Article: The 2004-2005 treatment of Alexander Calder's last and largest mobile, *Untitled* 1976
Author(s): Michael Belman, Abigail Mack, and Shelley Sturman
Source: *Objects Specialty Group Postprints, Volume Thirteen, 2006*
Pages: 45-65
Compilers: Virginia Greene, Patricia Griffin, and Christine Del Re

Objects Specialty Group Postprints is published annually by the Objects Specialty Group (OSG) of the American Institute for Conservation of Historic & Artistic Works (AIC). A membership benefit of the Objects Specialty Group, *Objects Specialty Group Postprints* is mainly comprised of papers presented at OSG sessions at AIC Annual Meetings and is intended to inform and educate conservation-related disciplines.

THE 2004-2005 TREATMENT OF ALEXANDER CALDER'S LAST AND LARGEST MOBILE, *UNTITLED* 1976.

Michael Belman, Abigail Mack and Shelley Sturman

Abstract

Alexander Calder's last and largest mobile, *Untitled* (1976) has gently rotated in the air currents of the atrium of the East Building at the National Gallery of Art since it's opening in 1977. At Calder's request, artist and engineer Paul Matisse fabricated the mobile out of then cutting-edge materials to be both lightweight and durable. Over the course of the mobile's 29 year history, two separate attempts were made, through the application of thermal spray hardfacing coatings, to combat the persistent divot shaped depressions that formed between the contact points of the aluminum hooks and loops. The mobile was exhibited with its original molybdenum coating for 11 years. In 1989 a new two layer coating of nickel-molybdenum-aluminum plus a titanium dioxide top-coating was applied that lasted another 15 years until 2004, when further treatment was required.

The depressions that formed between 1989 and 2004 were much deeper on some of the aluminum hooks than those that formed during the first decade, possibly because a longer period of time elapsed between treatments, increased movement from air currents in the atrium as the air handling systems were updated, and oil that leaked onto the mobile from its hanging assembly on the roof. Nearly all of the aluminum hooks and loops exhibited depressions with the degree of damage being proportional to the lessening load at each junction. A few of the aluminum hooks that were connected to steel elements were subject to preferential wear.

Through consultation with experts in the field of friction science and the use of an ASTM test for thermal spray wear resistance, a better understanding was obtained of the wear mechanisms occurring on the mobile and a treatment plan was devised using newly developed hardfacing materials. Treatment of the sculpture involved aluminum TiG weld-filling of the worn depressions, adding steel liners to four sensitive aluminum and steel junctions, complete replacement in steel of one structurally compromised aluminum element, and application of a tougher hardfacing coating: tungsten carbide with cobalt applied by High Velocity Oxygen Fuel to select hook and loop contact points. The design and execution of the treatment was performed through close consultation with Paul Matisse. After repainting using the same manufacturer's paint as originally applied, the mobile was returned to its soaring state.

Figure 1. *Untitled*, Alexander Calder, 1976, painted aluminum, steel, 358 1/2 x 912 inches. Gift of the Collectors Committee. Photo courtesy of Board of Trustees, National Gallery of Art, Washington.

1. Introduction

Alexander Calder's last and largest mobile, *Untitled*, has rotated in the air currents of the atrium of the East Building at the National Gallery of Art since its opening in 1977 and has become one of the iconic symbols of the Gallery's East Building. Calder worked on this commission in collaboration with the visionary architect I.M Pei, as the mobile was meant to provide the finishing touch to Pei's design of the East Building (Marshall and Sturman 1991). For clarity throughout the rest of this paper, *Untitled* will be referred to simply as "the mobile".

Calder made only a small scale model of the mobile, and entrusted its enlargement to Paul Matisse, (son of his dealer, Pierre Matisse, and grandson of the painter, Henri Matisse), owing to complications with the mobile's projected weight. In the National Gallery Archives, a note handwritten by Calder to Matisse states: "You go ahead and build the thing and I'll come and see it when it is finished"(Calder 1975).

Figure 2. Calder working with Matisse during the enlargement of his model. Photo courtesy of National Gallery of Art.

In order to make the mobile light enough so that it could move freely on the slightest air currents, Matisse used cutting edge aircraft grade materials such as aluminum honeycomb panels and heat treatable 6061 aluminum alloy tubing which achieves its strength through heating rather than work hardening. Although Calder was able to approve the construction and final appearance of the work, he died shortly before the mobile was installed and was never able to see the completed work in the intended space (Marshall and Sturman 1991).

2. Nomenclature for the Elements of the Mobile

Matisse developed a nomenclature for the mobile that groups the parts into the general categories of "blades," "planes," "wings," and related "arms." (see Fig 3). The mobile consists of six red (ovoid shaped) vertically oriented blades, five black (chevron shaped) horizontally oriented wings, and two large (triangular) planes, one blue, the other black, also horizontally oriented (Matisse 1976).

