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Principal Investigator: Martin McDonnell
Phone: 586-282-7999
Project Scientist: Dr. Guru Dinda
Phone: 313-494- 4452
Project Engineer: Bruce O'Neill
Phone: 313-494-4476

Direct Deposition of Metal (DDM) as a Repair Process for Metallic Military Parts

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14. ABSTRACT
In 2005 Focus: HOPE began working on a Technical Area Task to investigate advanced manufacturing in the area of Direct Deposition of Metal (DDM) for the Tank and Automotive Command (TACOM). In 2006, the scope was expanded to include basic research areas of Direct Deposition of Metal applicable to repairing military equipment and Focus: HOPE demonstrated the feasibility of conducting repairs on military equipment using Direct Deposition of Metal (Work Directive WD-FH -0001). The study also demonstrated that there could be a potential cost saving by repairing parts using DDM over purchasing new replacement parts. The overall project was extended in 2010 to provide additional time to conduct additional certification testing of repaired components and demonstrate the effectiveness of the parts repaired using Direct Deposition of Metal. For the present project, extensive studies were conducted on the metallurgical properties and bonding between the newly deposited metal and the parent metal substrate. The findings, results and conclusions of this process certification testing are provided in this report.

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Executive Summary

Background

In 2005 Focus: HOPE began working on a Technical Area Task to investigate advanced manufacturing in the area of Direct Deposition of Metal (DDM) for the Tank and Automotive Command (TACOM). In 2006, the scope was expanded to include basic research areas of Direct Deposition of Metal applicable to repairing military equipment and Focus: HOPE demonstrated the feasibility of conducting repairs on military equipment using Direct Deposition of Metal (Work Directive WD-FH -0001). The study also demonstrated that there could be a potential cost saving by repairing parts using DDM over purchasing new replacement parts.

The overall project was extended in 2010 to provide additional time to conduct additional certification testing of repaired components and demonstrate the effectiveness of the parts repaired using Direct Deposition of Metal. For the present project, extensive studies were conducted on the metallurgical properties and bonding between the newly deposited metal and the parent metal substrate. The findings, results and conclusions of this process certification testing are provided in this report.

Task Objectives

- Work toward certification of the DDM process as a method to effectively repair parts as demonstrated under WD-FH-0001.
- Complete corrosion and mechanical properties testing started in WD- FH-0001.
- Repair CTIS front wheel spindles from the M939 truck to validate the DDM repair process. Four repaired spindles are to be installed on the M939 truck and tested in the field for further testing and validation of the Direct Deposition of Metal (DDM) process.
    - Note: The M939 truck is no longer supported within the PM community but the process and practices discussed here are applicable to all military ground vehicle systems where worn metallic parts are to be repaired.

Discussion

The DDM parts repair process replaces metal material of parts that have been damaged or compromised by corrosion, wear, surface cracks or by other causes. First, the damaged metal is removed by typical machining processes leaving a clean surface of undamaged metal. Next, new metal is deposited to replace the damaged surface metal that was removed. The newly deposited metal is then machined to the original production dimensions. The DDM process allows certain parts to be repaired and reused with a potential cost savings compared with new replacement parts.

During the DDM process, the energy of a high power industrial laser beam and a concentric stream of metallic alloy powder are used to melt and solidify material onto a freestanding substrate (base metal). Typically the metal powder has properties metallurgically compatible with the substrate material. As the laser beam advances along a predefined tool path in a layer by layer fashion, metal powder is deposited and eventually forms a predefined solid shape. Use of CAD/CAM and CNC control technologies are integral to the DDM process. The DDM process creates a metallurgical bond between the substrate and the deposit which typically has a finer microstructure due to high cooling rates associated with laser processing and yields improved mechanical properties. To validate the mechanical performance of the DDM process

for use as a repair process, side bend, lap shear, tensile, and corrosion tests were conducted on DDM-manufactured test specimens of 4340 steel, Hastelloy C276 and Stellite 6 powder individually deposited onto 4140 steel substrates.

