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Study of International Published Experiences in Joining Copper and Copper-alloys

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1 Abstract

This study has revealed a number of joining processes to be used when manufacturing copper-canisters for the final storage of high level nuclear waste. However, the decision on which material and which joining process to be used has to be based on the design criterions. The welding procedure has to be qualified i.e, it shall be demonstrated whether the procedure is capable of fulfilling specified requirements.

2 Introduction

2.1 Aim/Goals

The aim of this literature-study is to gain an understanding of the methods and problems in joining copper and its alloys. It includes consideration of base-material, filler-metal, welding-methods and techniques, shielding gases and other essential variables.

2.2 Procedure

A first file-search only covered electron beam welding of copper in ESA-IRS files, specifically the Metadex file, it resulted in 37 hits and 9 were ordered after a check on the abstracts. After that a more extensive file-search was executed, it covered any technique of joining copper and its alloys in STN Internationals network. (STN International is a scientific and technical information network which provides access to worldwide databases and files in the STN database catalogue and homepage.)
A search conducted in the Metadex, Compendex, INIS and ISMEC files using the key words/ query "Weld or Join with Copper" yielded 182 references of which 43 were selected for study.

3 Results

3.1 Base-materials:

There are three different types of weldable copper to be considered; oxygen free high conductivity (OFHC), electrolytic tough pitch (ETP) and phosphorous-deoxidized copper (DHP/DLP) [7][31]. According to [5] the most readily weldable are the oxygen free types, deoxidized coppers, oxygen-free silver bearing coppers and phosphorous bearing oxygen free coppers. According to [10] the most weldable are phosphorous deoxidized coppers (DHP).

Both reference [7] and [31] sais that the phosphorus-deoxidized copper was originally developed as an alternative to ETP copper in order to improve weldability by the oxyacetylene-process. It remains as the standard weldable copper for general construction. [31] continues to say that phosphorus-deoxidized copper is the standard grade used in the construction of such items as chemical and food process plant, pressure vessels and calorifiers, and [7] that the high conductivity grades are used in applications where high electrical conductivity is required.

[10] indicates that generally, the same procedures used for coppers (metal with a minimum of 99.3 % Cu), can be applied to high copper alloys (metal with 96.0 to 99.3 % Cu).

However, extra care must be taken because many are used in the heat treated, age hardened, cold worked or precipitation hardened condition. In general, when high copper alloys are welded, reduced temperatures and welding currents are possible because high copper alloys are not as thermally conductive as coppers. [5] emphasizes that when OFHC, the purest commercial grade, is welded, it is important that impurities, which reduce conductivity, be kept out and that no oxides, which weaken a joint, be allowed to develop. Ref [21] considers the difficulties encountered in copper welding and says that they are primarily connected with the physical and metallurgical properties of the material, in particular with the very high thermal conductivity, the high coefficient of expansion, the absorption of oxygen and hydrogen and with increased brittleness in certain temperature ranges. At this time (1976) all the known copper welding methods could be applied easily where relatively thin cross-sections were to be joined because in such cases cold welding (without preheating the material, writers comment) could be used. The thicker the copper plates, however, the more difficult they became to weld, irrespectively of the method of welding. For joining copper plates up to 2 mm thick, no preheating was necessary in most cases, whereas 10 mm thick plates often had to be preheated to 500 °C, or higher. Even the most up-to-date methods, such as welding in Ar or He atmospheres, had failed to solve the problems completely, and in some instances the welding of copper was simply not possible. However a development of unique coated copper electrodes made it possible to weld copper of any thickness without the need to pre-heat items before and during welding, using MMA (manual metal arc welding).

The metallurgical factors affecting the weldability are mainly those encountered when welding the ETP copper. The wrought form of this material contains cuprous oxide as transgranular stringers which interfere little with the general strength and properties. However ref. [16] mentions that ETP copper as used in electrical switchgear and cables poses problem in welding. This is because porosity and embrittlement are frequently encountered in the heat-affected region due to formation of oxide particles, which are no longer present as stringers. When welding the common phosphorous-deoxidized coppers, the phosphorous content is not high enough to guarantee deoxidation in the case of autogenous welding. Therefore filler materials containing compensating deoxidants must be used. Further, [7] continues, in the heat affected zone (HAZ), temperatures may be sufficiently high to allow diffusion and migration of the otherwise harmless oxide particles to the grain boundaries.

The effect is both time and temperature dependant and therefore one main aim in welding tough-pitch copper is to carry out the welding operation as rapidly as possible and to restrict the overall heating of the component. This consideration must be weighed against the overall requirement for adequate fusion and a satisfactory weld profile.In the cast form, there is a tendency for the oxide in ETP to occur as a grain boundary deposit, weakening the structure and seriously affecting the properties.
Cast tough-pitch grades of copper are therefore not suited to autogenous welding and must be welded with a deoxidant-containing filler alloy to provide a completely deoxidized weld deposit.Oxygen-free high conductivity and phosphorus-deoxidized grades of copper present no special metallurgical difficulties. In both grades, despite the presence of residual phosphorus in the latter, there is likelihood of porosity in the weld pool and heat affected zone caused by inevitable atmospheric contamination or by the diffusion of gaseous impurities up the thermal gradient from the colder regions of the parent metal towards the weld metal. The situation is corrected by the use, where possible, of special copper filler alloys containing powerful deoxidants. An improvement is also gained by shrouding the underside of the weld with inert-gas and by improving the flow -characteristics of the shielding gas from the torch by, for example, the use of a gas lens that gives a smoothed protective shielding gas column at a greater distance from the torch nozzle. However effective the shielding gas may be in preventing atmospheric contamination, some form of deoxidant must be introduced to the weld zone to ensure complete freedom from porosity. For this reason, a series of filler alloys containing elements having a high affinity for oxygen have been developed. See filler materials/electrodes [7].

The American Welding Society [19] point out that copper and copper alloys normally have excellent corrosion resistance, electrical and thermal conductivities, and formability. Some alloys combine high strength and corrosion resistance, a combination desirable for marine applications. Others, because of their wearing properties, high hardness or corrosion resistance, are used as surfacing metals etc. Except for the highly-leaded free-machining alloys, copper and copper alloys can be welded if certain basic precautions are taken. Brazing and soldering can also be performed readily.
The CDA's numbering system used to classify the compositions of these metals is the standard of the industry. According to American Welding Societys manual (writers comment), the only copper used when an application require s welding or soldering is the oxygen-free copper, with a copper content of 99.95 % or better. In comparison to steels, copper and its alloys have higher thermal conductivities and higher coefficients of shrinkage and thermal expansion. As a result, welding sometimes requires preheating and high rates of heat input are necessary. Also, joints should be more open and joint spacing should be wider.
The manual discusses the physical metallurgy.Two-phase alloys harden rapidly during cold working and compared to single-phase alloys of the same elements, they usually have superior hot working and welding characteristics. Ductility usually decreases and yield strength increases as the proportion of second phase increases.

Small additions of certain elements can often improve corrosion resistance e.g. Fe, Si, Sn, As and Sb. Pb, Se, Te, and S improve machinability without significantly affecting conductivity or corrosion resistance, however, they adversely affect hot-working and weldability. B, P, Si and Li are deoxidizers; Ag and Cd inhibit softening. Cd, Co, Zr, Cr and Be produce high strength from precipitation during ageing, or through a combination of precipitation hardening and cold-working. They also cause an increased rate of work hardening during cold working.

The oxygen bearing coppers include the fire-refined and the ETP copper grades. Fire refined copper is produced from the non-electrolytic processing of scrap copper or from the treatment of ores. It contains varying percentages of impurities as well as, from 0.02 to 0.05 % oxygen in the form of a copper-copper cuprous oxide eutectic. These impurities may cause porosity and other defects during welding. ETP copper is the major commercial type of copper. It contains fewer impurities and, as a result, it has more uniform mechanical properties. The oxygen content is the same as that of fire-refined copper. The copper-cuprous oxide eutectic is scattered as globules throughout wrought metal, and has no serious effect on mechanical properties or electrical conductivity. But it does make the copper susceptible to gas embrittlement when heated in a hydrogen atmosphere. Hydrogen rapidly diffuses into the metal and reacts with oxides to form steam, this creates porosity at the grain boundaries of the copper. Carbon monoxide that may be present in oxyacetylene flames or reducing environments, can contribute to weakness if moisture is also present, as carbon monoxide may reduce water vapour to yield hydrogen, which will then diffuse into the metal. When oxygen-bearing coppers are heated above 907.2 °C for prolonged periods, as during welding, copper oxide concentrates in the grain boundaries and causes major reductions in strength and ductility. Thus, welding with oxyacetylene and other flame processes and brazing in a hydrogen atmosphere can be expected to reduce joint strength and ductility of oxygen- bearing coppers. Arc welding also reduces the strength and ductility of the joints as a result of oxide concentration at the grain boundaries, but this reduction is not as severe as the reduction produced by gas welding. Oxygen-bearing coppers are of medium strength and low hardness; if the copper oxide is uniformly distributed they are tough, ductile, and highly malleable. These coppers are plastic through a wide range of temperatures, and are commercially hot-worked between 648 and 891 °C. They are also cold-worked. They may be softened at temperatures of 243 to 810 °C, depending on the properties desired. Annealing in a hydrogen-bearing reducing atmosphere should be avoided because of the potential for the production of voids or fissures, which weaken the material. (Oxygen bearing coppers have excellent resistance to atmospheric and sea water corrosion).

The next group includes phosphorous-deoxidized copper and oxygen-free copper. Phosphorous deoxidized copper is copper from which oxygen has been removed by a precasting addition of 0.01 to 0.04 % phosphorous. If the phosphorous addition is closely controlled to obtain less than 0.01 % residual, the copper is a high conductivity deoxidized copper.

Oxygen-free copper is copper from which the oxygen has been removed.

Copper cathodes are melted and recast under an atmosphere which eliminates oxygen and prevents the formation of oxides during casting. Since no deoxidizing agent is introduced into the cast copper, copper produced in this way can absorb some oxygen from the air, during long heating at very high temperatures, and loose its oxygen-free characteristics, at least near the surface. The oxygen-free coppers have very nearly the same mechanical properties as the oxygen-bearing coppers, but are more uniform in microstructure. However, in the absence of inclusions of copper oxide, superior ductility and resistance to fatigue may be obtained. As compared to oxygen-bearing copper, phosphorous deoxidized copper containing less than 0.01 % phosphorous has the same or slightly lower electrical and thermal conductivities, and phosphorous deoxidized copper with 0.01 to 0.04 % phosphorous has lower electrical and thermal conductivities.

Phosphorous-deoxidized coppers are highly ductile. The absence of the copper-copper oxide eutectic improves the cold-working properties of these coppers, over those of oxygen-bearing coppers, particularly those for deep drawing and spinning operations. These coppers can be annealed between 243 and 810 °C in reducing atmospheres, since they will not be embrittled by hydrogen. Corrosion resistance is the same as that for oxygen-bearing coppers.

Special coppers are alloys that offer high electrical conductivity in addition to special properties unavailable in ordinary coppers. Leaded, tellurium-, selenium-, and sulphur-coppers have machinability ratings of about 80, compared to 20 for ordinary coppers (based on rating of 100 for free cutting brass). However, ductility and workability are reduced somewhat by the presence of the inclusions that impart the free machining characteristics. These free-cutting coppers can be supplied with a matrix of deoxidized or oxygen-free copper to prevent embrittlement or gassing when the special coppers are heated in hydrogen atmospheres. They are widely used in the manufacture of electrical connectors. These free-cutting coppers are difficult to weld by fusion methods without cracking.

The high copper group includes materials with enhanced mechanical properties due to the addition of small amounts of alloying agents. Chromium-copper combines a tensile strength of about 75 000 psi with a conductivity of about 80 % of the International Anneal copper Standard (IACS) after age hardening. Zirconium-copper is also heat-treatable, but is normally cold worked before it is aged. Ageing increases electrical and thermal conductivity. Zirconium-copper develops somewhat lower strength than chromium-copper, but it has a conductivity of 90 % IACS. Both alloys maintain good mechanical properties to approximately 324 °C. They are used for electrical and electronic components, and as resistance welding electrodes. Copper-beryllium alloys are of two types. One has a 1.5 to 2 % beryllium, while the other has about 0.5 % beryllium. Cobalt additions are made to these alloys to restrict grain growth during annealing. Alloys with about 0.5 % beryllium have higher conductivity but lower strength. Beryllium-containing alloys have a moderate tensile strength in the cold-rolled (but not age-hardened) condition. When age-hardened (by heat treatment at temperatures in the neighbourhood 324 °C) they have the highest tensile strength and hardness of all copper alloys.

Electrical and thermal conductivities are lower in the unaged condition than in the aged condition. These alloys are characterized by high endurance limits under fatigue stresses. Copper-beryllium alloys are generally good for hot working, but first care must be taken to ensure complete solution of large particles of copper-beryllium or cobalt-beryllium compounds. This is done by heating them for prolonged periods above the hot-working temperature range. These alloys are suitable for cold-working if they have not been age-hardened. They do not work-harden too rapidly and can be drawn, stamped or spun. The cold-worked or age-hardened alloys can be softened and made malleable by annealing in an exothermic atmosphere at 783 to 810 °C followed by water quenching. The age hardened copper alloy can be welded, but 100 % joint efficiency is normally not obtainable.

High-copper alloys generally possess many properties not available in ordinary copper (lower copper alloys), as good electrical conductivity, high hardness, high fatigue strength and high tensile strength. The special characteristics of each alloy should be considered, and welding procedures modified accordingly. Cadmium-copper is strengthened only by cold-working. Zirconium-copper, while it is heat-treatable is strengthened principally by cold-working. As-welded joints in these alloys will not have the maximum mechanical properties of the parent metal. Chromium-copper and beryllium-copper are precipitation-hardening alloys and should be heat-treated after welding. All high-copper alloys should be protected at high-temperatures from contact with the surrounding atmosphere to prevent oxidation of alloying elements. These alloys all have lower thermal conductivities than pure coppers, and therefore lower preheating and current requirements. Generally the procedures recommended for arc or gas welding deoxidized copper are good starting points for high-copper alloys, with the exception of the beryllium coppers. There are two main classes of beryllium-copper alloys: High strength alloys containing typically 2 % beryllium, 0.25 % cobalt, remainder copper; and high conductivity copper alloys typically 2.5 % cobalt, 0.5 % beryllium, remainder copper. Small quantities of nickel sometimes are added to replace some of the cobalt. Alloys with higher beryllium content are the more readily welded of the two classes. The addition of beryllium to copper lowers the melting point, increases the fluidity of the molten metal and decreases the thermal conductivity - all contributing to better weldability. Sound welds are also obtainable with alloys of lower beryllium content; however, weld cracking and cracking during postweld heat-treatment have been reported. Optimum mechanical properties are obtained by solution heat-treatment and ageing after welding. Welding is not normally performed on age hardened material. On heavy sections requiring multipass welding, the over-aged condition is more metallurgically stable than the solution-annealed condition, this may reduce welding difficulties, but post weld solution and ageing heat treatments will be required to develop the required mechanical properties.

The manual also deals with castings. Copper castings have been divided into twelve categories based on composition. Some of the alloys contain sufficient lead to render them non-weldable. However, welding may be performed on most of the nonleaded alloys, and with proper precautions welding may be done on some of the leaded grades. Welding of castings is required for rebuilding, repairing, surfacing and joining. Mechanical properties will vary with casting practice and design. Castings are more porous and have rougher surfaces than wrought products and, therefore, extra care must be taken during preparation for welding. Surfaces should be ground or machined smooth, unsound metal or porosity should be cut out, and the parts should be free of grease and scale [19].

When welding thicker sections, the high thermal diffusivity, four to five times that of mild steel, is responsible for a very large number of failures in copper. Unless adequate measures are taken to counteract the rapid heat sink effect, it is not possible to establish the fully fluid weld pool necessary for good fusion and deoxidation. Lack of fusion defects and porosity will therefore arise. Pre-heating copper before welding is generally considered necessary for thicknesses above about 3 mm when using argon shielding. The thermal expansion of copper is also high and due allowance must be made for the tendency for root gaps to close and/or open as the temperature of the metal changes during welding. Metallurgically, welding copper by gas-shielded processes presents no special difficulty, but the ETP coppers do require additional care during welding. Wrought copper contains cuprous oxide in the form of trans-granular stringers but these have only a minimal effect upon the overall strength and properties. In the cast form Oxides are present at the grain boundaries and this weakens the structure and seriously affects the mechanical properties, therefore a suitable deoxidant-containing filler metal must be used to provide a completely deoxidized weld deposit. In the HAZ of wrought ETP copper, temperatures during the welding operation may be sufficiently high to permit diffusion and migration of oxide particles to cause porosity in the HAZ, for this reason the welding operation should be performed as rapidly as possible and the overall heating should be restricted.

Defect-free welds in the cast oxygen-free (OF) and phosphorus-deoxidized grades of copper can be made without additional filler alloy by supplying effective inert gas-shielding to the weld area and the underside of the weld. Unless considerable care is taken however, there is a likelihood of porosity occurring in the weld metal and HAZ. This is caused by atmospheric contamination or by diffusion of gases up the thermal gradient from the colder regions of the parent metal towards the weld metal.

he residual phosphorus content of the phosphorus-deoxidised grade is normally sufficient on its own to act as a satisfactory deoxidant during welding.

Copper alloys, in contrast to copper, seldom require preheating before welding.

But attention must be given to the welding process. In many cases deoxidation of the weld pool is achieved by the elements already present in the parent metal. In particular instances deoxidants such as Ti and Al are added to the filler metal to ensure complete deoxidation and freedom from weld metal porosity.

Work hardening and precipitation-hardening alloys, whose strength depends upon previous cold working, suffer a serious and irreversible loss of mechanical properties when welded. Welded joints in such materials must therefore be designed to take account of this loss. A limited amount of welding is carried out on the heat treatable alloys that include copper-chromium and copper-beryllium alloys. These are normally heat-treated to give optimum mechanical properties by a solution treatment, followed by a subsequent low temperature precipitation-hardening treatment.

To avoid cracking of the hardened material during welding, and to facilitate subsequent heat treatment, welding is normally carried out in the solution-treated condition, followed by a re-heat treatment to regain some of the properties of the hardened material.

Both copper-chromium and copper-beryllium alloys form refractory oxides that are dispersed by AC working when using the TIG welding process. Filler metals of matching composition are used, the chromium and beryllium additions providing adequate deoxidation during welding. A TIG welding in argon is the conventional technique, but D.C. electrode negative working in helium has also proved very successful, particularly for copper-chromium on which there is some experience in the reclamation of worn components [31].

Small amounts of Bi and Pb promote cracking in copper welds; Bi is harmful in thousandths an Pb in hundredths of one per cent. It was at one time suggested that while copper welds are solidifying the impurities concentrates along the boundaries of the primary grains in the form of low melting films of eutectic composition; the eutectic alloy of copper and 99.85 % Bi has a melting point of 270 °C, while the eutectic alloy of copper and 99.94 % Pb has a melting point of 326 °C. It has instead been suggested that the embrittlement of the copper is caused by the adsorption of impurities at the grain boundaries rather than by the formation of low melting films. This article records the results of structural examinations of copper welds containing Bi and Pb with and without additions of As, and discusses the connection between this phenomenon and the crack resistance of the welds. The experimental material was grade MB deoxidized copper (TsMTU 3304-53). Full penetration welds were made on a clamped 6 mm thick plate (graphite backing strip was used). The SAW process was used. Bi and Pb powder were added to the weld metal along the axis of the weld and the surfaces containing 0.008 % Bi or 0.08 % Pb were affected by transverse cracks while those welds without these impurities where not. During metallographic examination of the welds a significant difference was observed between the microsections taken from the copper welds with and without Bi or Pb. In the first case with Bi or Pb the structure was cellular, but in the second the grain intercept surfaces on the microsections remained smooth.

Also a pattern of grain boundaries and a relief structure indicating the presence of cells could be seen. In some places the cell walls ran in close proximity to or coincided with the grain boundaries. It has been established that a cellular structure develops when metal containing impurities solidifies under certain conditions. The impurities segregate preferentially in the cell walls and when the cell walls coincide with the grain boundaries there is a high risk of crack initiating and propagating as the cooling metal undergoes strain.

Attempts where then made to neutralise the Bi and Pb effect on crack resistance of copper welds, by adding other alloys, on the grounds that it should be possible to combine the impurities into insoluble chemical compounds with melting points above that of copper, or take them into solid solution, but in any case prevent them from segregating and being adsorbed at the grain boundaries. Ce and Zr failed to improve the crack resistance of copper containing Bi or Pb, without converting Bi or Pb to insoluble chemical compounds it is necessary to minimise the chemical heterogeneity developing as the weld metal solidifies and prevent their adsorption at the grain boundaries while the metal is cooling. As the number of alloying elements is increased the hexagonal cells become distorted, and dendritic solidification takes over at certain ratios of alloy content, temperature gradients and rates of the solid-liquid interface. Under these conditions the low melting impurities will be distributed uniformly in the spaces between the dendrite arms. The authors reference to a report where they are choosing an alloying element to counteract the effect of Bi and Pb in copper welds relying on Kunins data on the surface tension of molten metals near the melting point. The surface tension of Bi is close to that of Pb and the theoretical value for As is of the same order. The writers had earlier discovered that no cracking occurs in welds containing up to 3 % As. Tests where then made with As and it was seen that 0.75 % As was sufficient to prevent cracking in copper welds containing 0.008 % Bi or 0.08 % Pb. The least pure copper according to the report is grade M3 copper containing a maximum of 0.003 % Bi and 0.05 % Pb. The structure has changed from cellular to dendritic as the As content is increased and the crack resistance of the weld metal increases without the precipitation of a second phase. A batch of wire was made to provide the optimum As concentration in the weld. The quality of the welds made with the As copper wire and of welds made with wires not containing As was evaluated in terms of the mechanical properties. No cuprous oxide inclusions were found in the latter but areas with temper colours were observed at the fracture, indicating the presence of internal cracks. There were no defects at the fracture faces of the joints welded with copper wire containing As [18].

