

*Presented at AISTech 2005
Iron and Steel Technology Conference
May, 2005
Charlotte, North Carolina*

High Emissivity Coatings for Improved Performance of Electric Arc Furnaces

Paul C. Sheil
North American Refractories Company
17830 Englewood Dr., Suite 1
Middleburg Heights, OH 44130
Tel: 330-697-1126
Fax: 440-239-2435
E-mail: paul.sheil@naref.com

Thomas R. Kleeb
Harbison-Walker Refractories Company
400 Fairway Drive
Moon Township., PA 15108
Tel: 412-375-6901
Fax: 412-375-6783
E-mail: tom.kleeb@hwr.com

Key words: Emissivity, Ceramic Coatings, High Emissivity Coatings, Energy, Electric Furnace, Roofs

INTRODUCTION

High emissivity coatings have been in use for steelmaking and other industrial high temperature applications for several decades. While the use of these materials has been relatively successful in some industries outside of steelmaking, they have failed to achieve widespread acceptance in the steel industry. Some of the negative experience with high emissivity coatings in steelmaking applications can be attributed to the misapplication of the coatings caused by a fundamental misunderstanding of emissivity. The inability of the coatings to withstand the intense physical and chemically corrosive environments typical in the steelmaking process and deficiencies in the coatings themselves have resulted in unsatisfactory longevity. The emissivity agents often aged and lost their high emissivity property and the coatings peeled off of the substrate due to binder failure during prolonged service at high temperatures. New high emissivity coating technology developed and patented by the National Aeronautical and Space Administration (NASA) in 1994 as thermal protection for the new-generation X-33 and X-34 orbiters was licensed two years later for use in non-aerospace applications (Figures 1 & 2).



Figure 1 – X-33 Orbiter



Figure 2 – X-34 Vehicle

COATINGS

The NASA thermal protection system was designed to be reusable, a requirement demanding emissivity agents that would not degrade in effectiveness over multiple missions. The patented NASA technology uses expensive emissivity agents that do not oxidize in service, thus maintaining their ability to efficiently absorb and reradiate energy during reentry at temperatures in excess of 3000°F. New high emissivity coatings developed around the proven NASA technology address the shortcomings of previously-available materials. A new family of ceramic coatings¹ has been developed having binder systems compatible with metal, ceramic, and refractory ceramic fiber substrates.

Since light weight is a requirement of coatings used on space vehicles, the new coatings are designed to be applied as paints, having cured film thicknesses in the range of 4 to 8 mils. The bond strength of the coatings to compatible substrates is greater than the strength within the coatings, so if properly installed, the coatings do not shear off of the substrates during thermal cycling. Stresses caused by differential thermal expansion of the substrate and the coating are accommodated by micro-cracking of the coating film. In service, these cracks heal by pyroplastic flow or sintering. The binders are generally siliceous and contain no organic materials. This imparts a natural resistance to acid and alkali attack. Some of the coatings designed to be applied to metals are virtually pinhole-free, making them particularly well-suited for applications where corrosion is an issue.

EMISSIVITY

The misapplication of high emissivity coatings often comes as a result of misunderstanding emissivity. High emissivity coatings are not reflectors. Reflective surfaces (low emissivity) can reflect up to 98% of radiant energy at low temperatures back toward the source at the same narrow infra red (IR) wavelength band. Reflectors cannot reflect convective heat. High emissivity coatings are not insulators, either. While their application on the hot face of ceramic or metal substrates may reduce the amount of heat that is conducted into the substrate, this reduction is not due to the low thermal conductivity of the coating. In fact, the high emissivity coatings used in the trials reported here have higher thermal conductivities than fireclay brick. In most steelmaking vessels, process heat is contained within the refractory-lined or water-cooled vessel walls and a certain amount of this energy is lost through the walls, depending upon the thermal conductivity of the wall materials (Figure 3). The classic solution to this loss of valuable energy when the substrate is a refractory is to insulate the cold face to reduce the thermal conductivity of the composite lining. While this helps reduce energy loss, it also causes hot face refractories to absorb and hold more heat, possibly requiring that the hot face refractory quality be upgraded.

