of copper ingots which will be used for the next step in the production chain for production of tubes used for the disposal canisters. This chapter is mainly based on the report by Nolvi (2009), and information from Luvata engineers during a visit at production site in Pori, 2013-05-20. This description is relevant for production at Luvata Pori OY.

The starting material for the manufacture of extruded copper tubes is a semi continuously cast ingot. The ingot, 850 mm in diameter is manufactured by a semi continuous casting process which has been developed for casting large round ingots. The process has been continuously developed from 1995 when the first reported casting was performed. The development is a joint effort of SKB and Posiva.

The process starts with melting of oxygen free copper cathodes which are preheated before being melted in a melting furnace. When the target temperature is reached the melt is poured via a channel to a holding furnace. The melt is kept in a reducing atmosphere and poured via a casting tube in to the mould. During the casting operation the melt temperature is controlled in a specified range. When alloying phosphorus it is feed into the melt in the launder. The casting speed is 4-5 cm/min according to Bowyer (1999) and the crater end of the melt is kept at typical 0.5 m from the bath level. The mould length is typical 1 m and after leaving the mould the ingot is cooled in a water bath. The mould which is a water cooled copper tube with a diameter of about 850 mm is used to transfer the extracted heat from the solidifying shell of the copper ingot.

Normally during continuous casting, at the start of casting the bottom of the mould is sealed with a starting bar. Casting begins when the mould is filled and when the level of liquid copper reaches the target level, typical 0.1 m from the top, the ingot starts to move slowly with a pre-set casting speed controlling the pre-set bath level in the mould and the mass flow of liquid copper. The filling part of the mould is static with enhanced cooling which is critical with regard to centre cracks (spider cracks) before reaching steady state conditions during the casting. In order to produce copper ingots with a minimum of inhomogeneity and discontinuities it is essential that

the relevant process parameters are accurately controlled according to pre-set values. The chill-mould oscillates affecting the heat transfer and the friction properties. Further, a casting flux is added to protect the top surface. The flux affects the heat transfer and the friction properties between the cast shell and the mould. Figure 2-1 shows a principle sketch of the casting machine with the different cooling zones according to Fredriksson and Åkerlind (2006).

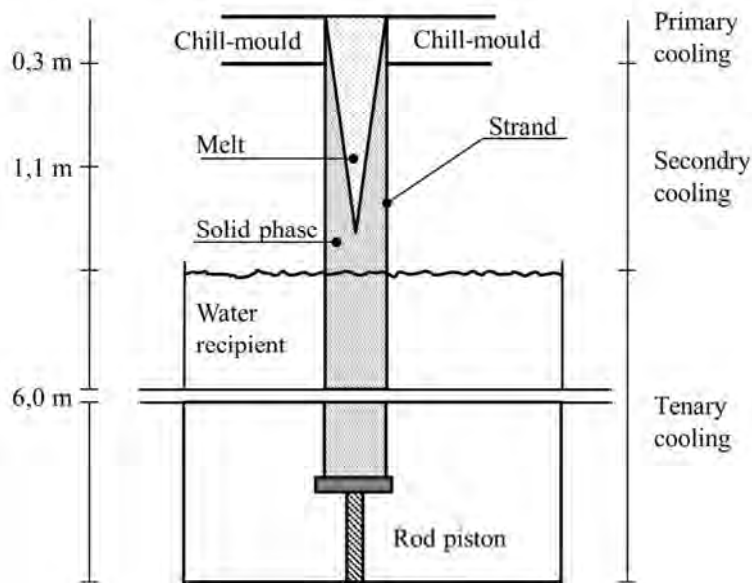


Figure 2-1. Materials processing during casting. Fredriksson and Åkerlind (2006).

2.3 Visit to the Luvata works

During a visit to Luvata it was possible to go through all of the production steps in a general way and discuss how the critical parameters were controlled by the operators during casting. It was explained by the Luvata engineers that all critical production steps as well as quality control and documentation was performed according to approved procedures and internal standards. Quality control such as visual inspection and penetrant testing is performed by a third party independent body, Inspecta. Luvata has a quality management system according to ISO 9001 and the system is certified and assured by Det Norske Veritas.