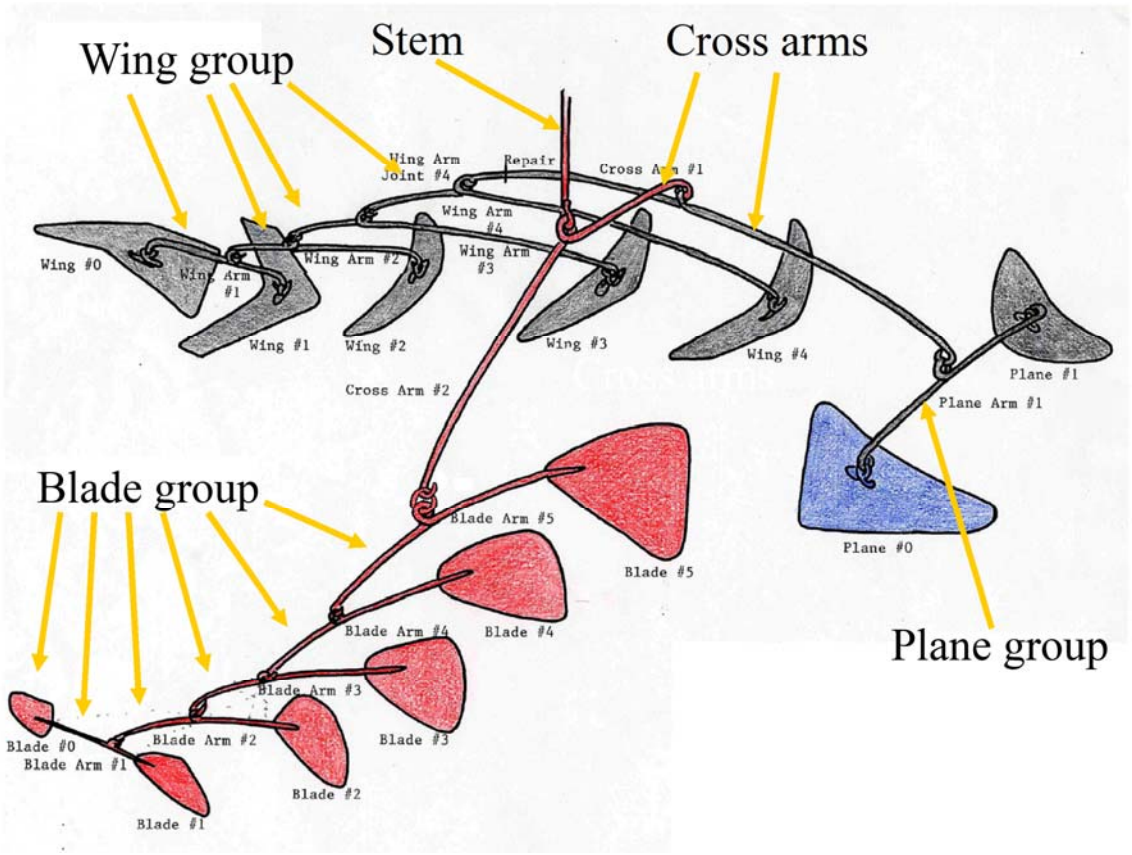


Figure 3. `Mobile diagram with the wing, plane and blade groups and arms labeled.

The mobile's blades, planes, and wings are suspended from a red central "stem" which fits into to a housing on the roof containing ball bearings in an oil bath. The entire mobile rotates and

individual parts pivot from the hook and loop interfaces in the air currents of the atrium.

There are two large central cross arms from which the blade, plane or wing arms are suspended. The nomenclature classifies "hooks" at the ends of each arm and "loops" in the center of the arms, referred to as end hooks and center loops respectively (see Fig. 4).

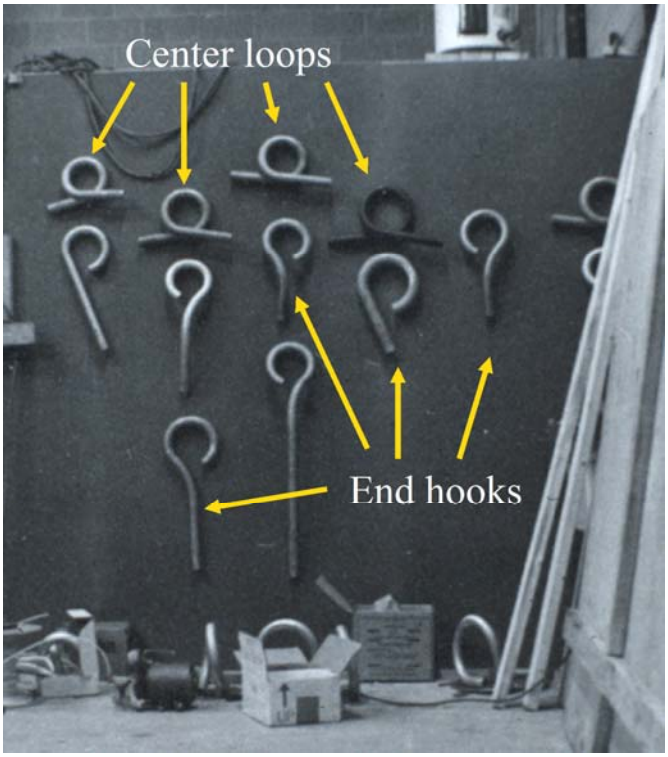


Figure 4. Image of mobile parts in Matisse's studio in the 70's. Photo courtesy of National Gallery of Art.

