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MOLD COATINGS NOT THE LIMITING FACTOR[1]

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Abstract
The UniMold® Division of SMS Millcraft has continued to develop and optimize a mold coating process that utilizes a ceramic/metallic coating in conjunction with electroplating technology to create a coating with superior wear resistance properties. A brief update of the various casters using ceramic/metallic mold coatings to extend mold copper liner beyond 300,000 tons will be presented as well as a checklist that all casters can follow in order to increase mold life. A specific focus will be on high speed casters who have had recent success in using ceramic/metallic coatings to protect against meniscus degradation.
Key words: Mold; Mould; Coatings; Continuous casting; Lateral strand guides; Internal corrosion; UniGuard.

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1 INTRODUCTION

Many casters have addressed the primary and highly visible issue of mold liner wear and are now in a position where the next limiting factor regarding mold maintenance centers around repairs to the foot roll containment directly below the mold, narrowface corner gaps, or internal corrosion issues. Recommendations for improving the longevity of lateral strand guides as well as operational recommendations for reducing corner gaps will be made. Many North American casters are dealing with scale exfoliation from the internal carbon steel surfaces of their mold supporting frames and water jackets. Varying solutions for dealing with these scale issues will be presented. The use of cold face coatings to control heat transfer rates and increase the useable hot face thickness of mold liners for thin and medium slab casters while maintaining product quality and campaign tonnages will be presented. The applications for similar cold face coatings within the conventional thick slab caster realm will be discussed.

2 WHAT IS THE LIMITING FACTOR?

Since the beginning of continuous casting extended mold life has been synonymous with high productivity. However, driving molds to the point where mold copper liners have been worn enough that suitable cavity or taper dimensions can not be held is not wise. After significant wear of the copper mold liners has occurred product quality will suffer and in the worst cases breakouts can be attributed to running a mold with excessive wear. Therefore, mold wear has been the primary reason for mold removal and subsequent maintenance.

The primary objective of coatings used on a continuous caster mold copper is to decrease wear within the bottom of the mold cavity. Uncoated mold coppers can also allow for the diffusion of the copper substrate onto the surface of the strand leading to quality defects such as “star cracking”.(1) Mold coatings applied in the meniscus of mold coppers have a thermal insulating effect which can allow for better development of the mold flux powder layer and tends to create a more uniform meniscus hot face temperature profile. These attributes can have positive effects on mold performance and product quality.(2)

Over the past 40 years there have been various coatings used to combat wear on mold coppers. The current variety of mold coating options available now on a global scale is impressive. From this menu of mold coating options most casters have found a protective layer that works for them to appropriately address wear and decrease the frequency of mold removals for wear on copper liners. While electrolytic nickel remains a good choice for coating many continuous caster molds, it is prone to fatigue and thermal cracking in the meniscus. When nickel is alloyed to increase its hardness or when it is plated in thicknesses greater than 0.120”, it can become internally stressed, which can lead to excessive cracking.(3) For CSP® casters and some other high speed casters applying electroplated nickel in the meniscus is not successful because the nickel tends to crack severely after only a few sequences, and subsequently spall from the copper liner. Caution must be taken when using nickel and/or nickel alloys in the meniscus of continuous casting molds and for some casters it is just not possible. Figure 1 shows how even a relatively thin layer of nickel in the meniscus of a high speed caster can crack severely.

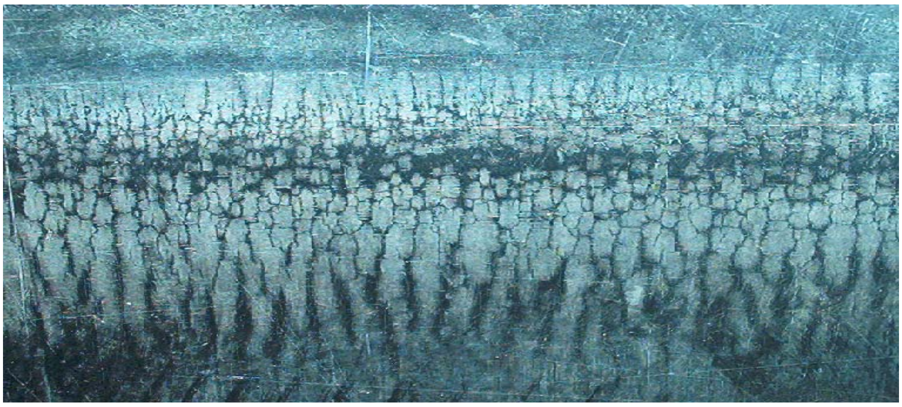

Figure 1. Meniscus area of a high-speed caster broad face, thermal related cracking.

The UniMold® Division of SMS Millcraft offers a wide variety of mold coating options. The mold coatings offered range from electroplated chrome, copper and nickel plating to harder more wear resistant ceramic/metallic coatings. The use of the cermet coatings such as UniGuard™ developed by UniMold® and introduced to a broad portion of the North American continuous casting community over the past several years has solved numerous wear issues for a variety of casters. There are a portion of casters for which a coating such as UniGuard™ may not be cost effective this is typically because mold wear is not the limiting factor. For example, most high speed casting molds in North America are removed for meniscus erosion and cracking of the substrate copper far before wear at the bottom of the mold becomes an issue.