3 Nomenclature and definition of defects

3.1 Different definitions for Hot Tearing

The term Hot Tearing was used in the investigation by Bowyer (1999). The purpose of that study was to identify material and manufacturing defects which could occur in serially produced canisters. The casting and extrusion process for large copper ingots was at that time not fully developed. The continuous casting and extrusion processes were not applied to large copper products prior to the canister development programme. Therefore no relevant information regarding possible defects in copper was found in the literature. The description and classification of defects by Bowyer (1999) such as Hot Tearing was based on information from investigations on other metals than copper. The term Hot Tearing is not unambiguous as it is found mainly in connection with casting and solidification of metals. Hot Tearing is not used by Luvata and the surface cracks that can be detected during the production of the ingots are referred to by Luvata Thermally Induced Cracks. The centre defect that is formed in both ends of the ingots is referred to by Luvata as Spider Cracks. The actual defects that are observed during casting at the Luvata works will be described in chapter 4.

3.2 Hot Tearing in extrusion as defined by Bowyer

The term “Hot Tearing” which was used by Bowyer (1999) refers to a defect which is formed during extrusion. It was defined by Bowyer as:

“Hot tearing arises from as a result of friction between the die and the workpiece and is manifest as jagged circumferential surface cracks. They would normally be visible to the unaided eye. If they escape visual detection there may be residual surface breaking cracks after machining. These cracks would be detectable by die penetrant testing. They would provide sites for crevice corrosion and would be reason for rejection”.

A similar description of defects in extrusion is described by Udomphol (2007) in connection with extrusion but this is referred to as Surface Cracking. Surface cracking is described in chapter 3.3.

No relevant information about Hot Tearing during extrusion of large copper pipes was found elsewhere in the literature.

3.3 Hot Tearing type defects under the name of Surface Cracking

Cracks in the surface can arise from roughened surface to repetitive transverse cracking called - Fir-Tree Cracking, see Figure 3-1. This type of cracking is proposed to be generated due to longitudinal tensile stresses generated as the extrusion passes through the die.

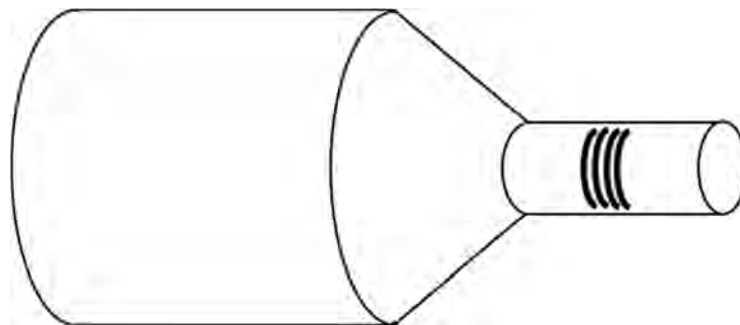


Figure 3-1. Surface cracks from heavy die friction and high temperature in extrusion.

In hot extrusion, this form of cracking is often inter granular and is associated with Hot Shortness. The discontinuities are formed as Circumferential Surface Cracks. The most common reason in this case is too high ram speed for the extrusion temperature. At lower temperature, sticking in the die land and the sudden building up of pressure and then brake away will cause transverse cracking.

3.4 Hot tearing in casting

According to McGraw Hill (2003), hot tearing is “a separation either internally or externally in a casting due to loadings or internal stresses or both; it results from improper solidification, and shrinkage near the temperature at which the casting is completely solid”.

Hot tearing occurs in some alloys during the final stages of solidification. It is a serious defect and occurs in castings that are restrained from shrinking in the mold. The characteristics of a hot tear are summarized by Campbell (1991, pp 17–31, 2004, pp 41–59).