Findings and Conclusions

The DDM process is well suited to repairing damaged or worn areas of metallic military equipment parts. Of the alloys investigated in this project, the strength of the metallurgically-bonded interface between the Hastelloy C276 DDM deposit and 4140 steel substrate exceeded that of each constituent material. However this study also found that deposit and substrate alloys having significantly different hardness or ductility, e.g. Stellite 6 deposited onto 4140 steel, produce a relatively weaker DDM bond than material combinations that have similar hardness and ductility properties. Test results show that the DDM process is superior to the flame spray method. As a final demonstration of the process, four corroded Continuous Tire Inflation System (CTIS) spindles from a M939 heavy truck were repaired using the DDM process (Hastelloy C276) and provided to U.S. Army TARDEC personnel for vehicle installation and evaluation.

Project Tasks & Objectives

- The Contractor shall work toward certification of the Direct Deposition of Metal (DDM) process as a method to effectively repair parts repaired under WD-FH-0001. The COR will make a determination of the Contractor's progress towards certification through the bi-weekly Situation Report. The contractor shall report the overall progress on paragraph 2.0 IAW CDRL A007 and CDRL A012.
- The Contractor shall propose a certification test plan 90 DAC for scientific studies conducted and repair process developed in WD-FH-0001 to the COR IAW CDRL AOO6. The COR will have 30 days to approve the certification test plan format. If the COR makes any recommended changes, the Contractor shall resubmit the revised test plan to the COR within 10 days. Additionally, the Contractor shall revise their test plan throughout the testing, coordinating with the COR and resubmit to COR.
- The Contractor shall complete corrosion, short-term endurance, and mechanical properties testing started in WD- FH-0001. The Contractor shall report the results to the COR in the Scientific and Technical Report IAW CRDL A006. Once the testing is complete, the Contractor shall upload the results to the Survivability Advanced Collaborative Environments (ACE) website ("ACE website") within 30 days.
- Following Government/COR acceptance of the certified test plan format (IAW paragraph 2.1), the Contractor shall present the results of scientific studies conducted on the material combinations and repair process developed in WD-FH-0001 IAW CDRL A006 for the CTIS spindle using Hastelloy C276. The CTIS Spindle is made of a base material of 4140.

General Methodology

Background

During the DDM process, the energy of a high power industrial laser beam and a concentric stream of metallic alloy powder are used to melt and solidify metal onto a freestanding metallic substrate (base metal). Typically the metal powder has properties metallurgically-compatible with the substrate material. As the laser beam advances along a predefined tool path in a layer by layer fashion, metal powder is deposited and eventually forms a predefined solid shape. The use of CAD/CAM and CNC control technologies are integral to the DDM process. The DDM process creates a metallurgical bond between the substrate and the deposit, which typically has a finer microstructure due to high cooling rates associated with laser processing and yields improved mechanical properties. In addition, the DDM system has the capability to monitor and control powder melt pool by adjusting laser power. Such real-time closed loop feedback control can produce near net shape parts. A schematic of the DDM process is shown in Figure 1.

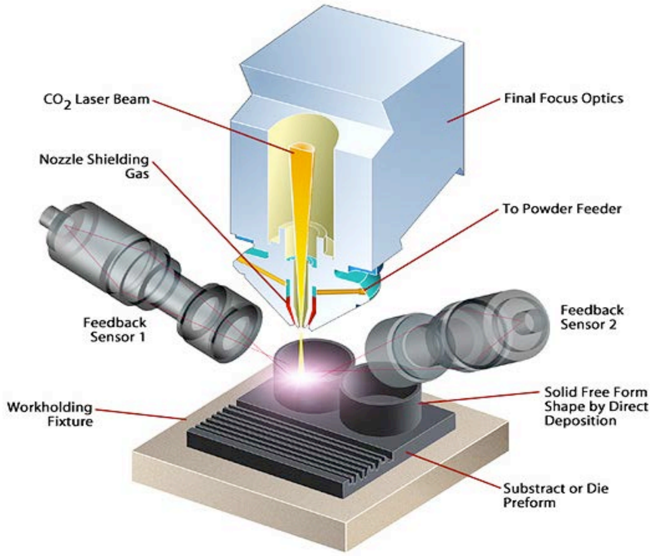


Figure 1: A schematic of DDM process with closed loop feedback (courtesy of POM Group)

Over the past decade, DDM has transitioned from mostly specialized laboratory efforts into an established technology for high quality and precise surface coating deposition. DDM repair methods have found wide application in a number of industries, including, the aerospace and power turbine industries. Numerous studies have shown that DDM has many advantages and benefits over the traditional plasma powder buildup and flame spray methods. To include but not limited to, improved metallurgical properties such as, better corrosion resistance, increased strength, increased toughness and finer microstructure. DDM also has improved ductility and can create a much thicker deposition layer and has better bonding, less porosity and higher tensile strength than flame spray methods.

