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Summary

Earlier studies[1,2,3] identified the material and manufacturing defects that might occur in serially produced canisters to the SKB reference design.

This study has considered the defects, which were identified in the earlier works and classified them in terms of their importance to the durability of the canister in service.

It has depended on, observations made by the writer over a seven-year involvement with SKI, literature studies and consultation with experts.

For ease of reference each section of the report contains a table which includes information on defects taken from the earlier work plus the classification arising from this work. A study has been conducted to identify the material and manufacturing defects that might occur in serially produced canisters to the SKB reference design.

The study has depended on cooperation of contractors engaged by SKB to participate in the development program, SKB staff, observations made by the writer over a five-year involvement with SKI, literature studies and consultation with experts.

The candidate manufacturing procedures have been described inasmuch as it has been necessary to do so to make the points related to defects. Where possible, the cause of defects, their likely effects on manufacturing procedures or on durability of the canister and the methods available for their detection are given. For ease of reference each section of the report contains a table which summarises the information in it and, in the final section of the report, all the tables are presented en-bloc.

Contents

1. Introduction

After many years of development effort SKB have made considerable progress towards the definition of a design and a manufacturing procedure for a canister to be used for deep geological disposal of nuclear waste.

The current reference design is a cylinder having outside dimensions 1050-mm diameter and 4.83m long. The wall thickness is 100mm and this is made up from a copper outer component of thickness 30–50 mm and the remainder in nodular cast iron. The copper is present as a corrosion protective layer and the iron is the load bearing structure. The inner cast component also carries an internal, cast in, structure to support and separate the spent fuel bundles. This design is considered by SKB to provide adequate radiation shielding against the contents of the canister together with the required durability in the disposal environment.

A design requirement is that no known hazard in the disposal environment will violate the container in the first 100,000 years after emplacement. The emplacement site will be at a depth of 500 m in the granitic rock of the Nordic shield. Canisters will be placed, with the long axis vertical, in holes bored in the base of tunnels. The bored holes will be lined with Bentonite clay before the canister is emplaced.

This design requirement will place exacting standards on the material quality and the reliability of the manufacturing procedures. SKI is responsible to approve the design of the canister, the procedures for manufacture and the approval procedures for canisters as fit for purpose. In order to discharge this responsibility it is necessary for SKI to understand, among many other things, the effects which quality factors such as material and manufacturing defects will have on the durability of the product in its service environment.

Whilst the materials and the dimensions of the proposed canisters have been defined, the manufacturing procedures have not. A number of manufacturing procedures are being considered and SKI need to understand the relative merits of each in terms of the effects of processing on the integrity of the product.

For the load bearing liner nodular iron to specifications published by SKB[1] will be used in cast form, although direct (downhill) casting is currently favoured, it is possible that it will be necessary to adopt indirect (uphill) casting when further knowledge is gained. The material for the copper overpacks (outer layer) has also been specified by SKB[1]. The process for manufacture is not specified. The starting material may be supplied in the form of rolled plate for fabrication or as continuously cast ingots for extrusion or pierce and draw processing. The fabrication and extrusion processes will produce tubes which need to have tops and bases attached whilst the pierce and draw process will provide a hollow tube with an integral base. Bases for fabricated or extruded tubes and tops for tubes from all three processes will be made by forging from ingots. These forgings will be attached to the tubes by welding using the electron beam process or the friction stir welding process, which is under development and has been described elsewhere[3].

An earlier study[2] has identified material and manufacturing defects, which could occur in serially produced canisters to the reference design. The purpose of this study is to classify the possible defects that have been identified according to their likely effect on durability of canisters in production and in the service environment.

As a first step it will be necessary to expand the list to include defects which may occur in friction stir welding. This will be done through an examination of the literature on friction stir welding and a discussion on the status of the development of the process and current knowledge of likely defects with TWI.

Following completion of the candidate list of defects it will be necessary to comment on the nature and magnitude of the effects which each could cause.

2. Results of the Study

2.1 Friction Stir Welding Defects

The process of friction stir welding has been described elsewhere[3]. A number of weld defects have been described in the literature as detailed below. It should be stressed however that, at this early stage in the development of the process, all defects have been attributed to lack of control of process parameters and development workers have claimed to produce defect free welds when controls have been adequate.

Near surface voids in the shear zone have been reported by several workers [4,5,6]. They appear to arise from a lack of consolidation of plasticised material behind the weld tool when the welding speed is too high. They may be detected by radiography or ultrasonic testing and, if they are confined to a surface layer, which is removed during final machining, they are of no consequence. If they do arise from a lack of consolidation however then there seems to be no reason why they should be confined to the surface and there is no apparent method of repair. Just as with electron beam welding, the presence of voids, which are linked to the surface, is unacceptable owing to the possibility of accelerated crevice corrosion cracking through the voids.

A surface groove with an underlying continuous or linked group of pores has also been reported [5,7,8] by several workers. The groove lies on the trailing edge of the weld on the boundary of the stir zone and the thermo-mechanically affected zone (TMAZ). This would seem to be a localised variant of the near surface porosity referred to above and is also related to control of welding parameters. As with the other case there is no apparent method of repair, this porosity is unacceptable unless it is removed by final machining.