- Ragged branching crack
- Main tear with offshoots along intergranular paths
- Oxidized fracture surface with dendritic morphology
- Location at a hot spot
- Apparent randomness in appearance
- Highly alloy-specific

The mechanism of hot tearing has been extensively investigated by Sigworth (1999) and Arnberg and Mo (2008). It is commonly believed that hot tears start to develop in the mushy zone at solid fractions close to 1, and the phenomenon is associated with excessive thermally induced deformations caused by the non-uniform cooling contraction of the casting and inadequate interdendritic melt feeding of the solidification shrinkage. More specifically, at the later stages of solidification, the dendritic network grows to an extent whereby it has sufficient strength to transmit thermal contractions, and tensile stresses will build up in a restrained casting that is not free to contract. Because the grain boundaries are still covered by a thin liquid layer, the material is still weak, and melt feeding to compensate for the solidification shrinkage is simultaneously taking place. Various investigators have explained hot tearing as a too-severe thermally induced deformation and/or an inadequate melt feeding of the solidification shrinkage. In addition to being controlled by these two macro mechanisms, a series of microscopic effects and phenomena play a significant role in hot tearing susceptibility, such as grain morphology, dendrite bridging (coalescence) (Rappaz et al. 2003) the local interplay between the coalescing dendrites and the localized liquid feeding (Vernède et al. 2006) and the alloy composition, including the effect of various trace elements.

Some conditions must be met for a hot tear to develop:

- The casting must be restrained from contracting.
- A coherent network must be established. It should be noted that dendrite coherency in this context, that is, when a network is withstanding tensile forces, is different from, and occurs later than, dendrite coherency in the context of fluidity when the shear strength of the network is important.
- A liquid film must still be present on the dendrite or grain boundaries.
- A significant temperature decrease must occur after coherency.
- The solid network must be sufficiently dense to prevent feeding of liquid into the tear.

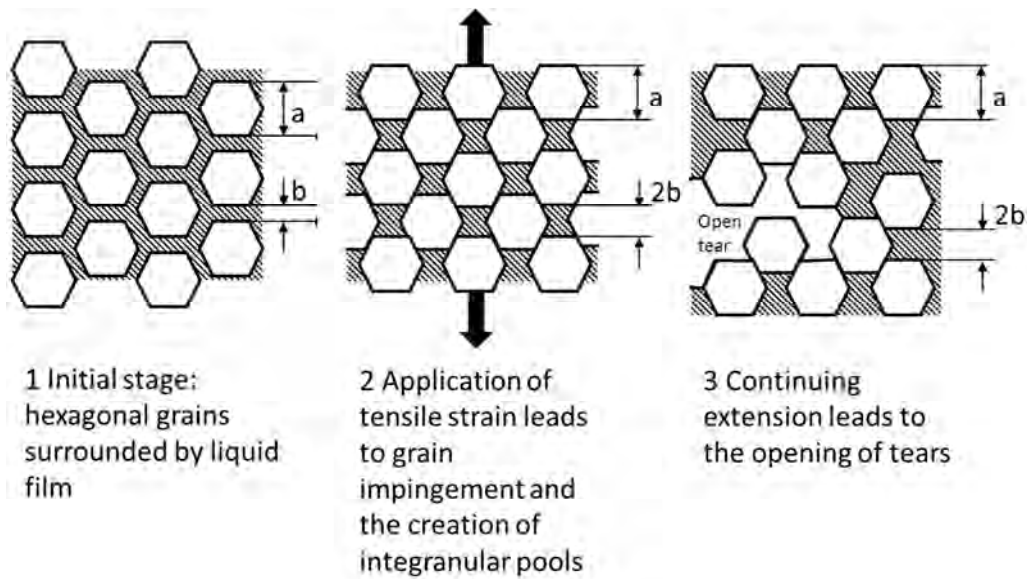


Figure 3-2. Hot Tearing mechanism proposed by Rappaz et al. (2003).

3.5 Speed cracking

The term “Speed cracking” which was used by Bowyer (1999) refers to a defect which is formed during extrusion. It was defined as:

“Speed cracking is a defect that arises in extrusion when the heat generated by the extrusion process is sufficient to cause localized melting in the extrudate. It is recognized by circumferential cracks on the extruded product. It is prevented by controlling the extrusion temperature and the extrusion speed. If speed cracking occurs it is likely than other defects such as coarse grains and segregations of impurities would also be present. It would be unacceptable and would lead to rejection.