Overall Project Plan

This project progressed thru several successive stages:

- DDM process parameter optimization experiments
- Manufacture of material coupons and the preparation of test specimens
- Specimen testing
- Developing a DDM repair process for a specific military component.
- Testing and evaluating the repaired parts.

Process Parameter Optimization

Experimental design array methodologies were used to develop a set of optimized DDM process parameters for each deposit/substrate material combination. Process parameters included laser power, beam spot size, laser deposit speed, powder flow rate, deposition pattern.

Preparation of Test Specimens

Using the optimized process parameters, 1-in. thick x 6-in. wide x 12-in. long material coupons were fabricated for the following material combinations. To simulate a repair process multiple layers of alloy were deposited onto substrate plates of 4140 tool steel which was chosen to replicate typical heat-treated steel used in many military component applications.

- 4340 steel deposit (see Appendix B for powder material specifications.)
- Stellite 6 deposit (see Appendix C for powder material specifications)
- Hastelloy C276 deposit (see Appendix D for powder material specifications)

From the material coupons, typical CNC machining methods were used to manufacture a series of mechanical testing coupons for each material combination and the comparison base material (See Figure 2)

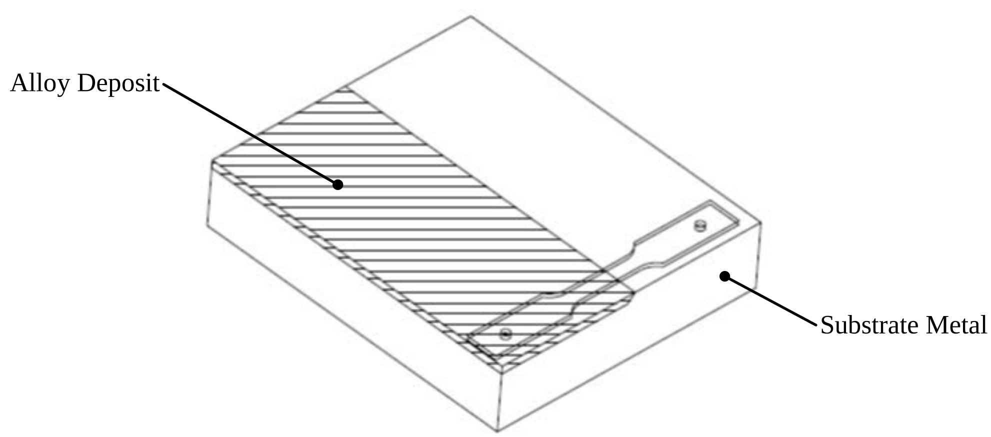


Figure 2: Example of material coupon and test specimen location (tensile shown)

Specimen Testing

Appropriate test specimens for each material combination was subjected to tensile, side bend, lap shear, and fatigue testing. The Hastelloy C276-4140 steel material also underwent corrosion testing.

- Side Bend Test - As specified in NAVSEA Technical Publication S9074-AQ-GIB-010/248, side bend tests are performed to qualify DDM of each deposit as an alternative to weld cladding/hard-facing repair. Since this military specification does not include specimen design and test condition requirements, ASTM E 290 Standard Test Methods for Bend Testing of Material for Ductility was used. Figure 3 shows the test specimen design and Figure 4 shows the test apparatus.

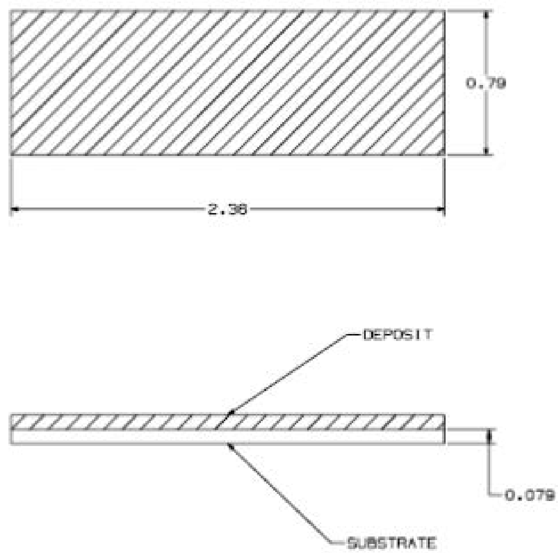


Figure 3: ASTM E290 side bend test specimen (in.)