This author [1], believes that in the future there will be modification and development of existing processes so that they can be more easily and reliably applied. The construction materials are still changing and developing so that joining procedures will have to be adapted to join them satisfactorily. Dispersion strengthened, particle and fibre reinforced copper are entering, bringing the problem of maintaining the enhanced mechanical properties of the material across the joint itself.

Cladding and surface coating applications of copper are growing due to its good corrosion resistance (and appearance). Their application to cheaper base metals is itself a joining process and one which requires the highest level of adhesion to the substrate in addition to integrity of the surface layer itself.

Recently the space program, offshore oil exploration and nuclear waste disposal have created new demands on materials and joining processes. As to last mentioned case thick copper sections requiring high integrity joints are needed and, due to the rapid heat dissipation in the thick material, high energy electron beam welding has been utilised to good effect.

3.2 Filler-materials/electrodes:

Coated electrodes are limited to welding phosphorus-bronze, cupro-nickel, and silicon-bronze coppers. Bare electrodes can be used on copper and its tin and silicon alloys.

Use copper or carbon backing strips, flat or grooved. Grooved strips leave a small bead on the underside of the weld [4]. (See also ref. [25] at section 3.11).

Normally, copper should be welded with filler metal containing deoxidizers. Although a flux is not necessary for gas-shielded welding, light fluxing is recommended to remove surface oxides produced by preheating. The usual method is washing with a standard brazing flux mixed with hot water. Filler metals suitable for use in brazing copper are generally alloys using phosphorus, silver, copper, boron, zinc, and other elements as needed. Their selection is usually a matter of picking the optimum melting temperature and corrosion resistance. Sections to be brazed must be fully heated to aid capillary action and to ensure deep penetration of the alloy. At brazing temperature, a clearance of 3 to 5 mm is good, and the length of overlap should be at least two to three times the thickness of the thinner member [5].

Boron-deoxidized filler material is normally used only where joint of high electrical conductivity is required according to both [8] and [16].When welding oxygen free or deoxidized copper a tin-bearing silicon-deoxidized rod will do, with some phosphorous and manganese to improve weldment properties [6]. [7] refers to BS 2901 Filler rods and wires for inert-gas arc welding, where the range of filler alloys available for welding copper by inert gas techniques are included. TIG welding filler material alloyed with Mn, Si, Sn and Fe or with B goes for all the copper grades, while filler material alloyed with Mn and S only goes for Phosphorous deoxidised-non arsenical copper. MIG welding filler material alloyed with Mn, Si, Sn and Fe or with B goes for all the copper grades, while filler material alloyed with Al and Ti goes for all the copper grades except for the oxygen-free-high conductivity copper. Finally, for phosphorous deoxidized non-arsenical copper, filler material alloyed with Mn and S should be used. The Boron deoxidized filler was developed primarily for high electrical conductivity applications, boron interfering very little with the electrical conductivity. Its excellent welding characteristics, however, favour its use in applications other than those requiring optimum electrical conductivity in the joint. Ref [19] recommendations are that when welding high-copper alloys, filler metal of the same composition as the material to be welded responds fully to postweld heat-treatment. Chemical analyses of filler metal and weld deposits have shown no loss of beryllium during either gas tungsten-arc or gas metal-arc welding. The difficult-to-weld lower beryllium alloys (see base-materials), can be joined more readily with filler metal of beryllium content higher than that of the parent metal. However, full response to postweld heat-treatment will not be obtained. SMAW with aluminum bronze electrodes, and TIG with silicon bronze filler rods, have been used for repair welding where high mechanical properties are not required. When beryllium-copper is heated in air, a tenacious high-melting oxide coating is formed. It does not melt or dissolve in the molten base metal, and precautions are necessary to retard the formation of the oxide and avoid its inclusion in the weld deposit. In multipass welds, interpass grinding is suggested to remove the oxide from the weld surface.

An investigation was conducted [20] into the effect of the composition of electrode wire on the properties of submerged-arc welded joints in copper. The author claims that designers, in evaluating the quality of welded joints made of copper, usually restrict their considerations to the characteristics of the strength properties determined by tensile testing flat specimens. If it is taken into account that the weld metal is subjected to the effect of only transverse tensile forces, it becomes evident that the effect of any hidden defects, detected in longitudinal tensile loading, may not be noticed. This investigation has according to the writer taken this into account. The author has through references found that alloying with small amounts of, for example, chromium and titanium greatly improves the mechanical properties and strain capacity of weld metals in copper. For comparison in the investigation welded joints also were produced with unalloyed electrodes. The butt joints in 18 mm thick plates of unalloyed parent metal (oxide content 0.002 %) were welded with a wire 5 mm in diameter, and a flux ensuring the highest resistance of the weld metal in copper against porosity was used. The parent metal, welding wires and welded joints were analysed to determine the hydrogen and oxygen content. Spectrographic analysis was also conducted. The mechanical properties showed a large reduction (halving) in the strength of the weld metal (in comparison with the parent metal) welded with unalloyed wire in deformation in the longitudinal direction. This was accompanied by brittle failure of the specimens with the formation of tears throughout the entire working necks. Oxidised regions appeared on the fracture surfaces. This indicates that the weld metal contains transverse microcracks of solidification origin, although they where not detected in examination of the microstructure on the longitudinal sections. The formation of microcracks is associated with the fact that copper has relatively low solidification cracking resistance. The latter can be improved by alloying. The author found in yet another reference that even alloying with small amounts or certain elements, including Cr and Ti, also greatly increases the crack resistance of the welded joint, which also was confirmed by the mechanical tests. The used weld metal alloyed with Cr, Si, Mn and Ti was deformed plastically, without tearing and its mechanical properties were similar to those of the parent metal. The positive effect of alloying was also detected in transverse deformation of the weld metals.

The mechanical properties of the welded joints were also improved by the absence of micropores in the weld metal. If weld are made using the non-alloyed wire micropores may form in the welds. The number of micropores depends on the thickness of the welded metal since it is well known that an increase of the thickness of the welded metal increases the porosity susceptibility of these welded joints. The authors conclusion is that alloying with small amounts of Cr and Ti ensures satisfactory solidification cracking resistance, prevents microporosity and improves the mechanical properties of the weld metals in copper at a relatively small reduction of electrical conductivity.

When joining and repairing copper-based castings one of the major considerations is the correct selection of filler metals. The filler metal must have closely matching corrosion resistance to the bulk casting when the component will experience a corrosive service environment. If it is necessary to employ a non-matching filler metal, it must be cathodic to the bulk metal to prevent galvanic corrosion on the smaller area of the weld. The filler metal must have comparable mechanical properties to the bulk casting alloy.

The filler metal must contain deoxidants to provide effective deoxidation and a sound weld. Colour match of filler alloy to bulk metal may be important [31].

When TIG welding pure copper plates 10 mm in thickness, using Cu-Ti alloys electrode wires and Ar-N_2 gas mixture shielding the Vickers hardness, yield stress and the tensile strength of the weld metal increases with the Ti content of the electrode wire. The elongation and the reduction of weld metal area shows maxima at Ti content of about 0,5 % in the electrode wire, and the elongation and reduction of area are also higher than achieved with electrode wires of pure copper weld metal. The increase of yield stress and tensile strength may be attributed to solid-solution hardening by Ti. The changes in the elongation and reduction of area with the Ti content can be explained in the following way; the elongation and reduction of area are lower in the pure copper weld (with many blow holes) than in the weld metals containing Ti (with few blowholes), because Ti hinders the blowhole formation of N_2; the Ti addition of more than 0.5 % doesn't have any more effect on the number of blowholes, but reduces the ductility of the weld metal, because of solid solution hardening by Ti. This may be the reason why the total elongation and reduction of area have maxima at about 0.5 % Ti.

The tensile properties e.g. yield stress, tensile strength, total elongation and reduction of area do not depend on the percentage of N_2 in the argon shielding gas.

The Vickers hardness increases with the amount of beta-phase. The precipitation of beta-phase increases with an increase in the titanium content of the electrode wire and with a decrease of the percentage of N_2 in the argon shielding gas [11].

3.3 Welding copper and its alloys:

Reference [6] suggestion is to, due to coppers high thermal conductivity, make all joint preparations with wide root gaps and to tack frequently so avoiding incomplete fusion and inadequate joint penetration. To avoid defects such as porosity and incipient cracking, one should be sure that weld pools are fully fluid for good fusion and deoxidation. Conductivity causes problems with parts 3.2 mm and thicker. Much of the heat supplied by the arc flows to areas removed from the weld zone, so deposited metal can form a heavy bead with incomplete penetration and overlap. This condition can be solved by preheating, as much as 425 to 540 °C is needed for 25 mm sections. To reduce the preheat requirement, substitute helium for argon in the shielding gas.

Make heavy root passes in all multipass welds to ensure deoxidation and to prevent cracking.

According to this author [10], proper selection of a welding process and filler material depends on factors such as; base metal composition, section thickness, thermal conductivity, elongation of both base metal and joint, degree of expansion, current and equipment available, fitup and joint design, application requirements, codes and specifications. Greater thermal expansion coefficients, higher thermal conductivities, and in some cases, a hot shortness tendency, account for many of the differences between welding copper materials and ferrous metals.

For example, joint openings have to be wider to allow for the difference in fluidity of the copper weld pool, and more tack welds during fitup are often required to help compensate for coppers higher expansion coefficient. Preheating is very important when welding any of the coppers. Insufficient preheat results in incomplete fusion and lack of penetration, especially when welding thick sections. Other practical suggestions for successful welding of coppers and its alloys include, flat position welding if possible, the use of spray arc with MIG and the use of short circuiting and pulsed arc MIG when welding out of position. TIG techniques are similar to those used for welding aluminum, the use of a dip technique, pulsed power sources, inert gases such as helium or argon or mixtures of both. A high percentage of weld deposit difficulties can be traced to either insufficient gas flow rates or incorrect gas selection. Welding in a drafty area or incorrect torch angle and direction of travel can result in deposit oxidation. Base metal cleanliness is another important consideration, the surfaces should be freshly ground or machined.

The ability of any welding method to make a good weld changes as copper changes from pure to an alloy. To pick the best welding method consider the size, shape, and joint-design of the weldment, the metallurgical properties you want and the jigs or fixtures the job needs. Once you have picked the method follow the rules; Leave a bigger gap than with steel, copper expands more, and a small gap will cause excessive warpage and stress. Another warp-and-stress reducer is frequent tacking. Use backups to offset the high heat conductivity of copper. Higher than steel preheats are needed, heat in copper dissipates fast. High preheat helps the welding method do its job fast so fewer alloying agents vaporize. It is necessary to use higher-than-steel arc welding amperages and to deposit filler metal fast. MIG and TIG welding make sound, strong and ductile welds in copper. They confine the pool to a small area by using a high current. TIG should be shielded with Ar or He, preferably Ar. Ar should be used for MIG welding copper of 3 mm thickness or less. For thicker sections, an Ar-He mixture (50 - 75 % He) should be used [4].

Unless adequate measures are taken to counteract the rapid heat sink effect, the fully fluid weld pool necessary to obtain good fusion and deoxidation by the filler alloy is difficult to establish. Full root and sidewall fusion may not be secured and the result is a defective and unsightly weld deposit. Preheating copper prior to welding is therefore essential at thicknesses above about 4.8 mm. The thermal expansion of copper is also high and due allowance must be made to counter the tendency for root gaps to close as welding proceeds. For thicknesses of copper up to about 6.4 mm the TIG process, plasma process, and fine wire MIG process should all be considered as possibilities according to the requirements of the joint, e.g. welding position, joint design, accessibility, controlled penetration, etc. Above about 6.4 mm the standard MIG process is normally considered best to meet the requirements for rapid metal deposition rates and good heat input. There are considerable advantages, whilst still maintaining spray transfer conditions, in using mixtures or Ar with He or N to reduce the high level of preheat required for thick sections [7].

When welding the high-copper alloy, beryllium copper, airborne particles of beryllium compounds are a health hazard to personnel.

Operations such as welding or grinding create a fine, inhalable dust or fume and should not be permitted to raise the beryllium in the air above specified tolerance limits. Ventilation will probably be required to avoid unsafe occupational exposures. In oxyacetylene or arc welding cadmium copper, a flux containing sodium fluoride as an addition to fused borax or boric acid is recommended to dissolve cadmium oxides. For chromium coppers, fluxes containing fluorides with or without alkali chlorides are recommended. Significant vaporization of cadmium can be expected in fusion welding processes. When it comes to chemical cleaning and pickling, standard solvents such as trichloroethylene, mixed acetates, and toluene may be used on copper and copper alloys. Alkaline cleaning solutions are used hot to remove thick oils, fats, and dirt. More examples are given in the manual to remove light tarnish, conduct pickling, remove scale etc [19].

This report [30] provides the information necessary to select which process of EB or Laser, if either, should be used (for welding small components). With an understanding of the considerations used in selecting the proper welding process, it is possible to improve quality, increase production and reduce costs of laser and EB welded components. When laser or EB welding small components, it is sometimes possible to achieve the desired results with either process. However, one process may be better suited for a particular application. Beyond the principles of operation of the laser and EB are the considerations of weld requirements, material-to-beam (laser/electron) interaction, joint design, fixturing, and equipment/ production costs. By evaluating these areas it may be possible to obtain the best process for the existing situation. The possibility that neither the laser nor EB process would be suitable should not be discounted. The similarities between the two processes are: high energy density beams; low total heat input; minimal/no part distortion after welding; excellent weld quality; autogenous - requires no filler metal; weld joints require minimal clearance; poorly accessible joints welded; weld thick or thin parts; high welding speeds with CO_2 and EB welders; weld metals with dissimilar melting points and thermal conductivities. The differences are: EB welds in vacuum - laser welds in open atmosphere;
EB deflected by magnetic field - laser beam not affected; laser beam partially reflected by materials with high reflectivities - EB not affected; EB requires parts to be electrically conductive - lasers require parts to absorb their wavelengths;
EB welders provide higher power levels and deeper penetration than laser welders do. The laser produces a high energy density beam that is focused onto the workpiece. The weld produced is the result of a sufficient amount of radiation, of the proper wavelength, being absorbed. The beam power and diameter are adjusted to provide the density necessary to increase the temperature of the parent metals above the melting points of the metals. Excessive vaporization can result if the density is too high. There are several types of lasers used for welding. The solid state Nd:YAG (neodymium-doped yttrium aluminum garnet) and the gas CO_2 (carbon dioxide) lasers are used most often when welding small components.

Each system has advantages, disadvantages, similarities and differences when compared to the other, as they do when compared to the EB welder. The Nd:YAG laser welder's beam is normally operated in a pulsed mode.

Although the Nd:YAG is available as a continuous wave (CW) or beam, the pulsing provides the means for achieving higher peak powers, resulting in deeper penetration. When continuous welding is used the speed is restricted to less than 8.5 mm/s. Average power outputs of the Nd:YAG laser range from 50 watts to 600 watts. Industrial CO_2 lasers are available with power outputs of 500 watts to over 20000 watts. Unlike the Nd:YAG, the CO_2 may be operated in a pulsed or continuous mode. A CO_2 laser operated in the pulsed mode is capable of pulsing at much higher pulse rates and widths than the Nd:YAG. Welding speeds over 42 mm/s are possible with the CO_2 laser.

An electron beam weld is the result of heat produced by electrons striking the work piece at high velocity. EB welding is usually performed in a vacuum chamber with workpieces and fixturing inside. The electron beam is focused onto the workpiece in a similar way to the lasers beam. The electrons are deflected by magnetic fields, therefore, they can be manipulated by this means. This allows the beam to be deflected off centerline, usually less than 10 degrees, and oscillated into circles, ellipses, and squares. EB welders are classified by the vacuum and acceleration voltage used for welding. There are high vacuum (above 10-5 torr), medium vacuum, low vacuum and non vacuum systems. Low voltage machines operate in a range between 60 kV and 200 kV. High voltage EB welders can provide greater penetration than low voltage systems. With high vacuum welders, contamination levels (due to air) can be reduced to less than one part per million (ppm). Also, the higher the vacuum, the less dispersion of the beam, thus, the greater the penetration and farther the allowable operating distance between the electron gun and the work piece. There are certain restrictions and requirements that should be considered when welding in vacuum. In order to produce a flow of electrons onto the workpiece, the workpiece must be electrically conductive. Also, magnetized workpieces and fixturing can cause undesirable deflection of the beam, if the field is strong enough. Proper degaussing can aid in reducing this problem. Since EB welding is performed in a high vacuum, the workpiece or assembly must be able to withstand this environment. This restricts the use of EB welding on assemblies that are coated with, or contain, substances that vaporize under high vacuum.

Weld requirements should be restrict to those necessary. Requesting an excessive penetration along with minimal distortion may be costly, if not impossible, due to the extra heat input required to produce unnecessary penetration.

Laser and EB welders are used extensively for hermetic sealing. A hermetic seal is characterized by its ability to prohibit intrusions. Leak rates are tested by the use of a helium mass spectrometer for critical seals. The principle objective of the laser / EB weld on a hermetic assembly is to produce a seal that has no leak path. Defects can be the result of the weldability of the material, contamination due to the welding atmosphere, joint design, or improper weld settings. Discontinuities, such as microfissures, are not necessarily defects. A defective hermetic seal would have to produce an unacceptable leak rate by providing a leak path. The depth of penetration produced by the EB welder is affected by acceleration voltage, degree of vacuum, and working distance between the electron gun and work piece. The depth of penetration required may be determined by the strength requirements of the weld, thickness of material, or amount of sealing required.

Due to power limitations, deep or shallow welds may not be produced with certain welding systems. Therefore, it is important to be able to select the best joining method for the desired penetration. The parameters affecting the penetration may be due to the components being welded and the welding process e.g.: material grade and properties (melting point / thermal conductivity); welding speed; weld atmosphere; focus of the beam; joint design.

Factors affecting the grade of penetration of laser welders include pulse shape and width (for pulsed laser systems), material surface finish. The Nd:YAG laser has currently restricted use in welding components that require more than 2.5 mm penetration. Recently (1985) developed Nd:YAG slab crystals, as compared to present cylindrical crystals, will allow for higher powered Nd:YAG lasers to be more competitive with the CO_2 and EB welders. CO_2 and EB welders are capable of producing over 20 kW and 100 kW, respectively. The ability to alter the depth-to-width ratio of the weld bead has several advantages. Distortion can be minimized by welding with a high ratio, producing a weld with almost parallel sides. A high dept-to-width ratio also allows for the maximum penetration with minimal heat input. Welding with a high depth-to-width ration also has its disadvantages. Beam alignment onto the weld joint becomes very critical. Run out of the workpiece must also be minimized to assure consistent penetration with high depth-to-width ratios. A lower dept to width ratio will cause the weld bead to flow more evenly when excessive gaps in weld joints are welded. The dept to width ratio is regulated by the lasers and the electron beams mode of operation, focus, and welding speed. The key hole process (continuous wave) produces high depth to width ratio but can also produce welds with lower ratios, by adjusting power, focus and speed. By focusing to increase the power density of the beam, e.g. reducing the spot size, greater penetration with narrower width can be achieved. Welding at a high rate will normally produce a higher ratio, but the maximum depth of penetration is achieved at lower welding speeds. Under constant power conditions, an increase in acceleration voltage will provide an increase penetration and decrease in weld width (higher ratio).

The total heat input of the welding process is an important consideration when welding heat sensitive components. Laser and EB welding processes provide lower total heat inputs, as compared to conventional welding methods. Pulsed beam welding systems offer even lower total heat input than continuous wave or beam systems.The material being welded are considered due to their effects on the laser and electron beams, as well as the effects of the beams on them. Weldability may be influenced by materials chemical composition and physical, mechanical and thermal properties. When using EB, as mentioned earlier, the workpiece must be electrically conductive. To produce a laser weld, a sufficient amount of energy must be absorbed by the workpiece. This absorption is dependent on the wavelength of the laser beam, and the reflectivity and surface finish of the material being welded. Materials such as gold, silver and copper are highly reflective of both Nd:YAGs and CO_2 s wavelengths. This sometimes restrict the use of laser welding on these materials. However, reflectivity and absorption are not always a major concern since higher power levels can sometimes initiate melting by increasing the metals temperature and decreasing reflectivity.

The thermal conductivity of materials can influence the selection of a welding process. Welding a material with a high thermal conductivity will require greater heat input than one with a lower value when requiring equal penetration. It also affects the rate of solidification (increases it), and can be responsible for weld bead cracking. Due to higher power levels, the CO_2 laser and EB can achieve greater depths of penetration than the Nd:YAG, under these conditions, due to higher available power. Also the pulse mode restricts the use with materials sensitive to rapid solidification, e.g. with high thermal conductivity. The extremely high temperatures achievable with laser and electron beams can cause excessive vaporization and porosity when welding materials containing elements with high vapour pressure. Materials containing zinc and magnesium react severely to these processes. Aluminium-magnesium alloys and copper-zinc alloys (brasses) are limited in use with laser and EB welding. Some materials are extremely reactive to the atmosphere in which they are welded. For those materials which are sensitive to the welding atmosphere, or gas shield, the vacuum of the EB process can provide an excellent welding environment. Although the laser process can be adapted to weld in a vacuum chamber, it is normally used with gas purging nozzles. Contamination can be reduced, when laser welding, by using a helium or argon atmosphere. The laser and EB processes are autogenous, therefore they require no filler metal. This eliminates the need for grooves, bevels, or chamfers on weld joints. The clearance between the parts being joined should be minimized according to the parent material thickness and desired penetration depth. Components requiring limited total heat input should be designed with minimal gap at the weld joint that allows for proper heat flow between the parent metals. The Nd:YAG or CO_2 laser can provide excellent cycle time since these systems do not require a vacuum atmosphere for welding. When EB welding, pumping down the vacuum chamber may take between five seconds to several minutes. A solution is, for welding large quantities of a single part, most EB systems can be equipped with a large continuous transfer system that puts a part into a pre-evacuation chamber, then into the welding chamber. This continuous transfer and the multi-station system (where several parts can be loaded at the same time in the chamber), allow the electron beam welders cycle time to become competitive with that of the laser [30].

