Keeping Your Cool with Copper

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Water-cooled copper technology for containment and solidification of molten metals has been around for decades now and has been used in a variety of melting and casting processes for commercial applications. During the middle of the last century non-consumable and consumable electrode melting under vacuum (VAR), electro-slag remelting [the Hopkins Process] (ESR), continuous casting and even small commercial melts using electron beams (EB) all seemed to evolve within the same time frame.

The progression of these processes plus the commercialization of EB along with the advent and commercialization of plasma arc melting (PAM) have made it imperative that proper cooling of copper be fully considered and implemented.

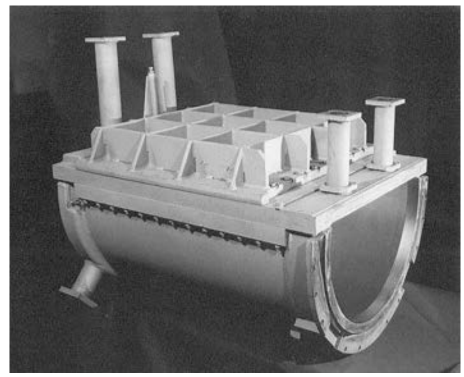
- The first consideration of proper cooling of copper is velocity of the water. The requirement of 10 ft/sec or 3 meter/sec is mandatory. Anything less allows vapor bubbles to coalesce, anything more nullifies heat of vaporization efficiency.
- The second consideration of proper cooling is directed and controlled water flow. This compares water wall cooling, drilled water passage cooling and slotted channel or finned cooling. All comparisons presume high velocity water flow.
- The third consideration of proper cooling is the use of conditioned water at a uniform inlet temperature. This is out of our realm of expertise and is best left to others. The only input we have in this area is our study that indicated .004" or more of soft scale deposit on the copper cold face elevates the hot face temperature by approximately 50°F and increases as deposit thickness increases. The same holds true for inlet water temperatures of over 115°F.

Because the original VAR water jackets were what we call the "bathtub type", the jacket was being cooled better than the copper crucible. The crucible received convection current cooling with coalescing vapor bubbles being rather common – some bordering of film boiling. Water walls were thick (3" and up) and low water availability of 150 to 200 GPM's made for ambient flow.

This was improved upon by furnace manufacturers who provided separate water guides that were placed into the water jacket and sized for each crucible. Low profile clamps for the crucible base plate reduced water walls and did improve water flow rates and direction but the guides were somewhat fragile and subject to damage. Most of these got relegated to the melt shop yard.

The advent of ESR saw some VAR furnaces being adapted for this newer melting process. Unfortunately, the old bathtub jackets couldn't provide adequate cooling for the increased heat load on the copper crucibles, therefore repair and resize cycles for ESR was about twice the frequency of that for VAR crucibles. This prompted a new crucible design where with a water jacket that remained assembled throughout the melting and ingot stripping operations. The unitized construction allowed water walls of about 5/8" thickness and provided reduced water flow cooling to the copper crucible liner during ingot stripping.

In the late 1970's, ESR focused on melting rectangular (slab) ingots, also in static full-size crucibles. Starting with 12" x 24" adjustable to 30" wide, these sizes increased to 12" x 42", 12" x 53", 20" x 60", 30" x 60" and 30" x 80". Up to 53" widths were 4-piece (book) molds with mechanical seals whereas the 60" and 80" widths were welded construction with no mechanical seals. High velocity water was achieved through the use of narrow water walls down to ¼" thickness.



Support for the flat copper sides was provided by blind tapped bolts on a grid pattern connected to a structural strong back jacket. The copper experienced its classic thermal cycle creep shrinkage which on a per inch basis affected the broad sides of the 4-piece crucible leading to crankshaft support bolts and leaking seals. The all welded construction incorporated "creep restrictors" which reversed the shrinkage by forcing the copper into yield and back to its original dimension. Support bolts stayed intact.

Obviously, we did not invent any of these cooling methods. What we did was to analyze each one in relation to the metals melting processes and put relative comparison numbers on each method. This allowed us to make recommendations for the proper application of the cooling methods

In the late 1960's, we were made aware of a melting operation in Berkeley, CA where a vacuum induction furnace fed a ceramic lined launder that fed into four consecutive cascade flow refining hearths that were EB heated. The last hearth cascaded onto an "F" shaped runner (today it would be called a refining hearth) with each leg of the "F" alternately feeding drilled water passage ingot withdrawal type slab molds that discharge into separate ingot cans. We built the molds and runner and were introduced to drilled water passages that were already implemented in that operation.

In 1981, we were approached for design assistance on a "D" shape crucible for non-consumable electrode melting of titanium scrap consolidation in an ingot withdrawal system. Knowing that water wall cooling was not the way to go, we suggested a two-piece drilled water passage design as being best for the application.

The final design, which utilized a welded stainless steel strong back on the flat side, lasted an uninterrupted 920 heats. Placed in operation in 1984, it was taken out of service three years later. Our prediction had been maybe 900 heats. A previous crucible with no strong back on the flat side resulted in premature deformation of the flat side (shrinkage) at less than 250 heats.

In 1981 we were asked to design and build 12" and 18" diameter ingot withdrawal molds for an electron beam melt shop. At that time, we believed that a high velocity water wall cooling design was economically sound for any size up to 20" ID. Our basis was hoop strength consideration and the fact that resizing of these relatively small diameters was inexpensive. These molds were all welded and had no mechanical seals.