A tool exit defect has been reported[9]; it consists of a region of unsoundness related to the close out process of the welding tool. Visual evidence of the defect may be provided by the shape of the exit hole but confirmation is required by ultrasonic or X-ray inspection. The defect per-se is unacceptable because it signals a zone of porosity extending from the surface to an undefined depth. However there seems to be a strong possibility that if it is detected it may be repaired by a limited FSW pass.

Residual stresses will arise in the TMAZ[9], their magnitude is not defined but they are said to be less than stresses caused by fusion processes. It seems likely that such stresses may be relaxed during the very early stages of service but this is not demonstrated. If the stresses are not relaxed, their effects in relation to stress corrosion cracking or localisation of strain during the collapse of the copper canister onto the liner are unknown.

Herring-bone cracking, which occurs at the root of the weld owing to inadequate penetration of the weld tool[9], may be very difficult to detect from the surface if it is deep in the weld. However this defect is always remote from the surface and therefore it should not be significant from the point of view of corrosion. The fracture toughness of the copper is such that small cracks, which are deep in the weld, will not grow during emplacement or storage. It should be safe to say that if the defect is not detected it does not present a problem. If it is detected, inspectors may take a view as to whether or not the weld should be accepted. This will depend on size and location.

Table 1 summarises the above information on defects in friction stir welds.

Table 1 Defects in friction stir welds

Defect Type	Comment	Method of Detection	Classification
Near surface voids/line porosity	Arise in the shear zone when the welding speed is too high	U/S or radiographic inspection	Unacceptable if they are not removed by final machining
Surface groove with underlying pore defect	Occurs on the boundary of the stir zone and the TMAZ	Groove is visually detected, The underlying pore requires U/S or radiographic inspection	Unacceptable if they are not removed by final machining
Tool exit defect	Unsoundness	Visual inspection of weld, U/S or radiography	Unacceptable-may be repairable by FSW
Residual stresses	Occur in TMAZ and are of undefined magnitude, less than fusion welding	X-ray diffraction	Effects on stress corrosion unknown
Herring bone cracking on the back face/weld root	Arises when tool penetration is inadequate	Difficult to detect in canister welds. U/S inspection may work.	Present evidence suggests minor importance.

2.2 Castings of the load bearing liner in nodular iron.

2.2.1 Direct casting

2.2.1.1 Background

Earlier work[2] identified the defects, which might occur in direct castings. They may be divided into two categories, those, which change the mechanical properties of the material and those, which limit the effectiveness of the material in providing its specified performance. Segregation and bad structure comprise the first category and inclusions, cold shuts, shrinkage cavities or cracks and porosity form the second group.

To judge the likely effects of defects it is necessary to consider the extremes of mechanical property variation which might occur against the margins, or safety factors allowed in the design calculations.

It is reported[10, 14] that corrosion from the inside of the liner may be neglected, and exposure of the outside of the liner to corrosive influence would lead to rapid failure irrespective of defects[14, 15, 16]. Thus we need only to consider the stress environment when judging the importance or otherwise of material or manufacturing defects in the liner.

The magnitude of the effects of defects on the durability of the canister will depend on the service stress and the relative magnitudes of the effects of different defects will differ with variations in the stress environment. For example surface cracks may be unimportant in a purely compressive stress field but under bending conditions they could lead to failure.

The standard mechanical properties for the selected cast iron grade (SS 0717-00) are given in table 2 below after Werme[10].

Table 2. Standard Mechanical Properties for Cast Iron Grade SS 0717-00

Properties	At 20ºC	At 100ºC
Yield strength (MPa)	250	235
Tensile strength (MPa)	400	375
Elongation at failure (%)	22	22
Young s modulus (GPa)	170	162
Poisson s ratio	0.3	0.3

No compressive data are given but Andersson[1] has demonstrated that the compressive yield stress is some 10% higher than the tensile yield stress and this is as expected for a nodular iron. It is also reasonable to expect a nodular cast iron with these tensile properties to have a compressive ultimate strength of 600 to 800 MPa[11].

Werme[10] has presented data on peak loads, which would be experienced for a range of load cases, which may occur in service. Table 3, overleaf, lists the load cases reported by Werme[10] and presents calculated effective safety factors based on the mechanical property data of table 3 and the peak load calculations for each case.

The failure loads are taken from Werme[10]. For cases 1 and 2 are they from SKB data on compressive buckling loads, which are based on yield strength / 0.2% proof stress data. For cases 3 to 6 failure loads are 0.2% proof stresses in the cast iron and for cases 7A and 7B the failure stress is the yield stress/ 0.2% proof stress of the copper. Discrepancies between yield /proof stress values in tables 3 and 4 or between these values and other published work are small. They arise as a result changes that have occurred as the development programme has progressed.

It is clear that substantial safety margins are designed in for all cases considered. SKB have stated[10] that a safety factor of 2.5 is desirable for cases 1, 6A and 7A. However cases 2, 3, 4, 5, 6B and 7B are extreme cases which they consider do not require safety factors.

For cases 3, 6A and 6B maximum stress values were calculated using engineering formuli and assuming no flow in the bentonite, this is a conservative approach but nevertheless the calculated available safety factors are substantial. The same approach applied to cases 4 and 5 yielded maximum stress values which were close to or above the 0.2 % proof stress for the iron. A more sophisticated finite element method (FEM), which takes account of flow in the bentonite, was therefore adopted for these cases and the calculated values resulting from this approach are given in the table. The resulting safety factors are substantial, even though for the extreme cases SKB consider that no safety factor is required. There is no doubt that if the FEM method was applied to case number 3 the predicted peak stress would be reduced and the safety factor would be improved in line with cases 4 and 5.

