HIGH EMISSIVITY COATINGS FOR IMPROVED PERFORMANCE ON REFRACTORY AND METAL SUBSTRATES

Thomas R. Kleeb*
ANH Refractories Company, United States of America

John Olver
Wessex, Incorporated, United States of America

ABSTRACT

A family of high emissivity coatings based upon a patented thermal protection system licensed from NASA and modified to adhere to numerous substrates has been in use for over three years to protect refractory and metal substrates and to affect significant energy savings. These coatings have been shown to be effective on the above mentioned substrates in the following industries: steel, glass, non-ferrous metals, power generation, and chemicals production.

INTRODUCTION

High emissivity coatings have been used for application on refractories for over a decade. Most of these coatings contain materials capable of absorbing and re-radiating thermal energy, such as compounds containing zirconium, chromium, and cerium. Commercial coatings have phosphate and silicate binder systems designed to provide high coating film strength, thermal expansion characteristics similar to their intended substrates, and adequate bond strength with the substrate. Good performance of these coatings has been reported for many applications where temperatures do not exceed 1100°C, such as ceramics and many chemical production processes.

Loss of effectiveness of these coatings usually occurs as a result of the emissivity compound oxidizing and its emissivity decreasing after a certain amount of time in service, or when subjected to high temperatures. Another mode of failure often experienced with high emissivity coatings is loss of the coating entirely. Under cyclic thermal conditions, even small differences between the thermal expansion coefficients of the coating and the substrate can result in shearing of the bond between the two.

The high emissivity coating evaluated in the trials reported here is actually a family of coatings that have different binder systems designed to adhere to various ceramic and metallic substrates.[+] These coatings have binder systems designed to be compatible with lightweight and dense refractories, refractory ceramic fibers, carbon-containing refractories, ferrous alloys, and most non-ferrous metals. Instead of designing the coating to have a thermal expansion matching the intended substrate, the binder was formulated to optimize the bond strength between the coating and the substrate.[1] Under thermal cycling conditions, bonding of the coating to the substrate allows the coating to move with the dimensional change of the substrate, preventing shearing between the coating and the substrate. Dimensional change of the substrate is accommodated by micro-cracking or viscous flow of the coating. With increasing time and temperature, the bond between the coating and the substrate continues to develop strength. Another advantage of having a binder that strongly bonds to the substrate is that one coating can be used for several substrates. For instance, the high temperature emissivity coating designed for metal substrates can be applied to carbon steel, stainless steel, or aluminum, all metals with significantly different thermal expansion coefficients.

The emissivity agents employed in these coatings are primarily borides that do not oxidize in service, lowering their emissivities. These extremely expensive materials were chosen by NASA for use in coatings for the X-33 and X-34 orbiters, now under development (Fig. 1). Emissivity coatings used on orbiters must be able to withstand multiple re-entries where the coating is subjected to temperatures of 1650°C. Few of the industrial emissivity coatings currently available have

Fig. 1: The X-33 Orbiter

[+] EMISSHIELD™, Wessex, Inc., Blacksburg, VA this capability. The coatings studied in this work maintain emissivities of 0.85 to 0.92 within the temperature range of 800°C to 1650°C and do not degrade with sustained service.

USE OF HIGH EMISSIVITY COATINGS

When contemplating the use of a high emissivity coating on refractories or metal structures exposed to high temperatures, it must be remembered that high emissivity coatings are not insulators. They are not a barrier to the conductivity of thermal energy through a furnace wall. Insulating refractories are generally placed behind dense refractories at the cold face of refractory designs. While this prevents heat loss from a furnace, it keeps heat in the refractory working lining. These refractories, therefore, must be capable of sustaining higher soaking temperatures and they act as a heat sink, absorbing valuable process energy (Fig. 2).

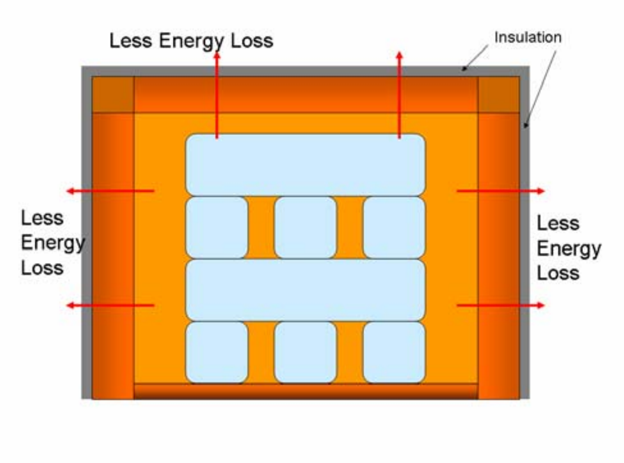

Fig. 2: Reheat furnace with insulating refractory backing up dense refractory working lining.