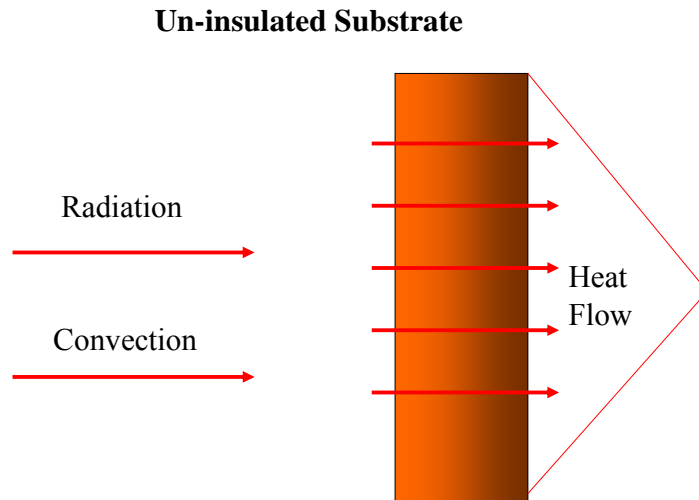


Figure 3 – Heat flow through an uncoated substrate

¹ EMISSHIELD, Product of Wessex, Incorporated, Blacksburg, Virginia

A surface with high emissivity has the ability to absorb radiant and convective energy at high temperatures and re-radiate up to 95% of that energy, to be absorbed by a surface or gas that is cooler than the coating. When the hot face emissivity of a substrate (Figure 4) is increased by applying a coating, radiant energy from burners or electrode arcs, and convective heat from contact with furnace gases, are absorbed and re-radiated by the coating. Provided there is a cooler load present to receive the larger component of radiant heat, the energy is conserved in the furnace rather than being conducted to cooling water or the ambient environment. This load may be cooler air, a steel ingot to be reheated, or in the case of an electric furnace, a colder scrap charge. The result of using high emissivity coatings under these conditions is less heat loss through EAF furnace walls and roofs and more energy available for melting.

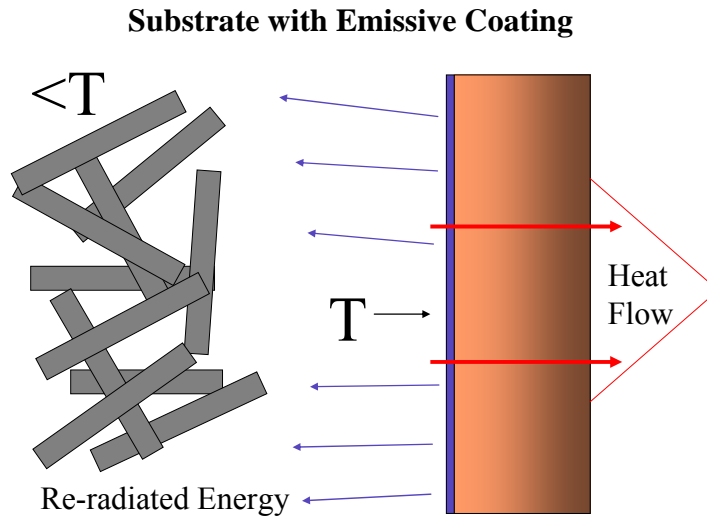


Figure 4 – Heat flow through substrate after applying a high emissivity coating

The amount of heat re-radiated from a high emissivity coating is predicted by the following equation:

$$Q = E_w \cdot \sigma \cdot (T_C^4 - T_L^4) \tag{1}$$

- Where:
- Q = re-radiated energy
 - E_w = emissivity of the coating
 - σ = Stefan-Boltzmann constant
 - T_C^4 = coating temperature
 - T_L^4 = load temperature

E_w is 0.85-0.95 for the coating being discussed. This means that 85 to 95% of the energy absorbed is re-radiated if a suitable cold load is present. Emissivity is a property of the coating, which in this case, remains between 0.85 and 0.95 up to temperatures in excess of 3000°F. At steelmaking temperatures, most refractories and metals have E_w in the 0.2-0.3 range. Sigma is a constant. The only variable, then, that is of concern when deciding whether to use a high emissivity coating is the difference in temperature between the coating and the load, $T_C^4 - T_L^4$. Since delta T is raised to the fourth power, the amount of re-radiated energy increases exponentially as the temperature difference between the coating and the load increases. If $T_C^4 - T_L^4$ is small or zero, then a high emissivity coating will be of no value or will not be cost effective.

The final consideration in deciding whether the use of a high emissivity coating is appropriate is whether conditions are right for radiation emission. High emissivity coatings may lose their effectiveness if the conditions don't permit heat transfer by radiation. Applying a high emissivity coating in a steel ladle where the coating is in contact with liquid metal will provide no benefit. Similarly, applying a coating between dense refractory brick and lightweight backup linings or between refractories and a furnace shell where a load might be in contact with the coating will not allow absorbed energy to be re-radiated.