The edge preparation selected for a particular welding operation depends upon the following factors: the alloy; the thickness of the joint; the welding process; the welding position and accessibility of the joint area; the type of joint, e.g. whether butt or fillet; whether distortion is likely and requires control; the control required on the profile of the penetration bead; economic aspects of weld metal consumption and wastage of metal in edge preparation. Pre-weld cleaning must remove all traces of oxide, dirt and grease using a bronze wire scratch brush to expose clean metal, followed by degreasing with petroleum ether or alcohol. Wire brushing should also be carried out after each run to remove as much as possible of the oxide film formed during welding. The purpose of jigging and backing techniques is to ensure that the parts to be joined are accurately positioned to prevent excessive distortion during welding and to provide a means of controlling and supporting the weld penetration bead. The design of jig etc. will depend upon the pre-heat requirements, alloy thickness and type of joint.

Where accessibility is limited, integral backing bars may be used. These are of matching composition intended for fusing into the weld itself to become an integral part of the joint. When welding copper with argon shielding, it becomes increasingly more difficult to form and maintain a fluid weld pool without pre-heating as the thickness of the material increases. The use of argon-helium, argon-nitrogen mixtures, or pure helium or nitrogen in place of argon can substantially reduce pre-heat levels.

Most copper alloys, even in thick sections, do not require pre-heating because the thermal diffusivity is much lower than for copper, if needed the temperature will seldom be over 150 °C.

For metallurgical reasons unnecessary heating should be avoided therefore also inter-run temperatures and time allowed for the structure to cool after each weld run should be restricted. The reason for this is that most copper alloys suffer a fall in ductility from about 400 °C to about 700 °C, therefore the heat should be restricted to as localised an area as possible to avoid bringing too much of the material into the critical temperature range.

When welding castings the basic principle to be successful is the establishment of a sound metal base from which to work. Gas and shrinkage porosity in the cast structure can seriously impair the achievement of a fully sound weld deposit. Therefore, good preparation to remove all traces of defective metal is the utmost importance. This means that some form of non-destructive testing technique must be applied to monitor preparation work. Radiography is indispensable in this respect, supported by intermediate dye-penetrant checks to guide progress.Ultrasonic techniques are making rapid strides as an improved and handleable NDT method giving an instant read-out signal, but their application in the foundry is not yet fully developed because of the difficulties in interpretation of the defect signal from what are often random effects. Conventional grinding and chipping are used to prepare the welding site, although the amount of metal removed in the case of a weld repair should only be sufficient to clear defective metal since the more weld metal required to fill the cavity, the greater will be the overall heat input during the operation and the consequent risk of distortion and undesirable metallurgical effects, as well as the extra time and effort. The final shape of the preparation or excavation must be such as to permit full access of the welding electrode to the root, since complete fusion at this point is essential for satisfactory results. All traces of metal chipping, dirt, grease and dye-penetrated fluids must be removed from the weld area before welding is commenced.

When selecting the process and the technique for a repair operation, the use of gas-shielded arc welding is recommended except for minor repairs because of the inherent risks of slag and flux inclusions present with manual metal arc and gas welding [31].

3.4 Gas shielded arc welding. Generally for both MIG, metal arc inert gas welding and TIG, tungsten inert gas welding:

In TIG and MIG welding the inert gases supplied to the torch tip keep oxygen out and do not react with the copper being welded. Of the various inert gases used, argon produces the lowest arc voltage and power output for a given arc length and current flow. Nitrogen, however, results in the highest ratings and is the cheapest inert gas, but at normal arc lengths, it may produce voltage high enough to blow molten metal out of the pool. Holding an unusually long arc length can reduce this effect, but then you risk losing the protective atmosphere. Helium at a flow rate of 20 to 40 is the preferred shield gas, requiring less preheating than argon and resulting in higher metal penetration, higher weld speeds, and less oxide entrapment. As a rule of thumb, argon, which is less costly, may be used for welding copper up to a thickness of 1.6 mm, helium being the usual choice for heavier stock. Mixtures of these gases are often used for greater economy. If Argon is the shielding gas, no preheat is necessary for sections up to 6.4 mm, about 108 °C preheat should be added for thicknesses up to 9.6mm, with another 108 °C for each additional 3.2 mm of thickness. Above 15.9 mm, as much as 405 °C may be required. When helium is used as the shielding gas, preheat temperatures may be 10 to 15% lower. Oxyacetylene-torch heating is suitable for thinner stock, but propane burners are better for heavy sections. Extra welding current is not a good substitute for preheating because it may blow the metal, destroy the gas shield, and produce porosity and poor beads. Also, preheat should be maintained during the welding process, with the use of asbestos blankets or asbestos-lined fixtures, if necessary. As with any welding process, flat downhand welding is preferred because it is cheaper and better. Although all-position welding is possible, it is only used when the preheat required by arc welding is not practical. For full penetration in butt-joints, the 90-deg V-groove is usually used for stock thicker than 4.8 mm, in heavy plates the angle should be at least 75 deg. U-grooves , however, are often applied to heavy sections because they tend to keep the width of the weld within reason. Minimum root space of 4.8 mm is suggested, with graphite backup plates to contain the molten metal [5].

It is generally recognized that the TIG process is most suitable for use on material thicknesses up to and including 9 mm. For above this figure travel speeds decrease and arduous working conditions prevail. Beyond this thickness, the MIG process is preferred, although when using small diameter wires and a spray type arc welding can be performed on the thin sheets normally welded by TIG. This is now made easier with the advent of the pulsed MIG system. Where positional welds are required, the MIG process can be used, but it must be emphasised that welding in the flat position is preferred whenever possible. One of the outstanding problems encountered with MIG positional welding of copper is the maintenance of the correct balance between holding the weld pool in position and the preheat level necessary to ensure adequate fusion.

It is the authors opinion that consideration should be given to the use of the TIG process for these positional welds (especially overhead) despite its slower and somewhat laborious operation.

The choice of edge preparations for welding copper is influenced mainly by the material thickness and the welding process to be used. Other considerations such as degree of penetration required, welding position and accessibility and control of distortion of the joint, and whether or not a backing bar or strip is to be used will have to be taken into account. Square edge, single and double V or U preparations can be employed with copper.

The high thermal conductivity of this material and the preheat required to obtain penetration between weld metal and parent plate results in a relatively wide area near the weld pool being very near its melting point. Sudden collapse of the joint area is likely to occur, especially where narrow V preparations, 40 - 50° included angles, are used on material thicknesses greater than 6 mm. Wider V preparations, 60 - 90 °, allows the arc to impinge upon the root of the V without the risk of side wall collapse. When setting-up for welding copper, successful jigging and the provision of backing bars for supporting the resultant penetration bead, can be accomplished by several methods. The design of the jig must allow welds to be made without causing unnecessary chilling, and must therefore be related to the type of joint, the thickness of the material, and the preheat requirements to effect fusion. Mild or stainless steel backing bars may be used to support the penetration bead. To prevent possible sticking the backing bars should be lightly coated with colloidal graphite or a graphite-based anti-spatter compound. Integral backing bars are used where joint edges are critical. Asbestos sheets and carbon blocks are useful as weld backing supports, since they resist the initial heat input, and are not prone to fuse to the underside of the joint. Asbestos placed between the clamping bars and the back up plate to sandwich the copper is most effective in preventing rapid heat dissipation during welding. On such fabrications as storage vessels that exceed the capacity of a jig, tack welding, or alternatively clamps and wedges, can be used for maintaining joint alignment and root gaps. Tack welds must be made in the manner that a main weld would be deposited, e.g. with preheat at the required level and with filler. As an alternative to tack-welding, the employment of tongue-grooved clamps may be used to maintain alignment and specified root gaps. Controlling root openings with the use of tongue-grooved clamps is a practice often preferred, as the chances of a tack weld breaking or the possibility of a root defect occurring when refusing a tack weld is eliminated.

The usual cleaning procedures are necessary before commencing to weld copper, e.g. wire brushing to remove all dirt, oxides etc. During preheating operation oxide scale forms rapidly above about 300 °C. The scale contains two types of oxides, the outer layer, black cupric oxide, can easily be removed but the oxide layer in contact with the material, red cuprous oxide, is impossible to remove.

In the welding of copper, the heat is conducted away from the joint area so rapidly that it becomes increasingly difficult to form and maintain a weld pool as the material thickness increases.

Copper can be welded without preheat up to a point, but higher welding current is required and the chances of producing a defective weldment is increased, such defects as lack of side and/or inter-run fusion, oxide folds, and elongated concavities may occur.The optimum preheat temperature for any given plate thicknesses will depend upon the welding current, joint design, position, and material mass. A range of preheating temperatures ~ 150 °C to 600 °C has been given for TIG and MIG welding material up to 19 mm, though it is not uncommon practice in the U.K. to increase this to 650-700 °C for 19 mm thickness. The welding current also has a significant bearing on the degree of preheat needed especially where argon shielding is employed. It is bad practice to use high welding currents in conjunction with low preheats, as it will be found that the arc force will create a gouging effect with consequent undercut.

When MIG welding on thicker materials ~13 mm very high welding currents are required, unless high levels of preheat are used, resulting in excessive arc-forces creating worm-holes (tunnelling) in the weld deposit. To avoid this defect it is necessary to limit the current level although by employing twin consumable electrode wires preheating can be virtually dispensed with on thicknesses up to ~13 mm.

Helium and nitrogen significantly increase the ease of acquiring and maintaining a fluid weld pool. This in turn allows some relaxation over the overall preheating requirements, thus reducing the arduous conditions experienced when argon shielding is used. The inter-run temperatures should allow a maximum of 50 °C rise or fall. On massive work a continuous preheat will be necessary to maintain the desired temperature. This can be achieved with oxy-acetylene or oxy-propane heating torches using a neutral flame. When deposition filler metal by either the TIG or MIG processes, a weaving technique may be thought to be more advantageous than the stringer bead method, since more filler metal can be fused into the joint, thus reducing the total number of runs necessary to complete the weld. Extreme care is needed with this technique, for the surface oxide, which forms when the gas shroud is drawn away from partially solidified metal at the toes of the welds, can be trapped on the side walls of the joint when the pool freezes. The stringer bead sequence is generally preferred for thinner plates. Thin layer technique should be avoided particularly in the initial root runs because of the risk of weld cracking. Another advantage with thick layer root runs is that, when subsequent layers are made, excessive weld sinkage or burn through is greatly reduced.

Where controlled root penetration beads are required on unsupported butt joints, the "keyhole technique" will produce satisfactory penetration bead shapes. This particular technique is usually confined to TIG welding, since the introduction of a separate filler rod is essential. To achieve the necessary penetration, root gaps are required, and gaps up to 5 mm can be tolerated. The "keyhole technique" can be applied to positional welds on either butt or open corners joints. The "block sequence technique" / "terrace method" is extremely useful on thick copper, when using the MIG process, although it can be applied with TIG. The method involves the deposition of short lengths of weld made by superimposing a number of runs to form the block, before continuing with the next. The advantages is that the preparation can be filled in short lengths, thus encouraging heat build up, without the need to apply additional preheat.

It has also been stated that the sequence eliminates the need for initial preheat, but this will depend upon material thickness and mass [8].

Copper and copper alloys respond well to the application of gas shielded arc welding provided that careful control is applied against a background of a broad appreciation of the metallurgical and physical factors involved. The basic principle underlying gas-shielded arc welding technology is the reduction in oxidation during welding by the provision of an inert gas shield that eliminates the need for a flux and a weld more likely to be free from porosity and flux inclusions. Combined with arc heating, the overall result is a more efficient and satisfactory system of welding than either gas or manual metal arc welding [31].

A United States Patent makes it possible to weld thick copper plates without causing the oxidation of the weld bead and occurrence of blow holes in the weld bead. Furthermore, this process can be carried out without pre-heating or grooving the copper plates and does not require post-treatment of the underside bead of the weld. It is thus, very economical. It claims to solve two problems. Copper or its alloy weld metals have good fluidity and they tend to fall off the welding part or area. For this reason a backing support can be used consisting of a heat-resistant inert material such as asbestos or carbon. Carbon has been found to be particularly good since it is not just heat resistant and inert but it also creates a reducing atmosphere in the vicinity of an underside or back bead due to the heat of welding. Thus it is possible to produce a sound weld by preventing the back bead from being oxidized without further shielding with an inert gas. Also, the carbon backing support has an advantage in that it makes possible the formation of a flat back bead by welding from only one side of the copper plates to be welded without post-treatment after welding under suitable welding conditions because the support is non-reactive with molten metals. Further the carbon support is a good heat insulator. The carbon support can be composed of graphite, solid amorphous carbon, or a heat-resistant material such as ceramics with its surface covered with graphite or carbon.

The second problem of heat loss due to its thermal conductivity is more troublesome. Welding of copper materials requires a heat input that is about 7 times as much as that required in the welding of steel in order to obtain the same welding performance, because copper materials have a high thermal conductivity. If this large quantity of heat is not supplied, satisfactory welding results cannot be obtained. The heat loss problem obviously becomes particularly conspicuous when the pair of copper plates to be welded is increasing in thickness. This is because the heat capacity of the welding area or part is correspondingly increased. It has been solved not by increasing the welding current, using pre-heating or forming a groove but instead by increasing the voltage as high as 37 to 45 V higher than that used in a conventional welding process. Direct current is used for both the TIG and MIG-processes, were the copper electrode and /or the tungsten electrode is positive. This is because such an arc produces a rapid melting rate of the filler rod when the MIG process is adopted and has an excellent cleaning action on welding areas. An He-Ar mixture consisting of He in a concentration of 15 to 80 % and remainder Ar is preferable, it contributes to a stable arc and a constant depth of penetration.

The parent plate (parent metal) usable for the invention is claimed to be substantially pure copper or a high electrically conductive alloy composed primarily of copper, oxygen-free or deoxidized, and having an electrical conductivity of at least 65% of the International Anneal Copper Standard (IACS).The parent plate appropriate for this technique has a thickness of at least 5 mm. but it is possible to weld parent plates having a thickness of up to at least 25 mm, by one layer one side welding. 100 mm thick is also possible, when using the multi-pass technique The filler material is of the same composition as the parent plate [13].

3.5 MIG, Metal arc inert gas welding:

In MIG welding, the arc is maintained between a consumable filler wire electrode, fed through the welding gun, and the work [7].

MIG is mainly used for copper sheet welding and has many different uses. By adjusting shielding-gas composition from pure argon to about 50:50 argon:helium or argon:nitrogen, and adjustment of electrode-wire diameter and welding current, a comprehensive range of welding conditions is achieved. A mixture of argon with helium or nitrogen improves heat input while maintaining spray transfer, in contrast, a reduction in welding current can initiate globular transfer of filler metal [3]. Shielding gases for MIG are the same as with TIG. Helium-argon mixtures are normally employed for deoxidized coppers that are readily welded with tin-bearing and silicon-deoxidizes electrodes. MIG provides high deposition rate, low preheat and interpass temperatures, dense deposits, good properties and minimum distortion. For heavy sections, use a 90 ° V- or U-groove with a 3.2 mm root opening to assure penetration. The best welds are made flat, other positions using small-diameter electrodes or low-current-density techniques [6]. Above 6.35 mm the standard MIG process is normally considered best to meet the requirements for rapid metal deposition rates and good heat input. There are considerable advantages, whilst still maintaining spray transfer conditions, in using mixtures of argon with helium or nitrogen to reduce the high level of preheat required for thick sections [7]. Argon shielding is commonly used on thicknesses up to ~25 mm with auxiliary preheat. For thicker materials it will be found beneficial to employ helium-argon mixtures because helium offsets the high thermal conductivity of the copper and argon promotes good metal transfer characteristics. The combination gives higher travel speeds, better bead formation and deeper penetration than when argon alone is used. In addition, the helium-argon mixtures permit a reduction in the preheating temperature, thus making for less arduous working conditions. Nitrogen gas shielding also enables preheat temperatures to be reduced as in TIG welding, but unfortunately, in MIG welding, it produces coarse metal transfers across the arc that can lead to excessive spatter and rough weld deposits, when compared with argon or helium-argon shielding atmospheres. A reference in the report has shown and it is confirmed by the author that an argon-nitrogen mixture in the range of 20-30 % of nitrogen is capable of giving exceptionally deep penetration welds, accompanied by the fine droplet metal transfer that is to be found when employing pure argon shielding [8]. For high deposition rates the inert gas metal arc process is superior to TIG. Either argon or nitrogen can be used as a shielding gas. With nitrogen, spatter is inevitable because metal transfer is accomplished in the form of large globules and it is not possible to modify this mode by alterations to the machine output settings. A mixture of 25% nitrogen and 75% argon does however provide improved metal transfer in the form of the fine droplets without detracting greatly from the characteristics deep penetration obtained with a 100% nitrogen shield [16]. Argon, helium and nitrogen are used. Argon has the lowest energy output and nitrogen the highest. At currents above a certain minimum level (called the transition current) the metal transfer rather abruptly changes from drop transfer to spray transfer.

This latter is comparatively smooth and steady, so it is easily manipulated, and it produces a capillary penetration pattern that is deep in the centre but rather shallow at the edges. Spray transfer does not occur in helium or nitrogen at normally usable current levels. With these gases transfer is globular, with heavy spatter, and the penetration patterns tend to be broader and more uniform in depth than with argon. Spatter is particularly heavy with nitrogen, and the bead surface is shrivelled, uneven, and covered with droplets.

Mixtures of these gases provide the best characteristics of each. For instance, 3:1 helium:argon produces spray transfer with a broad and near uniform penetration pattern. Deposition rates are higher than in pure argon, and the arc is steady and easily controlled. Due to the presence of helium, it is also a high energy arc, so that preheat requirements are lower than with pure argon. Similar performance has been reported with nitrogen-argon mixtures of about the same proportions, although the arc force is so high that at currents of about 400 A or higher there is a danger of tunnelling (forming a long continuous void near the root of the weld) [19]. Gas mixtures may be considered, particularly for the purpose of reducing preheat temperature, increasing penetration, welding speed etc, but the addition of substantial quantities of nitrogen (> 30 %) to argon destroys the spray transfer condition. The addition of up to 50 % helium to argon improves the arcing behaviour and increases the heat input without destroying spray transfer. The higher cost of helium is in many cases offset by the significant improvement in welding conditions achieved [31].

In conventional MIG there are three major modes of metal transfer, namely dip, spray and globular. Using pulsed arc it is possible to utilize low background currents with a superimposed high current peak at regular intervals. Whilst preheating of heavy copper sections prior to welding is necessary. Its excessive use should be avoided except in an inert or reducing atmosphere such as would be provided by a hydrogen environment in the copper furnace brazing process [16].

The most usual power source for MIG welding is of the constant voltage type, providing direct current with the electrode wire connected to the positive pole. With the MIG process the thickness range increases over those for TIG. From 6 mm up to and including 19 mm single V preparations will be required. A 60 ° included angle will suffice for the 6 to 13 mm range but in excess of 13 mm the included angle should be increased to 70°.

While these angles are suitable for butt joints in the flat position, the V should be further increased to 80 °for vertical welding to facilitate weaving of the gun, and so exercise control over the molten pool in position. In general, single V preparations are often preferred to the double V, since the latter requires back chipping of the remote side of the joint after the deposition of one or two runs on the first side. An alternative, the double U preparation will be found more satisfactory, as this joint facilitates ease of back chipping, without removal of excessive metal. The depth of the root can have a significant influence upon the degree of penetration obtainable. As with the TIG process, feather edges with the V preparations are also suitable where backing bars or strips are to be utilised. In MIG welding of copper the gun angle and direction of travel have a significant influence upon the quality of the deposited weld metal. For leftward welding, the gun is directed towards the unfused joint, with the weld pool being carried forward at a uniform rate. Although this technique is most practised by welders, extreme care is needed to prevent the formation of oxide stringers in the weld. Rightward welding on the other hand, allows the arc to impinge continuously on the molten pool during welding. With this technique the oxide accumulation can easily be floated to the surface of the pool. It must be emphasised that gun angle is extremely important, and must be held between 70 to 80 ° from the vertical in order to produce good weld deposits. Also arc length and voltage are important, and on no account should the arc be allowed to become too long, as this will encourage the formation of oxide that prevents side wall and root fusion. If the arc length is decreased, deep penetration will be obtained together with turbulence of the weld pool and the end result will inevitably be a weld deposit having a poor bead shape with associated undercutting along the weld toes. In most cases with short arc lengths excessive spatter may well persist adding to the difficulty in controlling the weld bead shape [8].

When welding the coppers with the MIG process, a deoxidized copper electrode is required. The selection of a specific electrode is dependent on the plate used and the ultimate requirements of the weldment. This process is used with reverse polarity direct current (electrode positive) from a power source having either a drooping or a flat characteristic curve. The flat characteristic type is generally preferred. Regarding welding techniques, weld beads should be deposited as straight stringers or with a split weave technique. Wide weaves should be avoided, as oxidation of the bead edges is almost certain to occur. Both forehand and backhand can be used. Forehand produces a well-shaped bead but requires precise control and constant attention on the part of the welder to avoid entrapped oxide stringers. The torch angle is critical as well. Backhand produces a heavier and more convex bead, but the convexity can be controlled by the torch-angle. The risk of entrapped oxides is less than with forehand as the arc impinges directly to the weld pool , this ensures that any entrapped oxide will float to the surface. The arc length is also critical , if it is too short spatter, undercut and poor bead shape will be the result; if it is too long, reduced penetration and weld metal oxidation are likely to occur [19].

