JTTEE5 13:121-125
DOI: 10.1361/10599630418149
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Thermal Spray Vitrification Process for the Removal of Lead-Based Paint From Steel Structures: An Applications Note

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(Submitted 8 July 2002; in revised form 18 September 2002)

Lead-based paints and primers have long been used to protect steel structures from corrosion, but are now recognized as environmental hazards. During lead-based paint removal via abrasive blasting, federal, state and local environmental requirements mandate the use of containment structures to prevent contamination of air, soil, or water. The thermal spray vitrification (TSV) process was developed and optimized in laboratory experiments to remove hazardous lead-based paint. TSV consists of thermal spraying a molten glass onto the painted surface. As the glass strikes the substrate, it reacts with the paint, and organic components are pyrolyzed, while lead ions are trapped on the glass surface. Quenching stresses in the glass cause it to crack and spall off the substrate. The resulting glass fragments are collected, and further remelted to completely immobilize lead (Pb) ions in the glassy iron (Fe) silicate matrix. The glass waste is thus rendered non-hazardous, as determined by the Toxicity Characteristic Leaching Procedure (TCLP). The TSV process was field tested on a fire hydrant, using minimal personal protective equipment and without using a containment structure. The lead-containing paint was removed, without producing hazardous waste, leaving de-painted surfaces suitable for repainting.

Keywords lead-based paint, paint removal, steel structures, thermal spray, vitrification

1. Introduction

Red lead primer has been used on many steel structures to control corrosion. When old paint starts to peel, removal of the paint may be required prior to repainting. The most common method of removing paint from steel structures has been the use of a dense abrasive media, such as blasting grit. Often cheap material such as silica sand or coal slag can be used as highly effective blasting media. A collateral benefit of abrasive blasting is its tendency to roughen the surface, creating an anchor profile for repainting the structure. While the method is highly effective and the procedure itself is cost-effective, abrasive blasting creates large amounts of hazardous dust and waste material. Most of the waste material consists of large chips of the coating and piles of spent blasting media, which must be removed from the site. However, a significant portion of the debris consists of airborne dust and small particles. In removal of Pb-based paint systems, the presence of Pb particles in the airborne dust and waste media creates an environmental risk that must be contained. The U.S. Environmental Protection Agency (EPA) requirements mandate the use of containment structures to prevent the contamination of air, soil, or water. Inside the containment structures, stringent requirements must be met to protect the workers from the high concentration of Pb dust.[1]

Regulations that require the monitoring of exposed workers and the release of hazardous materials have greatly increased the cost of lead-based paint removal. The cost is dramatically escalated when the waste lead-based paint and removal media are determined to be hazardous waste by the EPA's Toxicity Characteristic Leaching Procedure (TCLP).[2] When TCLP reveals that concentrations of hazardous species in lead-based paint removal wastes exceed the regulatory limits, a licensed special waste hauler must be used to remove the material from the site and deliver it to a licensed hazardous material disposal site. Even if the waste material ultimately is found to be nonhazardous, the administrative and testing requirements add substantial costs to the overall project. Furthermore, the costs of worker health and environmental monitoring also dramatically raise the cost of lead-based paint (LBP) removal sometimes exceeding the cost of disposal by a factor of five.[3] Innovative technologies that could effectively remove LBP while rendering the wastes nonhazardous would be highly beneficial. One excellent candidate technology is thermal spray vitrification.[4]

Vitrification is the process of heating constituent starting materials (oxides, carbonates, etc.) such that upon cooling, an amorphous noncrystalline glass is obtained. Vitrification technology has proven to provide superior leach resistance compared with other available forms of waste treatment. Due to the environmental stability of the glass based waste form, vitrification has been selected to be the Best Demonstrated Available Technology (BDAT) for high level nuclear waste and is being considered for treatment of other hazardous waste.[5] In the thermal spray vitrification process, molten glass is applied to a painted surface; the Pb components of the paint react with the hot glass and are immobilized in the glass upon cooling. This process was patented by Kumar and Patreanu and assigned to the U.S. Army.[6]

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1.1 Thermal Spray Vitrification Process Description