No relevant information about Speed Cracking during extrusion of copper pipes was found in the literature. The term speed cracking is used by Peng and Sheppard (2004) in a study of surface cracking during extrusion of aluminum alloy AA 2014.

4 Observed defects in the actual casting process at Luvata

During the visit to the Luvata plant one as cast ingot was visually inspected. This ingot was produced for the development of the process of manufacturing of pipes for canisters holding nuclear waste. The discontinuities which could be observed were longitudinal cracks, cold laps, oscillation marks and uneven colour on the surfaces.

Relevant information on the characteristics for the discontinuities in semi continuously cast copper ingots was not found in the open literature in this investigation. This means that the mechanisms for forming the actual centre and surface discontinuities at Luvata need to be further investigated by means of cutting samples and making metallographic examinations.

4.1 Cold Laps

On the ingot surface Cold Laps could be observed as shown on the left side of Figure 4-1. Cold laps will occur when the solidified ingot shell has shrunk away from the mould wall making a gap that allows liquid copper to flow in between the solidified shell and the mould wall. It is assumed that the depth of this type of surface discontinuity is very shallow and the no sharp edges are observed. These discontinuities are likely to be removed in the turning operation that is performed after casting.

4.2 Oscillation marks

During continuous casting the mould is oscillated with the aim to improve the casting performance. The oscillating parameters are optimized with a combination of stroke length, oscillation frequency and casting speed. By optimizing the oscillating parameters the mould the friction is reduced between the solidified shell and the mould wall. The oscillation movement will also influence the heat transfer rate due to the folded thin shell affecting the heat transfer resistance in the gap between the mould wall and the thin folded shell. During the oscillating movement the thin solidified shell will be folded leaving circumferential grooves. Using normal operation conditions these grooves are shallow and will be removed in a turning operation.

4.3 Poor surface

According to Bowyer (2000) "Circumferential grooves arising from the casting process may be several millimetres deep and oxide containing". "These may mask circumferential cracks". According to information during a visit to the production unit in Pori and discussions with Luvata engineers, 2013-05-20, to date no detected circumferential cracks has been observed. The observed transversal discontinuities are shallow oscillation marks and other discontinuities are cold laps.

4.4 Thermally induced cracks

Luvata explained that the detected surface cracks are longitudinal Thermally Induced Cracks which will have a depth in the range 2-10 mm after the first turning. Typically the initial turning removes approximately 10 mm of the surface. According to Luvata these surfaces cracks are formed due to uneven heat transfer between the solidified shell and the copper mould and will be detected by ocular and die penetrant inspection and removed by turning or grinding. Figure 4-1 shows a photo of the ingot surface with a thermally induced crack. The length of the crack is approximately 100 mm.