3.6 TIG, Tungsten inert gas arc welding :

In TIG welding the arc is struck between a tungsten electrode and the work within a protective shield of inert-gas [7]. TIG is most commonly used for copper and its alloys in sheet form where neat and accurate joints are essential. An alternative to argon shielding gas with AC would be a helium mix with D.C. especially when welding thick copper where its higher cost would be outweighed by gains in performance. For heavier workpieces, above 6 mm, preheating is necessary for both TIG and MIG [2]. TIG is mainly used for copper sheet welding. Helium shielding is of particular value in the welding of thick copper where its higher cost may often be outweighed by gains in performance. The Helium arc is hotter by virtue of its higher arc voltage, and gives improved penetration. On pure copper, preheat levels may also be reduced to give improved working conditions and better metallurgical control. Nitrogen shielding also offers some of these benefits, but renders the process somewhat more difficult to control. It is really only applicable to pure copper to which it is metallurgically inert. With Helium shielding, more efficient D.C working may be used. The author mentions a filler metal with 2 % manganese that is favoured for its fluidity and generally improved welding characteristics [3]. When working with D.C., the electrode is always negative to reduce electrode erosion and to provide maximum heat input at the workpiece. Improved directional stability of the arc is achieved by tapering the tip of the tungsten electrode. Doping the electrode with thoria or zirconia also improves the arcing characteristics by increasing electron emissivity [7].

Preheating is very important when welding any of the coppers. Insufficient preheat results in incomplete fusion and lack of penetration. Preheat temperatures as high as 540 °C are often used and are required when welding thick sections. An adequate interpass temperature is difficult to maintain because of coppers high thermal conductivity, although proper shielding gas selection can help. Pure helium with TIG or, in some instances, a helium-argon mixture with MIG is preferred. Helium's high ionization potential is beneficial because it results in an increase in heat input. Deoxidized copper filler metal provides maximum conductivity for the electric welding processes [10].

When sections exceeding 1.6 mm thickness are welded an argon-helium mix is preferred because the higher voltage and energy outputs allow deeper penetration or faster welding at equal currents. With argon the transfer mode changes from drop to spray above a certain minimum current. Spray transfer is smooth, giving excellent control of the weld pool and deep penetration in the centre. A helium-nitrogen (75% - 25 %) mix when using the spray transfer mode gives beads with more uniform penetration. For out of position welding 2-3 parts helium to one part argon is used. The Helium to balance penetration, and the Argon to give ease of control. Direct current straight polarity D.C.S.P are used. The author recommends 2 % thoriated tungsten electrodes for their high current rating, arc stability, ease of arc starting and resistance to loss of tip geometry. Welders should deposit beads as straight stringers or use a split weave technique.

Avoid wide weaves, because bead edges will most certainly oxidize. When welding oxygen free or deoxidized copper a tin-bearing silicon-deoxidized rod will do, with some phosphorous and manganese to improve weldment properties, preheat a 13 mm thick section to about 315 °C, i.e preheating temperatures varies with thickness and shielding gas [6].

In TIG (and MIG) welding the inert gases supplied to the torch tip keep oxygen out and do not react with the copper being welded. Of the various inert gases used, argon produces the lowest arc voltage and power output for a given arc length and current flow. Nitrogen, however, results in the highest ratings and is the cheapest inert gas, but at normal arc lengths, it may produce voltage high enough to blow molten metal out of the pool. Holding an unusually long arc length can reduce this effect, but then you risk losing the protective atmosphere. Helium at a flow rate of 20 to 40 cfh (cubic feet per hour), is the preferred shield gas, requiring less preheating than argon and resulting in higher metal penetration, higher weld speeds, and less oxide entrapment. As a rule of thumb, argon, which is less costly, may be used for welding copper up to a thickness of 1,6 mm Helium being the usual choice for heavier stock. Mixtures of these gases are often used for greater economy. If Argon is the shielding gas, no preheat is necessary for sections up to 6.35 mm, about 108 °C preheat should be added, with another 108 °C for each additional 3.2 mm of thickness. Above 15.9 mm, as much as 405 °C may be required. When helium is used as the shielding gas, preheat temperatures may be 10 to 15% lower. Oxyacetylene-torch heating is suitable for thinner stock, but propane burners are better for heavy sections. Extra welding current is not a good substitute for preheating because it may blow the metal, destroy the gas shield, and produce porosity and poor beads. Also, preheat should be maintain during the welding process, with the use of asbestos blankets or asbestos-lined fixtures, if necessary [5].

A D.C. steeply drooping characteristics welding set is almost invariably used for TIG welding, with the electrode connected to the negative pole. The efficiency of the shielding gases is governed primarily by their arc-voltage/current relationships that have a significant bearing on the degree of preheat that will be required for any given material thickness. Of the three shielding gases nitrogen displays the highest arc voltage for any given current level, followed by helium and then argon. Because of this voltage/current characteristics that has an effect on the heat input to the work, tangible benefits can be achieved by careful selection of the shielding gas or mixture of gases with respect to plate thickness. For thin sections up to 2.4 mm. argon is generally preferred as it allows a more controllable, less forceful arc to be used, which is easily handled manually. As the material thickness increases, however, auxiliary preheating will be required to promote effective fusion but this can be markedly decreased by switching from argon to helium.

Because of the higher arc voltage obtained with helium, hotter arc conditions are produced, which in turn, increase the heat input and promote deeper penetration into the workpiece. In addition, when helium is used, weld pools are formed instantaneously and weld travel speeds in excess of those with argon can be readily obtained.

Helium also enhances the arc cleaning action and the appearance of the finished weld is excellent. By substituting nitrogen, which is virtually inert to copper, even greater heat can be introduced into the workpiece and weld travel speeds are increased. Auxiliary preheating can be dispensed with on thicknesses up to 6 mm but will be required for greater thicknesses. Nitrogen may however have some disadvantages that outweigh its advantages. For example, weld deposits may not be so pleasing to the eye and some porosity may occur on the weld surface. For plates above 13 mm and up to and including 19 mm either single or double V or U preparations can be employed. The U preparation is particularly advantageous for pipe work, since the control of root penetration is simplified, because of the joint design. When choosing between pure tungsten electrode and thoriated the following should be considered. According to the author, the pure copper electrode tends to form a small hemispherical tip, and consequently, on deep V joints or at the root of filler joints, a fan shaped arc is formed which often leads to lack of root fusion. The thoriated electrodes concentrates the arc stream which retains its tip shape, but creates a gouging action which in turn promotes deep undercutting of the parent plate. This undercutting can be eliminated if adequate preheat (when required) has been applied and careful manipulation of the torch and filler rod. Additional advantages obtained with thoriated tungsten electrodes are that the arc stability is increased and the arc is more readily initiated. Both pure and thoriated electrodes will perform satisfactorily in a shielding atmosphere of argon or helium. With nitrogen shielding however the thoriated types are recommended to prevent excessive tungsten loss. Changing the shielding gas will have a significant influence on the welding practice, and apart from generating additional heat into the work, the physical arc length and arc forces necessitate a change in manual welding techniques. Shielding with argon produces a weld pool that tends to have a tenacious oxide film and agitation of the pool must be avoided at all times to prevent the occurrence of oxide coated pores. Helium produces a clean highly fluid weld pool that behaves under the arc rather like water under an air jet. Nitrogen also produces a fluid pool, but the deoxidation products from the filler rod form a substantial film that effectively reduces the mobility of the pool and also obscures the welder's view of it [8].

Using TIG with reversed electrode polarity (negative) and an atmosphere of pure argon copper plate up to 0.25 in. thick can be welded satisfactory. Helium may be used as an alternative shielding gas giving a hotter more penetrative arc and an increase in welding speed but its cost in Great Britain when this article was written (1968) makes it prohibitive except for special applications. For welding copper of 6.35 mm thick and upwards by TIG, preheating is required and a nitrogen atmosphere giving hotter arc conditions can be used. Arc voltage in nitrogen is higher and extra heat is also provided by the dissociation effect of molecular nitrogen N_2, in the arc atmosphere, but care must be taken to provide N_2 that is water free or porosity may occur in heavy sections. Another advantage to be gained from the use of N_2-shielding is that preheat temperature can be proportionally reduced. This means that the operator fatigue factor - which is high for the welding of copper - is reduced [16].

The TIG process is considered to be most effective for joining light gages up to 3 mm thick, although its usable range can be extended to include heavier sections, particularly where out-of-position welding is required. Welding is done straight polarity direct current (electrode negative) using a power source having a drooping voltage-amperage static characteristics. Pure tungsten or 2 % thoriated tungsten electrodes are used. The thoriated electrodes have the advantage of higher current ratings for equal sizes and they do not tend to form a ball at the end. Argon, helium and nitrogen as well as combination of these gases, are all inert to copper and may safely be used for shielding. Argon, for a given arc length and current level, has the lowest arc voltage of the three and, therefore, the lowest power output. For this reason it is preferred for welding gages up to 1.6 mm thick. For thicker sections, the weld pool tends to be too viscous so that low travel speeds and high preheat are required to allow oxides to float to the surface. Helium has an appreciably higher voltage and energy output than argon and is therefore preferred for welding sections over 1.6 mm thick. Compared to argon, it gives deeper penetration or higher travel speeds at equal current levels. The weld pool is more fluid and cleaner, so the risk of oxide entrapment is considerably reduced. Nitrogen has the highest voltage level and energy output and is also the cheapest of the three gases. It is usually not used in the United States, but can be if proper precautions are taken. Its voltage is so high as to constitute a serious drawback; that is, at normal arc length the arc force is so great that it often expels the molten metal from the pool. In order to reduce this force, it is necessary to hold a very long arc, thereby introducing the risk of loss in shielding. Also, weld surface appearance is usually poor and surface porosity is often encountered. Mixtures of these gases result in intermediate characteristics. For instance, in out-of-position welding a 2-to-1 or 3-to-1 helium-argon mixture produces a good balance between the penetrating quality of helium and the ease of control or argon.

Either the forehand (leftward) or the backhand (rightward) technique is used, although the forehand is more widely practised, particularly for out-of-position welding. It produces a better locking and smaller bead than the backhand technique. However, smaller bead size means more passes per joint. Wide weaving should be avoided because it intermittently exposes each edge of the bead to the atmosphere and consequent oxidation. Passes should be stringer beads or, at most, of the split weave type. Root passes should be fairly heavy to insure deoxidation and to prevent cracking. Since the thermal conductivity of copper is so high, and the drain of preheat away from the joint area is so strongly affected by the mass and geometry of the workpiece and fixture. It has been shown that two welders working simultaneously can weld copper with simplified edge preparation and no preheating. One of the welders may use an oxyacetylene torch [19].

Argon is the standard shielding gas. It has the lowest arc voltage and thus the lowest heat input for a given welding current. The arc voltage for helium is higher and it therefore gives a greater heat input than argon. It can be substituted for argon completely, or used as a mixture with argon to increase the heat input in order either to reduce the preheat temperature, particularly on copper, or to increase penetration or welding speed. In helium, refractory oxide films prove less troublesome and for this reason D.C. working on helium is a suitable alternative to normal A.C.

Because of the high heat input of the helium arc, its use is especially recommended for welding thick copper. Nitrogen displays the highest arc voltage and, for copper, produces an even greater reduction in preheat temperature and increase in weld travel speed than helium. But welds made with nitrogen alone, or with argon and nitrogen mixtures, tends to be of rough appearance, although the weld metal itself is sound [31].

The weld metal produced in welding with nitrogen-plasma is susceptible to pore formation.The porosity is caused by metal from the plasma jet and generation of the gas in the pool volume. The most rational method of suppressing porosity is complex surface alloying the active surface of the metal with nitride forming elements such as Ti, Al and Zr [32].

TIG is applicable to any thick component over 25 mm using helium as the shielding gas that gives higher heat input and greater ease of welding. Even on very thick sections, pre-heat temperatures may be cut drastically allowing far more comfortable working conditions and a significant reduction in thermal expansion, oxidation and distortion problems. The key to the problem is the provision of a feather edge V-preparation with a 2-3 mm root gap. The first root run, which is of prime importance in securing a high integrity weld, is deposited to bridge this root-gap with little melting of the parent metal. The root run therefore consists mainly of fully deoxidized filler metal, and the need for excessive pre-heat to melt large quantities of parent metal is avoided. This is quite sufficient to secure a metallurgical bond between the filler metal and the parent metal and after two to three runs have been done the remaining runs can be conducted using conventionally TIG (or MIG). The major difficulties arise in the welding of thick copper through attempts to melt excessive parent metal in the initial weld runs at high preheat temperatures. Using TIG when repairing thick copper such as continuous casting moulds damage is successfully done by using a helium shielded TIG technique in conjunction with copper - 2 % manganese filler alloy. This filler metal is very fluid under the helium arc and are highly suitable for filling small defects and repair areas, giving a weld deposit slightly harder than normal cast copper. The technique permits weld repair to be carried out with no pre-heat and consequently very little disturbance to the mould surfaces beyond the immediate localised area of the repair site. It is possible to keep the main surfaces completely cool by immersion in water of all but the actual repair site. This technique is being used as a routine industrial procedure in the U.K. [9].

Studies have been made on the significance of weld defects in phosphorous deoxidized copper weldments. 6 mm thick PDO copper (BS 2870, C106) was welded by the TIG process using a filler alloy to BS 2901 part 3 C7.

It could be seen that there is a direct and effectively linear relationship between the loss in cross sectional area due to a defect (or defects) and the ultimate tensile strength and elongation. This correlation appears to hold irrespective of the defect type or, within the limits of the experimental programme, the individual defect size and aspect ratio. This is not surprising, the report continues, as it is analogous to the situation with other very ductile metals (e.g. aluminum and its alloys). The fatigue tests showed that all the porous welds failed at a lower endurance than the sound welds that indicates that there is an effect.

The use of 100% nitrogen shielding gas produced welds with a considerable volume (up to 8-10%) of very fine microporosity (some pores <0.1 mm in diameter) that caused a significant reduction in tensile strength. This porosity is not always detectable by radiography and, therefore, it is essential that if nitrogen shielding is used, then the correct filler, BS 2901 part 3 C8, must be used with it [12].

3.7 SAW, submerged arc welding:

See Base-materials, ref [18].

3.8 MMA, metal arc welding:

Shielded metal arc welding of copper is used for minor repair jobs on light gauge stock, difficult to reach fillets, or dissimilar metals. In this application, SMAW is performed with reverse polarity direct current. Above 3 mm, preheating to 270 °C and higher is necessary. Filler metal containing deoxidizers must be used. Also, covered electrodes of the type ECuSn, ECuSi, ECuAl-Al have been used for welding copper [19].

3.9 OFW, oxyacetylene welding:

Although other fuel gases, such as propane and natural gas, can be used for welding of copper, the very high flame temperature and reasonably good heating value of acetylene make it very suitable for the purpose. The flame should be neutral or very slightly oxidizing. The tip size should be one to two sizes larger than would be required for an equivalent thickness of steel. A deoxidized copper filler metal is required and the joint should be fluxed. Although MIG is preferred to thickness greater than 6 mm, when such a joint must be done by gas welding, it is preferably done in the vertical position by two operators welding both sides of a double-V or double-U joint simultaneously [19].

3.10 LW, Laser welding:

According to the writer laser beams are normally reflected from copper and copper alloy surfaces due to an incompatibility of the lasers wavelength and the atomic spacing of copper and copper-alloy crystals. But by careful design of the joint, the laser beam can be reflected back and forth across the joint surfaces so that adequate heating for fusion takes place. The Welding Institute (TWI) has developed a laser beam spinning technique that can fuse joint surfaces without special geometry in the joint design [1].

Under normal processing conditions, copper absorbs from 1.4 to 1.7 % at room temperature and from 3.6 to 4.0 % near the melting point of the incident energy on the target.

It is obvious that these absorption coefficients are much to low and the actual absorbed power is 28 to 34 % at room temperature and 72 to 80 % near melting, using a 2 kW CO_2 laser. Furthermore, these few watts are transferred into the material down to depths of tens of nanometres and are then converted into heat and quickly distributed from the surface throughout the whole thickness by means of a simple heat conduction process regulated by the high thermal conductivity.

In copper, the thermal conductivity has much higher values (3.9 W/cm ° C) than in carbon (0.75 W/cm ° C) and stainless steels (0.15 W/cm ° C). Hence, reaching and dynamically maintaining the melting point for copper sheets is very difficult both for cutting and welding. Given the above information, one has no choice but to look for ways of reducing the surface reflectivity and increasing energy absorption if one is successfully to cut and weld copper using a laser. Metal surfaces can be oxidized by continuous wave lasers, and this oxidation leads to an increase in energy absorption and increase in temperature. In the experiments presented in this paper two different laser sources have been used, 500 W CO_2 or 2 kW CO_2 and Nd-YAG (Yttrium Aluminum Garnet), with two different setups of lenses and nozzles etc. Different shielding gases were used; For example N_2, He, O_2 and the base material was deoxidized high phosphorous copper (Cu-DHP) of 0.2 to 4.0 mm thickness. Also five different coatings, deposited on the copper plates, were used; copper oxides ($CuO+Cu_2O$); Titanium Oxides (Ti_2O); glossy chromium; colloidal graphite dispersion and finally black chromium that gave the best result which was strongly correlated to the coating thickness.

Laser welding of copper can be achieved by two different techniques. The first method utilizes the technique used for cutting, e.g. the growth of cupric and cuprous oxides, to increase the surface absorption and thence to produce the melted zone (the weld). In this process, however, the melted material must not be ejected as it is with cutting. By means of the former technique, laser welding of copper has been carried out on sheets up to 3 mm thick. In these experiments two assist gases, helium and oxygen, were used simultaneously. Helium, as a shielding gas, flows coaxially to the laser beam while the oxygen is fed through a nozzle directly onto the laser- metal interaction point. When the oxygen flow becomes very intense it is reasonable to suppose that it plays a double role: the first in the oxide growth, the second in the heat removal from the target, thus reducing the critical speed. In these experiments, it was immediately clear that the oxygen-assistance gas is detrimental to the weld quality owing to oxidation effects. In fact, as a consequence of the oxygen gas used to obtain the process and the high value of thermal conductivity of copper, a number of inclusions in the weld bead and an unwanted growth of the copper grains surrounding the weld were always observed. All this makes the welds both mechanically and metallurgically poor (e.g. oxygen embrittlement).This method is currently (1991) very expensive, owing to the high reflectivity of copper a large quantity of the laser power is reflected back onto the focusing lens and this often causes lenses to break.

The second technique for welding copper sheets uses a surface coating deposited before the welding process. This improves surface absorption.Using a coating pre-deposited on the surface, it enables us to obtain better copper welds with an increasing surface absorption, no inclusions and/or microporosity, a longer lens life (e.g. no breaking), good mechanical performances of the welds and interesting critical speeds. Experiments have shown that it is possible to weld copper at 2 kW, 1.5 kW, 1.0 kW and even 500 W. Today (1991) there is only one problem with this technique; by utilizing this special coating in a precise thickness it is not currently possible to weld copper sheets thicker than 1 mm [14].

An experimental evaluation and finite element analysis of laser welded copper-copper joints has been performed. Copper joints were welded with a required melt-depth of 1.25 mm, using a neodinium (Nd)-glass laser operated in a pulse mode at 40 to 48 J per pulse. Although the wavelengths of glass and YAG lasers are essentially the same and their operating characteristics are similar, the YAG laser has the advantage of faster pulse rates.

The finite element analysis was used to determine the actual amount of energy absorbed when welding with a pulse laser. This was accomplished by comparing the analytically determined melt zone with the actual weld nugget region. The energy difference between predicted and an actual energy used to affect a laser weld is the amount of energy that reflects from the workpiece during welding. Conventional welding of electrolytic tough pitch (ETP) copper usually produces poor results because of the presence of dissolved cuprous oxide. Oxygen scattered homogeneously throughout the base material makes a good weld almost impossible. When the base metal is heated to its melting point, oxygen is precipitated to the grain boundaries and forms a cuprous oxide that coats each grain and makes it more difficult for the heat to penetrate. This oxide breaks down the bonding between the grains and also causes a reduction in strength of the fusion welded zone. The diffusion of oxygen is primarily due to the long periods of time necessary to raise the temperature of copper to its melting point by conventional welding methods. Heating ETP copper over shorter time periods would prevent the migration of oxygen to the grain boundaries. Such short time periods are achievable with pulse laser heating.

A Nd-glass laser has been used with some success to weld copper. Analysis of the laser beam parameters required for successful welding, has been made using a combination of modeling and experimental measurements. It was concluded that this approach helps to determine how much energy is absorbed from a laser pulse and to optimize the laser pulse conditions for specific welding applications of different materials with various dimensions. Physical tests were performed to determine the properties of the welded joints made under the optimum conditions. The tensile strength of butt welded joints was reduced to 60% of the value for annealed material. The reduction, according to the writers, can be explained by the appearance of the grain-structure. As the weld-nugget begins to solidify, a solid/liquid interface moves towards the centre of the weld, and dendritic columnar grains, which are characteristic of directional solidification, begin to grow. As the columnar grains grow inward from opposite directions, they meet at a fusion plane, at the centre of the weld nugget. Failure under tensile load occurs in the centre of the weld nugget and the fracture plane is coincident with the fusion plane.