The principal equipment for the thermal spray vitrification process consists of a commercially available thermal spray torch (Metco 6P-II, Hicksville, NY), powder feeder (Miller Thermal, Inc, Appleton, WI), gas manifold, and flow controllers, as well as compressed air, fuel, and oxygen sources. These are connected with a series of gas and powder feed lines. The pressure of the oxygen and acetylene is controlled by the manifold and flow controllers. These are connected by separate gas feed lines to the thermal spray gun where they are combined. The glass powder is mixed with compressed air in the powder feeder and the air is used to transport it to the thermal spray gun. The oxygen and acetylene are ignited in the torch and the powder introduced into this flame. The flame melts the glass powder and propels the molten droplets onto the surface. The temperature of the flame from the thermal spray torch is about 2000 °C (3600 °F). This is sufficient to melt the glass powder. As the glass is propelled towards the substrate, it cools in the air and sticks to the substrate at a temperature of about 475 °C (800 °F).

The glass strikes the substrates and solidifies within a few seconds. The glass is reheated with the thermal spray torch 2-3 times and remains molten for a total of about 10 s. This allows the Pb ions to diffuse into the glass network and become trapped in the silica tetrahedra of the glass structure, achieving partial vitrification. The difference in the thermal expansion coefficient between the sprayed glass layer and the metal substrate causes the glass to crack and spall from the surface as it cools. The paint is vitrified at the surface of the glass and additional layers of the paint are attached to this vitrified layer. They are removed when the glass spalls off the surface. The crumbled glass fragments can be easily removed from the steel substrate, leaving it free of Pb-based paint. However, 2-3 applications of the vitrification process are required. The glass fragments may be remelted to ensure that the vitrification process is driven to completion.

During rapid cooling, the glass develops thermal stresses that cause it to crack and spall off the substrate. The Pb-based paint is attached to the glass surface and falls off with the glass. The small pieces of glass fall into the catch basin of a collector unit. The subsequent remelting of the glass immobilizes the lead inside the glass network, thereby preventing leaching. The concentration of lead in the leachate for the remelted glass as determined by TCLP analysis was below 5 ppm, the EPA's regulatory limit for classification as a hazardous waste.

The molten glass is very corrosive and acts like a cleaning agent that will restore the surface to a dull finish with the profile that it had before it was painted. For atmospheric exposure, the surface finish is not as critical as for immersion coatings. The surface finish produced by the thermal spray vitrification process requires a surface tolerant coating which is expected to provide up to 25 years of performance for atmospheric exposure. After application of the thermal spray vitrification process the steel surface has a dusting of loosely adhered powdery residue. This loosely adhered material must be removed prior to painting. The resultant surface needs to be free of all loose mill scale, loose paint, and other loose detrimental foreign matter prior to repainting with a surface tolerant coating system.

Table 1 Glass Compositions

Species	Initial Composition A, wt.%	Modified Composition B, wt.%
SiO_2	54.1	54.1
B_2O_3	6.8	10.0
Al_2O_3	4.1	5.1
Na_2O	10.3	16.5
Li_2O	4.7	2.0
MnO_2	2.9	…
NiO	0.9	…
CaO	1.5	…
MgO	0.8	…
Fe_2O_3	12.3	12.3
ZrO_2	1.2	…

2. Experimental

2.1 Glass Composition

Thermal spray vitrification technology uses a glass compound designed for high Pb solubility and resistance to crystallization. These characteristics provide immediate reaction with the lead and upon subsequent remelting ensure containment of the hazardous material. The initial iron borosilicate glass system, Composition A, as shown in Table 1, was selected due to its ability to accommodate a wide variety of hazardous species, its outstanding long-term chemical durability, and its corrosion resistance to a wide range of environmental conditions.[1]

A series of crucible melt experiments was conducted in the laboratory with Composition A prepared with between 0 and 40 wt.% PbO added to the glass. The Pb loading experiment showed that the Fe borosilicate glass was able to successfully immobilize up to 25 wt.% PbO such that it leached less than the 5 ppm Pb regulatory limit as determined using TCLP testing, as shown in Fig. 1.