A through explanation of mold wear commonly seen on slab casters coppers can be referenced in previous AIST papers published in 2004 and 2006 by SMS Millcraft. These technical papers outline the development of the proprietary UniGuard™ coating process and provide more information regarding the physical properties of the cermet coatings in comparison to other mold coatings.[4,5] To provide perspective reference Figures 2 and 3, as they are excellent photographic examples of excessive narrowface wear commonly seen on thick slab caster narrow face coppers.

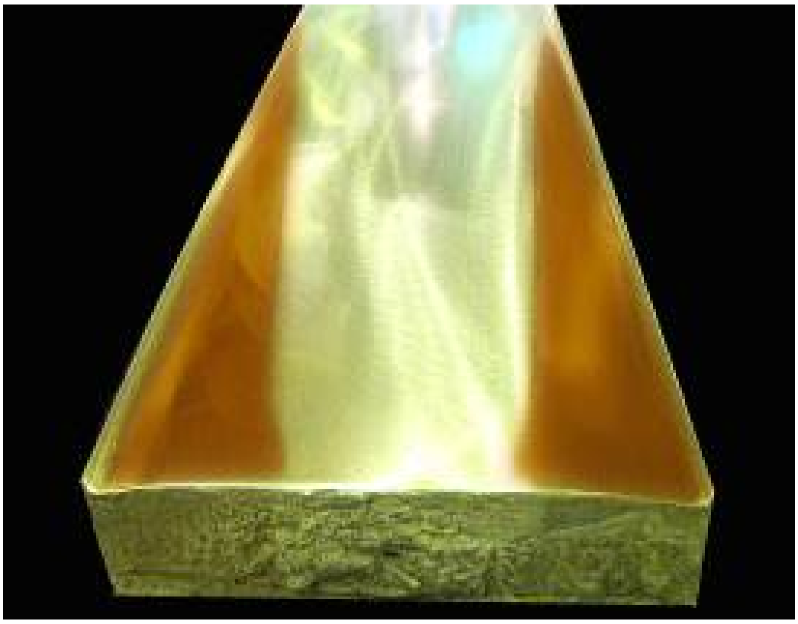

Figure 2. Typical narrow face wear.

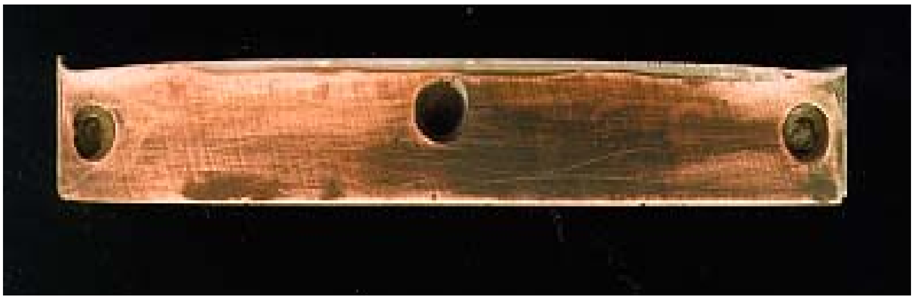

Figure 3. End view of the “guttering” that occurs at the bottom of a worn narrow face copper.

3 ADVANTAGES OF THE UNIGUARD™ COATING

The primary advantages of using the UniGuard™ coating on mold coppers is reduced wear. In many cases UniGuard™ coated coppers are now in service two to three times as long as conventional nickel plated broad faces or narrow faces and may only be worn 0.1 mm to 0.3 mm. This lack of wear into the copper substrate means slab product quality will not be affected by copper pick-up, and less copper removal will be required during refurbishment. Mold taper is consistent throughout the campaign, unlike when using nickel-plated coppers where some taper is lost as a result of wear. The full face configuration of the UniGuard™ coating also provides meniscus protection from thermal cycling and attack from zinc, cadmium, or other elements floating in the meniscus.

Other benefits discovered by those casters who have replaced traditional nickel plating with UniGuard™ include improved slab shape and a decrease in edge related defects. Several customers have also noticed a decrease in corner gap issues between the narrow face and broad face coppers, each coated with UniGuard™, even after much longer campaigns than what was previously cast on conventional nickel-plated molds. A similar benefit to the improved corner gaps, is a decrease in the occurrence of broad face scratching over the upper half of the copper where the narrow faces traverse.

The UniGuard™ process is flexible and can easily be customized to aid in solving caster-specific wear and/or quality issues. The coating can be applied very precisely over a range of thicknesses, allowing customized coating configurations on individual coppers to achieve, for example, a higher hot face temperature. All types of copper alloys used in the manufacturing of mold coppers are able to be coated. The physical properties of the copper substrate are not harmed or altered during coating and copper or nickel edges are available on narrow face coppers. Furthermore, the alloy of the ceramic-metallic coating can be altered to achieve different objectives.