Amortized new and repair mold costs of a couple of cents per product pound validated our hypothesis. These molds are still in customer inventory and can be used in the future should those sizes be required.

From that point in time, mold sized increased in diameter, multi-strand casting became a requirement and small slab shapes progressed to jumbo slabs in excess of 30,000 pounds. Multiple hearths and pour lips for enhanced refining became a permanent part of the EB melting process. In 1983 our designs turned exclusively to drilled water passage style for all sizes, shapes and configurations. By the way, the 1983 mold and those thereafter are still in operation today.

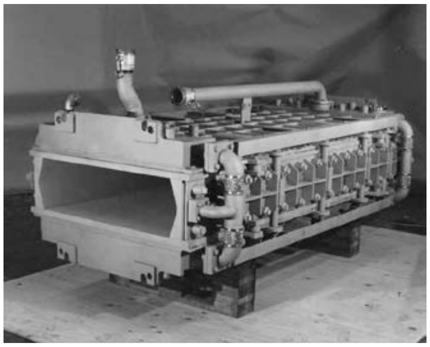
Meanwhile, plasma arc melting (PAM), which uses a plasma torch as the heat source, started to compete with the EB process for reactive and refractory metals melting. Heat loads on the copper components closely paralleled that of EB and while water wall cooling of molds was the initial thrust, drilled water hole cooling in massive copper forgings remained the construction of choice for the PAM hearths. Because of the exposure of the top of the mold and pour lips to torch impingement, proper water passage design became mandatory. Similar to EB the mold designs quickly progressed to drilled water passage designs.

At about the same time, EB drip melters of Zirconium and Niobium alloys, who were using water wall cooled molds with O-Ring water seals were experiencing seal failures caused by copper deformation. Frequency was about every two weeks, which resulted in aborted melts, expensive downtime and degraded metallurgy. A change to drilled water passage molds extended furnace uptime to over one year, a considerable benefit. The drilled water passage, properly designed, has these advantages:

- In order to accommodate the cooling holes, wall thickness of copper is greater than in water wall design. Result is stiffer wall and starts to reduce creep deformation.
- The cold face to hot face ratio is greater than in water wall design. This further reduces creep deformation. (Needs further explanation)
- The outer periphery of the copper can be strengthened by supporting it with a stronger metal such as stainless steel. This drastically reduces creep deformation. We use stainless steel welded to the copper for non-magnetic purposes and because of the closeness of coefficient of expansion of both metals. Rounds as well as slabs and shapes can be accommodated in this type of construction.
- Being an all welded structure where the crucible or mold is also the jacket, there are no mechanical seals to create leak problems. The only seals are on the pipefittings of the water supply lines.
- By using a combination of parallel and series water flow circuits that are incorporated within the vessel, water volume and therefore pumping requirements are significantly less than in a water wall system.
- Water pressure in the cooling holes, that should not have to exceed 60 PSI, is easily handled within the hole. This negates the unit becoming a pressure vessel as it does in water wall cooling. Hydrostatic stresses on the vessel are not a concern.

Bearing in mind that withdrawal molds have no taper and rely on ingot shrinkage solely for withdrawal clearance, they are somewhat sensitive to inside diameter creep shrinkage. This does not impact the ingot itself but rather the ability of the ingot puller to reach the proper level to initiate ingot casting. It has been reported to us that round molds can operate for over three years before the ingot diameter reduces below customer acceptance specification. A 1/8" inward deformation is the criteria for resize. On slabs, a similar deformation over similar times occurs. Since slabs are usually conditioned prior to rolling, dimensionals prevail that affect yield.

Totally amortized mold costs of less than 2 cents a pound are not unusual and in some cases these costs can drop to below 1 cent a pound. While those numbers are impressive, we feel that the reliability of a properly designed mold that allows an expensive furnace to be devoted to production, rather than maintenance and downtime is even more impressive.



It has taken close to 20 years for this type of performance data to become available from a variety of melt shops in both EB and PAM. What started out as encouraging is now impressive. For those melters involved with static molds that contain the ingot, there is also some preliminary optimistic data. An ESR drilled water passage slab crucible, size 9" x 42" x 110" high with standard taper small faces was commissioned in December of 1996. It has completed 140 heats as of early this year and the customer reports no signs of deformation. Encouraged by this performance, several crucibles of a more popular size, 12"x 42" utilizing the same basic cooling concept have been installed more recently and are currently at the 50 heat level and show no signs of deformation. This report is from a melt shop that saw lots of deformation on its previous water wall cooled crucible designs.

We would predict that properly cooled and drilled water passage ESR slab crucibles should last approximately 1500 heats before repair/resize. If the 1500 heats is correct, amortization cost of .8 cents per product pound cost would prevail. Not factored in this cost is furnace uptime and reduced crucible inventory.

For VAR melters, limited to round static ingot crucibles with standard taper, the hoop strength of the round coupled with the external stiffeners should render even more impressive results. We would not be surprised with 2500-3000 heats before resizeing required. On that basis, amortized crucible costs would be expected to drop to below .5 cents per product pound.

Admittedly, the capital costs of properly cooled crucibles and molds is high. Electron Beam and Plasma Arc Melters already know this and so does one ESR melter. But the point of this paper is to tell the melting community that payback is there and is based on operating results. For safety (especially reactive metal melting), reliability, productivity and service life economy, proper cooling of copper is hard to beat.