To reduce the cost of the glass frit, the chemical formulation was modified by removing the elements considered nonessential. These included Ca, Mn, Mg, and Zr. The modified composition B was scaled to 100% and is listed in Table 1. A series of laboratory experiment was conducted to determine the immobilization of Pb, Cd, Cr, and Cu. Cd can be present on metal fasteners, chromium is a component of lead chromate primers, and copper is used as an antifouling agent in some paints for ship hulls. TCLP analysis was conducted on glass samples of composition B melted with 25% waste loading of the following hazardous permutations: (1) Pb only, (2) 50% Pb and 50% Cu, and (3) 80% Pb, 10% Cd and 10% Cr, as shown in Table 2. The regulatory limits for Cd and Cr release by TCLP testing are 1.0 and 5.0 ppm, respectively. However, there is currently no Federal regulatory standard for release of Cu by TCLP testing. The results showed that Composition B successfully immobilized Pb, Cd, Cr, and Cu.

2.2 Processing Parameters Optimization

Although the spray parameters were optimized in this research, minor adjustments must be made in the field depending on the specific characteristics of the compound being flame sprayed. Spray parameters, such as fuel and oxygen pressures

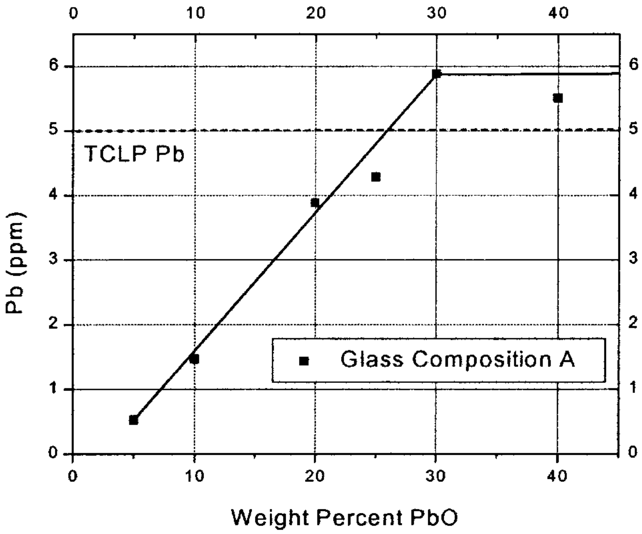

Fig. 1 Effect of lead loading on the TCLP concentration of Pb

Table 2 TCLP Results for Glass Composition B

Hazardous Components 25% Loading	Pb, ppm	Cd, ppm	Cr, ppm	Cu, ppm
Pb	2.8			
50% Pb/50% Cu	2.4			3.9
80% Pb/10% Cd/10% Cr	3.1	0.5	0.1	
Regulatory Limit	5.0	1.0	5.0	

and flow rates, standoff distance, powder flow rate, and powder carrier gas flow rate were optimized, as shown in Table 3. The use of a reducing atmosphere during the preheating of the substrate was found to improve the removal.

2.3 Paint-Removal Optimization

The goal of the thermal spray vitrification process is to remove the lead-based paint from the substrate for subsequent recoating with a surface tolerant system. Following removal of the lead-based paint, there may be a small amount of residual Pb on the substrate surface. When the surface tolerant coating eventually needs to be removed for repainting, Pb monitoring will have to be conducted to determine the airborne Pb concentration and the necessary extent of work protection. Due to the significantly lower Pb concentrations, reduced requirements for worker protection would be expected. Traditional paint removal processes such as abrasive blasting can be used for the subsequent paint removal.

C steel coupons measuring 4 × 6 × 0.5 in. were painted with lead oxide-containing primer followed by an aluminized topcoat. These panels were cured in an oven at 60 °C for 7 days for use as test specimen. The remnant Pb in the panel was measured using x-ray fluorescence (XRF) Pb-detection equipment. The test panels were preheated to about 150 °C (300 °F) to drive away the moisture, and the feedstock powder was sprayed and fused using the oxy-acetylene spray gun. Pb removal was tracked by XRF testing of the surface. The initial Pb concentration ranged from 6 to 13 mg/cm^2. Following application of the thermal spray vitrification process the surface Pb concentration ranged from 0.4-1.2 mg/cm^2. The accuracy of the XRF measurements is questionable at or below 1.0 mg/cm^2. Supplementary testing using scrape samples are recommended before making Pb hazard control or worker protection decisions. Visual observations and XRF analysis showed that the thermal spray vitrification process successfully removed the Pb-based paint from the substrate, as shown in Table 4. The resulting surface was suitable for repainting using a surface tolerant coating.