4 MAXIMIZING THE LIFE OF UNIGUARD™ COATED COPPERS

Over the past five years the number of casters using UniGuard™ coating on at least narrow face coppers has grown from a mere handful to over twenty. The UniGuard™ mold coatings are now distributed globally to four continents. This exposure has allowed the coating to be subjected to a tremendous variety of casting conditions and operations. The casters that have had the most success with this coating are those casters who have utilized the ceramic/metallic coating on all four mold faces. In the past few years the “strategic” use of electroplated nickel has been invaluable in allowing some casters who originally had issues with chipping and coating loss to become dedicated users. To minimize any potential operational issues, the heat

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removal rate of the previous coating configuration was mirrored over the upper third to half of the copper by the initial UniGuard™/nickel trial configuration.

In order to maximize the longevity of the coppers coated with UniGuard™ the following recommendations should be followed:

- arrange for a UniMold® Engineer to meet with both maintenance and operating personnel to discuss how the use of the coating might affect assembling the coppers into a mold or packing and positioning of the dummy bar head in the mold;
- all packing and prying tools utilized on the cast floor should be made of hardwood or at the very least coated with a bright rubberized type coating to remind employees to carefully use any steel tools in the mold cavity;
- focus on careful dummy bar insertion and maintenance of the dummy bar head to alleviate unplanned movements of the dummy bar head during insertion. (particularly important on top fed dummy bars);
- for bottom fed dummy bars, operators should never use the bottom edge of one of the narrow face coppers to guide, center or push the dummy bar head into the cavity;
- recommend using a product such as V-board to pack around the edge of the dummy bar head this provides operators with a wider contact surface and decreases the chances of contact with the mold wall when packing;
- excessive narrow face taper above 1.3% is not recommended. More importantly, if you are not confident of what your narrow face taper is correct this situation;
- train operators to understand moderate coating loss in the bottom third of the mold does not always necessitate mold removal;
- steam evacuation below the mold should be maintained to allow for adequate removal. Be vigilant in checking for and correcting misaligned foot roll sprays.

In general many of recommendations provided above if addressed will help maximize the life of any coating applied to continuous casting mold coppers. A number of the recommendations above deal with operational issues outside the scope of most maintenance supervisors or managers but to allow the greatest chance at successful conversion. Operational personnel must be included in the training to maximize mold life since they are normally the group that is very involved in packing the mold and determining when a mold needs to be changed due to hot face condition. Even where proper training has been conducted with both maintenance and operations personnel, accidents can happen and the ceramic/metallic coating becomes damaged. This is why most UniGuard™ configurations include an underlying layer of electroplated nickel to allow for a secondary layer of protection against copper pick-up when ceramic/metallic coating loss occurs across the bottom third of the copper.

The photos in Figures 4 and 5 and the corresponding graph in Figure 6 illustrate why coating loss across the bottom third of a UniGuard™ coated narrowface can appear to be visually worse than it is. UniGuard™ coated copper #350 below exhibited documented coating loss in multiple areas across the bottom third of the copper after less than 100,000 tons cast. Subsequent casting on #350 resulted in the additional coating loss as seen in the photograph below. The wear comparison shown graphically compares a UniGuard™ coated copper #350 to a standard nickel plated copper #352. The UniGuard™ copper #350 having casting nearly twice the tonnage

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cast on nickel plated copper #352. Overall support offered by the UniGuard coated copper is still significantly better than that of the nickel plated copper. Wear on the UniGuard coated copper is less than 1 mm while the wear on the nickel plated copper is 2.5 mm and there are large areas of exposed copper.


Figure 4. Nickel plated copper with typical wear.

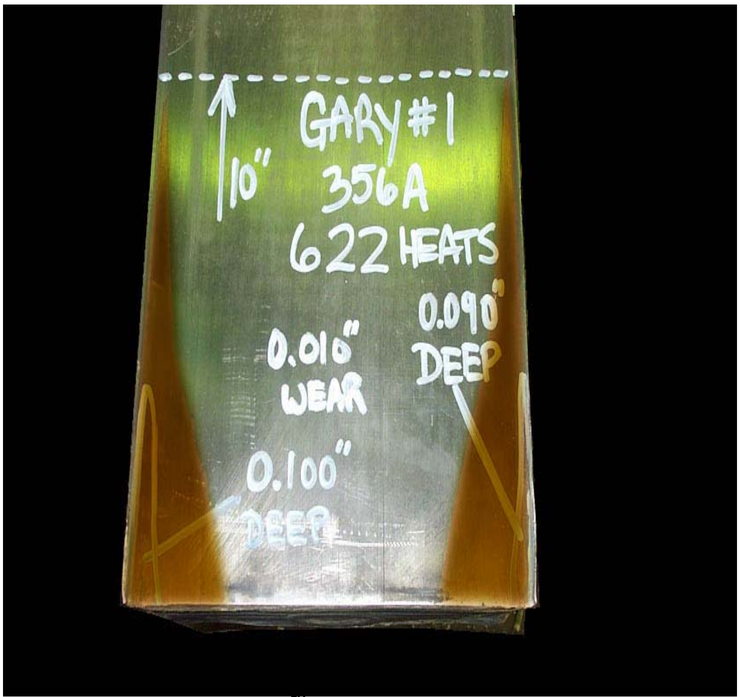

Figure 5. UniGuard™ coated copper with coating loss.