3. Making the Mobile

3.1 Materials Details

Matisse constructed the mobile to be as robust and at the same time as light as possible. He used steel tubing for five of the center loops that bore the most weight and attached them to the tubular aluminum arms with solid steel splices and epoxy adhesive.

The blades, wings and planes on the mobile are made of aluminum honey-comb panels with shaped epoxy putty edges (see Fig. 5). When complete, the mobile was 76' feet long, 54' wide and 29' feet deep, and weighed a total of 920 lbs (Marshall and Sturman 1991).

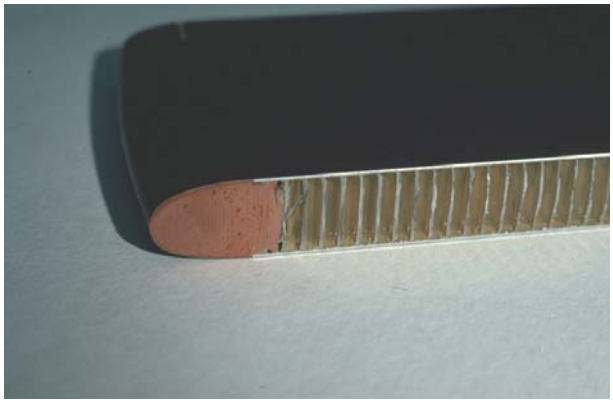


Figure 5. Cross section of a honey-combed aluminum panel prototype.

3.2 Thermal Spray Technology in the Mobile's Construction

To mitigate wear on the hook and loop join surfaces which bore an intermediate amount of weight, Matisse applied a thermal (plasma) sprayed hardfacing coating of molybdenum. (Marshall and Sturman 1991) [1].

Thermal sprays can create very tough and dense coatings of both mechanically and physically bonded particles owing to the lamellar structure created by the spray process and the different types of particles within the coating– both flattened and spheroidal (see Fig 6). Metal particles that are still molten when they strike the substrate flatten or splatter on contact, while other particles solidify into spheroidal shapes while traveling though the air and become embedded in the molten particles (England 2004).

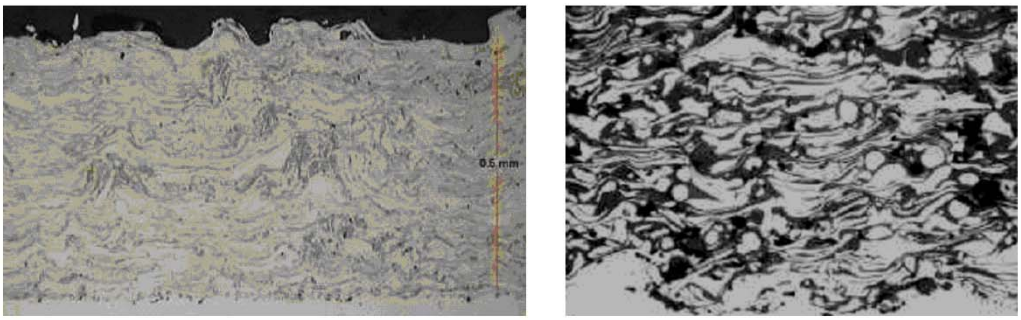


Figure 6. Photomicrographs of thermal spray coatings. Note the scale in the left image which shows that the coating is half a millimeter thick. Images are from www.gordonengland.co.uk

4. 1988 – 89 Conservation Treatment of the Mobile

As is expected with kinetic sculptures, some parts of the mobile exhibited wear over time and needed to be repaired or replaced in order to allow the sculpture to move as originally intended. Following its installation in 1977, the mobile hung for over 11 years until divots in the aluminum tubes at the hook and loop interface from the constant motion were discovered during routine maintenance.

To correct the depressions forming on the loops and the associated loss of mobility, the mobile was deinstalled in 1989 for major conservation treatment (Marshall and Sturman, 1989 and 1991). Depressions in the bearing surfaces of 5 loops and hooks were filled with TiG welded aluminum filler rod [2], and a total of 16 loops and hooks were hardfaced using a then state of the art hardfacing system: a bond coat of a nickel, molybdenum and aluminum alloy followed by a top coat of titanium dioxide, a type of ceramic coating chosen for its extremely hard and smooth surface (Snow 1988).

5. Recurring divot formation on the bearing surfaces of the end hooks

Following treatment the mobile was reinstalled and hung for another 15 years until 2004 when once again, movement became inhibited and depressions had reformed, but this time they were significantly deeper than during the previous examination. Given the nature of the materials used in the fabrication of the mobile, it was clear that the damage was likely to be recurring, and a new approach was sought that would mitigate the need for a major treatment every 10 to 15 years. The sculpture was de-installed in April of 2004, and all parts were carefully examined.