The glass fragments from the experimental samples were collected. TCLP analysis detected Pb leaching from the glass collected. The rapid cooling of the glass on the substrate evidently had provided insufficient time for the Pb to completely diffuse into the glass network while on the surface. Instead, Pb was trapped on the surface of the glass where it was quickly liberated by the acid used in the TCLP test. However, remelting the glass fragments yielded a nonhazardous waste as determined by TCLP testing.

Fig. 2 TSV process on Fire hydrant at Fort Drum to remove lead-containing paint

Table 3 Thermal Spray Processing Parameters

Parameter	Initial Conditions	Reducing Preheat Condition
Acetylene Pressure, psi	15.0	15.0
Acetylene Flow Rate, %	42.0	42.0
Oxygen Pressure, psi	40.0	40.0
Oxygen Flow Rate, %	32.0	10.0
Carrier Gas (N_2) Pressure, psi	42.0	42.0
Carrier Flow Rate, %	40.0	40.0
Powder Feed Rate, g/min	88.0	0

Table 4 Results of Lead Removal Experiments

Sample	Initial Pb XRF Concentration, mg/cm^2	Final Pb XRF Concentration, mg/cm^2
1	6.9	0.5
2	8.1	0.9
3	6.7	1.2
4	6.7	0.7
5	6.0	0.9
6	10.5	0.6
7	11.5	0.4
8	12.3	1.1

2.4 Worker Exposure and Air Monitoring

Both emission monitoring and personal monitoring of the airborne concentration of lead were conducted during laboratory testing of the thermal spray vitrification process. Personal breathing zone samples were collected on the operator during each day's operation; i.e., the operator wore a personal sampling pump with filter assembly positioned in the worker's breathing zone. The personal breathing zone samples were collected on closed-face, 37 mm diameter, 0.8 μm pore size mixed cellulose ester membrane filters contained in a three-piece cassette. The filter assembly was attached to a battery-powered vacuum pump operating at a constant flow rate of approximately 2l per minute.

The area air sampler was located in the exhaust hood area of the laboratory to determine the concentration of airborne lead particulate in the general area during the operation and until all work was completed. The air samplers were located in the same position at the same locations during all sampling events. Identical filters, filter assemblies, and pumps were used for the area-air sampling. Air cartridges were sent to an EPA-certified laboratory for analysis.

Occupational Safety and Health Administration (OSHA) standards require all employers to conduct an initial exposure assessment for all jobs involving the use or removal of Pb or Pb-containing materials. The purpose is to determine if any employee is exposed to Pb equal to or greater than the action level of 30 μg/m^3. The exposure assessment can include current results from exposure monitoring of employees, previous monitoring results, or other objective data. The specific product, process, operation, or activity involving Pb cannot result in exposure above the action level under any circumstances. When the initial determination shows that no employee is potentially exposed to lead at or above the action level, further exposure assessment is not necessary until there is a change in the workplace.[7]

Previous results where the employer has monitored employees for Pb exposure can be used to satisfy the requirement for the initial determination providing the data was collected during the previous 12 months during work conditions closely resembling the processes, material types, control and containment methods, work practice, and environmental conditions used and prevailing in the current workplace.[7]

The certified results show that airborne lead emissions during laboratory testing fell below the National Ambient Air Quality Standards (NAAQS) limit[8] of 1.5 μg/m^3 lead. The results of personal exposure monitoring during thermal spraying were below the OSHA action level of 30 μg/m^3 (8 h exposure).[9]

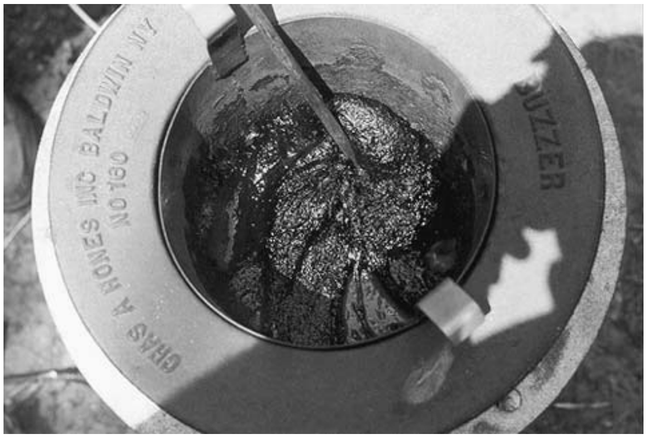

Fig. 3 Vitrified paint debris being remelted and stirred in pot-type furnace to immobilize lead