The authors suggest that if additional strength were required, this fusion plane could possibly be eliminated by: welding under a compressive load that would generate a forging action; using a heat sink to alter the temperature gradient; and/or adding some filler material. (The authors conclusions is that when proper operating parameters are established for welding ETP copper with a monochromatic radiation (1,06 μm) supplied by a Nd-glass laser, good tensile strength (and low electrical resistance) can be obtained). The results reported were achieved while welding under ambient conditions, and because of the nonlinear nature of the material properties during phase changes, numerical techniques are required for the transient thermal analysis. The finite element method has been shown as a powerful tool for determining the true energy absorption during laser welding [15].

Laser are high energy beams that can be used for cutting and welding in a similar manner to electron beams but usually in air rather than in vacuum. Due to the powers currently available (-94), penetration is restricted to thinner materials.
The process has not been used widely on copper and copper alloys, due to reflectivity problems although some welding of brass tube has been reported recently where careful design of the joint has used reflectivity to concentrate the heat on the surface to be joined. Beam spinning is another technique that has been used to overcome the reflection problem [31].

3.11 EBW, Electron beam welding:

Electron beam welding has been used for various grades of copper and it has been reported that sound porosity-free welds can be produced by this technique. penetration depends on parameters such as travel speed, beam focus and beam power. Specimens studied in this manual with various values of these parameters was of thickness 12.5 mm and a penetration of approximately 10 mm maximum was achieved [19].

This author has made some observations on the electron beam welding of copper. Studies were made on 12.5 and 3.2 mm thick OFHC (oxygen free high conductivity), DLP (deoxidized low phosphorus) and DHP (deoxidized high phosphorus) copper alloys. The conclusions of the report were: porosity in all three grades of copper increased with increasing beam power and depth of focus. Power had a greater effect than depth of focus on resultant porosity; Decreasing travel speed caused a very noticeable increase in porosity.
Compared to all other single parameters, travel speed had the greatest effect on porosity in copper; material impurity level had no apparent effect on porosity in copper. Welds made at higher travel speeds provide higher power efficiency than welds made at low travel speeds. Increasing thermal conductivity causes a decrease in power efficiency. There is an interaction between power and travel speed, implying that any theoretical relationship between penetration and speed will need a variable power dependence term. Penetration is not directly dependent on power level; Penetration increases as the optical focus position moves from 6.35 mm above the surface to 6.35 mm below the surface; Increasing impurity level in copper causes a decrease in penetration.

Beam spot size (energy density) is a very important parameter in electron beam welding. It is important that it be monitored quickly and accurately. The impurity level in copper affects the width of the HAZ more than does the degree of cold working in the base metal. This indicates that slight amounts of impurities in cold-rolled copper exert more control over recrystallization and growth than does the stored energy of cold working; The recrystallization-growth inhibiting effects of high impurity levels are most pronounced at low travel speeds; The high rates of heat input at high travel speeds in EBW make it possible to retard recrystallization and growth phenomena in copper [24].

The conclusion of this report is that the use of square oscillations of the electron beam along the weld results in the stable penetration of the weld root and makes it possible for joints in a copper-alloy called "high temperature copper alloy 4", to be produced without hot cracks, when a backing strip is used. Performing the experiments cylindrical workpieces were used with circular welds. The cylindrical form of the workpiece were produced by forming sheet blanks 15 mm in thickness using a press. The blanks were deformed in the cold condition in 5 to 7 stages with intermediate annealing at 700 °C to remove internal stresses. Prior to welding, certain structural elements were brazed to the external surfaces of the cylindrical blanks at a temperature of 1000 °C for 10 minutes. Two other identical blanks were welded after the mechanical machining of the metal in the welding area to a thickness of 2 mm. Grooved backing strips were also used.

The experiments showed that cracks in the welds formed in the specimens deformed to more than 10 %. The intercrystalline character of the cracks confirms that they formed during the solidification of the weld. The given alloy is very sensitive to overheating (increase in the power of the electron beam leads to marked grain growth in the weld metal). It was observed that the probability of hot cracking depends on the shape of the weld root (penetration). The weld surface remained almost constant during variations in the welding conditions, but the weld root shape varied in the case of complete penetration. In the case of non-uniform penetration, the probability of cracking was almost 100 %. This is explained presumably by a marked variation in the character of heat removal and solidification, and consequently in the strain rate of metal regions arranged in rows, contacting and not contacting with the backing strip.

In the stable penetration of the backing strip, solidifying together with the metal of the component, the number of cracks formed at the weld root was markedly lower, and the cracks were distributed at the boundaries of a fine-grained structure formed as a result of intense heat removal into the backing strip. The probability of cracking was even lower when the backing strip was not melted. This is explained by a reduction in the difference in the grain size over the weld cross-section because of reduced heat removal into the backing strip. From this viewpoint it is expedient to weld without backing strips, because in this case there is no fine-grained zone in the weld root.

The experiments showed that in welding without backing strips cracks did not form in the weld root; but this method cannot always be used in production, because of difficulty in achieving the permissible concavity of the weld cross-section.

With regard to the difficulty of obtaining the required penetration shape in welding with a static electron beam, the possibility of avoiding hot cracking by means of using an oscillating beam was examined. The use of square beam oscillation made it possible to produce joints without hot cracking on using backing strips because of the suitable shaping of the weld root. The basic reason for the elimination of cracks on the weld surface is the closing up of hot cracks formed from the first penetrating pulses, by the second pulses following at a distance of one amplitude from the first pulse and penetrating the weld metal. The cracks did not reappear, because at the time of the effect of the second pulses the metal in the HAZ is already heated up, thus preventing marked heat removal during the solidification of the remelted metal, and also preventing the formation in the weld of zones with various grain sizes in which liquated impurities can accumulate at the grain boundaries. The removal of cracks in the weld root is according to the writer predetermined by the stability of penetration obtained using a oscillating beam; in this case the specific probability of crack formation after welding during service loading is retained if the backing strip is fully penetrated [25].

This report is a review of porosity in electron-beam welding. The particular features of EBW (the vacuum, the high specific power density and vaporization of the metal, and the fast rate at which weld pools solidify) create conditions under which pores may form in welded joints. In EBW the pressure is always $\geq 1.33 \times 10^{-4}$ Pa, and is a function solely of the hydrostatic pressure of molten metal in the weld pool. This makes it much easier for gas bubbles to be initiated and develop in the pool than in the case of arc welding. Allowance must also be made for the fact that the solubility of hydrogen, whose presence is one of the principal reasons for pore formation when many metals and alloys are welded, is lower in a vacuum than in atmospheric pressure, in accordance with Sievert's Law.

The high temperature gradients caused by the high specific concentration of beam energy mean that there is considerable thermal diffusion of hydrogen from the HAZ into the fusion zone. This process is likely to result in increasing the volume of the gas bubbles in the weld pool, and is followed by the formation of pores in the HAZ. The high energy density in the beam, causing the molten metal to be overheated, and consequently volatile components to be vaporised intensively when certain metals are welded, as well as the high solidification rates, are together likely to result in formation of pores in EBW.

All this is further aggravated by the fact that the actual shape of the weld, usually deep and narrow, impedes movement of gas bubbles in the weld pool. Porosity is one of the principal defects in welds in the EBW of other non-ferrous metals and their alloys, particularly Al, Cu and Nb. If there are pores in the metal in EBW joints, their service properties, particularly the mechanical ones, may deteriorate seriously. The deposition of welds containing no pores, or the minimum of them, is thus very important from the point of view of the service reliability of welded joints and providing them with mechanical properties equivalent to those of the parent metal.

The extent to which welds are affected by pores caused by the presence of gases depends greatly on different technological factors, primarily the parameters of the welding conditions: beam power; position of the focal point and welding rate and the gas impurity levels in the material. Most research experts, he says, consider that, by comparison with the other parameters, welding rate has most effect on gas porosity in welds. However, when metals whose composition does not include easily vaporized components are electron-beam welded, the best results may be obtained with reduced welding rates (studies on 16 mm thick VT6 titanium alloy and 8 mm thick VMSt3s steel have been performed).

Other conditions being equal, welding with full thickness penetration is preferable, and this is likely to result in additional degasification of the molten metal through the root of the penetration channel. The porosity may be much worse if the metal welded contains volatile components that are easily vaporised into gas bubbles, when the weld is overheated. The principal parameters affecting the vaporisation of metal during EBW are the power of the electron beam and the welding rate, which govern the temperature of the metal in the weld pool and length of time spent by it in the molten state. These parameters also include the dimensions of the electron beam focal spot and its position relative to the surface of the work. The rate of vaporisation depends greatly on the beam power. As the latter is increased and the dimensions of the focal spot are reduced, vaporisation also becomes greater.

In EBW, porosity may also be due to the processes taking place at the end surfaces of components being butt joined. These have been extensively investigated for arc-welding. It follows from references that there is a zone, ahead of the weld pool, which is acted on by compressive forces so much that welding of the ends occurs in the solid state, this is accompanied by the formation of closed micro- and macro-cavities. What are called "primary pores" form in these. When VT6 titanium alloy is welded, primary pores may form in joints ahead of the weld. They are not however the principal reason for weld porosity in EBW. To prevent them from appearing it is necessary to clean the surfaces of the weld edges, removing any possible contamination. Transverse corrugation in the weld edge surfaces is recommended for certain metals such as titanium and copper alloys. The general method of preventing porosity in EBW is to use refined metals and alloys for welding, which have for instance been subjected to electroslag or electron-beam remelting, which according to the writer is not a justifiable economic proposition. Other measures that are effective preventing porosity in electron beam welds are either vacuum pre-heating of the weld edges (for instance with an electron beam) or heating the entire work on a vacuum furnace, or preheating the weld edges and remelting the weld metal. The latter course however, may cause excessive deformations and internal stresses in welded structures and it must be borne in mind that porosity may not always be effectively reduced by remelting the weld metal, indeed under particular welding conditions, at lower welding speed, the amount of porosity can be increased. It is some-times necessary to remelt the metal three to five or more times to reduce porosity appreciably. When this is contemplated it is necessary to take into account the fact that repeated remelting greatly reduces the amount of alloying elements with high vapour pressures in welds. This may have a bad effect on the other properties of welded joints.

Sound electron beam welds are made when the weld pool is alloyed with elements that reduce the solubility of gases in the molten metal or combine them into stable compounds, and there are many different ways of feeding the weld pool with these elements: Through the filler wire fed beneath the electron beam during welding, or through metal foil or sheet first laid in the joint to be welded, also by spray deposition of alloying elements on the weld edges or introducing them within the composition of a metallic-organic compound. When the welds are made using a backing piece, the number of pores in the weld can be reduced by using a backing piece metal which contains alloying elements and causing the backing plate to be partly melted during the EBW process . Porosity can also be reduced in EBW by introducing sheets of metal with the same chemical composition as the parent metal, but initially vacuum melted, into the joint.

It has also been established that the number of pores in welds could be greatly reduced using high-frequency longitudinal oscillations of the beam or rotating it during welding. Circular or elliptical movement of the beam is preferable to its oscillation. This method is however not always effective. The number of pores can also be reduced by the correct selection of the three-dimensional positions of welding.

Welds made in the vertical plane, with the electron beam running horizontally, are the least susceptible to formation of pores, and this is due to the fact that degasification of the molten metal is easier with the weld pool horizontal. In the case of flat position, the number of pores in the weld decreases when the electron-beam is inclined in a forehand angle [26].

An investigation of the feasibility of using EBW for the final closure of copper containers for nuclear fuel waste disposal was conducted, and this report describes the results of the second phase. It was shown that square butt electron beam welds (depth of penetration > 25 mm) can be made without preheat in both electrolytic tough-pitch (ETP) copper and oxygen free (OF) copper plates using more than one combination of weld parameters. The measured penetration of the welds ranged from 16.6 to 32.3 mm. In phase one in the investigation, it was demonstrated that single pass EB welds could be made without preheat in 50 mm thick ETP copper plates. In addition, a preferred joint design with integral backing support was proposed. The dimension of the test-blocks in the second phase were 25 mm thick, 113 mm long and 24 mm wide. As the joint design contains an integral backing support it requires a weld penetration greater than 25 mm, preferably 30-35 mm. The dissolved amount of oxygen in the OF copper is maximum of 0.001 %, and the copper content is 99.99 %. ETP is 99.90 % pure and contains 0.02 to 0.07 % dissolved oxygen. The electron gun was rated at 42 kW beam power, with an accelerating voltage of 60 kV and a maximum beam current of 700 mA. The welding parameters investigated were beam current, acceleration voltage, welding speed and beam focus position, (the power varied between 8.75 to 42 kW and the welding speed between 3.4 to 33.9 m/s).

The second phase of the investigation showed that for both copper alloys the power efficiency increased with increasing welding speed. The beam power, and thus the weld penetration, can be increased by increasing either the voltage or the current.

At higher power levels there are indications that the fusion zone becomes more parallel-sided and the underbead wider. With other parameters held constant, the focus position did not appear to affect the weld penetration, but when the focus was 8.5 mm below the surface, the fusion zone of the weld was more parallel-sided with a wider underbead than other welds focused at greater depths. The focus position did not affect the gas porosity in the fusion zone noticeably in the ETP welds. The weld penetration and fusion zone area increased with increasing beam power and increasing weld speed. An explanation why an increased welding speed promotes greater penetration is that since little time is available for lateral melting a greater depth can be melted, leading to greater penetration. For materials with a high thermal conductivity, such as copper, a relative high welding speed is thus preferred, to promote penetration and to reduce excessive lateral melting. The combination of high beam power and high welding speed provide optimum penetration with minimum heat input in the copper plate.
Slightly greater penetration was obtained in OF copper than in ETP copper, with the same welding parameters. OF copper has slightly higher thermal conductivity than ETP copper, therefore a greater penetration should be expected in the ETP copper. In earlier studies, which the report referred to, a greater penetration also was observed in OF copper than in phosphorus deoxidized copper (DLP/ DHP), despite the fact that OF copper has the higher thermal conductivity. The explanation to this was that the vapour pressure caused by impurities during welding affected the depth of penetration more than did slight variations in conductivity. High welding speed, compared to other parameters, appeared to have the greatest effect on porosity in copper when it suppresses the evolution of dissolved gases, such as oxygen, and the formation of gas porosity in the fusion zone, in ETP welds. In ETP welds when extremely high welding speed were used it seemed to promote cavities. Referring to previous studies these cavities can be minimized by using the beam oscillation technique.
Compared to ETP copper welds, the OF copper welds displayed only a small quantity of gas porosity. A slightly greater penetration and upper bead width was achieved when welding OF copper with the same parameters as used when welding ETP copper. Extremely high welding speeds also promotes erratic metal overflow and blow holes on the surface of the ETP weld, which was not observed in OF welds. The explanation for this is that the fused metal cooled at a much faster rate at high welding speeds, which for ETP copper, led to violent gas-metal interaction as dissolved gases such as oxygen evolved from the surface of the weld. In ETP welds, root cavities occurred mostly in welds with a narrow fusion zone at the root of the weld, probably because the metal vapour generated at the centre of the molten column was unable to escape through the narrow slot at the bottom of the joint interface. A wide weld should minimize the occurrence of root cavities since this would provide a greater opportunity for metal flow into the cavity. The OF welds contained only a small quantity of gas porosity. Welding parameters, including the welding speed, appeared to have no significant effect on the quantity of porosity observed. Due to the low dissolved gas content, erratic metal overflow and blow holes on the weld surface were not observed, but at a high welding speed of 25.4 mm/s a cavity was detected at the bottom of the weld.

Copper oxides were found as discrete particles in the grain interior and as semi-continuous film at the grain- boundaries, near the centres of several welds, when melt runs were made on a 50 mm thick ETP copper plate in phase one of this investigation. In the present studies of 25 mm thick copper, all ETP copper welds displayed a considerable amount of copper oxide as discrete particles in the grain interior, however no grain boundary oxide films were detected in these welds. Variations in the welding parameters appeared to have no effect on the distribution and morphology of the copper oxide particles. For the OF copper welds very little copper oxide was found in the form of discrete particles and no oxide films were detected. Small volume fractions of copper oxide, when dispersed uniformly throughout the structure, have little effect on the properties of the joint while oxide films at the grain boundaries may cause weld embrittlement.

Regarding misalignment between the electron beam and the weld joint the writer recommends a wide underbead . The explanation of the misalignment that occurred in several welds, was that the electron gun carriage rails were not parallel with the copper plate [27].

The report of the third phase [28] of the earlier described investigation [27], describes the selection of welding parameters that provides the welds with minimum gas porosity, no fusion zone cavities and a satisfactory surface finish, in oxygen free copper plates of the same dimensions as earlier tests. The parameters investigated were beam current, accelerating voltage and welding speed (Beam power between 13.5 to 42 kW and welding speed from 2.5 to 19.1 mm/s). The welded samples were examined visually as well as metallographically, and both hardness, bend and tension tests were performed.

In this investigation it was found that with high beam power and high welding speed erratic overflow, blowholes, and undercutting were found in all the OF copper welds (compare with [26]). Also an excessive amount of surface defects were found (from a beam power of 22 kW and welding speed of 5.9 mm/s). Despite the variation in weld geometry with different combinations of beam power and welding speed, no significant difference in fusion zone grain structure was found during metallographic examination. Hardness test were performed on one test piece and revealed a Vickers hardness of 42-51 in the fusion zone and 54-63 in the base metal. The tension tests performed on 3 welds that were made at low, intermediate and high beam power and welding speed respectively, revealed a ductile failure in the welds. Also side bend tests were performed resulting in no visible cracks. The measured penetration of the welds ranged from 29.1 to 46.2 mm.

The large cavity that was found in phase two [27] above, at the bottom of the weld made at the welding speed of 25.4 mm/s can according to this report be prevented by using a lower speed at or below 19.1 mm/s. Small cavities that only seemed to appear at lower power levels in phase two, seems in this report to form at a wide range of beam power. This, according to the writer, is not believed to have a significant detrimental effect on the integrity of the joint. No cracking or other types of internal weld defects were observed in this investigation. As mentioned earlier erratic overflow, blow holes and undercutting on the surface was shown when using a high beam power.

The writer is in this report discusses how to solve this, either by lower beam power or by using a low power cosmetic pass over the main weld.To obtain a weld penetration of 30 to 45 mm the heat input should be kept to a minimum to reduce the weld distortion, lateral heating and overheating of the contents of the copper container. This is obtained by a high beam power and a high welding speed, but this promotes undercutting and blowholes. However the highest tolerable beam power and welding speed has been observed. Finally the beam spot size seem to have a significant effect on the penetration characteristics of copper EB weld, but in order to predict weld penetration more accurately, empirical equations must be defined [28].

A vacuum component which is used for accelerator systems in nuclear physics, must be vacuum tight and must not be destroyed by the inadmissible thermal degasification of the material. For this reason copper of the highest purity, the SE-grade, which is a non-oxygen-containing copper, predominantly de-oxidised with phosphorus and exhibiting minimal degassing rates compared with other copper grades, was chosen. Because of the high degree of vacuum tightness required in association with low shrinkage rates, electron-beam welding is the only feasible process for joining these components. The problem described in the report is that EB-welded SE-copper (30 ppm P, 41 ppm ± 8 ppm oxygen), especially when it has been de-oxidized with phosphorus, tends to develop extensive porosity depending upon the particular beam mode. Even minute amounts of impurities which are in the ppm-range can lead to the formation of pores. Tests were made to evaluate the possibility of minimising the amount of pores, by using different types of beams e.g. oscillating, pulsating and continuous. A 30 kW EB unit was used for the welding tests. The different weld seams were made in 10 mm thick copper discs and evaluated by radiography and metallurgical examinations. The semi-finished product used for welding had undergone forging. When using the oscillating beam, a parabola type was used that according to the writer is representative of a variety of oscillation modes. Almost a complete degasification of the weld pool could take place since the fusion zone is kept in a molten stage for a longer time then by not oscillating.

Pores could anyway be found in the upper third of the weld seam and attempts were made to remove these, by overwelding one to five times at constant parameters. This did however reduce the quality of the weld, possibly by the additional fusing of the base material and by the higher thermal load. When using a continuous un-deflected beam, the energy input i.e the energy per unit length was lower than that of the oscillated beam. Also a higher welding rate lowered the heat/energy input. These measures were used to suppress the metallurgical reactions in the molten metal. When comparing the highest welding rate possible by this equipment, 50 mm/s, with a lower rate it could be noticed that a decrease of porosity was obtained at the highest rate, although a weld completely free from porosity was not obtained. A theoretical conclusion is that there could be a welding rate, higher than 50 mm/s, where no porosity will be obtained. Welding with a pulsating beam also minimises the thermal load.

According to this report, tests indicate that the welding of a low defect seam in which porosity is substantially reduced, is possible through an accurate correlation of the pulse parameters.

A beam pulsating frequency of 500 Hz, pulse duration of 0.5 ms, yielded a seam with a low number of pores, not taking into account so called "rootspiking". When welding at a higher frequency a seam with a higher amount of pores was produced, nearly as many as was obtained when welding with an oscillating or continuous beam. An attempt was made with the aid of chemical analysis of copper used and taking into account the chemical reactions possible under the welding conditions, to find a possible explanation for the formation of pores. In general such a residual oxygen content of 41 ppm should not cause an injurious effect. A rough qualitative calculation, however, shows up the expansion of this gas content and the volymetric quantity resulting from this small amount.