Table 3 Expected maximum stress levels in the cast iron liner and effective safety factors for load cases studied by SKB

Load case		**Expected maximum stress (MPa)**	**Failure load (MPa)**		**Safety factor**	
			BWR	**PWR**	**BWR**	**PWR**
1	Normal load (hydrostatic head + bentonite swelling)	14 Uniform Pressure	81	114	5.8	8.1
2	Normal load + Glaciation load	44 Uniform Pressure	81	114	1.8	2.6
3	Bentonite swelling pressure from one side with ends rigidly supported.	122 Bending	240	240	2	2
4	Bentonite swelling pressure from one side only with simple supports to the opposite side	<55 Bending	240	240	4.4	4.4
5	Rigidly fixed at one end with Bentonite swelling pressure from one side only	<55 Bending	240	240	4.4	4.4
6A	Uneven Bentonite swelling pressure across the canister	29 Bending	240	240	8.3	8.3
6B	Extreme case of 6A	71 Bending	240	240	3.4	3.4
7A	Uneven Bentonite swelling pressure along the length of the canister	7.7 Tensile	45	45	5.8	5.8
7B	Extreme case of 7A	3.0 Tensile	45	45	15	15

The single case where the safety factor is less than 2.5 is case 2 for the BWR waste container. This is one of the cases referred to above where SKB require no safety factor.

In the following sections the effects of defects are considered in the light of safety factors which are available.

2.2.1.2 Segregation and bad structure

The ideal structure, which would provide the specified properties for this case, would be a uniform distribution of fine graphite nodules in a ferritic matrix.

When the solidification time is prolonged, as it is in this case, segregation of graphite nodules can occur by floatation. Further, “fade” of the effects of graphitising additions can occur during an extended solidification process through reaction with sulphur or through reaction with oxygen in the air during pouring.

In the extreme cases, floatation leads to a gradation in carbon content from the bottom of the casting to the top whilst fade of the nodularising additions (Mg and Ni) could lead to localised changes in structure from nodular iron to compacted graphite cast iron. In this structure the graphite nodules of nodular iron are replaced by graphite shapes, which are intermediate between flakes and nodules. For the very unlikely case where nodularisers are not added or are lost, for instance by reaction with sulphur, then a grey cast iron would be produced.

Segregation of graphite to the top of castings could lead to a reduction in strength in the high graphite regions (the strength of the graphite nodule approximates to the strength of a spherical void) but the region of high graphite concentration would be removed as the top discard. The reduction in the concentration of graphite nodules at lower levels in the casting could lead to increased shrinkage during cooling, which in turn would lead to an increased tendency to form shrinkage cracks, and to an increased tendency to form pearlite in the matrix[**].

Cooling rate after solidification controls the matrix structure and a slow cooling rate should ensure that the ideal 100% ferrite condition is achieved. A more rapid cooling rate would lead to the mixed ferrite plus pearlite structure.

The development of a ferrite plus pearlite matrix structure would lead to an increase in proof stress and ultimate tensile or compressive strength (both by up to a factor of 2) at the cost of a reduction in ductility which in the extreme could be as low as 2%[11]. Clearly the strength improvements would present no problem. The associated loss of ductility would be coupled with increased brittleness and sensitivity to crack like defects but the improvement in safety factors above those given in table 4 which would arise from the increased strength should compensate for this. Only the very extreme case, coupled with other defects would be likely to present a problem.

If segregation, loss or fade of graphitising additions were to occur to the extent where the compacted graphite cast iron structure was developed then ductility could be reduced to less than 6%[12]. The properties of the compacted graphite cast iron lie between the properties of the ideal nodular cast iron and grey cast iron. The graphite flakes that are formed in grey cast iron have the same strength as cracks and the same effect on ductility. Typically the proof strength and ultimate strength properties would be reduced by a factor of 2 compared with nodular iron and strain to fracture would be reduced to less than 1%. This would be unacceptable even with the high safety factors in the design. The acceptability of the compacted graphite cast iron is therefore questionable. At the nodular iron end of the structure and property spectrum the material would be fully acceptable whilst at the other (grey iron) end they would be totally unacceptable. The only non-destructive way known to the writer for detection of the transition from the nodular iron to the grey iron structure is through measurement of ultrasonic pulse velocity, which shows a gradual decrease as the transition from nodular iron structure to the grey iron structure develops.

[**] Andersson[1] has reported a 10-20% increase in proof and ultimate tensile strength values (compared with specification) on test pieces cut from an early casting trial. These increases were associated with a structure containing 10% pearlite and a reduction in ductility from 18% to 10%. Test pieces from the bottom of the casting were more seriously affected than test pieces from the mid-height.

2.2.1.3 Gas porosity and shrinkage cavities

The earlier work[2] indicated that gas porosity and shrinkage cavities should be very limited in the direct cast liner. The near spherical shape of gas pores coupled with their small size and the substantial safety factors indicates that they will have little significance in this casting, unless they are large and the structure is very wrong. This would only happen as a result of errors in casting procedures or in composition of the charge and the structure defect would then dominate behaviour.