APPLICATION IN ELECTRIC FURNACES

In November, 2004, North American Refractories and Harbison-Walker Refractories began an extensive series of high emissivity coating trials in dozens of industrial and steel plant applications where the criteria for using these coatings and the operational delta Ts appeared to be favorable for energy and maintenance savings. One area of concentration for North American Refractories was electric arc furnaces.

Water-cooled Panel Roof

A high emissivity coating capable of re-emitting heat at temperatures in excess of 3000°F with a binder designed to adhere to steel substrates was applied to a 25 foot diameter water panel EAF roof that had seen prior service. In this shop this roof design typically runs an average of 500 heats before requiring major maintenance to remove slag and scale and to repair leaks. During these 500 heats, the roof usually must be taken out of service twice to repair small leaks. The cost of these interim repairs and the downtime was estimated at \$25,000 each by the customer. The cooling water temperature typically increased by 11°F to 13°F before the high emissivity coating was applied.



Figure 5 – Application of high temperature high emissivity coating to a water panel EAF roof

All slag was mechanically removed from the roof and all corrosion and scale removed by grit-blasting down to bare metal. Water leaks were repaired and any required maintenance was performed before the roof was pressure tested. Any additional leaks identified in the test were repaired and these areas were grit-blasted again. The roof was then washed with a solution of alkaline detergent in deionized water to remove any grease and raise the pH of the metallic surface above neutral. The binder system in the high emissivity coating is designed to adhere tightly to the metal under alkaline conditions. The detergent was rinsed using deionized water and the surface dried. The coating was then sprayed on the roof approximately 6 mils thick using a commercial grade high volume, low

pressure (HVLP) sprayer (Figure 5). It was air dried for approximately four hours, at which time it had developed enough strength so that it couldn't be damaged in handling the roof. No additional curing or dryout steps were taken.

The roof was put into service using the typical commissioning procedure for water-cooled roofs in this shop. After several heats the effect of the coating first became apparent during charging. When the roof was swung off of the furnace it quickly turned from glowing red to black as the coating emitted most of its absorbed energy from its surface to the cooler shop atmosphere. Any slag that adhered to the coated roof also dropped off during every charge. This suggested that the slag was weakly adhered to the coating and this weak bond was probably broken by the thermal shock between the slag and the rapidly-cooling roof.

Temperature measurements of the cooling water at the roof water output indicated that the water temperature increased only 2-5°F, compared to the 11°F to 13°F temperature increase in the uncoated roof. This lowered energy loss to the cooling water translated into a savings of about \$100 per operating hour. Since less heat was lost to the cooling water, more heat was available to heat the furnace charge. As a result, the arc time for each heat was reduced by about three minutes, netting an additional savings of \$94,000 during the life of the roof. It is important to note that the cooling water temperature reduction remained relatively constant during the roof's service life. This indicates that the coating remained strongly adhered to the roof during hundreds of thermal cycles between tapping and charging temperature. The coated roof was taken out of service after 940 heats, compared to the 500 heats typical for uncoated roofs. This almost doubling of the service life saved 88% of the cost of a major maintenance turnaround. What was even more gratifying was that while an average of two interim repairs valued at \$25,000 were necessary per 500 heats in the uncoated roof, none were necessary during the entire 940 heat campaign of the coated roof. This realized an additional savings of almost \$100,000.

While a definite value could not be put on some of the benefits of using the high emissivity coating on this water panel EAF roof, savings in actual dollars clearly exceeded \$200,000, a return on investment that could be as high as 10 to 1. Additional roof and partial panel trials are in progress. Different high emissivity coating compositions, some containing corrosion inhibitors and binders that glaze during service are also being evaluated.

Water Spray-cooled Roof

A water-cooled roof having cooling sprays between an inner and outer shell was coated with the same high emissivity coating as used in the trial described above and is now in service. It was not feasible to measure the cooling water temperatures in the coated and uncoated roofs. However, in preliminary feedback from this trial, significant maintenance savings from reduced leaks have once again been reported.