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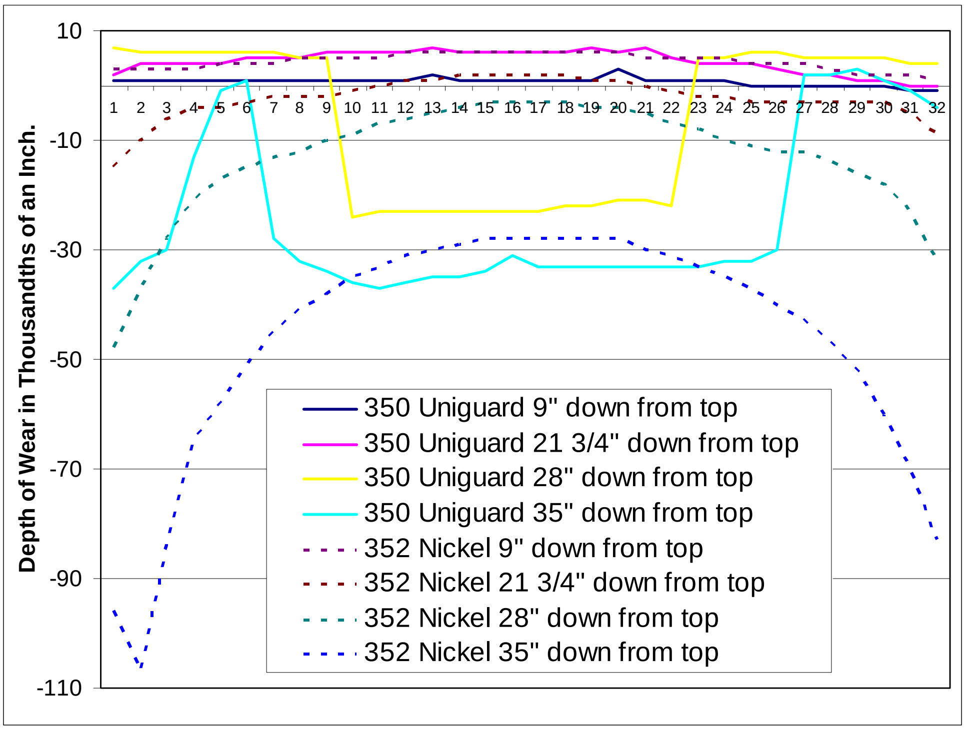

Figure 6. Wear comparison of UniGuard™ coated copper #350 and nickel plated copper #352.

5 CASTER CASE STUDIES

In previous papers, written in 2004 and 2006, regarding UniGuard™ mold coatings there was a significant number of case studies presented.[4,5] All previous casters presented in case studies continue to utilize the UniGuard™ mold coatings and have had continued success with medium slab casters averaging over 250,000 tons cast and multiple thick slab casters averaging over 300,000 tons cast with some mold campaigns exceeding 500,000 tons cast. The only UniGuard™ caster case study presented as part of this paper will be for the demanding CSP® casting operation at Gallatin Steel.

5.1 Gallatin Steel – Ghent, Kentucky

Gallatin Steel operates a CSP® thin slab casting and rolling operation along the Ohio River in Northern Kentucky and has run numerous UniGuard™ coating trials in the meniscus area of their broad face mold coppers once they reach a predetermined thickness. The coating helps prevent surface cracking and increases the thermal resistance of the casting surface so thinner coppers can be made to mimic thicker coppers during casting.
In thin slab casting it is extremely important to prevent mold cracking at meniscus height that can result in longitudinal cracks in the cast shell. Over cooling the shell while running thinner coppers can also lead to longitudinal cracks that can result in customer claims or downgraded product. By applying UniGuard™ coating onto the casting surface, the operating temperature of the mold is elevated back into the range where good product quality can be assured. As such, coppers that previously would have been considered too thin for continued use can run one or two additional campaigns. This increases the overall life expectancy of copper mold liners, which in turn can lead to operational cost savings.

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In 2006 Gallatin resumed trialing the UniGuard™ coating on broad face coppers and has seen a tremendous improvement in the amount of copper removed during refurbishment on those coppers which have utilized the coating. As can be seen in Figure 7 those coppers which utilized the UniGuard™ coating over the upper 300 mm of the copper had nearly half the copper removed during refurbishment (removal shown in tons cast per mm of copper removed) as compared to the rest of the mold fleet which had no meniscus protection. It should be noted that all UniGuard™ coated Gallatin broad face coppers where thin coppers approaching minimum thickness. The graph below compares these thin coated coppers to coppers over a range of copper thickness from maximum to minimum thickness. Most high speed casters see a moderate improvement in copper removal during the life of their mold coppers as they near minimum thickness.