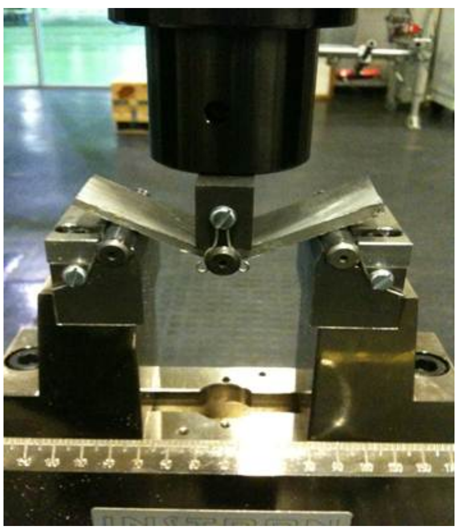


Figure 4: 3-point bend test fixture

- Lap Shear Test - Because a test specification for bimetallic shear strength does not exist, ASTM D3846 Standard Test Method for In-Plane Shear Strength of Reinforced Plastics was used for this project's lap shear tests. The dimensions of lap shear test specimens are prepared as per standards. Test specimen design is shown in Figure 5 and the test apparatus is shown in Figure 6. Due to the inapplicability of the standard ASTM method for Shear Testing of bonded metallic samples, ASTM D1002, a substitute process was developed because the D1002 samples significantly distorted in non-shear plane areas which invalidated the tests. An examination of the failure led to the adoption of a shear test protocol originally specified for testing of reinforced plastics, ASTM D3846. In this standard the samples are tested using compressive force instead of tensile force, and the shear area is surrounded in a fixture to prevent buckling. By this alternative test procedure, consistent results were obtained for the shear samples.

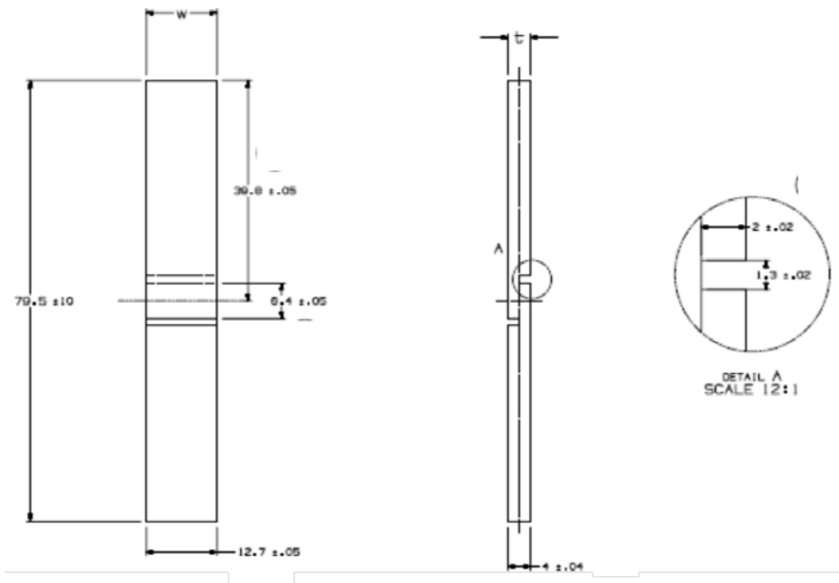


Figure 5: ASTM D-3846 lap shear test specimen (mm)

Figure 6: Lap shear test fixture

- Tensile Test - Tensile testing was conducted per ASTM E8 standards. Specimen design is shown in Figure 7 and the test apparatus shown in Figure 8.