When an emissivity coating is used, it is applied to the hot face of the furnace (Fig. 3). Radiant energy from the burners and convective energy from the kiln atmosphere are absorbed at the surface of the coating and re-radiated to the cooler furnace load. It is important to remember that for a high emissivity coating to be effective, the temperature of the coating surface must be greater than the temperature of the furnace load. 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

Since the temperature of the coating and the temperature of the furnace load are raised to the fourth power, it is evident that high emissivity coatings absorb and re-radiate the greatest energy when the temperature difference between the coating and the load is great.

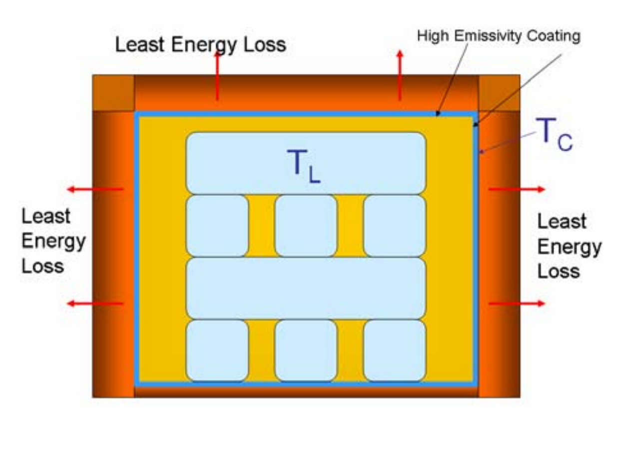

Fig. 3: Reheat furnace with high emissivity coating applied to the refractory hot face. The thermal energy absorbed by the coating, T_C, is re-radiated and absorbed by the colder load, T_L. The refractory lining is cooler and retains less heat energy.

In a tunnel kiln, the coated kiln walls absorb radiant and convective heat in the pre-heat and firing zones. The cooler ware being fired absorbs the re-radiated heat from the coating. These areas are ideal for the application of a high emissivity coating to gain energy savings. Using the coating in the cooling section of the same kiln, however, would not be cost effective because the ware being fired is hotter than the kiln walls and crown. Another application where the use of high emissivity coatings is not effective is on refractories in contact with molten metals, such as transfer ladles. In this case, energy transfer is by conduction only and since the metal is always hotter than the coated refractory, there is no energy transfer back to the metal by any means. Energy savings in this application are best accomplished by insulating the refractory cold face.

In applications such as power plant boilers, there is no cooler load to absorb re-radiated energy from the coating. The use of a high emissivity material to coat the boiler water tubes is still appropriate, however. The load in boilers is the boiler atmosphere and it is always hotter than the coating. Since the coating is cooler than the load in boilers, Q in equation 1 is negative and no absorbed energy re-emission into the boiler fire box is possible. Heat always flows from a hotter body to a cooler one, so the absorbed energy is conducted through the coating and the water tubes into the cooler water and steam within (Fig. 4). Under operating

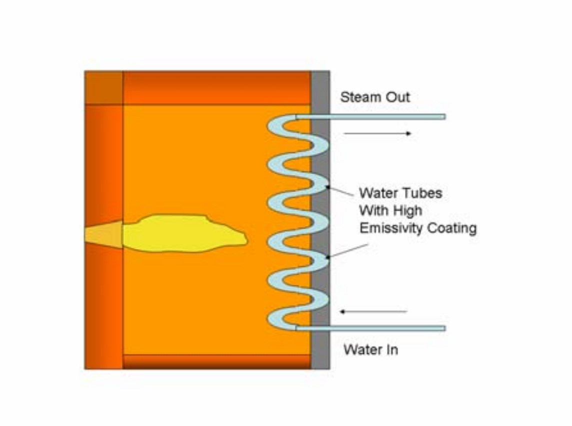

Fig 4: Boiler showing high emissivity coating on water tubes.

conditions where the water tubes are not coated, non-conductive scale and slag often adhere to the tubes, reducing thermal conductivity and eventually leading to shortened service life and poor thermal transfer efficiency due to tube corrosion. The use of a high emissivity coating designed to adhere to metals and formulated to provide a virtually pinhole-free barrier to oxidation will maintain optimum thermal conductivity in the tubes and reduce costly tube maintenance. These coatings are routinely used to coat steel tubes in boilers and reformers. Figure 5 shows the resistance to slag adherence of a tube shield covered with a high emissivity coating.