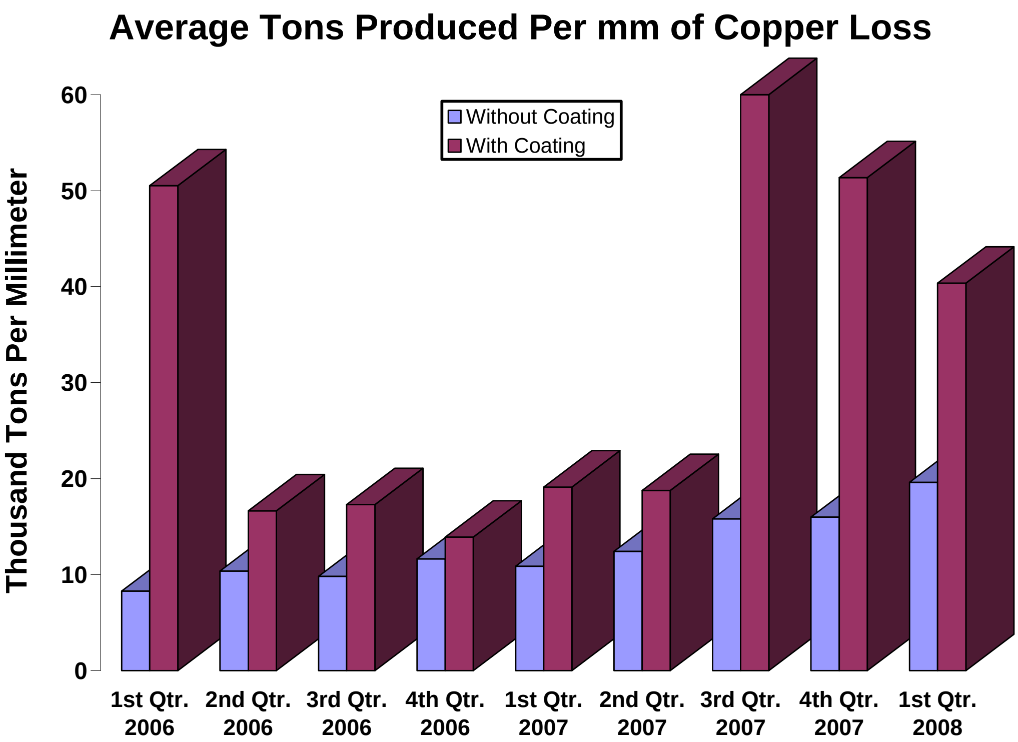

Figure 7. Comparison showing copper removed during refurbishment coated versus uncoated Gallatin BF coppers.

An added benefit of using the UniGuard™ coating for Gallatin has been drastically reducing the time spent buffing the mold meniscus area between casting sequences to remove "brassing" that occurs on the casting surface. "Brassing" is a common occurrence on high-speed molds casting EAF derived steel. This condition is caused by zinc and other tramp elements infiltrating the grain boundaries of the exposed copper surface. If left unbuffed, cracking quickly develops in these meniscus areas. Mold powder and other materials can easily be dislodged from the UniGuard™ hotface coating with the same power tools previously used for their normal buffing. Because there is absolutely no surface material loss due to buffing (when coated with UniGuard™), corner gaps are virtually eliminated and the hotface surface profile is maintained in its original shape for extended periods of time.
At the present time Gallatin Steel continues to run controlled trials using the UniGuard™ hot face coating with good results.

6 THE NEXT LIMITING FACTOR

The improvements made in mold coating technology this decade have brought to light other issues which have now become the cause of mold removal. Those casters which have addressed mold copper life must now focus on these areas to further improve on caster efficiency and productivity. The equipment designers for most casters never assumed molds could be run for 300,000 tons to 500,000 tons in one campaign before having to be refurbished but this is what is being asked of a growing number of thick and medium slab casters today. Other common reasons for mold removal besides worn coppers are, a loss of strand support below the mold, narrow face corner gaps, internal corrosion issues, and water leaks resulting from excessive corrosion of equipment.

6.1 Foot Roll Support Issues

Although some casters have strand support issues with their broad face foot rolls, primarily significantly longer campaigns on narrow face coppers have resulted in an increase in narrow face foot roll/lateral strand guide issues. Depending on the original design, these issues may be the result of deflection in the roll bracket, excessive clearance in the roll holder, excessive clearance of the bearing or shaft due to wear during the increased campaign length. Some casters utilizing UniGuard™ on the narrow face coppers have reported having to switch out foot roll assemblies on the narrow faces 2 to 3 times over the campaign of the coppers. The loss of support for some casters can result in bulging or product cracking due to excessive strain put on the delicate shell exiting the mold.
The UniMold® Division of SMS Millcraft has completed narrow face foot roll or lateral strand guide redesigns for three casters in the past 24 months. The goal of these redesigns was to strengthen all components making up this sub-component but specific focus was given to making the bracket more robust, improving shaft durability and provisions were made to allow the rolls to provide more consistent support for the strand. Additionally, the design was optimized so that a full length bushing could be used and the shaft was modified so that it could be more reliably lubricated. The shaft was also coated to improve its corrosion and wear resistance and o-rings were added at each end to help retain lubrication and keep foreign materials from entering between the shaft and the bushing. Figure 8 is a schematic of a narrow face foot roll assembly showing examples of some of the design improvements.