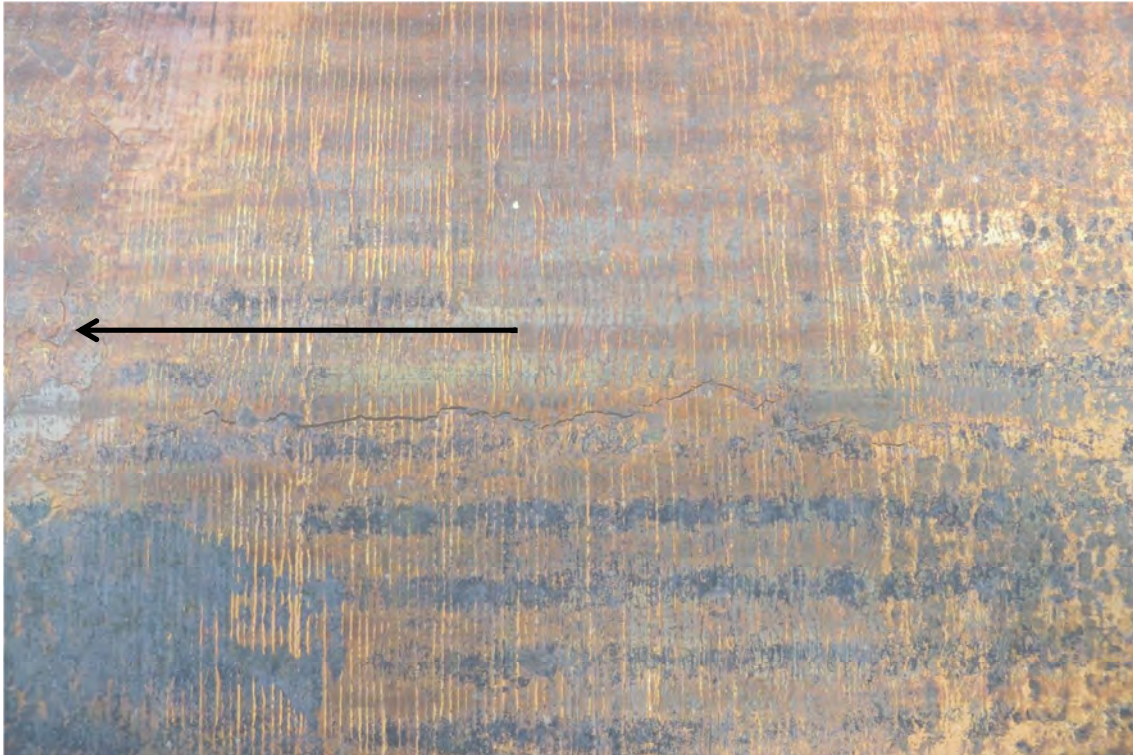


Figure 4-1. Ingot surface with a longitudinal Thermally Induced crack. Length: approximately 100 mm. An area with cold laps is indicated with the arrow.

4.5 Centre line cracks- spider cracks

According to Bowyer (2000) “Large ingot size leads to slow cooling which limits cracking due to shrinkage stresses. Large star cracks at the top of ingots arise from primary pipe and will be oxidised”. Referring to Luvata the ingots contain discontinuities in the centre and are located in the starting end and in the top end of the cast ingot. These discontinuities are referred to by Luvata as Spider Cracks. According to Luvata these Spider Cracks are located in positions where they are removed more or less when the ingot is cold sawn to a shorter length. Both ends of the cast ingot are visually inspected and dye penetrant tested after cutting. If discontinuities can be detected after each dye-penetrant test more material will be cut away and a new dye penetrant inspection will be done until no discontinuities can be detected. The cast weight is typical 16 tonnes and the shipped weight for extrusion is 12.4 tonnes \pm 0.1 tonnes. If the specified weight is not within specified limits the ingot will be rejected.