Assuming an ideal gas the oxygen attains at fusion temperature and normal pressure a volume of 1.8 cm^3 per 1 cm^3 copper. Both the oxygen content and the temperature are being taken into account in this rough calculation in direct proportion to the expanding oxygen content.The environmental pressure during welding must also be taken into consideration. Accordingly, similar conditions exist as under vacuum de-gasification; the solubility of oxygen in copper decreases in accordance with the partial pressure of the gas.The consequence therefore can be that a large amount of the expanding volume of oxygen can escape, but due to the high cooling rate during welding and due to coppers heat conductivity, not all can escape. The explanation why, when welding with pulse-shaped energy input (duration of 0.5 ms), it gives such a good result can be that the reactions cannot take place for kinetic reasons so that the release of the oxygen within the weld cannot occur. This is according to a diagram of Pressure of Decomposition of Metallic Oxides by Pfeiffer and Thomas, which says that a partial pressure of 10^{-5} atm. is sufficient to decompose the copper oxide at 1100°C, but again the duration of 0.5 ms is not long enough to release the oxygen. Another explanation in the report is that during the short heating pulse relatively few gas bubbles can form, also the surface tension and the metallostatic pressure of the melt cause such high pressure that the gas bubbles already formed are redissolved [29].

High energy electron beams are well suited to welding, since the rapid melting restricts the heat affected zone so reducing energy loss and parent metal distortion. This is particularly useful in high conductivity metals such as copper. Originally the process was mainly used for joining small thin components but as beam powers increased larger sections could be joined. Up to 150 mm thick copper has now been satisfactorily welded by electron beam. Normally welding is carried out in a vacuum chamber - i.e. under clean metallurgical conditions. Large vacuum chambers can be made to accommodate large components. Recent work has demonstrated that very good results are possible using quite modest levels of vacuum or the order of 1 mBar. Since the weld is very narrow and penetration is deep, plain butt joints are normal, but edge finish and fit up must be good. There is usually no joint gap but small gaps, up to a millimetre or so, are possible in thicker sections [31].

3.12 Brazing and soldering:

The brazing process is a cheap, reliable and efficient way of making a joint. It is characterised by the use of filler metals having a lower melting point than the parent material such that fusion of the parent metal does not occur. It is relatively simple but particular attention must be paid to the principles of this process. Brazing takes advantage of capillary action by the penetration of a molten filler metal between the joint gap of the parent metals [2]. Therefore to achieve a good brazed joint, the maximum area of capillary bond must be obtained. The strength of a sound brazed joint in copper or a copper alloy is generally greater than the parent metal. It is particularly efficient where the joint is designed so that the main stress is in shear rather than in tension. This takes full advantage of the surface area between brazing alloy and parent metal[2, 3]. Joint strength then becomes less dependent of the actual strength of the "as cast" brazing alloy and more dependent on the filler-to-parent metal bond. For these reasons the brazing of butt joints is not good practice.

Good brazing practice takes into account filler-alloy selection, flux requirements, heating method and, above all, an overall regard for cleanliness of operation. Successful brazing depends on two major factors; joint design and joint gap, or clearance between the parts to be joined [3]. The clearance between the parts to be joined must be controlled within 0,05-0,12 mm. Firebricks or other heat insulating materials are necessary for supporting the workpieces, as a metal hearth or base may conduct heat away from the components. In brazing the component should be preheated quickly (150-200 °C) and uniformly before applying the filler rod by stroking the joint area [2]. Brazing is an effective means of joining copper alloys. A widely used design rule-of-thumb is that an assembly will develop the full strength of annealed copper in a lap joint with a lap three times the thickness of the thinner member. Actually, a deoxidized copper lap joint develops the full strength of the base metal at a lesser overlap. At greater than two times the thickness, short-time tensile fracture generally occurs in the base metal, even when specimens are deliberately made to fail in the joint area, the location of failure generally is partly or wholly through the base metal in a plane parallel to the joint interface. This is because the room-temperature strengths of the BAg and BCuP filler metals are greater than that of the annealed copper. At elevated temperatures, the brazing alloy decreases in strength more rapidly than the copper, and eventually joint failure occurs through the filler metal [19].

Brazing depends on the ability of the filler metal to penetrate, by capillary attraction, small gaps between the metal surfaces to be joined. Under suitable conditions the brazing alloy wets and bonds by surface diffusion alloying to form a strong joint. As with soldering the three most important conditions to achieve an effective bond are: chemically clean surfaces; correct joint gap and correct heating pattern. In a well designed, properly executed joint, the mechanical strength of the finished joint will exceed that of the parent metal when the joint is stressed in shear. This takes full advantage of the surface area of bond between brazing metal and parent metal. Typically the joint gap lies between 0,04 and 0,20 mm. It is also important to appreciate that the clearances must be maintained at brazing temperatures.

Under ideal capillary conditions, most brazing filler alloys are capable of penetrating the joint to a depth of at least 12 mm, often as much as 50 mm. Excessive penetration is neither desirable (for economic as well as practical reasons) nor essential for the purpose of achieving a full strength bond. It should be noted that unless full penetration by the brazing filler metals is achieved, an internal crevice will remain as a potential site for flux and residue entrapment [31].

Brazing of oxygen-free and deoxidized copper can be readily accomplished with torch or furnace in neutral or reducing atmospheres. Furnace-brazing ETP copper in an hydrogen atmosphere, however, causes embrittlement, and so a neutral or inert atmosphere should be provided. Torch-brazing ETP copper should take place with a neutral or slightly oxidizing flame [5]. Oxygen-free high-conductivity copper and deoxidized coppers are readily brazed by furnace or torch methods. Boron deoxidized copper is sometimes preferred because it experiences less grain growth when brazed at high temperatures. Oxygen-bearing (tough pitch) copper is susceptible to oxide migration and/or hydrogen embrittlement at elevated temperatures. Therefore, oxygen-bearing copper should be furnace brazed in an inert atmosphere and torch-brazed with a neutral or slightly oxidizing flame [19]. Brazing is widely applied to copper and copper alloys that have particularly good brazing characteristics when compared with most other common metals. With the exception of alloys containing more than about 3 % lead or 10 % aluminium [31]. Brazing filler alloys are compounded to give a range of melting temperatures, differing flowing characteristics, joint strength and corrosion resistance.

When brazing copper and its alloys, the majority of requirements are met by silver-copper and copper-phosphorous based filler alloys, having an application temperature range between about 630 and 750 °C. Silver is added to the phosphorous based filler alloy to improve the mechanical properties, particularly ductility. In controlled-atmosphere or vacuum brazing of copper-alloys, flux is not necessary. Bronze-welding is extensively used as a low temperature, low-distortion joining technique for ferrous metals as a substitute for welding. Its use in the cooper-alloy field is largely confined to pure copper where, as distinct from most copper-alloys, the difference in melting points between the filler alloy and parent metal is sufficiently large to permit brazing rather than welding to take place [3].

The term Bronze-welding is misleading since it implies fusion of the parent metal and the use of a bronze filler metal. Neither in fact is the case. Bronze welding, until the development of low temperature capillary brazing, was the classic brazing process in which brass was, and still is, used as the filler metal to form a surface bond between unfused parent metals. However, unlike capillary brazing, the strength of the bronze welded joint is derived from the tensile strength of the actual " as cast" filler metal deposited in a joint preparation similar to that used infusion welding, as well as the actual bond strength developed between filler metal and parent metal. According to British Standard (BS 499) terminology, where the term "braze welding" is used, the process is described as the joining of metals using a technique similar to fusion welding and a filler metal with a lower melting point than the parent metal. General design concepts are similar to to those applying to fusion welding, particulary regarding edge preparation. The strength of the bronze welded joint is, given a sound deposit and good bonding, at least as good as an as-cast brass of similar composition, i.e better than 400 N/mm ^{2}. Optimum strength, as in brazing, is achieved by placing at least some reliance on the shear strength of the parent/filler metal bond by creating joint assemblies in which some of the stress is in shear rather than in tension. Bronze welding filler metals are, in general, less corrosion resistant than capillary brazing metals but since in neither case is an alloy match obtained between the joint material and parent metal, care should always be excercised in filler metal selection with particular regard to galvanic corrosion between the dissimilar metals, dependent on the service conditions. The brass alloys used in bronze welding may, in certain environments, suffer more general dezincification corrosion [31].

When brazing in air a flux must be used, but the use of copper-phosphorous alloys for brazing pure copper has the advantage of not requiring an application of flux. However the joint area must be thoroughly clean and free from oxide and grease [2, 3]. Prior to brazing the copper oxide surface film should be removed by either abrading or, for larger areas by pickling in cold 5 % sulphuric acid. Silver-base filler metals with brazing temperatures from 618 to 864 °C and copper-phosphorous filler metals that require 702 to 810 °C are commonly used. Higher temperature filler metals include copper-zinc alloys. Gold alloys are used primarily in electronic applications when a low vapour pressure filler metal is necessary. Standard brazing procedures apply to copper and copper alloys. Joint design employs capillary action to distribute the filler metal into the joint, which can be either lap or butt type. A flux is necessary for most of the base metals in this group. Virtually all of the silver filler metals can be used either with a flux or in suitable atmospheres. The copper-phosphorous and copper-silver-phosphorous filler metals are self fluxing on copper. However, flux is beneficial for heavy assemblies where prolonged heating would otherwise cause excessive oxidation. Since some phosphorous is consumed during brazing, the remelt temperature of the joint is somewhat higher than the original flow temperature of the filler metal. This is advantageous for assemblies with sequentially-brazed joints. Joints with filler metal containing phosphorous should not be exposed for long periods at elevated temperatures to sulphurous atmospheres due to the danger of corrosive attack. With the copper-zinc filler metals, care should be taken not to overheat the metal, since volatilization of zinc causes voids in the joints. When torch brazing an oxidizing flame will reduce zinc fuming. A problem with this type of fillers is that their resistance is inferior to that of copper [19].

When brazing many different types of brazing filler metals are employed. The most commonly used being those based on copper and phosphorus, these providing relatively low cost alloys with low melting points. Such alloys have a unique property, the ability to join copper in air, without using a flux, this is because the phosphorus within the alloys acts as a fluxing agent. These filler metals can also be used for joining copper alloys, but a flux must be employed to ensure good wetting and bonding of the filler metal to the parent materials. With certain copper alloys, where the addition of alloying elements is low, fluxless brazing can also be achieved. The copper phosphorus based brazing filler metals fall into three distinct groups.

Straight copper phosphorus alloys; silver copper phosphorus alloys; and alloys that are modifications of the two standard groups, where a further alloying addition has been made. When referring to the brazing characteristics of an alloy, it is really the alloys flow properties that are of interest. The more free flowing the alloy, the finer the joint gap it can penetrate. However if the joint gap is too large, a free flowing alloy will run through it, producing a joint containing a large number of voids. An indication of an alloys flow characteristics in simple terms can be gained from its melting range. A narrow melting range means a free flowing alloy, a wide melting range, a sluggish alloy. As with the make up of all alloys, there is not a set composition, but a composition range over which the alloys can be manufactured. Typically a tolerance of plus or minus 1 % on the nominal composition is the variation allowed on most brazing filler metals, however as will be realised from information previously stated in the text, such a tolerance would result in alloys based on the copper phosphorus system having extremely variable flow properties from one cast batch to another.

When studying a Cu-P phase diagram it can be seen, if 7 % P is considered, the melting range for 6 % P is 714 to 900 °C and for 8 % P 714 to 760 °C, whilst the latter is an extremely free flowing alloy, the former has very sluggish flow characteristics. To avoid this variety in flow characteristics much tighter tolerances of the composition than the standards are set by the manufacturers of these alloy. Manufacturers also control their alloys to a much tighter degree than is required by the standards, on those alloys where this is necessary, where the alloy composition is at extreme limits of the compositional range. This means that the same alloy (by designation) can display somewhat different flow characteristics, due to different manufacturers composition specifications. This questions are even more complex on an international scale when there also are differences between the international standards. The author summarises the effect of phosphorus by this statement: "The higher the phosphorus content of the brazing alloy the better its flow characteristics." It should not be forgotten that it only takes a small change in phosphorus content to produce a large change in the flow characteristics of the alloy. The author says that discussing the mechanical properties of a brazing alloy is generally irrelevant, since the physical properties of a brazing alloy bear very little relationship to the physical properties of the joint made with that alloy. A properly designed joint, brazed with a copper phosphorus alloy, when tested either in shear or tensile fashion will predominantly fail in the parent materials. The copper phosphorous alloys are inherently brittle, being both notch sensitive and sensitive to the rate of loading. Very little data exists on the ductility of these alloys. Some evaluations however is done and the impact resistance with 7.25 % P being around 0.4 J with the fracture taking place in the brazing alloy itself. The conclusion of this and of experiences is that the higher the phosphorus content, the less the ductility, and the more notch sensitive and the more load sensitive the alloy becomes. A good compromise between good brazing characteristics and good ductility is one that contains between about 7-7.8 % phosphorus. The ductility of this alloy in the as-cast condition will, as already indicated be around 2 %. However in a joint situation where the alloy takes into solution a certain amount of the parent materials, this will be increased.

Higher phosphorus contents gives an improvement in brazing characteristics, but it will be less ductile and more liable to cracks in service. This can seriously affect the leak tightness of the joints and could initiate a fatigue failure. The lower phosphorus content alloys have greater ductility but do not flow readily, unless the brazing temperature is increased. These poor flow characteristics can be of advantage where poor joint fit ups exist, the alloys being far more capable of forming fillets.

The author continues to discuss the effect of silver alloying of the copper phosphorus alloy and says there are two reasons for doing so, namely: The silver alloys have lower brazing temperatures and hence at the same temperature exhibit better flow properties and it is possible to have an alloy with similar brazing characteristics to a straight copper phosphorus alloy that exhibit much better ductility. An extra consideration must be taken into account regarding the cost of the alloy itself, since the silver content of the alloy dramatically affects its cost. Other less expensive alloys, which lower the copper phosphorus alloys melting point and improve its ductility are antimony and tin where the latter is the latest alloy that has been developed (late 70s early 80s).

Tin can also replace some of the silver, and has similar effect to that of silver on depressing the melting temperature. It also seems to impart to the alloys a greater degree of fluidity, but it improves its ductility to only a small extent. The surface finish is also much superior to that of the conventional phosphorus alloy [22].

The most commonly used brazing filler metals for copper and its alloys are those based on the Ag-Cu-Zn and the Cu-Ag-P alloy systems. All the filler alloys are fully molten below 800 °C. There are two main types of copper-silver filler alloys; copper-silver-zinc filler alloys and copper-silver-zinc-cadmium filler alloys. The effect of cadmium is to lower the melting point significantly giving a range of filler metals with melting at temperatures down to about 600 °C. Cadmium can produce toxic fumes during brazing, therefore proper ventilation must be provided. The lower the silver content, the wider the melting range so that alloys become more "pasty" and have the ability to bridge and fill wider joint gaps. When brazing in air, a flux is required. The flux should be compounded to be active over the brazing temperature range. Straight copper-phosphorus filler alloys with silver added improves the ductility, if resistance to torsional, flexing or shock loading is required, an addition of 15 % silver has the best mechanical properties, but 2 to 5 % are satisfactory for common applications. The copper-phosphorus alloys do not require flux when used to braze pure copper in air. The phosphorus acts as a deoxidizer and permits good wetting and the formation of a sound bond.

The surfaces to be joined must be clean and free from grease. For use in copper alloys however, flux of the normal silver brazing filler type has to be used.

There are precautions concerning the use of copper-phosphorus-silver filler alloys. They must not be used on copper alloys containing nickel or iron as brittle phases of nickel- or iron-phosphides can form. The alloys are not suitable for use in sulphurous atmospheres at temperatures above 200 °C. In high pressure hot water and steam, preferential attack on certain phases present in the alloy may occasionally occur. On slow heating a good bond is not achieved as the portion that first is molten tends to flow into the joint leaving behind a useless skull of higher melting point constituent.

A good bond is not achieved under these conditions. Pre-placing of the brazing filler metal in the joint prior to heating instead of hand feeding at brazing temperature has a number of advantages, particularly in mechanised brazing processes. It ensures that the correct amount of brazing filler metal is available in the joint to give uniform results and economic brazing alloy consumption at optimum brazing temperatures. Pre-placing should always be kept in mind as component production numbers increase, since it is the major factor contributing to the technical and economic efficiency of the brazing process. Brazing alloys are also available as pastes incorporating flux. These are dispensed directly on the work adjacent to the joint, so that in the correct heating pattern, the flux runs into the joint, followed by the brazing metal, leaving binder residues behind. Brazing filler metal can also be fed automatically onto a pre-heated and pre-fluxed joint by means of a specially constructed wire feeding mechanism. Uses of this type are, however, generally limited to those carried out on custom built rotary, or on-line indexing brazing machines.

Joint design, heating method, the selection of parent metal and filler-alloy, mechanisation and component numbers are all inter-related factors that must be considered if the optimum production is to be achieved.

Other factors such as the formation of refractory surface oxides may interfere with the wetting and bonding action of the filler alloy, or metallurgical changes in the parent metal during the brazing cycle may affect the final joint strength. The main problem arises in the brazing of oxygen-tough-pitch grades of copper. The cuprous oxide particles in the metal are reduced by hydrogen at brazing temperatures, one of the products of this reaction is steam that can rupture the grain boundaries of the metal and cause embrittlement. This situation is particularly critical in gas torch brazing or furnace brazing in a reducing atmosphere. The solution is to avoid using a heating process involving contact with hydrogen from any source, avoiding reducing or incomplete combustion flames, or to use the phosphorus-deoxidised of hydrogen-free grades of copper. Alloys in a cold-worked or highly stressed condition, particularly those with comparatively high recrystallisation temperatures, such as the cupro-nickels, may crack during brazing through penetration of molten brazing filler metal along the grain boundaries of the parent metal. This phenomenon is somewhat akin to stress-corrosion cracking. Where there is a risk of failure by this mechanism, consideration should be given to the following: The use of annealed rather than cold-worked material; annealing prior to brazing; heating at a slower rate to avoid steep thermal gradients and to permit stress-relieving prior to contact with the molten brazing filler metal; selection of brazing filler metal of higher melting range to permit stress relief before the brazing filler metal melts; re-designing the joint to avoid undue external stressing of the component parts. With the exception of the precipitation-hardening alloys, cold-worked copper alloys and pure copper suffer an irreversible loss of strength during brazing. Design calculations must therefore always be based on the mechanical properties of annealed material.

Precipitation hardening alloys such as copper-beryllium, copper-chromium and some varieties of aluminium bronze, are heat treated for optimum mechanical and electrical properties.

The brazing temperature range 600 to 750 °C lies, in most instances, between solution and precipitation temperatures. This is unfortunate because, if brazing is performed on fully hardened material, over-ageing and softening may occur. Alternatively, if brazing is carried out after solution treatment, adverse precipitation may occur during the brazing process. The best way to solve this problem is by brazing in the fully hardened condition for the shortest possible time at brazing temperature. Chromium, zirconium, beryllium and aluminium form refractory oxide films on the surface of the alloy. Therefore pre-cleaning and fluxing must be performed to obtain good wetting by the brazing alloy, where freshly machined or ground surfaces perform best [31].

A detailed study has been made on changes in the joint width, microstructure and the charpy impact energy of copper-to-copper joints brazed with copper-phosphorus-base filler alloys under loading. Two different filler foils was used, 37 micrometer METGLAS 2005 and BCuP-5. The loads used varied over 0.02 - 4 MPa. With both filler alloys the impact strength increased tenfold.

Particularly strong effect was achieved on the METGLAS 2005 joints when after brazing under the highest load a Charpy impact energy approaching that of pure annealed copper was achieved. This effect is a result of the gradual change in the brazement microstructure with the load increase, i.e. the initial unloaded (conventional) brazement is comprised of a crystalline zone at each of the base metal interfaces and a wide eutectic zone. The two interface zones consist of copper-base solid solution crystals while the central eutectic zone is a mixture of relatively large brittle copper phosphides and crystals of copper-base solid solution phase. Under loading during brazing, when these filler metals are melted, a part of the liquid phase is squeezed out of the joint, thus decreasing the amount of liquid in which the copper-base metal dissolves. This in turn increases the copper concentration in the brazement. Thus with increasing load, the brazement has an increasing amount of the copper base, solid-solution phase with ductile crystals, while the central eutectic zone shrinks and breaks into isolated regions. Two copper-base solid solution crystalline zones eventually joint together, forming a much more ductile uniform brazement. The brazing gap decreases with load from about 50 to 20 μm, but only at rather low loads. At higher loads the brazing gap stabilizes at about 20 μm. And even at 4 MPa the liquid phase is retained over the entire brazing gap so there is no direct contact between two copper parts. A possible reason for this is a dramatic increase in the characteristic flow time of the liquid phase in the capillary brazing gap. Finally the author says that the observed effects may have a general character because analogous results have been observed in the low carbon steel joints brazed with Cu-Mn-Ni-Si brazing filler metal [23].

Where hard silver solder is used for its higher strength as opposed to soft tin alloy solder some thought must be given to the effects of the higher heating temperature involved (above 700 °C). According to the writer traditional tin-lead solders are under close scrutiny as concerns over pollution and effect of toxic substances when these products are to be recycled increase. Research is pointing toward tin-zinc solders. For corrosion resistant applications the joint design needs extra care since a joining alloy dissimilar in chemical composition from that of the parent material may set up an electro-chemical corrosion cell, that will destroy the joint well within the expected life of the whole system. On larger and heavier pipework flanged joints are the norm. These entail welding or silver soldering flange plates to the ends of the pipe and a sealing gasket may be necessary between them [1].

Like brazing, soft soldering generally relies on capillary penetration of the filler metal into controlled narrow joint gaps to provide strength, although the absolute strength is low in comparison with brazed or welded assemblies. Soft solders generally contain substantial proportions of tin and/or lead, and melt usually at temperatures below about 300 °C. Soft soldering is used extensively in the copper alloy field to give mechanical strength to an assembly, and here it is often used in conjunction with a mechanical joint such as a lock-seam. It may also act as a gas or liquid seal.