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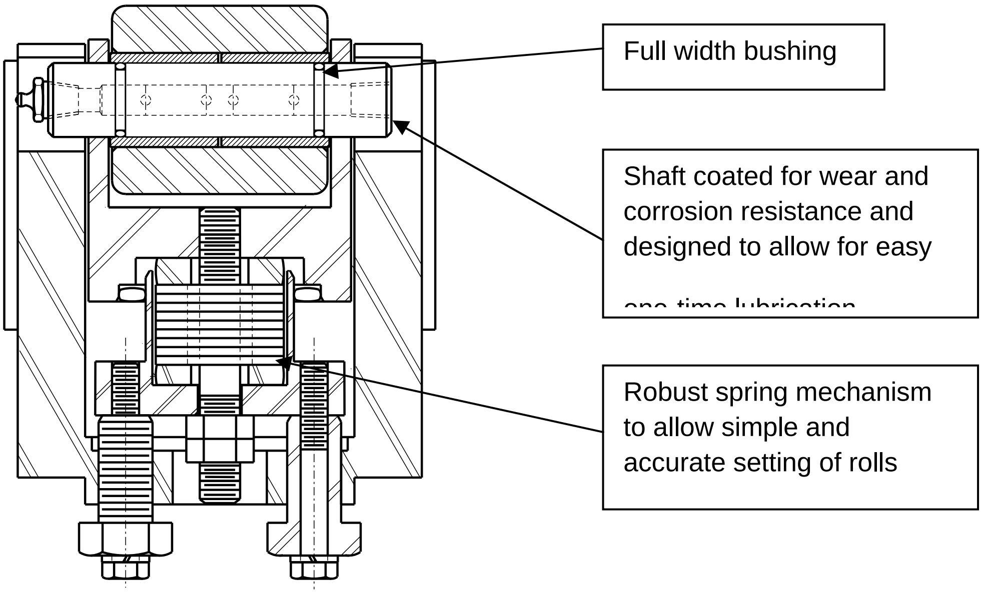

Figure 8. Schematic of narrow face foot roll assembly.

6.2 Corner Gap Issues

Corner gaps are typically decreased for those casters who use UniGuard™ on all four mold faces. This is primarily a result of decreased wear and meniscus scratching on the broad faces as compared to what is seen on nickel plated broad faces. However, the use of mold coatings can only do so much to decrease corner gaps as there are many other variables which can contribute to corner gaps. Those casters who continue to utilize silver copper (CDA107Cu) for their narrow face coppers rather than copper chrome zirconium (CuCrZr) should consider using the superior CuCrZr material. Although CuCrZr is slightly more expensive and has less thermal conductivity than AgCu it expands far less and therefore is less prone to crushing and shrinkage after cooling. Many casters continuing to use AgCu narrow faces have corner gap issues just below meniscus height and during operations have a greater frequency of galling and scratching type issues due to expansion of their narrow face coppers during casting. The resulting corner gap after the casting process is completed is caused by the phenomenon known as plastic deformation of the edges of the narrow face.

Those casters which utilize a “dynamic” or “soft” clamping mechanism of some type tend to see less chipping along the edges of ceramic/metallic coated narrowfaces as well as less corner gap issues regardless of the hot face coating used. Managers and supervisors can not emphasize enough the importance of cleaning the mold powder and debris from between the narrow face and broad face between sequences or whenever possible. The entrapment of significant amounts of mold powder behind the narrow face assembly can in some cases be so severe that normal operation of the spindles for the width adjustment mechanisms are inhibited. Redesigning mold covers to provide a better seal and/or using a shroud draped over the mold beneath the cover have been successful for some casters in addressing these mold powder issues.

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6.3 Equipment Corrosion Issues

Regardless of whether campaigns are 100,000 tons or 500,000 tons many of the aging casters in North America are suffering from severe internal and external corrosion issues. Many of these casters are utilizing casting machines which are at least 20 years old and are constructed primarily of carbon steel. External corrosion issues resulting from being in the atmosphere of the continuous caster can do significant damage to the exterior of the broad face and narrow face water jackets as well as the mold frame itself.
There are numerous options available for protecting the exterior of continuous casting equipment. The UniMold® Division of SMS Millcraft has had success in coating mold fames and broad face water jackets with a two part epoxy paint. Narrow face water jackets can be cost effectively powder coated to allow for moderate erosion as well as excellent corrosion resistance. In Figure 9 a complete mold frame is shown with the frame and all its related components having been coated with two part epoxy to offer extended multiple campaign protection from corrosion.