Each one of the aluminum hooks and loops exhibited some depressions with the degree of damage being determined by several factors. Most damaging was the preferential wear of the aluminum bearing surfaces in contact with the five steel center loops.

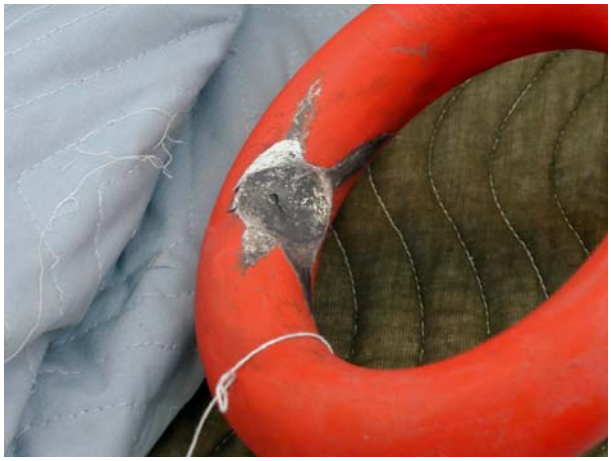


Figure 7. The aluminum end hook of blade arm 5 (left) and the aluminum ring (right), both areas of aluminum to steel contact, were the most badly damaged.

The end hook of blade arm 5 exhibited the worst damage from aluminum to steel contact as the divot had actually penetrated the wall of the aluminum tubing (see Fig. 7, left). Several significant depressions, also from aluminum to steel contact, were worn in the aluminum ring that connected the end hook of cross arm 2 and the entire upper portion of the mobile with the lower blade group section. In fact, the entire inside surface of the aluminum ring was damaged to the extent that its replacement became a major consideration.

6. Analyzing the wear system on the mobile

The recurring damage posed a potentially serious safety problem, in that the mobile is suspended 60' in the air above the public. Also troubling was the fact that several new divots formed in areas that had been re-hardfaced in 1989.

Another factor affecting the degree of damage was the proportional lessening of the load and the amount of movement at each junction on the blade group, which is subjected to nearly constant back and forth movement on the slightest air current. Depressions were also observed on end hooks at aluminum to aluminum interfaces. These decreased in size as the blades arms themselves decreased in size and supported less weight. Very little damage was seen in the hooks and loops at the horizontally oriented wing and plane groups, which have a more of a gentle up and down movement, rather than the more aggressive wear of the blade group.

Another possible cause of the increased damage was an oil leak from the bearing housing on the roof that dripped onto the lower hanging red blade group (see oil stained ring image in Fig. 7). The oil acted as a lubricant and caused greater mobility at the hook and loop interfaces. Further exacerbating the problem, the oil trapped particulates such as paint, aluminum, and hardfacing particles which acted as abrasives thereby cutting the divots even deeper. The oil also dripped onto the blades, wings, and planes, covering them with oily tidelines.

In addition to structural repairs, the other major component of the treatment was to find a more durable thermal spray hardfacing that could better protect the hook and loop interfaces than the coatings used in the previous treatments. Initial research involved friction scientists at the US Naval Research Laboratory in Washington, DC. After examining the components they observed that the hook and loop interfaces were basically two cylinders lying perpendicular on top of one another, making contact in one small point, known as a point load (see Fig. 8).

Figure 8. Diagram showing the point load of the mobile's hook & loop interface. The wear scar is typical of this type of wear system.

A critical observation was that the softer aluminum became compressed under its steel counterpart causing the hardfacing at the surface to fail. The back and forth movement of the hook and loop joins on the point load (fretting wear), created the distinctive craters in the center of the "x" shaped wear pattern (Singer 2004). It was also observed that the steel elements withstood the wear system much better than the aluminum ones and exhibited virtually no damage.

7. Investigating Potential Treatment Options

It was feared that the structural integrity of the perforated aluminum end hook of blade arm 5 and the heavily abraded aluminum ring might be compromised to an extent that they warranted replacement. One promising option was to replace the aluminum ring with steel tubing of the same exterior dimensions, but with slightly thinner walls so that the appearance and balance of the mobile would not be affected.

Repairing the end hook of blade arm 5 was more complicated and the initial ideas were unacceptable as they relied too heavily on the strength of a single weld or involved extensive alterations to original material. Of concern was the possibility that repairs involving heat would anneal the work hardened state of the heat treatable aluminum and diminish its strength even further. Results of radiography demonstrated that replacement of the perforated end hook of blade arm 5 with a newly fabricated one of the same aluminum alloy, or with thinner walled steel, was not a viable option. X-radiographs of the end hook revealed that the internal splice attaching the end hook to the rest of the blade arm travels deep inside the arm tube beyond the join (see Fig. 9). Replacing the end hook would require cutting the blade arm tube above the splice, refabricating an entirely new end hook, and reattaching it with a new aluminum splice

and epoxy bond as in the original manufacture.