2.2.1.4 Inclusions

The effects of inclusions arising from mould erosion would have little significance, providing that they are in the normal size range (grains of sand) and the structure of the casting is acceptable. Very large inclusions such as might arise from erosion of the brick bottom of a mould could reduce the load bearing area of the casting in critical regions to an unacceptable level; this would be cause for rejection of the casting.

2.2.1.5 Cold shuts and shrinkage cracks

The effects of cold shuts and shrinkage cracks would depend on their size and position. Cold shuts can act as cracks and either defect could extend through the full thickness of the outer skin or the central webs of the casting. In the central regions of the casting neither would present a serious problem since they would not respond to compressive stresses and bending stresses tend to zero on the neutral axis.

A detailed fracture toughness study is required to provide comprehensive information on the effects of cracks in the outer skin and that is beyond the scope of this work. It would not be straightforward since the grade of iron specified is very tough and the material thickness is such that linear elastic fracture mechanics (LEFM) would not apply (because plain strain conditions would not be realised). Under these conditions the use of LEFM provides a conservative result.

An estimate made, using LEFM, parameters from the literature[11], and a graphical method[11], indicates that material stressed to the 0.2% proof stress would be safe against rapid crack growth in the presence of a disc shaped surface breaking crack with a depth of 15 mm and an aspect ratio of 10:1 (i.e. a surface length of 150 mm). When the applied stress is reduced by a factor of 2 (safety factor) the critical depth becomes 60 mm. This estimate should be conservative and it indicates a very high degree of damage tolerance in the canister if the specified structure is realised.

2.2.1.6 Classification of defects in the cast iron liner

Table 4 opposite, takes its first three columns from the earlier work[2] and adds a classification column drawn from sections 2.1.1.2 to 2.1.1.5 above.

Table 4 Classification of defects that might arise in castings for the load bearing liner

Defect Type	**Comment**	**Method of Detection**	**Classification**
Dross Inclusions	Should float out in direct casting owing to turbulence	Ultrasonic	Safety margins are adequate, providing the target structure is achieved.
Cold Shuts	Should be prevented by rapid pour in direct casting	Ultrasonic	Very large defects may be tolerated providing the target structure is achieved.
Gas Porosity	Should float out	Ultrasonic	Should not present any problem
Shrinkage Cavity	Should be very limited in direct casting, more extensive in indirect casting	Ultrasonic	Casting should tolerate large cavities providing the target structure is achieved.
Segregation	Graphite may segregate to top of casting during long solidification period.	Microstructural examination / Mechanical test	Extreme case could lead to higher levels of pearlite and of shrinkage cracks. Not expected to cause serious problems unless structure is wrong.
Bad Structure	Graphite may coarsen during long solidification and cooling periods. Nodules may degenerate in the extreme case to flake graphite. Degeneration coupled with loss of mechanical performance and toughness	Microstructural examination / Mechanical test. Ultrasonic pulse velocity may be used to check for nodule degeneration.	Coarsening of nodules presents no problems. Degeneration of nodules is accompanied by loss of strength and toughness. Flake graphite is unacceptable, minor degeneration to compacted graphite is acceptable.
Shrinkage cracks	Could occur in webs as a result of rapid cooling. Slow cooling should minimise any problem	No satisfactory test procedure.	Large cracks may be tolerated in the target structure.
Inclusions	Particles from the mould may be included in the casting.	Ultrasonics	Large inclusions unacceptable. Sand particles do not present a problem

2.2.2 Indirect casting

The defects listed in the earlier work[2] for direct castings are the same as the list for indirect castings. Table 4 above has therefore been made to be applicable to both direct and indirect castings. The comments regarding the effects of loss of or fading of or failure to make nodularising additions on structure are the same for indirect casting as for the case of direct casting.

2.3 Continuous castings of OF grade copper ingots

2.3.1 Composition

Details of the specification of the composition of the material for the copper overpack and the casting procedure have been presented elsewhere[2].

The likely difficulty, which has been identified, is lack of control of phosphorus content and variations in phosphorus content through the ingot. The reason for difficulty is in the processing[2]. Unfortunately the safe band of phosphorus content has not been defined. It is considered that 50 ppm is a safe level but the level of variation, which may be permitted, is unknown. Levels, which are too low, will fail to exert a beneficial effect on recovery and recrystallization temperatures or the claimed benefit in creep strain to fracture.

Levels which are generally too high will interfere with the electron beam welding process and prevent the base being attached to the tubular. This would lead to rejection of the canister early in the production process. Locally high levels of phosphorus, which do arise in the present manufacturing procedure, can lead to failure of the lid weld if it is performed by electron beam welding, even though the base weld had been satisfactory. Such failures are expensive but not catastrophic.

2.3.2 Segregation

Impurities, including phosphorus, bismuth, lead and sulphur may be segregated to the centre of the ingot during casting. Homogenisation should occur during thermo-mechanical treatment. For the case of phosphorus there is no convincing evidence to indicate that segregation would cause problems after hot working providing that the total phosphorus content is within specification and that gross segregation does not arise as a result of poor dispersion of the master alloy during manufacture.

2.3.3 Centre Line Cracks

Centre line cracks in ingots cast for this work are claimed to be remnants of primary pipe.