3. Field Demonstration

The field demonstration of the TSV process was on a fire hydrant at Fort Drum, NY, in a field location remote from utilities and buildings. Figure 2 shows the TSV procedure being performed on the fire hydrant. The soil directly below the hydrant was found to be contaminated with paint chips, containing lead, as determined by using disposable field lead detection chemical ampules. The chips and soil were placed in the furnace to be vitrified along with the paint debris. Personal protection equipment consisted of gloves, face shield, and a national institute for occupational safety and health (NIOSH) certified half-face air purifying respirator equipped with high efficiency particulate air (HEPA) filters.

The hydrant was preheated, followed by application of the molten iron silicate glass to the painted substrate using the thermal spray torch, allowing the substrate to reach a temperature of 230 °C (450 °F) for 15 min. In some areas a blow from a paint scraper removed the glass. The glass fragments, which were less than 5-8 cm (2-3 in.) in size, were allowed to fall into a sheet metal collection basin, placed around the hydrant for collection. One to three passes of the thermal spray gun were needed to remove the paint.

The vitrified paint debris resulting from the TSV process was remelted in a pot-type furnace (Charles A. Hones, Baldwin, NV) (Fig. 3) to immobilize the Pb using the following procedure: (1) heat the furnace to 800 °C (1470 °F) and maintain for 3 h, stirring every 15 min until melting occurs; (2) deactivate the furnace and allow the vitrified waste to cool; (3) reheat the furnace to 800 °C (1470 °F) and maintain for 2 h; (4) quench the glass waste in water. The remelted waste passed the TCLP, leaching less than 5 ppm lead; therefore the waste was classified as non-hazardous and disposed of in a non-hazardous waste landfill.

Approximately 7 pounds of vitrified Pb-containing waste were produced. The resultant waste passed the regulatory limit of less than 5 ppm of lead as analyzed by the TCLP test.

The estimated cost of the TSV process to remove Pb-containing paint from fire hydrants is about $191 per hydrant. The alternative to the TSV process for hydrants is removal of the hydrants to a central facility, grit blasting, recoating and replacement, estimated at $219.50 per hydrant not counting consumables such as grit, grit blast nozzles, etc. In addition, there is a central grit blasting facility that is contaminated with Pb. The cost of painting is assumed equal for both processes.

4. Conclusions

Thermal spray vitrification is an innovative process that uses molten glass to remove Pb-containing paint from steel structures, while minimizing airborne Pb and reduces the need for total containment. Laboratory experiments have resulted in a glass composition and thermal spray procedure that optimized the process.

A field demonstration of the thermal spray vitrification (TSV) process has shown that the process can: (1) remove Pb-containing paint in the field from steel structures, (2) meet applicable environmental standards, (3) meet applicable worker health and occupational safety standards, (4) restore the profile to the steel structure suitable for repainting using a surface tolerant coating system. On-site remelting of the waste required a minimum of five hours at 800 °C (1470 °F) to insure the homogenization of the melt and full immobilization of the hazardous species to render the waste non-hazardous as determined by RCRA.

The economic advantages of thermal spray vitrification for Pb-based paint removal would be the savings realized through the reduction of containment and minimization of worker and environmental monitoring. Because the final glass residue would be chemically verified as nonhazardous, the waste material could be disposed to a municipal waste landfill using a standard waste hauling service. The Department of Defense has more than 200 million square feet of steel structures coated with Pb-based paint. The savings of avoiding hazardous waste disposal would be substantial.

5. Recommendations

The TSV process at this time is best suited to niche markets where the cost of full containment structures cannot be spread over a large area. This includes zone painting for large structures, and small fixed structures such as fire hydrants, posts, highway overpass rails, fence posts, light stands, fire call boxes, and small power plant fixtures such as pump casings, catwalks, railings, etc.

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