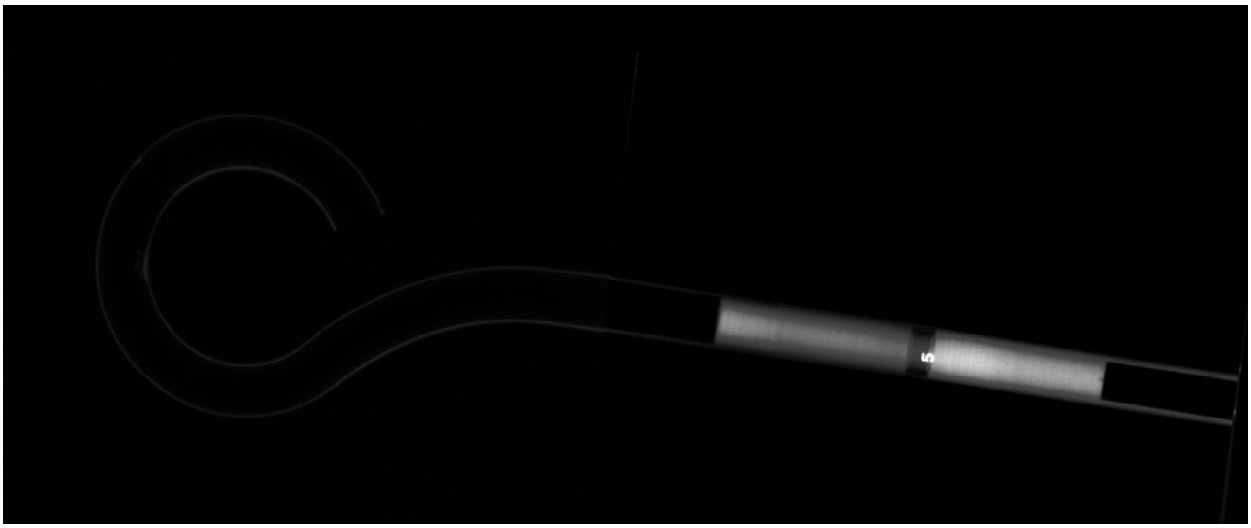


Figure 9. Composite x-ray of the epoxied aluminum splice that attaches the end hook of blade arm 5 to the rest of the arm.

Replacing an original epoxied join was seen as an overly aggressive approach and one that could critically alter the balance of the piece. It was ultimately decided to replace the aluminum ring with a thinner walled steel ring and to adhere custom formed steel liners to the two most seriously damaged aluminum end hooks (blade arms 5 and 4), following TiG weld filling of the depressions as had been done during the previous conservation treatment. The liners would act to stiffen the aluminum bearing surfaces against the pivoting steel and aluminum counterparts and considerably reduce the future formation of depressions. Steel liners were also planned for the aluminum end hook of cross arm 2, to protect it from the steel interface of the newly fashioned steel ring and for the aluminum hook of the supporting stem that also has an interface with a steel center loop of cross arm 2.

The engineer originally involved in the fabrication of the mobile was consulted and he calculated that the projected less than 1% of added weight of the new ring and liners would not affect the balance and or provide any structural complications. The engineer also determined that the small amount of very localized heat involved with the TiG welding and thermal spray made any changes in the temper of the heat treatable aluminum unlikely (McCoy, 2005).

8. Fabricating Replacement Pieces

8.1 The Steel Ring

A search was conducted via standard metal fabricators and pipe bending specialty companies that supply parts to dairies and oil refineries to fabricate the new steel pieces. Surprisingly, the curve radius required in bending the replacement pieces was tighter than any of these shops had previously encountered.

The replacement steel ring (1018 alloy) of the required dimensions was produced from two 180° bends by Osage Piping & Fabricating of Steelton, Pennsylvania. Although the option of making the ring in three pieces was offered to the workshop because the original mobile ring had been made in three pieces, it was reasoned that fewer welds lessened the chance of future weld failure.

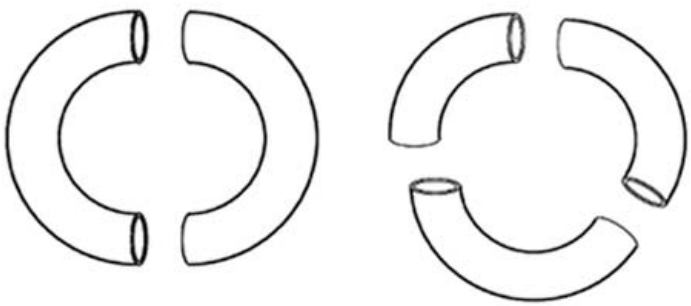


Figure 10. Drawings showing possible methods of making the thinner walled, steel replacement ring.

8.2 The Steel Liners

The liners proved to be far more problematic to make than the ring. The Steelton shop did not have the bending equipment needed to meet the required specifications nor did any of the companies they consulted on behalf of the National Gallery. As a last resort the workshop produced a set of four steel liners with faceted curve surfaces but these were impractical because of the excessive amount of additional smithing that would be required to fit the individual end hooks.