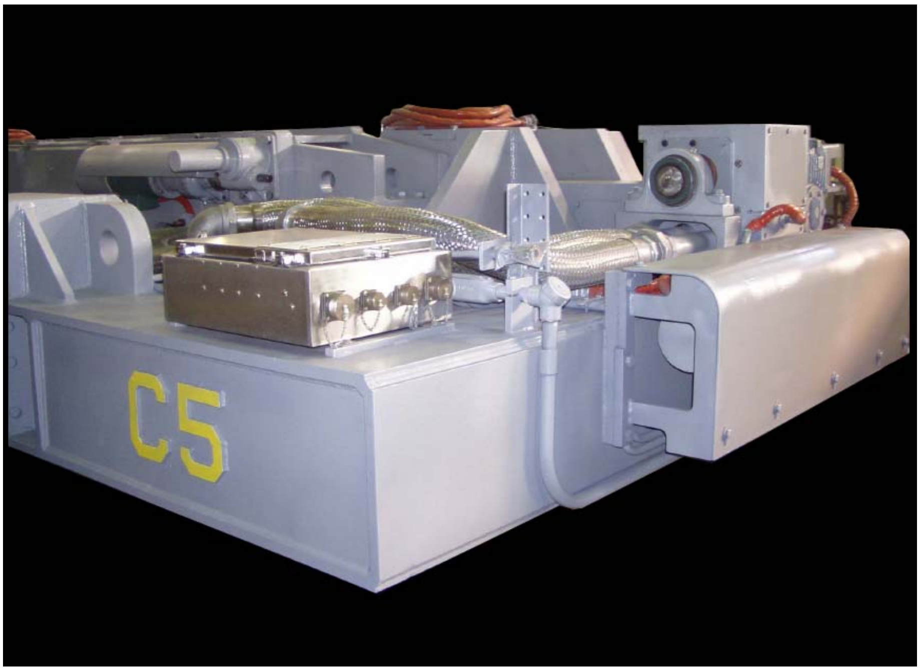

Figure 9. Conventional slab casting mold protected with two-part epoxy.

In some extreme cases of erosion typically along the bottom of broad face cassette back-ups and water jackets exposed to highly corrosive hydrofluoric acid (HF) a more substantial protective coating must be considered. In these instances only an aggressive approach utilizing stainless steel overlay then clad in nickel-chrome based thermal spray will stand up to such highly reactive chemicals for 300,000+ ton campaigns. The use of these exterior coating solutions listed above add more cost to equipment refurbishment; however, the cost of doing nothing will lead to added cost in refurbishing components after the lengthy campaign. Aggressive wear issues can erode equipment down to the o-rings which seal these water jacket and copper assemblies and result in water leaks which require molds and equipment to be removed from service. Figure 10 shows a badly eroded bottom edge of a broad face cassette back-up plate while Figure 11 shows the same surface after being stainless

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steel weld repaired, machined and then coated with nickel-chrome based thermal spray.


Figure 10. Eroded broad face back-up plate.


Figure 11. Broad face back-up plate after being repaired.

Internal corrosion issues are on the minds of many managers currently, maintenance and operations alike. The best efforts of those companies treating the water pulsing through the aging carbon steel components is not enough to keep exfoliating scale from breaking loose. Once free the scale is swept into the molds where large debris can be trapped in the cooling slots of the mold coppers. The worst cases can usually be quickly identified when an excessive pressure drop is noted across the mold which of course requires premature removal of a mold for maintenance. However, it is the moderate cases which may cause insufficient water pressure and velocity to reach the meniscus resulting in uneven cooling that can be most damaging. Such partial blockages can result in uneven meniscus heat extraction which can lead to “caster folds” or longitudinal cracking on the slabs produced. A fairly common example of the type of scale found in many conventional slab caster broad face copper/water jacket assemblies (Figure 12).

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Figure 12. Scale found trapped against the slots across the bottom of a copper.

Approximately five years ago the UniMold® Division of SMS Millcraft began internal blasting water jacket cavities of broad face water jackets to remove all loose scale for particular customers who requested this service. This is a fairly time consuming and complex process which requires specially modified blasting and descaling equipment to complete. In many cases additional clean outs must be incorporated into the water jacket or mold frame design to allow for increased access for blasting all surfaces and removal of scale and blasting media post cleaning. Shown in Figures 13 and 14 are internal photos showing before and after blasting the interior surfaces of a conventional broad face water jacket.

Figure 13. Interior of broad face water jacket before blasting.

Figure 14. Interior of broad face water jacket after blasting.

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Subsequently, UniMold® began offering powder coating to seal and protect these blasted surfaces. At the present time two casters in North America are successfully trialing powder coating over these internal surfaces. Some of these trials have been in service for three years and appear that they will meet or exceed our goal of four to five years of protection. An additional benefit reported by casters utilizing the powder coating is a significant decrease in pressure drop across the mold. It appears the slick coated surface and the blasting of the internals has allowed the water to pass through these assemblies with less friction resulting in less pressure loss. Blasting and/or blasting and powder coating the water jacket internals combined with coating of the copper mounting surfaces of newly restored water jackets allows for complete protection of the carbon steel water jackets.
Many carbon steel water jackets have had the copper mounting surface and main o-ring groove re-machined numerous times to restore these critical surfaces to the drawing tolerances. For a caster that is 20+ years old the thickness of the plate which the copper rests or bolts up against is approaching its minimum thickness in many cases. An effective way to limit the corrosion and maintain the flatness and integrity of the copper mounting surface of the broad face water jackets for years is to cover this surface with a thin layer of Ni-Cr based thermal spray. Most importantly having a machined and coated copper mounting surface allows for the copper to float and expand freely. In those instances where a copper is restrained and not allowed to move and expand it can result in cracking of the mold coppers. In Figures 15 and 16 are before and after photographs showing the internal powder coating of a mold supporting fixed side frame.

