Abstract:
Copper and copper alloys offer a unique combination of material properties that makes them advantageous for many manufacturing environments. They are widely used because of their excellent electrical and thermal conductivities, outstanding resistance to corrosion, ease of fabrication, and good strength and fatigue resistance. Other useful characteristics include spark resistance, metal-to-metal wear resistance, low-permeability properties, and distinctive color.

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Welding Processes
In manufacturing, copper is often joined by welding. The arc welding processes are of primary concern. Arc welding can be performed using shielded metal arc welding (SMAW), gas-tungsten arc welding (GTAW), gas-metal arc welding (GMAW), plasma arc welding (PAW), and submerged arc welding (SAW).

Arc Welding Processes. Copper and most copper alloys can be joined by arc welding. Welding processes that use gas shielding are generally preferred, although SMAW can be used for many noncritical applications.

Argon, helium, or mixtures of the two are used as shielding gases for GTAW, PAW, and GMAW. Generally, argon is used when manually welding material is less than 3 mm thick, has low thermal conductivity, or both. Helium or a mixture of 75% helium and 25% argon is recommended for machine welding of thin sections and for manual welding of thicker sections of alloys that have high thermal conductivity. Small amounts of nitrogen can be added to the argon shielding gas to increase the effective heat input.

Shielded metal arc welding can be used to weld a wide range of thickness of copper alloys. Covered electrodes for SMAW of copper alloys are available in standard sizes ranging from 2.4 to 4.8 mm.

Gas-Tungsten Arc Welding. Gas-tungsten arc welding is well suited for copper and copper alloys because of its intense arc, which produces an extremely high temperature at the joint and a narrow heat-affected zone (HAZ).

In welding copper and the more thermally conductive copper alloys, the intensity of the arc is important in completing fusion with minimum heating of the surrounding, highly conductive base metal. A narrow HAZ is particularly desirable in the welding of copper alloys that have been precipitation hardened.

Many of the standard tungsten or alloyed tungsten electrodes can be used in GTAW of copper and copper alloys. The selection factors normally considered for tungsten electrodes apply in general to the copper and copper alloys. Except for the specific classes of copper alloys, thoriated tungsten (usually EWT-2) is preferred for its better performance, longer life, and greater resistance to contamination.

Gas-Metal Arc Welding. Gas-metal arc welding is used to join of the coppers and copper alloys for thickness less than 3 mm, while GMAW is preferred for section thickness above 3 mm and for the joining of aluminum bronzes, silicon bronzes and copper-nickel alloys.

Plasma Arc Welding. The welding of coppers and copper alloys using PAW is comparable to GTAW of these alloys. Argon, helium, or mixtures of the two are used for the welding of all alloys. Hydrogen gas should never be used when welding coppers.

Plasma arc welding has two distinct advantages over GTAW: (1) the tungsten is concealed and entirely shielded, which greatly reduces contamination of the electrode, particularly for alloys with low-boiling-temperature constituents such as brasses, bronzes, phosphor bronzes, and aluminum bronzes, and (2) the constructed arc plume gives rise to higher arc energies while minimizing the growth of the HAZ. As with GTAW, current pulsation and current ramping may also be used. Plasma arc welding equipment has been miniaturized for intricate work, known as microplasma welding.

Plasma arc welding of coppers and copper alloys may be performed either autogenously or with filler
metal. Filler metal selection is identical to that outlined for GTAW. Automation and mechanization of this process is readily performed and is preferable to GTAW where contamination can restrict production efficiencies. Welding positions for PAW are identical to those for GTAW. However, the plasma keyhole mode has been evaluated for thicker sections in a vertical-up position. Generally, all information presented for GTAW is applicable to PAW.

**Submerged Arc Welding.** The welding of thick gage material, such as pipe formed from heavy plate, can be achieved by continuous metal-arc operation under a granular flux. Effective deoxidation and slag-metal reactions to form the required weld-metal composition are critical and the SAW process is still under development for copper-base materials. A variation on this, process can be used for weld cladding or hardfacing. Commercially available fluxes should be used for the copper-nickel alloys.

**Alloy Metallurgy and Weldability**

Many common metals are alloyed with copper to produce the various copper alloys. The most common alloying elements are aluminum, nickel, silicon, tin, and zinc. Other elements and metals are alloyed in small quantities to improve certain material characteristics, such as corrosion resistance or machinability. Copper and its alloys are divided into nine major groups. These major groups are:

- **Coppers**, which contain a minimum of 99.3% Cu
- **High-copper alloys**, which contain up to 5% alloying elements
- **Copper-zinc alloys (brasses)**, which contain up to 40% Zn
- **Copper-tin alloys (phosphor bronzes)**, which contain up to 10% Sn and 0.2% P
- **Copper-aluminum alloys (aluminum bronzes)**, which contain up to 10% Al
- **Copper-silicon alloys (silicon bronzes)**, which contain up to 3% Si
- **Copper-nickel alloys**, which contain up to 30% Ni
- **Copper-zinc-nickel alloys (nickel silvers)**, which contain up to 7% Zn and 18% Ni
- **Special alloys**, which contain alloying elements to enhance a specific property or characteristic, for example machinability

Many copper alloys have common names, such as oxygen-free copper (99.95% Cu min), beryllium copper (0.02 to 0.2% Be), Muntz metal (Cu40Zn), Naval brass (Cu-39.5Zn-0.75Sn), and commercial bronze (Cu-10Zn).