A freelance museum mount maker experienced with fabricating custom formed metal pieces, was able to make the liners to the needed specifications [3]. To provide him with the closest possible dimensions, epoxy casts of the damaged end hooks were made together with rubber templates for the liners that completely covered the wear scar (see Fig. 11). The liners were fashioned from pre-bent 1018 steel alloy tubing, then heated and smithed into the proper shape. The epoxy forms were sufficiently durable that the steel could be shaped and hammered directly on the epoxy casts.

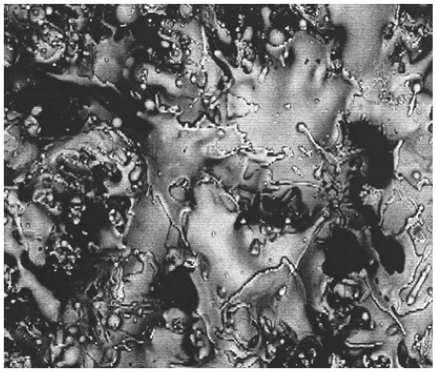
Figure 11. Epoxy casts of the damaged end hooks and the corresponding rubber templates were given to the mount maker for exact fitting of the steel liners.

9. Hardfacing Component of Treatment

9.1 Hardfacing Research

Since the 1989 treatment, many new developments have been made in the field of thermal spray hardfacings including less invasive application methods and the formulation of more durable materials. Consultation with experts in the thermal spray field led to two promising hardfacing alloys considered the toughest coatings available: Armacor M, a high chrome steel with a Rockwell C hardness of 70; and tungsten carbide with cobalt, a cermet, or ceramic/metal coating, with a Rockwell C hardness of 62 (see Fig. 12). Both of these coatings are commonly used on coal crushers, aircraft landing gear and brick dies (Berndt 2004). The original molybdenum coating had a Rockwell B hardness of 36 and is not on the Rockwell C scale, which is another magnitude harder.

Armacor M

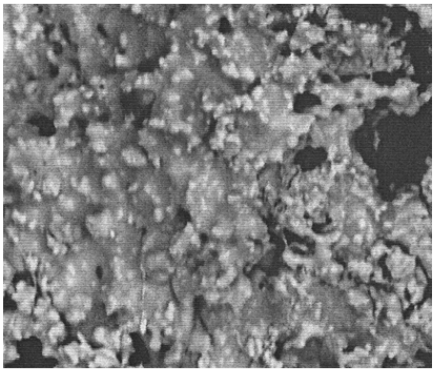


SEM image (x400) of surface.

High chrome steel
50% Fe, 45% Cr, 4% B, 1% Mn

Rockwell C 70 hardness

Tungsten Carbide w/Cobalt



SEM image (x3700) of surface.

Tungsten carbide with cobalt
83% WC, 17% Co

Rockwell C 62 hardness

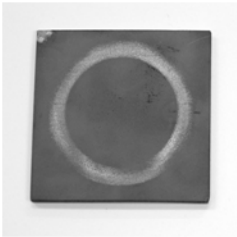
Figure 12. SEM images of aluminum coupons with as-sprayed coatings, and material data of Armacor M and tungsten carbide with cobalt.

9.2 Comparing the Durability of Select Thermal Spray Coatings

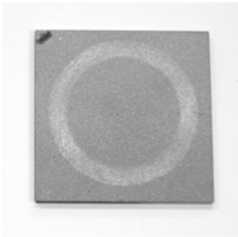
It was decided to compare the performance of the two recommended coatings with the ASTM standard test F1978-00 for thermal spray wear resistance [4]. The test made use of a Taber Abraser (see Fig. 13) that involves dragging weighted, abrasive stone wheels in a circular pattern around test coupons coated with the two hardfacings (Woods, 2004). The change in the weight of the coupons was recorded after each revolution [5].

Figure 13. Image of the Taber Abaser along with a diagram of the abrading action. Image courtesy of Taber Industries.

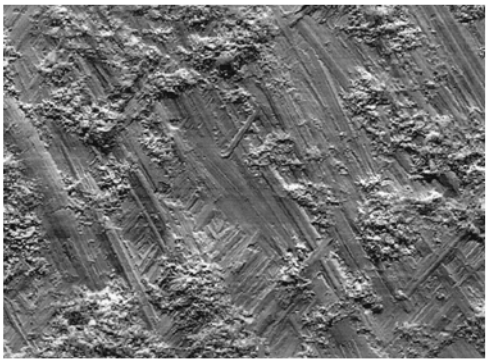
According to the test results, the tungsten carbide with cobalt is the tougher of the two hardfacings, as it lost less material in weight and dimension than the Armacor M (Pepke 2005). Further, the tungsten carbide with cobalt had a smoother surface texture than the Armacor M in the "as sprayed" condition. Because of the favorable test results and appearance, together with recommendations from experts in the field of friction science, the tungsten carbide with cobalt was chosen for the thermal spray treatment of the hook and loop interfaces.