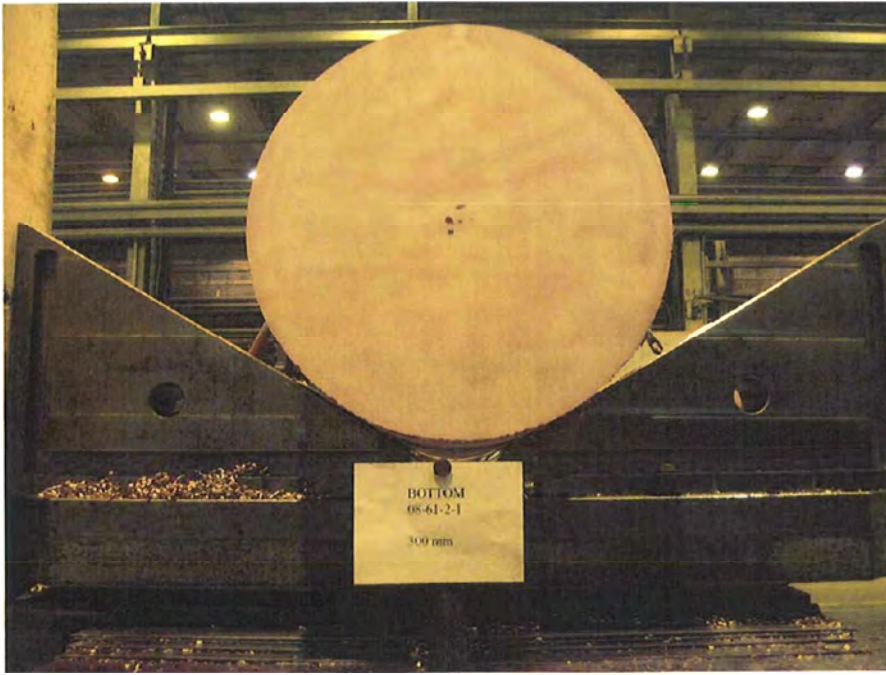


Figure 4-2. Photo showing an example of the appearance of spider cracks in the centre after 300 mm machining. Luvata.

5 Quality control of ingot production, inspection and documentation

This chapter contains a compilation of the most important parts of the quality system, documents and procedures that are used by SKB and its supplier Luvata in connection with the procurement and production of copper ingots for extrusion. The compilation shows that the quality management system is comprehensive but the knowledge and the definition for the acceptance criterion for surface defects is not totally determined and implemented. The surface requirements are according to SKB discussed case by case.

5.1 Quality control documents

SKB has an implemented quality management system which fulfills the relevant requirements according to ISO 9001:2000.

The quality management system contains the following main parts:

- A Quality Handbook
- Technical specifications
- Drawings
- Procedures
- Forms
- Quality plan

In order to achieve the specified quality of the cast copper ingots in a specific order a number of quality documents are produced by SKB and by the supplier. These documents form the conditions for the production, inspection and certification of the copper ingots for extrusion.

Governing documents for an order are request for quotation and the suppliers offer.

The offer contains an internal quality plan from Luvata. The offer also contains instructions for final inspection and a number of SKB specifications. These are included in the offer from the supplier which means that they form a part of the agreement.

Examples of SKB specifications are listed below:

KTS001	Copper ingots and billets for canister components
KT1102	Request for Concession
KT1103	Control of non-conformities
KT0701	Final Inspection and Testing
KT0702	Handling, Storage, Packing and Transport of Canister Components and Assembled Canisters
KT0703	Delivery of Canister Components and Assembled Canisters and Associated Documentation
KT0704	Requirements on 1) Quality Plan and 2) Manufacturing and Inspection Plan
KT0705	Identification of Canister Components and Assembled Canisters

6 Investigations to determine the acceptance criteria for surface defects on ingots

The requirements for the surfaces of the copper ingot and the acceptance criterion for the inspection have been developed during several manufacturing experiments, and by means of ultrasonic testing and investigations on artificial defects. This is described by SKB (2010). An investigation of how the discontinuities move in the billet during piercing of a billet has been done with the pierce and draw method (Koivula and Pihlainen 2003). A study on postulated defects in the extrusion process including a sensitivity analysis on start diameter was done by Swerea MEFOS “Main study - Copper tube extrusion” (SKBdoc 1377246). This study can be used to derive acceptance criterion for surface defects. Another study to determine which size of postulated defects those are critical during forging of copper lids was performed by Swerea MEFOS “Main Study - Simulation of copper lid manufacturing” (SKBdoc 1399827).

6.1 Postulated defects in extrusion and forging

From the investigation on defects in extrusion “Main study - Copper tube extrusion” (SKBdoc 1377246) it was concluded that some longitudinal cracks on the starting ingot will be removed during turning of the blocker after piercing and finally another 10-11 mm will be removed from the outside after extrusion during favorable conditions. The sensitivity study indicates that the result will be the same for both 850 mm and 820 mm starting ingot diameter. The conclusion is made under the assumption that the turning operation will remove material in a uniform way from the thickness. Non-straight or oval pipes will lead to less material removal and hence the acceptable initial defects must be smaller.

The same investigation shows that particles from the centre region in the ingot will remain in a centre position during upsetting and blocking. Material in this region will therefore be cut away during the subsequent piercing.