Its prime advantages are low process temperatures and the ability to remelt and reflow - a considerable benefit in mass production. As with brazing, joints must be designed to be stressed in shear rather than tension because solders generally have low resistance to tearing or peeling caused by non-aligned tensile stress [3]. Soft soldering makes a good to excellent joint in all copper alloys if service is to be below 121° C. Between 121 and 177° C, braze with silver alloys or copper-phosphorous brazing filler metal (for hotter and for stronger joints weld) [4].The most widely used solders are alloys of tin and lead. Tin, the active component, readily reacts and diffuses with copper. Copper base metals will accept a certain amount of tin into solid solution. However, where the solid solution limit is exceeded, an intermetallic phase, probably Cu_6Sn_5 is created. This intermetallic is formed at the interface and grows. Since intermetallics tend to be brittle, it is advisable to keep their thickness to a minimum. Alloying additions to the tin-lead system are made to improve properties of solders. Tin-lead usage is based upon good solderability in the temperature range 195 to 297 °C and relatively low cost. Above the eutectic temperature, the phase equilibrium between the liquid and solid phases results in a pasty range, which allows for wiping or working of the solder to shape. However, alloys at or near the eutectic composition exhibit the sharp melting or solidification desirable for electronics applications, because they quickly immobilize components on cooling.

The success of soldering is dependent on fluxing. Fluxes are generally placed into two categories: protective and chemically active. Protective fluxes are resin based and do not produce chemical fluxing action, e.g., reaction between the flux and the base metal. Protective fluxes are less likely to cause corrosion after soldering and are very important to the electronics industry, but they require that base metal surfaces be very clean prior to soldering. Chemically active fluxes may be activated protective fluxes or the acid type. Activation of protective fluxes is achieved by the addition of chlorides or bromides. Temperature and the method of applying heat are important in the use of flux.

The soldering methods most commonly used with copper are conductive solder iron, molten solder pots (baths, waves, jets, cascades), flame, oven, induction, hot oil bath, electrical resistance, and electro-magnetic radiation (infra-red). With few exceptions, rapid heating and cooling is desirable. The reasons for this are: Flux tends to degenerate when hot and could lose its effectiveness before soldering is completed.

The base metal surfaces may oxidize and become difficult to solder. Prolonged contact with molten solder could case unacceptable changes in the base metal through intermetallic formation, erosion and solution. Degradation of desirable characteristics (such as electrical properties of electronic devices) may occur. The mechanical properties of a soldered joint are different from those of the bulk solder itself and depend on a number of process variables in addition to solder composition. Of importance are joint width, substrate composition, cleaning procedures, flux, soldering temperature, soldering time, and cooling rate. Design for structural applications will usually have soldered members loaded in shear. Shear strength (under rapid application of load) and creep strength in shear are the important mechanical properties. For specialized applications such as auto radiators, peel strength and fracture initiation strength are thought to be important. In a few cases tensile strength is of interest. There are no known techniques for relating one mechanical property to another [19].

There are soft solders, using alloys melting below 350 °C such as tin solders and hard solders using stronger alloys with a higher melting point, such as silver solders. Soft solders are used where mechanical strength is not so important. Due to the relatively low strength of the filler metal compared with the copper and copper alloys being joined, lap type joints should be arranged. This ensures an adequate area of filler metal to carry joint loads. Such joints need three conditions for successful soldering: the correct heating cycle to allow the molten filler to flow and completely fill the joint; the provision of the correct joint gap and chemically clean metal surfaces obtained by degreasing, mechanically abrading and using suitable flux. A clearance between 0.07 and 0.25 mm is permissible between overlapping parts, with 0.01 mm being optimum for capillarity and joint strength. Self-locating designs or temporary solder tagging is recommended, but consideration must be taken that these jigs can act as local heat sinks. Organic-based fluxes have been developed, now forming four main groups, resin, synthetic, synthetic resin and water-based organic fluxes. Dependent on the application and the extent to which subsequent corrosion must be avoided, resins may be mildly activated, with a halide content of less than 0,2 % activated with 0,2 to 0,5 % halide or super-activated with even higher halide levels. The choice of flux is influenced by many factors including type and mass of metal to be soldered, cleanliness, heating techniques, type of solder and after cleaning requirements. For example, the use of torch soldering techniques will require the use of a more active flux to deal with the extra tarnish caused by the flame [31].

3.13 Non-fusion Welding:

A non fusion welding process is where true welding is achieved without fusion of parent metal. The advantage is a stronger joint area because there is no "as cast" welded structure present. Cold pressure welding is where true metallurgical bond can be produced by the relative movement of metal surfaces under pressure. The relative movement cleans the surfaces, the pressure irons out surface roughness and brings the component parts into a contact close enough for atomic bonding to occur.

The other important "non-fusion" process for sheet metal is diffusion bonding. The most common form of this in the copper-alloy field is the formation of a silver-copper eutectic alloy bond between copper sheets by plating the joint surfaces with about 0.01 mm of silver. The sheets are clamped together and heated to just above the melting point of the silver-copper eutectic. Diffusion of the silver into the copper takes place to form the eutectic in situ and a metallurgical bond is formed [3].

The basic principle of the friction welding process is simple. The heat required for the welding operation is generated purely by friction between the two components, one that remains stationary whilst the other rotates rapidly. When the two components are brought into contact, the metal at the interface is rapidly heated to the plastic condition. The rotation is stopped and pressure is applied between the two components, the result is an extremely strong joint with a forged structure, which, because heating is extremely localized, has a very narrow heat-affected zone.

Only one post-welding operation is required and that is the removal of the circumferential flash caused by the upsetting and squeezing out of metal during the welding operation. By gradually increasing the pressure, frictional heat is built up by the rotation of the component, and this also has the effect of cleaning the faces to be welded free from any surface oxide or other contamination. The advantages, briefly, of friction welding over more conventional welding techniques are as follows; Economical - low power input and low material wastage; Flexible - a wide variety of dissimilar metals and alloys can be welded; High quality - reliable, strong, clean joints free from porosity and inclusions; Fast - the welding cycle is rapid once the parameters for a particular job have been established. The author also notes that no flux, filler metal or inert atmosphere is required for completely successful welding. A copper to copper joint is more difficult to make than copper to dissimilar metals, but it have been used with some success (in 1968) [17].

Friction welding offers several very real advantages The heat-affected zone (HAZ) is narrow and contains no cast structure, so that its properties are excellent. Filler metal, flux and shielding gas are not required and the weld is made quickly, at low power requirements. However, there is a flash of upset metal that must be removed. At the present time, the process is limited to the joining of copper to other materials, principally brasses, aluminum, silver, mild steel, stainless steel, and aluminum bronze. Copper-to-copper joints have not been made with any appreciable degree of success. Solid state or diffusion bonding have been used to fabricate strong, conductive, and leak tight joints in copper structures [19].

Friction welding has been used for joining similar and dissimilar metals for several decades. Originally the process was only applied to those joints where at least one component was circular and could be rotated against the other to provide the frictional heat for welding before a forging end force was applied. Later developments have been orbital friction welding where one component is moved in a small orbit against another surface like an orbital sander so that a variety of sections can be joined, and most recently, friction stir welding in which a welding wire or rod is rotated or "stirred" between the surfaces to be joined. In all these processes the relative movement between the interfaces causes the asperities to heat up, soften and plastically deform so that when the relative motion is quickly stopped and load applied normal to the interfaces, surface oxides are squeezed out into a flash that can be cropped off leaving a metallurgically clean, sound weld with the metal in a forged rather than cast condition.

When ultrasonic welding the small mechanical vibrations can be used to generate energy for joining thin metals. This process is widely used for microjoining of fine copper wire to microelectronic devices [31].

4 Discussion

Copper and copper alloys have excellent corrosion resistance, electrical and thermal conductivity and formability. Copper has very high thermal conductivity (5-7 times that of ferrous metals) and a high coefficient of expansion. Therefore consideration must be given to this by the use of high rates of heat input, pre-heating and correct joint-preparation. Especially when welding heavy sections the high thermal conductivity can cause a very large number of failures in copper. Copper can also have an increased brittleness in certain temperature ranges owing to the adsorption of hydrogen and oxygen.

There are oxygen-bearing coppers such as fire-refined and ETP copper (0.02-0.05 % Cu), oxygen free (Cu-content >99.95 %) and phosphorus-deoxidised copper (deoxidized low phosphorous < 0.01 % P = high ductility, or deoxidized high phosphorous copper 0.01-0.04 % P), special coppers (free cutting), high copper alloys, and other alloys such as brasses and bronzes etc.

The most weldable coppers seems to be, according to the references, the phosphorous-deoxidised copper and the oxygen-free high conductivity copper, but the others mentioned above can also be welded if consideration in relation to their condition and composition regarding heat-treatment, oxygen content, hydrogen environment and alloying elements is taken, for example the high coppers require lower temperatures and welding currents due to their lower thermal conductivity than pure coppers. Highly leaded free machining/ cutting alloys are however difficult to weld without cracking.

When welding the phosphorous deoxidized copper and oxygen free high conductivity copper, filler materials containing deoxidants and/or effective gas shielding to the weld and root area must be used, since the phosphorous content is not high enough and the atmospheric contamination or the diffusion of gaseous impurities up the thermal gradient can cause porosity. Welding oxygen bearing phosphorous copper requires deoxidizing filler metals, rapid operation and restriction of overall heating. The requirements of rapid operation and restriction of overall heating must however be weighed against the requirements of fusion and welding profile.

The ETP coppers contain impurities and oxides. In the wrought form the oxides are scattered as globules or transgranular stringers throughout the material, interfering very little with the mechanical properties. But in the cast form, the oxides are gathered in the grain boundaries, as in the weld and heat affected metal. This concentration makes the material less ductile.

To avoid this from appearing perform the operation as quick as possible and restrict the overall heating but consider the requirements for adequate fusion and a satisfactory weld profile. Oxyacetylene welding or other flame processes as well as brazing in an hydrogen atmosphere will cause porosity and gas embrittlement. For this reason use a deoxidizing filler metal or even better choose another welding process. ETP coppers have some advantages such as excellent resistance to atmospheric and sea water corrosion.

Hot working characteristics of single-phase alloys deteriorate with increasing percentage of the second element.Two-phased alloys of the same elements have superior welding characteristics than single-phase alloys. Two-phase alloys hardens rapidly during cold working and as the proportion of the second phase increase the yield strength increases and the ductility decreases.These high copper alloys have enhanced mechanical properties due to the addition of small amounts of alloying agents such as Cd, Co, Zr, Cr and Be. The elements produce high strength from cold-working and age-hardening (Zr), from increased rate of work hardening during cold working (Cd) or from precipitation hardening (Cr, Be and Co/Ni). The Co additions are made to these alloys to restrict grain growth during annealing, Ni can replace some of the Co. The first and the second of the previous mentioned heat treated conditions can be welded but 100 % joint efficiency will not be achieved. The latter should be heat treated after welding. High copper alloys have lower thermal conductivity than pure copper thus lower preheating and current requirements. The high copper alloys with a higher beryllium content are more readily welded than alloys with lower beryllium content where weld cracking and cracking during PWHT have occurred. The heat-treatment consists of solution heat-treatment and age-hardening. A beryllium copper in the age-hardened condition has the highest tensile strength and hardness of all copper alloys. Beryllium coppers are also characterized by high endurance limits under fatigue stress. Welding should take place between solution treatment and age hardening, but in the case of heavy sections the over-aged condition is preferred for welding since it reduces welding difficulties. In this context, when welding thicker sections, the high thermal diffusivity is responsible for a very large number of failures in copper. Unless adequate measures are taken to counteract the rapid heat sink effect, it is not possible to establish the fully fluid weld pool necessary for good fusion and deoxidation, which will result in lack of fusion defects and porosity.

Other elements added to the high copper alloys are Pb, Se, Te and S and they improve machinability without significantly affecting conductivity or corrosion resistance but they do also adversely affect weldability and hot working. The elements B, P, Si and Li are deoxidizers, while Ag and Cd prevent softening.

Copper castings sometimes contain enough lead to make them non-weldable, unleaded castings are weldable if it is recognised that that castings contains gas and shrinkage pores and have rougher surfaces than wrought copper. Such areas and surfaces should be cut or ground off. Finally there is confidence that new materials are to be developed and existing materials will be improved. Dispersion strengthened particle and fibre reinforced copper that maintains the enhanced properties of the material across the joint itself are predicted to enter the market/industry.

When choosing the proper filler metal to specified requirements consider the following. Normally, copper should be welded with filler metal containing deoxidizers. When welding OF or DLP/ DHP copper a Sn bearing Si deoxidized rod will do, with some P and Mn to improve weldment properties. When TIG welding the filler materials alloyed with Mn, Si, Sn and Fe or with B goes for all the copper grades, while filler materials alloyed with Mn and S only goes for phosphorous deoxidised non- arsenical copper. MIG welding filler material alloyed with Mn, Si, Sn and Fe or with B goes for all the copper grades, while filler material alloyed with Al and Ti goes for all the copper grades except for the oxygen-free-high conductivity copper. The boron-deoxidized filler has also good welding characteristics. Alloying with small amounts of Cr and Ti ensures satisfactory solidification cracking resistance. It also prevents microporosity and improves the mechanical properties such as the Vickers hardness, yield stress and tensile strength of the weld metals in copper as the Ti is taken into solid solution. The formation of microcracks is associated with the fact that copper has relatively low solidification cracking resistance. The mechanical properties of the welded joints are improved by the absence of micropores in the weld metal that otherwise will form when welding with a non-alloyed wire. The number of micropores increases with the thickness of the parent metal. Ti additions should be restricted below a certain percentage at which Ti has no further effect on the number of pores since Ti lowers the materials ductility, by solid-solution hardening. If residuals impurities of Bi and Pb are present in either parent metal or filler they have the effect of promoting transverse cracking in the welds, As can counteract this influence.

When joining and repairing copper-based castings one of the major considerations is the correct selection of filler metals. The filler metal must have closely matching corrosion resistance to the bulk casting when the component will experience a corrosive service environment. If it is necessary to employ a non-matching filler metal, it must be cathodic to the parent metal to prevent galvanic corrosion on the smaller area of the weld. The filler metal must have comparable mechanical properties to the bulk casting alloy. The filler metal must contain deoxidants to provide effective deoxidation and a sound weld. Colour match of filler alloy to parent metal may be important.

To choose the proper welding process variables such as the metallurgical properties, material thickness, size, shape and joint design as well as fit up of the weldment and above all application requirements, codes and specifications must be considered. Are jigs and backings, which may be integral, to be used for controlling and supporting the weld penetration and weld bead? Is there need to ensure accurate positioning, or to offset the high heat conductivity? The design of these items depends on pre-heat requirements, material thickness, joint type and it must allow welds to be made without causing unnecessary chilling. The backing bars made of mild or stainless steel should be lightly coated with colloidal graphite or a graphite-based anti spatter compound. Also graphite, solid amorphous carbon, or a heat resistant material such as ceramics with its surface covered with graphite or carbon can be used. A carbon backing bar is not only heat resistant and inert but does also create an inert atmosphere so that it is possible to produce a sound weld by preventing the back bead from being oxidized without further shielding with an inert gas.

The weld edges should be prepared in relation to process, material thickness, weld position, accessibility and to joint type. If possible weld in the flat position. The joints should be prepared with wide root gaps and tacking should be made frequently during fitup, using preheat and filler as when making the main weld.This will compensate for coppers higher thermal expansion coefficient and higher thermal conductivity. It will will therefor prevent distortion and so incomplete fusion and inadequate joint penetration. Small root gaps and or the absence of tack welds will cause excessive warpage and stress. As an alternative the employment of tongue and grooved clamps may be used to maintain alignment and specified root gaps, instead of tack welds. Tongue and grooved clamps has advantages as the chances of a tack weld breaking or the possibility of a root defect occurring when re-fusing a tack weld is eliminated. Insufficient preheat also results in incomplete fusion, lack of penetration and lack of deoxidation by the filler metal.

One should not forget the importance of weld pre-cleaning which removes oxides, grease, dye-penetrant fluids and dirt. A bronze wire scratch brush can be used followed by degreasing with petroleum ether, alcohol or alkaline solutions. Brushing between each run is also recommended. For chemical cleaning and pickling use trichloroethylene, mixed acetates or toluenes that reduce thick oils, fats and dirt. During preheating oxide scale forms rapidly above about 300 °C. If a repair operation is to be conducted the amount of metal removed when preparing should be minimised using conventional grinding and chipping. The greater the cavity the greater the metallurgical effect due to higher heat input. However, the weld area must be clean and permit access of the welding electrode to the root.

As has been mentioned earlier pre-heating is important and it should be to a higher temperature than that needed for steel, owing to coppers higher thermal conductivity (e.g. the heat dissipates fast from the welding area). The optimum temperature for any given plate thickness will depend upon the welding current, joint design, position and material mass. The problems described above arise from high conductivity and they increase in severity as the material grows thicker.

If the gas shielding arc welding methods, either the Metal Inert Gas method (MIG) or the Tungsten Inert Gas method (TIG) are to be used, the following should be considered. The need for pre-heating can be reduced when welding with MIG or TIG, if some or all of the argon (Ar) shielding gas is substituted with helium (He) or nitrogen (N_2). The inert gases Ar, He and N_2 keep oxygen out and do not react with the metal being welded. Ar produces the lowest arc voltage and power output while N_2 produces the highest with He in between, for a given arc length and current flow. N_2 is difficult to use for this reason and can blow the molten weld metal out of the pool. If this is compensated by a longer arc length the shielding and positioning will suffer. For this reason Ar is used for thinner material and He used for thicker material. A mixture of these two is common due to better economy. The pre-heating temperature required depends on the choice of shielding gas. He makes a reduction possible, by 10 to 15 % lower than that needed for Ar. Oxyacetylene torch heating is used for thinner stock, while propane burners are better used for heavier material.

The pre-heat should be maintained during the process with the use of asbestos blankets or asbestos lined fixtures on heavier stock, while the inter-run temperature should allow a maximum of 50° C rise or fall on thinner stock. Extra welding current is not a good substitute for preheating since it may blow the metal out of the pool, destroy the gas shield and produce porosity, cause undercut or wormholes and poor beads.
To avoid the risk of wormholes, when MIG welding, the employment of twin consumable electrode wires can dispense with preheating up to approximately 13 mm thick copper. If preheating isn't practical, flat down hand welding is preferred, any position is possible when preheat is used. There are alternatives to pre-heating, however, instead of increasing the welding current or forming a groove, the voltage could be increased by 37 to 45 V compared with the conventional welding process. D.C current would be used with the electrode positive to allow a rapid melting rate of the filler rod. When MIG welding, it also cleans the welding area. This technique makes it possible to weld copper from 5 mm to 25 mm by one layer and to 100 mm by the multi-pass technique.

When depositing weld metal by either the TIG or MIG processes thin layer methods should be avoided particularly in the initial root runs because of the risk of weld cracking. The weaving technique may be applied on thicker materials and the stringer method applied on thinner material. A further advantage of thick layer root runs is that when subsequent layers are made excessive weld sinkage or burn through is greatly reduced. When unsupported butt joints or corner joints are welded the "key-hole" technique is an alternative as it produces satisfactory penetration bead shapes. When welding thick copper the "block-sequence technique"/"terrace method" with MIG or TIG is useful. With this technique pre-heating is not necessary up to a certain thickness and mass. For high deposition rates MIG is superior to TIG. There are three different types of metal transfer, dip, spray and globular transfer when MIG welding. At currents (D.C. and positive electrode) above a certain minimum level the metal transfer changes from drop to spray transfer, which is desirable since the spray transfer is smooth, steady and easily manipulated. Furthermore the capillary penetration is deep in the centre and shallow at the edges. Spray transfer is not obtainable with either the He or the N_2 gas. When only one or a combination of these gases is used a globular transfer is obtained with heavy spatter, therefore an Ar-He or maybe an Ar-N_2 mixture is preferred. This provides higher deposition rates and an arc that is steady and easily controlled. Yet again the pre-heat requirements are lower when using Ar with a mixture of either He or N_2. Finally the gun angle and direction of travel have considerable influence upon the quality of the deposited weld metal, where the rightward technique and an angle of 70 to 80 ° C from the vertical is preferred.
TIG is preferred where neat and accurate joints in sheet form are required. An alternative to Ar-gas with A.C. current is He-gas with D.C. current, especially when welding thick copper. When welding with D.C. the electrode must be negative to reduce electrode erosion and to provide maximum heat input at the work piece. If the tip of the tungsten electrode is tapered the directional stability of the arc is improved. Doping the electrode with thoria or zirconia improves the arcing characteristics by increasing electron emissivity.

The pure tungsten electrode tends to form a hemispherical tip that creates a fan shaped arc and often leads to lack of fusion, especially when welding deep V joints or at the root of a filler joint. On the other hand a thoriated electrode can produce deep undercut, due to its concentrated arc stream if not pre-heating is performed when it is required. When N_2-gas is used the thoriated electrode is even more essential, since the nitrogen increases the tungsten loss. As with MIG welding, the metal transfer changes from globular to spray above a certain current level, spray provides a smooth transfer, an excellent control of the weld puddle and deep penetration in the centre.TIG is useful when repairing thick copper. With a combination of He shielding gas and filler metal containing 2 % Mn the melted filler is very fluid under the He-gas. This is suitable for filling small defects and repair areas. This technique permits weld repair without pre-heat and it causes very little disturbance to the surface beyond the local repair area. It is even possible to maintain the surrounding area cool by the immersion technique.

The shielded metal arc welding method, SMAW/MMA, is used for minor repair jobs on light gage stock, difficult to reach fillets, or dissimilar metals. Also when MMA welding there are pre-heat requirements.

The oxygen fuel welding method, OFW, can be used when welding copper, due to acetylenes very high flame temperature and reasonably good heating value.