Cracks related to primary pipe in these ingots, are unavoidable using the existing technology, they may be large and they are exposed to an oxidising environment during the cooling of the ingot. Hot working may disrupt and disperse the oxide and weld the surrounding material to provide a nominally sound product. However the size and location of the oxide particles depend on the hot working process. Even small particles in the surfaces to be electron beam welded can cause interruption of the welding, which leads to defects that may be difficult or impossible to repair. In this case the canister would be rejected.

The effects of near surface oxide particles on long term corrosion performance, is unknown.

2.3.4 Poor surface

The surface grooves which are characteristic of these ingots may be some millimetres deep and they will mask any surface cracks that may be present. The grooves as well as any shrinkage cracks will be oxidised. The oxide will eventually arise in the finished product unless measures are adopted to prevent it.

When further processing is by extrusion the surface is improved by machining to remove all the circumferential grooves. This machining may also remove any surface cracks that are present. If it does not then die penetrant testing would reveal them. If they are shallow they may be removed by dressing the surface and if they were judged to be too deep they would lead to rejection of the ingot.

The poor surface should not therefore present a problem when tubulars are extruded.

The effects of surface grooves and cracks are at present unknown for the case of ingots subjected to pierce and draw processing. It is possible that surface cracks will open up during processing but if so they would either be removed by machining after drawing or they would lead to rejection of the tubular. Cracks and surface grooves, which do not open up in processing, will lead to oxide inclusions and the comments for these are the same as in 2.3.3 above.

2.3.5 Classification of Ingot Defects

In table 5 overleaf columns 1 to 3 are taken from earlier work, column 4 is a classification of the defects according to the comments in sections 2.3.1 to 2.3.4 above.

2.4 Copper tubes made by extrusion

2.4.1 Inclusions

Inclusions arising from casting would be broken up and distributed through the tubular as fine particles during extrusion. Strings of such particles may or may not be near the surface depending on the original position of the inclusion in the ingot. They would be detectable by ultrasonic inspection. Similar comments apply to inclusions arising from forging laps that arise during the stages preliminary to extrusion. Their effect on the integrity of the canister is not established but they could have negative effects on corrosion resistance or weldability by the electron beam welding route. Serious cases should lead to rejection prior to extrusion. If they are not detected at that stage then there is a further opportunity at the tubular inspection stage which should detect near surface inclusions which might influence corrosion resistance. Inclusions remote from the surface which escape detection at this stage are very unlikely to influence the durability of the canister providing that they are not melted during electron beam welding. If melting of inclusions occurs during electron beam welding it could lead to failure of the weld and rejection of the canister.

Table 5 Defects that might arise in Continuously cast ingots for tubular production

Defect Type	**Comment**	**Method of Detection**	**Classification**
Composition	Difficulty controlling phosphorous level, within ingots or between ingots. Phosphorous known to have adverse effect on electron beam welding but sensitivity not established	Chemical analysis only indicates level at area sampled.	Large variations in phosphorus level arising from failure to distribute master alloy unacceptable. Limits are not defined.
Segregation	Impurities, including phosphorus are likely to segregate to the centre of the ingot. Chemical analysis therefore depends on analysis of input materials	Chemical analysis of the ingot is subject to serious sampling errors.	Should be removed by thermo-mechanical treatment and have no adverse effect on the finished product
Centre line cracks	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.	Visual inspection	Unavoidable, may be of no consequence, may lead to rejection of tubular at inspection stage, may lead to rejection of canister at lid welding stage.
Poor surface	Circumferential grooves arising from the casting process may be several millimetres deep and oxide containing. May mask circumferential cracks.	Visual inspection as cast, die penetrant after machining.	Could lead to rejection or repair before extrusion. Could lead to unacceptable oxide inclusions with pierce and draw process.

2.4.2 Coarse Grains

Failure to adequately control the extrusion temperature can lead to the development of very coarse grains. When this occurs, segregation of impurities to grain boundaries is promoted, even for the very low impurity levels present in the specified material. Under these circumstances bismuth and lead can lead to hot shortness. This would be manifest as grain boundary cracks and possible enhanced corrosion in the affected region. Normally the cracked region would be removed during final machining but this is not guaranteed, especially for the cases where tubulars are not truly circular. Sulphur can also contribute to hot shortness but its most serious effect is on creep properties. If the creep mechanism dominated by grain boundary deformation is induced in service then the presence of sulphur in grain boundaries can cause failure to occur at strains below those which are expected as the tubular shrinks onto the liner.

In material meeting the analytical specification segregation of these elements can neither be controlled, nor easily detected before they cause cracks. However all available evidence indicates that if the grain size is fine (not defined but up to 150 µm appears to be acceptable) then the permitted levels of these impurities are too low to cause a problem.

2.4.3 Hot Tearing

Hot tearing arises 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 of the tubular.

2.4.4 Speed Cracking

Speed cracking is a defect that arises in extrusion when the heat generated by the extrusion process is sufficient to cause localised melting in the extrudate. It is recognised 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 that other defects such as coarse grains and segregation of impurities would also be present. It would be unacceptable and would lead to rejection of the tubular.

2.4.5 Bad Shape

Bad shape would result in difficulty in achieving the target dimensions after machining. Clearly if this was the case the tubular would be rejected.

2.4.6 Classification of Extrusion Defects

In table 6, overleaf columns 1 to 3 are taken from earlier work; column 4 is a classification of the defects according to the comments in sections 2.4.1 to 2.4.5 above.