Fig 5: Boiler tube shield with baked-on high emissivity coating after 3 months of service. There was no change in appearance after 9 months service.

REFRACTORY LININGS WITH HIGH EMISSIVITY COATINGS

The high emissivity coatings applied to dense refractories, insulating firebrick (IFB), and refractory ceramic fiber (RCF) blanket and modules had similar, silicate-based binder systems, but they varied in their emissivity agent content. The RCF substrates were coated with a less viscous formula containing a lower solids loading. This better enabled the coating to penetrate the RCF somewhat, bonding to individual fibers. In practice, a thin coating of this type is less likely to pull away from the blanket or modules than thicker, heavier coatings that do not penetrate the RCF.

Electric Furnace Roof – Silver Melter

One of the earliest successful applications of the high emissivity coating was on a 60% alumina brick roof on a small electric furnace melting silver. This was a very severe application with refractory wear being caused by localized hot spots and alkali attack, in spite of the fact that the refractory was chosen for its alkali resistance. Typically, the roof was replaced monthly. When the high emissivity coating was applied, roof service came within a few days of doubling.

Heating of the roof appeared to be more even, as evidenced by the absence of hot spots until the last two weeks of service. In addition, the silicate binder system employed by the coating appeared to provide further resistance to alkali attack.

Electric Furnace Delta Refractories

One of the most successful applications of high emissivity coatings has been precast electric furnace delta shapes. Some electric furnace shops have furnace designs and operating conditions that do not make demands on the refractories beyond their design. With the use of premium, spinel-bonded corundum compositions, they can expect as many as 1200 heats service on a delta. These shops are not good candidates for high emissivity coatings because huge service improvements are needed to justify the coating cost. Other shops, however, have furnace designs where the delta is close to the melt. The refractory is subjected to severe thermal shock from arc flare and other undesirable operating conditions. Some of these shops experience delta lives of less than 100 heats. The use of high emissivity coatings in these shops has more than doubled delta life.

Over 80 coated deltas have been put into service as of this writing. The coating has been applied to the hot face and on the port walls of deltas in AC and DC furnaces. In one shop, delta service increased from an average of 80 heats to 167 heats when the high emissivity coating was employed. In a second shop, a coated delta was in service for 472 heats, compared to the typical 200-250 heat service for uncoated deltas.

The coated deltas are taken out of service due to refractory wear, similar to the uncoated deltas. As soon as the refractory begins to wear, the coating is effectively gone (Fig. 6). Extended service, however, continues to be reported. There probably is an immeasurable energy savings from using high emissivity coatings on precast deltas, but the greatest benefit is likely to be thermal shock protection. During the first few heats, the coating protects the delta from thermal shock cracking allowing strength from sintering to be built with time. Although the coating is lost earlier in the campaign, the integrity of the delta structure is maintained and long service life results.

Fig. 6: Precast delta with high emissivity coating after approximately 2/3 of its service life. The delta was put back into service, where it provided over 100 additional heats.

Glass Tank Overcoat Repair

In making overcoat repairs with thermal shock-prone chrome-alumina blocks to the original sidewall or previous glass tank overcoat block, significant cracking of the refractory is usually encountered. In practice, minor cracking can be tolerated to some degree, but the damage to the refractory, no doubt, leads to shortened service life. A high emissivity coating was applied to overcoat blocks having a chrome content of 52%. These blocks showed significantly reduced cracking when subjected immediately to molten glass contact, as compared to uncoated blocks.

Tunnel Kiln Burning Refractories

In late 2003, the preheat section of a tunnel kiln burning refractories was coated. The kiln was out of service to allow major repairs to be made to the sand seals and ductwork. Minor refractory repairs were made as needed, but for the most part the coating was applied to refractory brick that had seen decades of service. Some of the brick had crusty combustion and reaction products adhering to them, some had friable surfaces, and others showed a localized glaze on their surfaces. Surface preparation for the used refractories involved the removal of all adhering materials, reaction products and friable surfaces. The coating was applied at an approximate thickness of 0.15 to 0.20 mm without making any attempt to even the refractory substrate. Figure 7 shows that the textural features of the new and used brick surfaces are still evident after the coating application.

Fig. 7: Tunnel kiln preheat section (right 2/3 of photo) after application of high emissivity coating. The textural differences between the new and used refractory brick surfaces are obvious.