Laser and EB welders are usually used for hermetic sealing. When choosing between laser welding (LW) and electron beam welding (EBW) one should consider weld requirements, material-to-beam (laser/electron) interaction, joint design, fixturing, and equipment/ production costs. By evaluating these areas it may be possible to obtain the best process for the existing situation. Weld penetration should be restricted to that necessary for the mechanical property requirement in the joint. Requesting an excessive penetration along with minimal distortion may be costly, if not impossible, due to the extra heat input required to produce unnecessary penetration. By studying the similarities between the two processes: high energy density beams; low total heat input; minimal/ no part distortion after welding; excellent weld quality; autogenous - requires no filler metal; weld joints require minimal clearance; poorly accessible joints are welded; weld thick or thin parts; high welding speeds with CO_2 and EB welders; can weld metals with dissimilar melting points and thermal conductivities, and studying the differences: EB welds in vacuum - laser welds in open atmosphere; EB is deflected by magnetic field - laser beam is not affected; laser beam is partially reflected by materials with high reflectivities - EB is not affected; EB requires parts to be electrically conductive - lasers require parts to absorb their wavelengths; EB welders provide higher power levels and deeper penetration than laser welders, it is possible to decide which process to use when joining a specified product with a specific material.

There is the solid state Nd:YAG laser (50-600 W) and CO_2 laser (500-20000 W). The welding speed of Nd:YAG is less than 8.5 mm/s while the CO_2 laser can reach over 42 mm/s. The Nd:YAG laser is currently restricted from use for welding components that require more than 2.5 mm penetration,

although there have been developments of the laser crystals that makes the method generally more competitive with the EB and CO_2 laser welders. Both the CO_2 laser and the EB welder can produce over 20 kV and 100 kW.
EB welders are classified by the vacuum and acceleration voltage used for welding. Consequently there are high vacuum, medium vacuum, low vacuum and non vacuum systems. There are low voltage and high voltage EB welders, where low voltage operates in the range between 60 kV to 200 kV. The high voltage welders can provide greater penetration than the low. With high vacuum welders the contamination levels due to air can be reduced to less than one part per million (1 ppm). The total heat input of the welding process is an important consideration when welding heat sensitive components.

Laser and EB welding processes provide lower total heat inputs, as compared to conventional welding methods. Pulsed beam welding systems offer even lower total heat input than continuous wave or beam systems. Components requiring limited total heat input should be designed with minimal gap at the weld joint that allows for proper heat flow between the parent metals. The materials being welded are considered due to their effects on the laser and electron beams, as well as the effects of the beams on them. Weldability may be influenced by materials chemical composition and physical, mechanical and thermal properties. When using EB, as mentioned earlier, the workpiece must be electrically conductive.

To produce a laser weld, a sufficient amount of energy must be absorbed by the workpiece. This absorption is dependent on the wavelength of the laser beam, and the reflectivity and surface finish of the material being welded. Materials such as gold, silver and copper are highly reflective of both Nd:YAG and CO_2 wavelengths. This sometimes restricts the use of laser welding on these materials. However, reflectivity and absorption are not always a major concern since higher power levels sometimes initiate melting by increasing the metals temperature and decreasing reflectivity. By carefully designing the joint, the laser beam can be reflected back and forth across the joint surfaces so that adequate heating for fusion takes place. There is also a laser spinning technique that can fuse joint surfaces without special geometry requirements in the joint design. It is not clear if these techniques are applicable on heavy copper .

The thermal conductivity of materials can influence the selection of a welding process. Welding a material with a high thermal conductivity, such as copper and its alloys, will require greater heat input than one with a lower value when requiring equal penetration. It also affects the rate of solidification (it increases with increase in thermal conductivity), and can be responsible for weld bead cracking. Due to higher power levels, the CO_2 laser and EB welder can achieve greater depths of penetration than the Nd:YAG. Also the use of the pulse mode is restricted with materials sensitive to rapid solidification, e.g. with high thermal conductivity, such as copper and its alloys. Some materials are extremely reactive to the atmosphere in which they are welded. For those materials which are sensitive to the welding atmosphere, or the gas shield, the vacuum of the EB process can provide an excellent welding environment. Although the laser process can be adapted to weld in a vacuum chamber, it is normally used with gas purging nozzles.

Contamination can be reduced, when laser welding, by using a helium or argon atmosphere. The laser and EB processes require no filler metal. This eliminates the use of grooves, bevels, or chamfers from weld joints. The clearance between the parts being joined should be minimized according to the parent material thickness and the desired penetration depth.

Factors affecting the depth of penetration of laser welders include pulse shape and width (for pulsed laser systems), material surface finish, flashlamps (Nd:YAG) or gas mixture (CO_2). The depth of penetration produced by the EB welder is affected by acceleration voltage, degree of vacuum, working distance between the electron gun and work piece as well as travel speed. The depth to width ratio is regulated by the lasers and the electron beams mode of operation, focus, and welding speed. The key hole process (continuous wave) produces high depth to width ratio but can also produce welds with lower ratios, by adjusting power, focus and speed. By focusing to increase the power density of the beam, e.g. reducing the spot size, greater penetration with narrower width can be achieved. Welding at a high rate will normally produce a higher ratio, but the maximum depth of penetration is achieved at lower welding speeds. Under constant power conditions, an increase in acceleration voltage will provide an increase penetration and decrease in weld width (higher ratio).

When EB welding the work piece must be electrically conductive and it has to be de-magnetized, as has the fixture, before welding. De-magnetizing can partly be achieved by degaussing. EB welding is preferably performed in high vacuum and the workpiece or assembly must be able to withstand this environment. This restricts the use of EB welders on assemblies which contain substances that vaporize under high vacuo. There are also indications that it is possible to a use coarse vacuum of the order of 1 mBar when welding copper. When EB welding, pumping down the vacuum chamber may take from five seconds to several minutes. A solution is that, when welding large quantities of a single part, most EB systems can be equipped with a large continuous transfer system that puts a part into a pre-evacuation chamber, then into the welding chamber. This continuous transfer and the multi-station system (where several parts can be loaded at the same time in the chamber), allows the electron beam welders cycle time to become competitive with that of the laser. (The Nd:YAG or CO_2 laser can provide excellent cycle time since these systems do not require a vacuum atmosphere for welding).

When EB welding it has been shown in the result section that it is possible to avoid or reduce defects such as porosity, erratic overflow, blow holes under-cutting and hot cracks. When welding a high temperature copper alloy, it is possible to solve the latter problem by using square oscillations of the beam along the weld, and in this case the specific probability of crack formation after welding and during service loading is retained if the backing strip is fully penetrated. If there are pores in the metal of EBW joints, their service properties, particularly the mechanical ones, may deteriorate seriously. The deposition of welds containing no pores, or the minimum of them, is thus very important from the point of view of service reliability and of providing them with mechanical properties equivalent to those of the parent metal.

The vacuum, the high power density and vaporization of the metal, and the fast rate at which weld pools solidify creates conditions under which pores may form in welded joints. Increased beam power and depth of focus as well as decreased travel speed increases the amount of porosity. When metals whose composition does not include easily vaporized components are EB welded the best result may instead be obtained by reducing the travel speed. Porosity may also be due to the processes taking place at the end surfaces of components being butt joined. In this case, ahead of the weld pool, compressive forces may weld the ends in the solid state causing micro and macro cavities. So called primary pores are formed from these cavities. To prevent these primary pores from appearing it is necessary to clean the surfaces and to transverse corrugate the weld edge surfaces.

The shape of the EB weld, deep and narrow, impedes the movement of gas bubbles in the weld pool, for instance when welding electrolytic tough pitch copper (ETP), a copper that contains impurities and this promotes the formation of pores. Another reason to create a wider weld is that a predicted misalignment between the beam and the joint can be compensated. To prevent porosity the general method is to use refined metal, which has been subjected to electroslag re-melting, electron beam re-melting, vacuum preheating of the weld edges or heating the entire work in a vacuum furnace. Compared to copper this level of purity is similar to cathode copper, i.e OF-copper. Remelting of the weld metal in the electron beam is not a good approach since it does not always reduce the amount of porosity.This process also causes excessive deformation, internal stresses and a reduction in the amount of alloying elements with high vapour pressures. All these may have a bad effect on other properties of the weld. Sound welds can however be produced when the weld pool is alloyed with elements that reduce solubility of gases in the molten metal or combine them into stable compounds.

Full thickness penetration is preferred, since this is likely to result in additional degasification of the molten metal through the root of the penetration channel. A sound weld can also be produced as mentioned earlier by partly melting the backing piece that contains the alloying elements, by oscillating, or finally by controlling the weld position (preferably where the weld is made in the vertical plane and the beam runs horizontally, this configuration is least susceptible to pore formation).There are however indication that oscillation is not always the solution and that a pulsating beam hinders the oxygen from being released and causes pores to be formed.

It has been noticed that welded oxygen free copper only displays a small quantity of pores, compared to electrolytic tough pitch copper. Erratic overflow, under-cutting and blow holes can be avoided by either lower the beam power or using a low power cosmetic pass over the main weld. When EB welding the penetration and fusion zone area seems to increase with increasing beam power and increasing weld speed.

An explanation why also an increased welding speed promotes greater penetration is that since little time is available for lateral melting a greater depth can be melted, leading to greater penetration. For materials with high thermal conductivity, such as copper, relative high welding speeds are thus preferred, to promote penetration and to reduce excessive lateral melting.

The beam spot size seems to have some effect on the penetration characteristics, this is however not yet investigated. When compared to electrolytic tough pitch copper (ETP) the oxygen free copper (OF) has a slightly higher conductivity and therefore a greater penetration should be expected. It has however been shown to be the opposite in reality. The explanation to this is that the higher rate of impurities in ETP copper causes a vapour pressure during welding that promotes penetration. However, it has also been said that a higher rate of impurities decreases penetration. One has succeeded in obtaining penetration depths from 10 to 50 mm, and even as much as 150 mm. As mentioned earlier the backing support, if used, must be fully penetrated to avoid root cracks.

Good brazing practice takes into account filler-alloy selection, flux requirements, heating method and an overall regard for cleanliness of operation. Brazing takes advantage of capillary action by the penetration of molten filler metal between the joint gap of the parent metals. The quality of the brazed joint depends on two major factors namely the joint design and joint gap e.g. the clearance between the parts to be joined. The clearance between the parts to be joined must be controlled within 0,04-0,2 mm, and it must be maintained during the operation. The maximum area of capillary bond must also be obtained. Under ideal capillary conditions, most brazing filler alloys are capable of penetrating a joint to a depth of at least 12 mm, often as much as 50 mm. The filler can be fed in the form of foil, paste or wire. For optimizing production the latter can be fed automatically or the filler can be pre-placed. Excessive penetration is neither desirable (for economic as well as practical reasons) nor essential for the purpose of achieving a full strength bond. It should be noted that unless full penetration by the brazing filler metals is achieved, an internal crevice would remain as a potential site for flux and residue entrapment. The strength of a sound brazed joint in copper or a copper alloy is generally greater than the parent metal. It is particularly efficient where the joint is designed so that the main stress is in shear rather than in tension. This takes full advantage of the surface area between brazing alloy and parent metal. Joint strength then becomes largely independent of the actual strength of the "as cast" brazing alloy and more dependent on the filler-to-parent metal bond. For these reasons the brazing of butt joints is no good practice. An assembly will develop the full strength of annealed ETP copper in a lap joint with a lap three times the length of the thinner member but a deoxidized copper lap joint develops the full strength of the base metal at a smaller overlap. At greater than two times the thickness, short-time tensile fracture generally occurs in the base metal, even when specimens are deliberately made to fail in the joint area. The location of failure generally is partly or wholly through the base metal in a plane parallel to the joint interface.

Firebricks or other heat insulating materials are necessary for supporting the workpieces, as a metal hearth or base may conduct heat away from the components. When brazing the component should be preheated quickly and uniformly before applying the filler rod by stroking the joint area.

Brazing of oxygen-free and deoxidized copper can be performed with a torch or in a furnace in neutral or reducing atmospheres.

Oxygen-bearing ETP copper is susceptible to oxide migration and/or hydrogen embrittlement at elevated temperatures, therefore furnace-brazing in a hydrogen atmosphere must be avoided. A neutral or inert atmosphere should be provided instead. If ETP copper is to be torch-brazed a neutral or slightly oxidizing flame ought to be used. Boron deoxidized copper is sometimes preferred because it experiences less grain growth when brazed at high temperatures. Alloys in a cold-worked or highly stressed condition, particularly those with comparatively high recrystallisation temperatures, such as the cupro-nickels, may crack during brazing through penetration of molten brazing filler metal along the grain boundaries of the parent metal. This phenomenon is somewhat akin to stress-corrosion cracking. With the exception of the precipitation-hardening alloys, cold-worked copper alloys and cold worked pure copper suffer an irreversible loss of strength during brazing. Design calculations must therefore always be based on the mechanical properties of annealed material.

Precipitation hardening alloys, however, such as copper-beryllium, copper-chromium and some varieties of aluminium bronze, are heat treated for optimum mechanical and electrical properties. The brazing temperature range is in between the solution and precipitation temperatures and if brazing is performed on fully hardened material, over-ageing and softening may occur. Alternatively, if brazing is carried out after solution treatment, adverse precipitation may occur during the brazing process. The best way to solve this problem is by brazing in the fully hardened condition for the shortest possible time at brazing temperature. The alloying elements Cr, Zr, Be and Al form refractory oxide films on the surface of the alloy. Therefore pre-cleaning and fluxing must be performed to obtain good wetting by the brazing alloy, where freshly machined or ground surfaces perform best.

Brazing filler alloys are compounded to give a range of melting temperatures, differing flow characteristics, joint strength and corrosion resistance.The flow characteristics of the filler are determined by its melting range. A narrow melting range results in a free flowing alloy, a wide range results in a sluggish alloy. Also the higher the phosphorous content the better the flow characteristics but it only takes a small change in the phosphorous content to produce a large change. When brazing copper and its alloys, the majority of requirements are met by silver-copper and copper-phosphorous based filler alloys. Silver is added to the phosphorous based filler alloy to improve the mechanical properties, particularly ductility. It also has lower brazing temperatures and therefore exhibits better flow characteristics than copper phosphorous filler metal. The mechanical properties such as the resistance to torsional, flexing or shock loading can also be improved with silver additions. One could also say, regarding its influence in suppressing the brazing temperature, that the lower the silver content the wider the melting range so that it becomes more pasty and thus can bridge and fill wider joints. Some of the silver can be replaced by either tin or antimony, which also like silver suppresses the melting temperature. There are precautions concerning the use of copper-phosphorus-silver filler alloys. They must not be used on copper alloys containing nickel or iron as brittle phases of nickel- or iron-phosphides can form. The alloys are not suitable for use in sulphurous atmospheres at temperatures above 200 °C.

On slow heating a good bond is not achieved as the portion that first is molten tends to flow into the joint leaving behind a useless skull of higher melting point constituent. If a copper phosphorous filler is used the higher the phosphorous content the lower the ductility and thus the more liable the joint is to cracks during service. It is also more notch sensitive and more load sensitive. However the ductility is somewhat increased when the filler during the brazing process takes some of the molten parent copper metal into solution.

Interestingly it seems possible to increase the impact strength tenfold to reach the toughness of the parent metal in the pure annealed condition, when joining copper with copper phosphorous filler metal foil under loading. When brazing under loading, the filler metals are melted and a part of the liquid phase is squeezed out of the joint, thus decreasing the amount of liquid in which the copper-base metal dissolves. This in turn increases the copper concentration in the brazement. So with increasing load, the brazement has an increasing amount of the ductile crystals of copper base in solid-solution phase, while the central eutectic zone shrinks and breaks into isolated regions. Two copper-base solid solution crystalline zones eventually joint together, forming a much more ductile uniform brazement.

Flux must be employed to ensure good wetting and bonding of the filler to the parent metal. In controlled-atmosphere or vacuum brazing of copper-alloys, flux is not necessary. When brazing in air a flux must be used, but the use of copper-phosphorous alloys and copper-silver-phosphorous filler has the advantage of not requiring an application of flux providing that the sections are thin. Flux is still necessary when brazing heavy components where prolonged heating would otherwise cause excessive oxidation. Filler metal containing phosphorous should not be exposed for long periods at elevated temperatures to sulphurous atmospheres due to the danger of corrosive attack.

Soft soldering uses alloys melting below 350 °C such as tin solders and hard soldering uses stronger alloys with a higher melting point, as silver solders. Soft soldering generally relies on capillary penetration of the filler metal into controlled narrow joint gaps to provide strength, although the absolute strength is low in comparison with brazed or welded assemblies. Soft solders generally contain substantial proportions of tin and/or lead. Soft soldering is used extensively in the copper alloy field to give mechanical strength to an assembly or in conjunction with a mechanical joint such as a lock-seam. It may also act as a gas or liquid seal. Its prime advantages are low process temperatures and the ability to remelt and reflow - of considerable benefit in mass production. As with brazing, joints must be designed to be stressed in shear rather than tension because solders generally have low resistance to tearing and peeling caused by non-aligned tensile stress. Soft soldering makes a good to excellent joint in all copper alloys if service is to be below 121 °C. For service between 121 and 177 °C, braze with silver alloys or copper-phosphorous brazing filler metal. However, The tin-lead solders seems to be under close scrutiny as concerns over pollution and effect of toxic substances when these products are to be recycled increase. Research is pointing toward tin-zinc solders.

For corrosion resistant applications the joint design needs extra care since a joining alloy dissimilar in chemical composition from that of the parent material may set up an electro-chemical corrosion cell that will destroy the joint well within the expected life of the whole system.

Where hard silver soldering is used for its higher strength as opposed to soft tin alloy soldering some thought must be given to the effects of the higher heating temperature involved (above 700 °C).

A non fusion welding process is where true welding is achieved without fusion of parent or filler metal. The advantage is a stronger joint area because there is no "as cast" welded structure present.

Cold pressure welding/ friction welding is where the relative movement of metal surfaces under pressure can produce a true metallurgical bond. The relative movement cleans the surfaces, the pressure irons out surface roughness and brings the component parts into a contact close enough for atomic bonding to occur. The heat required for the welding operation is generated purely by friction between the two components. When the two components are brought into contact, the metal at the interface is rapidly heated to the plastic condition. The rotation is stopped and pressure applied between the two components, the result being an extremely strong joint with forged structure, which because heating is extremely localized, has a very narrow heat-affected zone. Only one post-welding operation is required and that is the removal of the circumferential flash caused by the upsetting and squeezing out of metal during the welding operation. The interesting advantage of friction welding over more conventional welding techniques is the strong, clean joint free from porosity and inclusions. No flux, filler metal or inert atmosphere is required for completely successful welding. There are indications however that a copper to copper joint is more difficult to make in comparison with joining copper to dissimilar metals. A development of the friction welding method is the friction stir welding technique in which a welding wire or rod is rotated or "stirred" between the surfaces to be joined.

The solid state or diffusion bonding method has however been used to fabricate strong, conductive, and leak tight joints in copper structures, but only when joining sheets of copper.

5 Conclusions

A literature study of the possibilities and limitations in joining copper and its alloys has been performed. It has covered base material selection, filler metal selection, conventional and non-conventional joining processes, difficulties and how to solve them. Since the aim of this report is to gain an understanding of welding in copper and its alloys, this will also be the topic of this conclusion. Joining of heavy coppers is of special interest.

Some reflections before the results are shown. Generally a number of variables have to be considered before manufacturing a product. First of all one has to decide the design criteria. Then decide the manufacturing process and if a joining process is needed. The material to be used must be able to meet both the design criteria and the requirements of weldability, heat-treatment and examination.
The joining process has to be qualified and a subsequent inspection has to be performed. Handling procedures such as pre-weld cleaning must be specified.

This study has revealed several weldable coppers and joining processes that can be used when manufacturing a product.

The use oxygen free copper, phosphorous deoxidized copper or high copper alloys will normally not lead to any welding difficulties. The high copper alloys have enhanced mechanical properties but some of them do however require post weld heat treatment. Although welding electrolytic tough pitch copper has its disadvantages the base-material has excellent resistance to atmospheric and sea water corrosion. Dispersion strengthened, particle and fibre reinforced copper which maintain enhanced properties of the material across the joint itself are predicted to enter the market.

The MIG welding process is a conventional method. It is used for its high deposition rates. For heavy sections the multi-pass technique is used. It requires both shielding gas and filler metal and thus grooves.

The TIG welding process is also a conventional method and can as MIG be used for high deposition rates, but its advantages is however in repairing heavy copper sections.

The EB welding process can provide deep and narrow welds. It produces high power levels and low total heat input with low distortion after welding. It requires a narrow clearance between the parent metals and neither filler metal nor grooves are used. High to low vacuum is used instead of shielding gas. Caution must be taken so that cavities, porosity, primary pores, root-cracks, blow-holes under-cutting and erratic overflow are avoided, this is possible with a correct combination of welding parameters.

Laser welding is difficult to perform on copper and its alloys as the beam is reflected from the metal surface. Therefore no heating and subsequently no melting can take place. However, by carefully designing the joint, the laser beam can be reflected back and forth across the joint surfaces so that adequate heating for fusion takes place. A spinning technique has also been developed to counteract this problem. It is however not clear weather these techniques are applicable on heavy coppers.

Brazing can be performed with deep penetrations and the joint is preferably designed so that the main stress is taken in shear rather than tension. The requirement of keeping the clearance between the parts during brazing must be followed. This process provides joints with improved mechanical properties if the proper filler is used or if the brazing is performed under loading.

Friction welding provides an extremely strong joint with forged structure and a narrow heat affected zone. The joint is also clean and free from porosity and inclusions. There are however indications that there are difficulties in friction welding copper to copper, in comparison with welding copper to dissimilar metals. A development of the process is the friction stir welding technique where an inconsumable rod or wire is rotated between the joint surfaces.

Although the diffusion bonding technique has only been used when joining sheets of copper, the results from these shows a strong, conductive and leak tight joint.

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