Table 6 Defects that might arise in extruded tubulars

Defect Type	**Comment**	**Method of Detection**	**Classification**
Inclusions	May arise as clouds or stringers of oxide or foreign material such as refractory. May disrupt Electron Beam Welding. Effect on corrosion performance unknown.	Ultrasonic inspection	Undesirable. Acceptable levels not yet established. Serious cases will lead to rejection at the ingot or tubular stage. Inclusions remote from the surface are unlikely to present problems unless they are in the weld region.
Coarse grains	Arise as a result of failure to control extrusion temperature. Lead to difficulties in inspection and possible difficulties due to segregation of impurities to grain boundaries.	Ultrasonic inspection	Unacceptable
Hot tearing	Cracks arising from friction at the extrusion die and/or segregation of impurities at the grain boundaries in the ingot.	Visual inspection as extruded, die penetrant after machining	Unacceptable if cracks are not removed by final machining.
Speed cracking	Circumferential surface cracks. Controlled by adjustment of extrusion temperature and extrusion rate.	Visual as extruded, die penetrant after machining.	Unacceptable if cracks are not removed by final machining.
Bad shape	Could lead to failure to achieve the specified dimensions after machining.	Measurement before machining, visual inspection after machining.	Unacceptable if prescribed limits are exceeded.

2.5 Copper tubes made by the pierce and draw process

2.5.1 Oxide Inclusions

Comments for oxide inclusions for the pierce and draw case are the same as comments for inclusions given in 2.3.1 above.

2.5.2 Circumferential cracks

The occurrence of circumferential cracks in the pierce and draw process has been described elsewhere[2]. They may or may not be coupled with hot shortness and they arise during the expansion steps of the process. They may be removed by the final machining operation but if they are not they are cause for rejection of the tubular.

2.5.3 Coarse grains

The cause and effects of coarse grains following the pierce and draw process are similar to those given for extrusion in section 2.4.2 above.

2.5.4 Classification of defects tubulars made by the pierce and draw process

In table 7 overleaf columns 1 to 3 are taken from earlier work, column 4 is a classification of the defects according to the comments in sections 2.5.1 to 2.5.4 above.

2.6 Copper plates suitable for fabricated tubes of the required dimensions

2.6.1 Coarse Grains

The difficulty of avoiding coarse grains in heavy copper plate has been discussed elsewhere[2]. The extra difficulty of ultrasonic inspection coupled with the increased probability of hot shortness render the coarse grain sizes, which are achieved unacceptable.

2.6.2 Surface cracking

Surface cracking which is related to coarse grains and hot shortness in heavy plate is difficult to avoid. If it is present in the as rolled plate it will open up on roll forming and is therefore cause for rejection of the plate.

Table 7 Defects that might arise in tubulars made by the pierce and draw process

Defect Type	Comment	Method of Detection	Classification
Oxide inclusions	Inclusions arising from oxidising of primary pipe may or may not remain in the bottom that is removed and discarded. Cracks formed during piercing or upsetting will be oxidised and may or may not be removed by machining before drawing. Inclusions from either source will appear as stringers in the finished pipe. They could cause problems in electron beam welding.	Ultrasonic Inspection, effectiveness depends on grain size.	Undesirable Acceptable levels not yet established. Serious cases will lead to rejection at the ingot or tubular stage. Inclusions remote from the surface are unlikely to present problems unless they are close to the weld.
Circumferential cracks	Arise during piercing, should be removed by machining. May be due to friction at the die or hot shortness. May also arise during drawing to increase diameter and reduce wall thickness.	Die penetrant testing after machining.	Unacceptable if cracks remain after final machining.
Coarse grains	Arise from processing at too high a temperature or by using inadequate reductions in individual working operations. Lead to hot shortness and difficulty in ultrasonic exam.	Ultrasonic inspection	Unacceptable

2.6.3 Laminations

Laminations caused by the rolling process are usually removed by edge trimming. If the trim is insufficient to eliminate the defect the plate must be rejected since the oxide enclosed by the lamination would lead to welding failure.

2.6.4 Bad surface

Bad surface arising from rolled in oxide would usually be removed by surface dressing.

2.6.5 Classification of defects in heavy plates

In table 8 overleaf columns 1 to 3 are taken from earlier work, column 4 is a classification of the defects according to the comments in sections 2.6.1 to 2.6.4 above.

2.7 Roll formed semi-cylinders in copper.

2.7.1 Surface defects

Surface defects present in the rolled plates and referred to above will persist in the roll formed plate. They are usually of little consequence and are removed by final machining.

2.7.2 Surface residual stresses

Surface residual stresses are produced by rolling. They may lead to critical strain grain growth during the stress relieving treatment after welding. This further aggravates problems arising from coarse grains produced by hot rolling. There is no reason for the residual stresses to be a cause for rejection on their own account.

2.7.3 Bad shape

Shape is invariably bad after roll forming owing to the difficulties associated with the craft nature of the process. This is undesirable as it complicates the “fit up” process prior to welding and could lead to difficulties in machining to final dimensions. It would rarely be a cause for rejection of the part.

2.7.4 Classification of defects in roll formed plates

In table 9 overleaf columns 1 to 3 are taken from earlier work, column 4 is a classification of the defects according to the comments in sections 2.7.1 to 2.7.3 above.