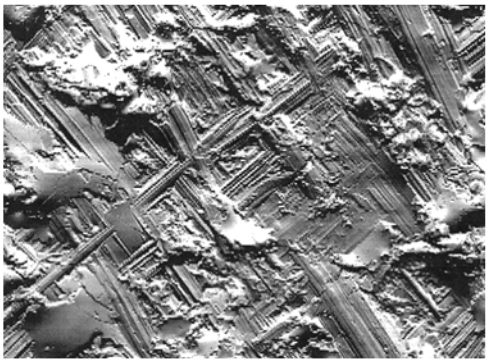
Tungsten carbide w/cobalt



Armacor M, high chrome steel,



SEM image (x250) of tungsten carbide w/cobalt wear test.



SEM image (x250) of Armacor M wear test.

Figure 14. Images of the coupons after testing with the Taber Abraser. The SEM images show the micro-patterns ground into the surfaces of the coatings.

10. 2004-05 Treatment and Reinstallation

10.1 TiG Welded Repairs

The depressions in the hooks and loops, the majority of which were minor, were filled by TiG welding using 4643 aluminum filler rod, which is specified for heat treatable 6061 alloy aluminum (Craig 2005). The filled areas were smoothed with rotary sanders and the structurally compromised aluminum ring was replaced with the new steel ring, formed from the two 180° bends, of the same weight and dimension.

Figure 15. Images show the end hook of blade arm 4 after TiG weld filling and grinding, and the attached replacement steel ring.

10.2 Imparting the Blast Profile

Prior to hardfacing, the hook and loop surfaces, including the steel liners and the new steel ring, were air-abraded with aluminum oxide to impart the necessary surface texture, known as a blast profile. The join surfaces of the four hooks fitted for liners were also air-abraded to provide a surface texture for adhering the liners in place with epoxy.

Figure 16. A surface detail of the blast profile.

10.2 HVOF Application of Tungsten Carbide with Cobalt

The HVOF, or High Velocity Oxygen Fuel application method was chosen after researching the many different thermal spray processes [6].

Figure 17. The HVOF process in action.

The tungsten carbide with cobalt hardfacing was applied to the standard 10 mil thickness on the surface of 25 hooks and loops, including the 4 steel liners, and the replacement steel ring. The thermal spray process is extremely loud and is usually performed in a sound tight booth, but the nearly 30 foot length of the largest arms made it necessary to do the work outside in back of the thermal spray contractor's workshop [7]. After the treatment, an eddy current measuring device was used to gauge the thickness of the coating [8].

As noted earlier some thermal sprayed coatings can have a rough texture. However, the surface of the tungsten carbide with cobalt had only a slight surface texture that proved beneficial in providing the appropriate amount of "tooth" prior to painting and would in no way interfere with the free movement of the mobile.

Figure 18 (top and bottom). Images show the steel liners coated with tungsten carbide with cobalt with their corresponding epoxy form. Note minimal surface texture imparted by the HVOF application.

10.2 Attaching the Steel Liners

After testing a number of epoxies rated for metal bonding, the liners were attached using Belzona 1111 metal filled epoxy putty (see Suppliers). Edges were carefully built up and smoothed to eliminate any visible profile on the surface.

Figure 19. Image shows a hardfaced steel liner being adhered to an end hook with an epoxy putty bulked with metal powder.

10.3 Repainting the mobile

Owing to the already faded and stained condition of the paint, it was decided in consultation with the curatorial department, the Calder Foundation and Paul Matisse, to repaint the entire sculpture using the original paint formulation: Keeler and Long Flat Poly-Silicone. One of the colors is actually named Calder Blue by the paint company.

Figure 20. Repainting the mobile arms.

10.4 Reinstallation

After more than a year of extensive collaborative efforts among conservators, engineers, machinists and fabricator, NGA staff met at 5 am on the re-installation day to begin the delicate, choreographed process of reassembling the mobile. Twenty minutes before the museum opened, the mobile was raised to its final position and museum staff, watching silently from various corners of the atrium, cheered the long awaited return of the grand icon.

Figure 21. The re-installation of the mobile after over a year of collaborative effort.

Acknowledgments

The authors wish to thank several individuals at the National Gallery of Art for their support throughout this project, including Michael Palmer, Conservation Scientist and Dr. Jeffrey Weiss, Curator of Modern and Contemporary Art; as well as Judy Ozone, Daphne Barbour, Katy May, Caitlin Jenkins, and Julia Sybalsky of the Object Conservation Department, without whose help and enduring patience, the treatment could not have succeeded. We appreciate the advice and consultation offered by Dr. Irwin Singer, Head of Tribology Section, US Naval Research Laboratory; Dr. Chris Berndt, Head of Thermal Spray Engineering, Stonybrook University; and John Pepke, Laboratory Tester, Taber Industries. Finally, we are grateful to Paul Matisse, Kalliroscope Corporation, for his guidance and encouragement at every step.