PRECAST REFRACTORY DELTAS

A variation of the high emissivity coating applied to the water-cooled roofs was applied to precast refractory deltas in several EAF shops. This coating has a different binder system that was designed to adhere to dense high alumina refractories. Since the deltas were all new refractory castables, the installation process did not require the removal of corrosion and slag, as was necessary with the steel roofs. Surface preparation required only that the delta be heated high enough to remove free and chemically-combined water and burn off any mold release still adhering to the shape. The coating was applied to the hot face and the electrode ports. One delta was cast into a water-cooled ring. In this case the ring was coated with the high emissivity coating composition designed to adhere to steel. The refractory compositions of the deltas were either coarse, bauxite-based compositions or coarse magnesium-aluminate spinel castables. The shops agreeing to run trials of the coated deltas ranged from those whose typical delta life is under 100 heats and about one week to a shop that routinely gets over 1000 heats over the course of several weeks.

The benefit of using high emissivity coatings was not cost effective in one electric furnace shop using silica-free refractory deltas and having a furnace design or melting practice that protected the delta from extreme conditions, such as thermal shock. This was the shop routinely getting over 1000 heats on a delta. This is not surprising since the refractory industry has been designing special refractory compositions for precast deltas that provide extended service under difficult operating conditions. New refractory compositions to address the EAF delta environment are continually being introduced. Still, there are those shops that have furnace designs that place the delta in closer proximity to physical, chemical, and thermal stresses and these operators realized a benefit in using coated deltas.

One of the first EAF shops to evaluate high emissivity-coated deltas was actively conducting a delta life improvement program with their refractory supplier when the coated deltas became available. Their standard delta composition, a coarse, bauxite-based ultra-low cement castable, was yielding an unsatisfactory service life of about 40 heats. Their refractory improvement program resulted in a service life increase to an average of 80 heats when they used a silica-free refractory. This refractory was a state-of-the-art castable based upon high purity alumina aggregate and bonded with a spinel binder designed to provide excellent hot strength and thermal shock resistance. The set of coated deltas evaluated in this shop were made with the premium, silica-free refractory. The trial deltas averaged 172 heats, more than double the life of the uncoated premium delta.

Another EAF shop was experiencing delta lives of one week, which necessitated scheduling furnace maintenance on one week intervals. Their desire in trialing a precast delta with the high emissivity coating was to increase delta life to a minimum of two weeks. As of this writing, the first of a three-delta trial came out of service after three weeks. Figure 6 shows the hot face of this delta when it was temporarily taken off of the furnace after 2-1/2 weeks of service.



Figure 6 – Magnesium-aluminate spinel delta with high emissivity coating after 2-1/2 week's service

It is also apparent from the refractory wear shown in this photo that the coating on the hot face is no longer there. This raises the question of how the high emissivity coating was beneficial when the surface it was attached to had obviously eroded. It is believed that the real benefit in using these coatings on precast deltas is not energy savings. More likely, the coating absorbs and re-emits energy allowing the cold delta to heat up more gradually during the first few heats. This would likely eliminate thermal shock cracking that would accelerate refractory wear in later heats. High emissivity coatings have also been found to provide conditions that promote even heating on refractory hot faces, further reducing potentially damaging thermal stresses.

No conclusions have been drawn on trials which are underway on coated precast deltas contained by a coated water ring.

OTHER ELECTRIC FURNACE APPLICATIONS

The above successes using high emissivity coatings to extend the life of water-cooled roofs and achieve significant energy savings suggests other EAF applications where the use of these coatings may be beneficial. These include water-cooled upper sidewall panels and electrode arms, both applications where heat exposure leads to corrosion and warping of the metal. Trials in the upper sidewall panels are underway. Their success may depend upon whether slag adheres to the coating. If it does, the absorption and re-emissive properties of the coating will be lost. Electrode arms represent a critical application since their dimensional integrity while exposed to high levels of radiant and convective heat can often result in excessive corrosion, electrical system damage, and warping. Warping is particularly troublesome if it results in electrode misalignment that leads to delta damage. No trials of high emissivity coatings are being conducted on electrode arms, but trials of coated electrode arm shields are underway. NARCO is optimistic about the success of these trials since prior experience in using high emissivity coatings on metal and refractory shields protecting personnel and equipment has been positive.

SUMMARY

At least one family of high emissivity ceramic coatings is commercially available that does not show degradation of emissive properties or failure of binder adherence to the substrate during service. In addition, these materials adhere to steel and all grades of refractories. The use of these coatings in electric furnace water-cooled roofs and panels, refractories, and shields have been shown to result in significant energy and maintenance savings that can return several times the cost of the coatings.