Table 8 Defects that might arise in heavy plates prepared for fabrication of tubulars

Defect Type	Comment	Method of Detection	Classification
Coarse grains	Unavoidable in plates of this size. Present extra difficulties in ultrasonic inspection and increase problems arising from grain boundary segregation.	Ultrasonic/microscopical examination.	Unacceptable
Surface cracking	Arising from hot shortness-coupled with problem of coarse grains. May or may not be removed by final machining.	Visual examination/Die penetrant testing	Unacceptable
Laminations	From rolling over of edges, should be removed by trimming.	Visual/Ultrasonic testing	Unacceptable unless removed by the edge trimming process
Bad surface	From rolling of oxide or debris, may be removed by final machining	Visual examination	Undesirable but usually acceptable

Table 9. Defects that might arise in roll formed semi-cylinders for tubular production

Defect Type	Comment	Method of Detection	Classification
Surface defects in the slab	Referred to earlier		undesirable
Critical strain grain growth	May arise during stress relief, results from strain induced during cold forming	Difficulty in ultrasonic inspection	undesirable
Bad shape	Leads to poor fit up	Measurement/Visual	undesirable

2.8 Welded Tubulars

2.8.1 Internal stresses

The process for joining semi-cylinders has been described elsewhere[2]. Defects in the welds per-se are dealt with in section 2.9.

Internal stresses arising from welding are added to internal stresses arising in roll forming. The process of relieving these stresses can lead to critical strain grain growth with the attendant risk of segregation of impurities to grain boundaries. Such coarse grains and segregation are undesirable. They can have a negative effect on corrosion resistance.

2.8.2 Distortion

Severe distortion arising during stress relieving can result in the machining allowance on the tubular being inadequate. If this occurs the tubular is rejected.

2.8.3 Hot tearing

The effects of coarse grains and residual stresses can combine to cause hot tearing during welding. If adequate machining allowances are available the cracks arising from hot tearing may be removed during final machining. If the allowance is inadequate then the tubular must be rejected.

2.8.4 Classification of defects in welded tubulars

In table 10 below columns 1 to 3, are taken from earlier work, column 4 is a classification of the defects according to the comments in sections 2.8.1 to 2.8.3 above.

Table10 Defects that might arise in welding of roll formed semi-cylinders to produce tubulars.

Defect Type	**Comment**	**Method of Detection**	**Classification**
Distortion	Leads to need for stress relief and distortion.	Visual after stress relief	Undesirable if final machining to shape is possible. Unacceptable if distortion prevents final shape being achieved
Coarse grains	Owing to Critical strain grain growth	Further reduces inspectability	Very undesirable raises uncertainty concerning segregation to grain boundaries.
Hot tearing	Owing to segregation of impurities to boundaries of coarse grains.	Visual/die penetrant testing	Undesirable. Unacceptable if cracks are not removed by final machining
Welding defects	See section 2.9		

2.9 Electron beam welds

2.9.1 Linear Defects

There are three common linear or crack like defects[13], which have been observed in the development programme for the canister. The first is a missed weld line and the second is weld-root defect and the third is incomplete penetration. They have been described elsewhere[2]. Repairs may be possible in some cases but all three defects are unacceptable in the finished canister as indicated in table 11 below.

Table 11 Linear Weld Defects

Defect	Comment	Detection Method	Classification
Missed joints	May be complete or partial	U/T-unless residual stresses are compressive across the joint-alleviate by rough surface on the joint	Unacceptable
Weld root defect	A series of cavities may link surface to full weld depth	As above	Unacceptable
Lack of penetration	Weld short of full depth	As above	Unacceptable

2.9.2 Cavities

Gas porosity is usually in the form of small pores, up to 0.5 mm diameter, but they may on occasions be very large, that is up to the full weld width. When they are close to the surface their effect on pitting or crevice corrosion is unpredictable therefore they may not be accepted. At greater depths, of order 15 mm or more, it is unlikely that they will ever be exposed to a corrosive environment and they are therefore of little consequence. (15 mm is given by Werme[10] as the minimum wall thickness required from a corrosion point of view).

Cavities are generally larger than gas pores. They are typically 3-4 mm in diameter and they might extend for long distances at the root of the weld or in the run out region. Their size makes them more serious than the pores referred to above when they are unacceptable in near surface positions but they are unlikely to have any effect when they are deep unless there are other factors operating which cause accelerated corrosion.

Information on cavity defects is summarised in Table 12 opposite.

Table 12 Cavity defects

Defect	Comment	Detection Method	Classification
Gas porosity	May be at fusion boundary or may float to top of weld before being trapped. 0.5 mm diameter to full weld width	Radiography or U/T Low frequency eddy current for near surface. May be difficult to detect when small or when grains are coarse	Unacceptable in near surface (up to 15 mm deep) positions. No problem at greater depths
Shrinkage cavities	Especially prevalent at run out. Could be 3-4 mm in diameter and very long	As above Difficult to size owing to irregular shape	Unacceptable

2.9.3 Underfilling

Surface underfill is often limited in its extent and may not be a problem since machining after welding cleans the surface. If the beam supply is interrupted however, such as when flash over occurs, a deep underfilling defect may be created. Such deep defects may not be visible at the surface but they may approach the surface and they often extend over a considerable area and to a considerable depth. They need to be machined out and repaired or the weld is rejected.