Many of the physical properties of copper alloys are important to the welding processes, including melting temperature, coefficient of thermal expansion, and electrical and thermal conductivity. Certain alloying elements greatly decrease the electrical and thermal conductivities of copper and copper alloys.

Several alloying elements have pronounced effects on the weldability of copper and copper alloys. Small amounts of volatile, toxic alloying elements are often present in copper and its alloys. As a result, the requirement of an effective ventilation system to protect the welder and/or the welding machine operator is more critical when welding ferrous metals.

- **Zinc** reduces the weldability of all brasses in relative proportion to the percent of zinc in the alloy. Zinc has a low boiling temperature, which results in the production of toxic vapors when welding copper-zinc alloys.
- **Tin** increases the hot-crack susceptibility during welding when present in amounts from 1 to 10%. Tin, when compared with zinc, is far less volatile and toxic. During the welding tin may preferentially oxidize relative to copper. The results will be an oxide entrapment, which may reduce the strength of the weldment.
- **Beryllium, aluminum, and nickel** form tenacious oxides that must be removed prior to welding. The formation of these oxides during the welding process must be prevented by shielding gas or by fluxing, in conjunction with the use of the appropriate welding current. The oxides of nickel interfere with arc welding less than those beryllium or aluminum. Consequently, the nickel silvers and copper-nickel alloys are less sensitive to the type of welding current used during the process. Beryllium containing alloys also produce toxic fumes during the welding.
- **Silicon** has a beneficial effect on the weldability of copper-silicon alloys because of its deoxidizing and fluxing actions.
- **Oxygen** can cause porosity and reduce the strength of welds made in certain copper alloys that do not contain sufficient quantities of phosphorus or other deoxidizers. Oxygen may be found as a free gas or as cuprous oxide. Most commonly welded copper alloys contain deoxidizing element, usually phosphorus, silicon, aluminum, iron, or manganese.
Iron and manganese do not significantly affect the weldability of the alloys that contain them. Iron is typically present in some special brasses, aluminum bronzes, and copper-nickel alloys in amounts of 1.4 to 3.5%. Manganese is commonly used in these same alloys, but at lower concentrations than iron.

**Free-Machining Additives.** Lead, selenium, tellurium and sulfur are added to copper alloys to improve machinability. Bismuth is beginning to be used for this purpose as well when lead-free alloys are desired. These minor alloying agents, while improving machinability, significantly affect the weldability of copper alloys by rendering the alloys hot-crack susceptible. The adverse effect on weldability begins to be evident at about 0.05% of the additive and is more severe with larger concentrations. Lead is the most harmful of the alloying agents with respect to hot-crack susceptibility.

**Factors Affecting Weldability**

Besides the alloying elements that comprise a specific copper alloy, several other factors affect weldability. These factors are the thermal conductivity of the alloy being welded, the shielding gas, the type of current used during welding, the joint design, the welding position, and the surface condition and cleanliness.

**Effect of Thermal Conductivity.** The behavior of copper and copper alloys during welding is strongly influenced by the thermal conductivity of the alloy. When welding commercial coppers and lightly alloyed copper materials with high thermal conductivities, the type of current and shielding gas must be selected to provide maximum heat input to the joint. This high heat input counteracts the rapid heat dissipation away from the localized weld zone. Depending on section thickness, preheating may be required for copper alloys with lower thermal conductivities. The interpass temperature should be the same as for preheating. Copper alloys are not post-weld heat treated as frequently as steels, but some alloys may require controlled cooling rates to minimize residual stresses and hot shortness.

**Welding Position.** Due to the highly fluid nature of copper and its alloys, the flat position is used whenever possible for welding. The horizontal position is used in some fillet welding of corner joints and T-joints.

**Precipitation-Hardenable Alloys.** The most important precipitation-hardening reactions are obtained with beryllium, chromium, boron, nickel, silicon, and zirconium. Care must be taken when welding precipitation-hardenable copper alloys to avoid oxidation and incomplete fusion. Whenever possible, the components should be welded in the annealed condition, and then the weldment should be given a precipitation-hardening heat treatment.

**Hot Cracking.** Copper alloys, such as copper-tin and copper-nickel, are susceptible to hot cracking at solidification temperatures. This characteristic is exhibited in all copper alloys with a wide liquidus-to-solidus temperature range. Severe shrinkage stresses produce interdendritic separation during metal solidification. Hot cracking can be minimized by reducing restraint during welding, preheating to slow the cooling rate and reduce the magnitude of welding stresses, and reducing the size of the root opening and increasing the size of the root pass.

**Porosity.** Certain elements (for example, zinc, cadmium, and phosphorus) have low boiling points. Vaporization of these elements during welding may result in porosity. When welding copper alloys containing these elements, porosity can be minimized by higher weld speeds and a filler metal low in these elements.

**Surface Condition.** Grease and oxide on work surfaces should be removed before welding. Wire brushing or bright dipping can be used. Miliscale on the surfaces of aluminum bronzes and silicon bronzes is removed for a distance from the weld region of at least 13 mm, usually by mechanical means. Grease, paint, crayon marks, shop dirt, and similar contaminants on copper-nickel alloys may cause embrittlement and should be removed before welding. Miliscale on copper-nickel alloys must be removed by grinding or pickling; wire brushing is not effective.