Figure 15. Inside of mold frame before blasting.

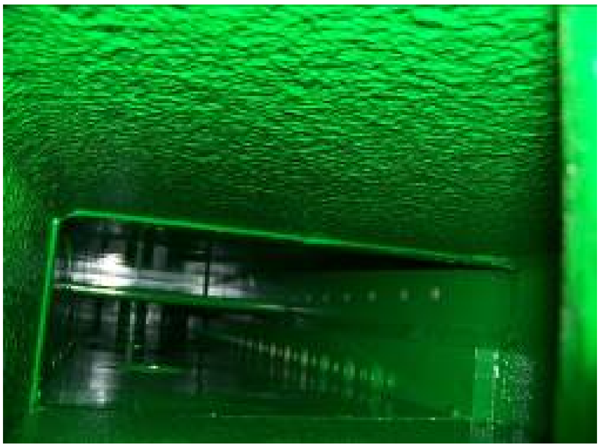

Figure 16. Mold frame after blasting and powder coating.

7 COLD FACE COATING

Over the past several years the UniMold® Division of SMS Millcraft has worked to create what is now a patented process to apply a thermal resistive coating to the cold face of continuous casting mold coppers. The developed process is now commercially viable on many medium and thin slab caster broad faces. Specifically, a coating is utilized to precisely inhibit heat removal in a controlled manner by applying a material of a known thickness and heat transfer rate to the water contact surfaces on the cooling side of a mold copper plate. The primary benefit is to allow for "soft cooling" in the meniscus area creating a more uniform meniscus hot face temperature profile on the hot face.

Most medium and thin slab casters scrap out broad face and narrow face coppers not for safety reasons but rather for quality reasons. Thin coppers and high casting speeds are not forgiving in regards to heat extraction. Nearly all mold coppers close to their minimum hot face or copper thickness show more erratic or inconsistent heat removal and as a result have an increased frequency of longitudinal type cracking defects commonly referred to as "caster folds" in the thin slab casting community. Due to the extremely high meniscus hot face temperatures of most high speed molds they are unable to use hot face coatings of any significant thickness, and therefore can not benefit from the slower heat removal rate offered by various hot face coatings.

A caster who scraps coppers for quality reasons now has a means for getting more life out of their expensive mold liners without sacrificing as cast product quality. Another benefit of using cold face coatings is the reduction of deposits on the cold face of the coppers should there be any issues with water quality or boiling. Some casters have chosen to use cold face coatings to narrow their operating window regarding hot face thickness by coating coppers once they reach a certain thickness. If a caster can keep all coppers within a 5 mm operating range this allows the hot face temperature to be relatively consistent regardless of coppers installed in a mold. This simplifies selecting mold powders and cooling water curves; moreover, it lessens the need for casters to match copper thickness and/or throttle cast speed in relation to grades being cast.

Many of the benefits listed above pertain mostly to medium and thin slab casters and therefore the acceptance and results of using cold face coatings have been most significant in this segment of the industry. As thick slab casters add more instrumentation they are now seeing variances in hot face temperatures and are investigating how to minimize differences in this temperature profile. For a conventional slab caster these temperature differences may not cause the defects as readily on their thicker slabs but improvements in quality are likely to be seen if the variance can be reduced. Some thick slab casters have also begun raising their minimum copper thickness to avoid the issues of erratic heat removal often seen on thin coppers. In the coming years it is expected that their will be a growing number of conventional casting molds who will begin utilizing cold face coatings to make life simpler for operations, the goal as always being increased productivity with improved quality.

8 SUMMARY

The UniGuard™ coatings offer the ultimate solution for medium and thick slab casters protecting both the meniscus from erosion and the bottom portion of the mold from

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wear. For a caster to realize the full potential of any coating used, it is vital that operations understand the coatings abilities as well as its deficiencies. Casters are now presented with other limiting factors shortening mold life such as, corner gaps, loss of strand support below the mold, and internal and external corrosion of mold components. The extreme length of mold campaigns seen at some casters has led to a need for additional coating technologies to control other corrosion issues. The use of cold face coatings in high speed casting has finally allowed these casters to reach a more uniform meniscus temperature profile at a reduced copper hotface thickness. Although the individual refurbishment cost per unit is increased for casters using much of the technology presented above, they have seen tremendous increases in campaign life which results in cost benefits for steel producers in the form of improved product quality and decreased annual refurbishment costs.

Acknowledgements

We would like to express thanks to the valued customers who have worked closely with us in the development of these new coatings and technologies and have allowed information concerning their operations and experiences in using the UniGuard™ coating to be shared in this paper. Special mention needs to be made of the diligence and professional dedication of the Oil City, UniMold® Division, employees who have worked hard to provide the flexibility needed for the customer-specific applications associated with these coating process and other technology improvements presented.

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