Details of underfill defects are summarised in table 13 below.

Table 13 Underfilling defects

Defect	Comment	Detection Method	Classification
Surface underfill	Metal loss by run out, through poor fit up, inadequate tack welding, lack of control / gun discharge.	Visual	Unacceptable, repairs may be attempted
Root underfill	As above	U/T	As above

2.9.4 Cracking

Hot tearing may occur, particularly in association with coarse grains. They may be seen in welds on the centre line and parallel to the welding direction and also in positions close to the weld, which are affected by the welding process.

In the welds they have been attributed to enhanced segregation of impurities during repair operations coupled with shrinkage stresses. In areas adjacent to the weld they are believed to be a result of hot shortness brought about by the segregation of impurities to the boundaries of very coarse grains coupled with the heating from welding operations and the welding stresses.

In either case they are symptomatic of segregation of impurities to grain boundaries. If this occurs it is unlikely to be restricted to the grain boundaries which are cracked and other areas of the structure may be susceptible to accelerated grain boundary corrosion or low creep strain to fracture. If all traces of surface cracking are not removed by final machining the structure should be rejected.

Information relating to crack defects is summarised in table 14 below.

Table 14 Cracking

Defect	**Cause**	**Detection Method**	**Classification**
In the weld	Hot tearing under residual stresses or during stress relieving. Assisted by enhanced segregation during repair operations	Visual, Die penetrant or U/T	If signs of grain boundary cracking remain after final machining the canister should be rejected
Close to the weld	Probably due to hot shortness arising from segregation of impurities to boundaries of very coarse grains coupled with effects of heating and reheating during welding and weld repairs.	Visual, die penetrant testing.	As above

2.9.5 Gun Discharge Defects

Gun discharge defects arise as a result of flash over. If welding is stopped following flashover it is necessary to restart by running in to full depth over a distance in the already welded material, this can lead to weld root defect in the run-in distance. If the defects extend to the surface repair and re-inspection is necessary. Discharges that do not lead to welding being stopped can result in a crack like defect that arises from shrinkage and can extend for the full depth of the weld. Such defects are unacceptable. Repairs, which may be attempted, require re-inspection in both the run in and run out region.

Information relating to gun discharge defects is summarised in table 15 below.

Table 15 Gun discharge defects

Defect	**Comment**	**Detection Method**	**Classification**
Shrinkage cracks	May extend for the full depth of the weld	Ultrasonic inspection of discharge position	Unacceptable, repairs may be attempted
Weld root defect	In repaired areas	Ultrasonic inspection	As above

2.10 Copper forgings for lids and bases

2.10.1 Oxide inclusions

Surface cracks in the ingot would be oxidised and if they went undetected before forging it is likely that they would then lead to clouds or films of oxide inclusion in the final forging. These may or may not be removed during final machining.

Forging along the length of the ingot (upsetting) may in some cases lead to opening up of the centre line cracks and oxidation of the crack surfaces. Subsequent reheating and forging steps may increase the total amount of oxidation and disperse the oxide within the structure of the forging.

The effects of the inclusions depend on their size and position. Fine dispersed oxides should not be a problem unless they are in the weld line. Large oxide particles at or near the surface after machining could be initiation sites for localised corrosion and would be undesirable. Such oxides in the region of the weld could lead to failure of the welding process. If they are detected therefore they require that the forging should be rejected.

2.10.2 Forging Laps

Forging laps arise when, during forging, an area of surface material, which carries scale or an oxide film is folded over so as to include the oxide as a film, which may be quite thick, running from the surface to the interior of the forging[16]. If they do occur, they should be revealed by visual inspection of the premachined forging or by eddy current inspection of the machined product. Their classification depends on severity. Large laps would lead to rejection before machining. Smaller laps may be removed by machining. If they are not removed by machining the casting will be unacceptable for both mechanical properties and corrosion resistance. If they are removed by machining there is still a risk that clouds of oxide particles related to the lap would lead to failure in the welding process or accelerated corrosion. NDE should reveal whether or not this is likely.

2.10.3 Coarse Grains

The distribution of grain sizes in the forging will be closely related to the entire forging process. It is important to produce fine grains throughout the structure to:

1. aid the inspection process, particularly near the welds,
2. control the mechanical properties, yield strength and creep strength in particular and
3. avoid undesirable concentrations of impurities in grain boundaries owing to the reduced grain boundary area, which accompanies coarse grains.

Information relating to defects that might arise in forged lids is summarised in table 16 below.

Table 16 Defects that may arise in forged lids

Defect Type	Comment	Method of Detection	Classification
Oxide inclusions	Arising from cracks in the continuously cast forging stock. Can be lines of weakness in the forging; can interrupt electron beam welding.	Ultrasonic inspection.	Depends on size and location. Small inclusions should not be a problem away from the weld line. Large oxides at the surface or near the weld site could cause rejection.
Forging laps	Should be rare, produce oxide films extending from the surface to the interior of the forging	Visual/ die penetrant and ultrasonic inspection after machining	Depends on severity. Large laps lead to rejection at the forging stage. Smaller laps may be removed by machining to final dimensions.
Coarse grains	Cause difficulties in ultrasonic inspection, reduce mechanical properties, and may lead to undesirable concentrations of impurities in grain boundaries.	Difficulty in ultrasonic inspection.	Unacceptable in the material specification

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