6.2 Possible future routes and acceptance criterion during production and inspection at Luvata

According to information from Luvata during a discussion at the works in May 2013 it is anticipated that it will be technically possible to specify and perform a process route for production and inspection of ingots with practically defect free barrel surfaces. The ingots could be machined from the cast diameter of 850 mm to a smaller diameter, for example 830 mm and then dye penetrant tested. The existing cracks (longitudinal sharp thermal cracks) should be removed by local grinding using soft grinding wheels and producing an open surface trench. The investigation “Main study - Copper tube extrusion” (SKBdoc 1377246) indicate that open trenches like handling defects with limited depth are not critical for the final surface quality of the extruded pipe. Repeated dye penetrant testing could be used to verify that the surface is free of cracks. Thereafter the ends could be cut and tested according to the existing procedure, taking into account the requirements on the minimum weight.

7 Results and discussion

During the last 10 years about 40 copper ingots have been cast and from these cast ingots 27 tubes have been extruded. The development has been focused of improvement of phosphorous control, lowering of the oxygen content, improved cooling control, surface quality improvements as well as reduction of center discontinuities. Methods for non-destructive testing like dye penetrant testing and eddy current testing has been introduced. By turning the barrel surface and cutting the end surfaces before using penetrant testing the possibility to find and delete surface defects has been improved.

Within the literature a number of types of discontinuities are defined for different alloys but these may not be relevant for casting and extrusion of almost pure copper ingots. The term Hot Tearing is not unambiguous and it is found mainly in connection with casting and solidification of metals. It occurs in some alloys during the final stages of solidification and typically in castings that are restrained from shrinking in the mold. According to McGraw-Hill (2003), Hot Tearing is “a separation either internally or externally in a casting due to loadings or internal stresses or both; it results from improper solidification, and shrinkage near the temperature at which the casting is completely solid”.

The term Hot Tearing is used by Bowyer for extrusion defects with a definition that is not widely established. According to this definition the defects are caused by die friction in combination with low ductility due to segregations and impurities at the grain boundaries. No relevant information about defects formed during extrusion of large copper pipes was found in the literature. The same conclusion was also made by Bowyer (1998) in an earlier investigation.

FE simulations of the extrusion process “Main study - Copper tube extrusion” (SKBdoc1377246) indicate that the friction coefficient is relatively low, typically 0.2. This is based on the fact that the coefficient 0.2 will give calculated press forces in correlation with the measured values.

The term Speed Cracking is usually found in the literature in the context of extrusion of alloys such as Al-Cu. In this process the speed cracking is caused by a combination of high temperatures, local melting and ductility loss. No relevant information about Speed Cracking during extrusion of copper pipes was found in the literature.

The temperature induced cracks as defined by Bowyer (1999) as Speed Cracks are not likely to be found in the actual copper extrusion process. Results from FE simulations of extrusion “Main study - Copper tube extrusion (SKBdoc 1377246) indicate that the relatively low extrusion temperature 675 °C combined with the limited friction and the high conduction of heat in copper will not result in sufficient temperature increase to provide local melting. FE simulations of the extrusion show that the temperature increase due to friction work and deformation is approximately 20 °C. The maximum material temperature in the extrusion moment is below 700 °C compared to the melting point of copper at 1085 °C. The ultra-low content of alloying and contamination elements does not give the necessary conditions to form more than infinitesimal amounts of secondary phases.

The supplier of ingots has detected surface cracks often visible for a naked eye. These cracks are longitudinally thermally induced cracks which will have a depth in the range 2-10 mm after the first turning. These surfaces cracks are said to be formed due to uneven heat transfer between the solidified shell and the copper mould and will be detected by ocular and die penetrant inspection. By turning the ingots after casting and removing some 10 mm from the barrel surface the eventual surface cracks can be further reduced. Further development of the route using dye penetrant testing and local grinding may give opportunities for a total crack free barrel surface.

According to information from this investigation it is anticipated that it will be technically possible to specify and perform a process route for production and inspection of ingots with practically defect free barrel surfaces. The ingots could be machined and then dye penetrant tested. Any existing longitudinal sharp thermal cracks could be removed by local grinding.