Endnotes

1. Plasma spray is a thermal spray process. Thermal spray is a general term for depositing a material in powder or spool-fed wire form onto a substrate through a pressurized super-heated gas jet. Metal alloys, ceramics, metal/ceramic composites, and polymers are materials commonly used in thermal spraying. The substrate is first prepared by air abrading with abrasive grit to impart the necessary surface texture, or blast profile to enable the coating to stick. Hardfacing is only one of the uses of thermal spray, in which a substrate is made stronger by coating it with a harder or tougher substance (Herman 1988).

2. TiG welding, or tungsten inert gas welding, is an arc welding process that uses a tungsten electrode, alternating current and a filler metal, usually in rod form to produce the weld. The weld area is protected from atmospheric contamination with a shielding gas such as argon or helium. TiG welding is particularly effective with welding aluminum, which forms a refractory oxide layer within minutes of exposure to air. This oxide layer must be removed for welding to occur (Craig 2005).

3. Paul Daniel, 2010 Clipper Park Rd, Baltimore, MD 21211, 410-366-5072, tdaniel@bcpl.net

4. The ASTM standard test F1978-00e1 for measuring abrasion resistance of metallic thermal spray coatings by using the Taber Abraser was originally developed to characterize coatings used on surgical implants (Woods, 2004).

5. Taber test was performed on a Model 5130 Rotary Abraser with H-22 wheels. A 250g weight was applied to each wheel. The coupons were seasoned in a test atmosphere of 70º F and 47% RH for 24 hours and then tested for a total of 500 cycles, with the change in weight being measured every 72 cycles (Pepke 2005).

6. Lower energy methods such as twin wire arc spray and flame spray were also considered because they could be could be performed in the immediate Washington, DC area at lower cost. Ultimately the HVOF method was chosen because it can produce extremely dense coatings with negligible porosity through the high velocity of the pressurized, super heated gas stream which reaches 1500 meters per second (Berndt 2004).

7. An HVOF applied coating is considered to be a cold application because the flame jet only touches a localized area, and the increase in temperature of the surrounding aluminum is negligible (Berndt 2004).

8. Eddy current measuring is a common non-destructive method used for testing the thickness of thermal spray coatings. The device measures the magnetic field created by the interaction of a conductive probe under alternating current and a conductive test surface (England 2004).

Supplier

Metal filled epoxy putty (Belzona 1111):
Belzona Inc., 2000 N.W. 88th Court, Miami, FLA 33172 (www.belzona.com)

References

Berndt, C. 2004. Personal communication. Director of the Mechanical Testing Laboratory at Stony Brook University in the Department of Materials Science and Engineering. Stony Brook University, Stony Brook, NY. 11794.

Calder, A. 1975. Copy of a handwritten letter to Paul Matisse. Conservation File 1977.76.1. Washington, DC: National Gallery of Art.

Craig, E. 2005. Aluminum alloys and welding data. www.weldreality.com/aluminumalloys.htm
Herman, Herbert. 1988. Plasma-sprayed coatings. *Scientific American*, 259:112-117.

England, G. 2004. Thermal spray coating page index. www.gordonengland.co.uk

Herman, Herbert. 1988. Plasma-sprayed coatings. *Scientific American*, 259:112-117.

Marshall, A. and S. Sturman. 1989. 1988-89 Treatment Report of the Calder Mobile, *Untitled* (1976). Conservation File 1977.76.1. Washington, DC: National Gallery of Art.

Marshall, A., and S. Sturman. 1991. Conservation of one of Alexander Calder's largest mobiles. *Proceedings of the symposium Saving the Twentieth Century: The Conservation of Modern Materials*. Canadian Conservation Institute, Ottawa. 301-305.

Matisse, P. 1976. *The Calder project: A large sculpture by Alexander Calder for the National Gallery of Art, Washington, DC.* Conservation File 1977.76.1. Washington, DC: National Gallery of Art.

McCoy, R. 2005. Structural check of the restored Calder mobile: *Engineer's Report*. Conservation File 1977.76.1. Washington, DC: National Gallery of Art.

Pepke, J. 2005. Rotary Abraser testing to evaluate abrasion resistance of two types of thermal spray coatings: tungsten carbide with cobalt and Armacor M: *Taber Industries Internal Test Request #C417.* Conservation File 1977.76.1. Washington, DC: National Gallery of Art.

Singer, I. 2004. Personal communication. Head of Tribology Section, US Naval Research Laboratory, Washington, DC. 20375

Snow, J. 1988. Letter to Paul Matisse. Conservation File 1977.76.1. Washington, DC: National Gallery of Art.

Woods, T. 2004. Personal communication. Mechanical Engineer in the US FDA Center for Devices and Radiological Health Office of Science and Engineering Laboratories, Rockville, MD. 20850.

Authors' Addresses

Michael Belman, Objects Conservator, Carnegie Museum of Art, 4400 Forbes Ave, Pittsburgh, PA 15213 , (312) 622-1978, (mbelms@yahoo.com).

Abigail Mack, Conservator in Private Practice, (abigailmack@gmail.com).

Shelley Sturman, Head of Objects Conservation, National Gallery of Art, 2000B South Club Drive, Landover, MD 20785.