While this particular kiln did not have instrumentation to measure gas usage in the preheat section alone, individual burner fuel settings indicate that a fuel savings of 5% to 8% may have been achieved. In early 2005, four more refractory tunnel kilns and one tunnel kiln firing crucibles were coated. All of these kilns have instrumentation capable of accurately measuring gas usage and they all have good baseline fuel usage data available before the coating was applied.

Ladle Covers

Ladle covers used to dry out refractory castable-lined steel ladles were sprayed with a high emissivity coating. In this particular shop, gas usage was closely monitored for each dryout. A 40 hour dryout schedule required 11.5% less gas after the high emissivity coating was applied to the cover. The spraying of the cover resulted in an even greater energy savings, 21.3%, when a faster 32 hour schedule was used. This was not surprising since the ladle cover refractory had less of a chance to absorb energy during the shorter schedule.

Tunnel Kiln Afterburner

A high emissivity coating was applied to the IFBs in an 80 foot long afterburner chamber that operates at 760°C. This equipment was installed to incinerate organic components of a tunnel kiln exhaust. After the coating was applied, the fuel required to operate the afterburner decreased by 23%.

Periodic Kiln

One of two identical RCF module-lined periodic kilns was sprayed with the high emissivity coating formulated for service on RCF blankets and modules. Both furnaces are used for tempering consistent loads of castings. Neither of these kilns was outfitted with gas meters, but the coated kiln had a 30% shorter heat-up time and a 35% shorter cool-down time. This functionally increased the productivity of the coated kiln and, presumably, lowered the amount of energy required to temper a load of castings.

METAL SUBSTRATES WITH HIGH EMISSIVITY COATINGS

Since the high emissivity coatings intended for application on metals were designed for maximum substrate adhesion, surface preparation is a critical step in their installation. In all cases, any materials adhering to the substrate, such as metal, slag, and scale, were first removed. The metal was sandblasted to bare metal and washed with an alkaline detergent to remove grease and oil. Application of the coating was usually accomplished by spraying, or in a few cases, by brush-coating. Potential application for these types of coatings include areas of furnaces where metals are exposed to heat, areas where alloy and refractory metals are used to provide extended service under high temperature conditions, metal shielding, exposed superstructures, and water-cooled panels.

Tunnel Kiln Skirts

A tunnel kiln used for firing refractories at 1500°C was showing an unusually short kiln car skirt life of three to five months under normal operating conditions. During this time, the skirts would oxidize severely and warp to the point that if they were not taken out of service, they would damage the sand seals.

Initially a high emissivity coating was applied to the hot face of the skirts. These skirts were in service a minimum of twelve months. Some were still in service after fifteen months. The use of the coating lowered the maintenance cost of the skirts and increased kiln car availability. Continuing tests indicate that even longer service life can be achieved by coating both sides of the skirt.

EAF Electrode Shields

Two steel electrode arc furnace shields protecting utility service to the electrodes were coated with a high emissivity coating. Prior to coating, these shields had to be replaced every six weeks. As of the preparation of this paper, the shields have been in service for twelve weeks and show no sign of wear or heat damage.

Water-cooled Electric Furnace Roof

An 8.5 meter water-cooled electric steel furnace roof that had already seen service was prepared and sprayed with a high temperature, high emissivity coating. Prior to coating, the cooling water increased in temperature by an average of 6.5°C. This roof typically showed a service life of about 500 heats before major repairs had to be made to it. Between repairs, the roof generally had to be taken out of service twice to repair small water leaks.

The effect of the coating was immediately obvious. When the roof was swung off for charging, its color immediately changed from cherry red to black as heat was emitted to the mill atmosphere. This roof was in service for 940 heats before it had to be taken out of service for repair. During its entire campaign, not one service interruption was required to repair water leaks. This saved the operator almost $100,000 in maintenance and downtime costs. The roof cooling water increased by only 1.5°C after coating. In addition to the reduced energy loss of 6910 mcal/hr. through the roof, additional energy was saved and productivity gained by a reduced arc time of about three minutes per heat. The cooling water exit temperature and the reduced arc time did not change appreciably during the life of the roof, indicating that the coating remained strongly bonded to it.

CONCLUSIONS

The high emissivity coatings evaluated in the applications enumerated here provided sustained service, even at steel-making temperatures. The emissivities did not degrade during prolonged service and the coatings remained firmly attached to the refractory, RCF, and steel substrates. Although significant energy savings occurred as a result of using the coatings, these savings were often eclipsed by reduced maintenance costs and the value of greater furnace availability.

REFERENCES

[1] NASA Center for Aerospace Information (CASI), "A Coating That Cools and Cuts Cost," *NASA Spinoff,* 98-99, (2004), ISBN 0-16-073179-8