Referring to the ingot supplier the ingots may contain discontinuities in the center region, typically in the starting end and in the top end of the cast ingot. These discontinuities are called Spider Cracks. The Spider Cracks are located in positions in the ingot where they are removed more or less when the ingot is cold sawn to a shorter length. The Spider Cracks can be discontinuous which means that the end surface can be defect free after cutting. The crack can appear again in a deeper position if the end surface is cut a second time.

The recent FE simulations that were performed by Swerea MEFOS “Main study - Copper tube extrusion” (SKBdoc 1377246) indicate that remaining centrally located Spider Cracks will be removed during the piercing operation before extrusion.

In the same investigation it is found that shallow handling defects, open trenches and surface cracks of limited depth will be removed during the upsetting, blocking, piercing and turning operation. The critical depth of the remaining surface defects that will be removed during the final turning after extrusion is dependent on the straightness and shape of the extruded pipe.

References

- Arnberg L, Mo A, 2008.** Castability – Fluidity and hot tearing. In Viswanathan S (ed). ASM handbook. Vol 15, Casting. Materials Park, OH: ASM International, 375–378.
- Bowyer W H, 1998.** Design basis for the copper/steel canister, stage four. Final Report. SKI Report 98:29, Statens kärnkraftinspektion (Swedish Nuclear Power Inspectorate).
- Bowyer W H, 1999.** A study of defects which might arise in the copper steel canister. SKI Report 00:19, Statens kärnkraftinspektion (Swedish Nuclear Power Inspectorate).
- Bowyer W H, 2000.** Defects which might occur in the copper-iron canister classified according to their likely effect on canister integrity. SKI Report 00:21, Statens kärnkraftinspektion (Swedish Nuclear Power Inspectorate).
- Campbell J, 1991.** The ten rules of casting. Oxford: Butterworth-Heinemann.
- Campbell J, 2004.** Castings practice: the ten rules of casting. Oxford: Butterworth-Heinemann.
- Fredriksson H, Åkerlind U, 2006.** Materials processing during casting. Chichester: Wiley.
- Koivula J, Pihlainen H, 2003.** Further development of the structure and fabrication of the final disposal canister. Test fabrication of a seamless overpack with an integrated bottom by pierce and draw process. Working report 2003-49, Posiva Oy, Finland.
- McGraw-Hill, 2003.** McGraw-Hill dictionary of scientific & technical terms, 6E. The McGraw-Hill Companies, Inc. Available at: <http://encyclopedia2.thefreedictionary.com/hot%20tear>
- Nolvi L, 2009.** Manufacture of disposal canisters. Posiva Report 2009-03, Posiva Oy, Finland.
- Peng Z, Sheppard T, 2004.** Study of surface cracking during extrusion of alumina alloy AA 2014. Materials Science and Technology 20, 1179–1191.
- Rappaz M, Jacot A, Boettinger, 2003.** Last-stage solidification of alloys: theoretical model of dendrite-arm and grain coalescence. Metallurgical Material Transaction A 34, 467–479.
- Sigworth G K, 1999.** Hot tearing of metals. AFS Transactions 106, 1053–1069.
- SKB, 2010.** Design, production and initial state of the canister. SKB TR-10-14, Svensk Kärnbränslehantering AB.
- Udomphol T, 2007.** Surface cracks from heavy die friction in extrusion [PowerPoint presentation]. Suranaree University of Technology. Available at: http://www.sut.ac.th/engineering/Metal/pdf/MetForm/04_Extrusion.pdf
- Vernède S, Jarry P, Rappaz M, 2006.** A granular model of equiaxed mushy zones: formation of a coherent solid and localization of feeding. Acta Materialia 54, 4023–4034.

Unpublished documents

SKBdoc id, version	Title	Issuer, year
1175208 ver 5.0	Tillverkning av kapselkomponenter	SKB, 2011
1377246 ver 2.0	Main study – Copper tube extrusion	Swerea MEFOS, 2013
1399827 ver 1.0	Main study – Simulation of copper lid manufacturing	Swerea MEFOS, 2013