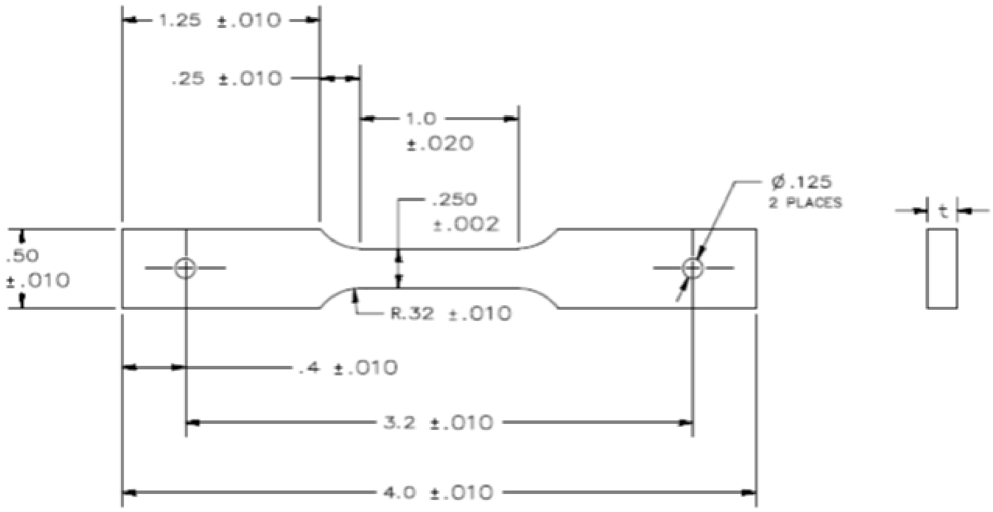


Figure 7: ASTM E8 tensile test specimen (in.)

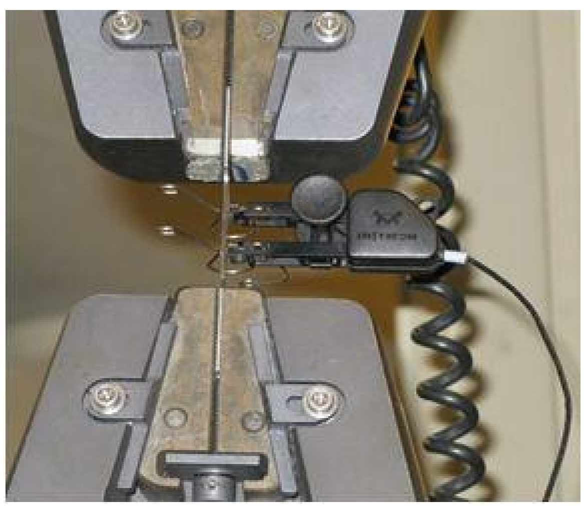


Figure 8: Tensile test apparatus

- Corrosion Test - Corrosion tests were performed per ASTM-B117 for three sets of Hastelloy C276 deposit and 4140 steel substrate material samples: 4140 steel substrate only, Hastelloy C276 only, and 50% Hastelloy C276 deposit / 50% 4140 steel substrate. (The 50%/50% corrosion specimen design was similar to the side bend specimens shown in Figure 3.)

- Additional Testing and Analysis - The following supplementary testing was conducted throughout the DDM process parameter development and mechanical testing stages:

- Optical Microscopy to evaluate the microstructure integrity, grain size distribution, and defects such as voids, porosity, and micro-cracks
- Micro-hardness tests to determine hardness resistance and distribution of different metallurgical phases.
- Scanning Electronic Microscopy (SEM) to view the microstructure under higher magnification for more detailed analysis and any smaller phases not resolved under optical microscopy.
- Energy Dispersive X-ray analysis (EDAX) to estimate the composition of the deposit and its penetration into the substrate.
- Electron Back Scatter Diffraction (EBSD) to provide an elemental distribution map from of the deposit/substrate interface.

DDM Repair Process Development

A manufacturing process which applied DDM technology as a repeatable, high quality repair method for damaged, worn, or corroded military vehicle parts was developed. The efforts involved in this stage of the project included mechanics (What, where, how, why did the physical damage happened to the part?), economics or cost (What are the tooling costs and engineering costs?), manufacturing time spans (How long does it take to set up?), process constraints (What are the process limits?), uncertainties and process reliability (What can go wrong?), skills (What operator skills are critical?), flexibility (Can this process easily do other parts of a different design and/or material?), and process capability (what are the accuracy and precision of the process), planning the ordering of materials and other resources, setting manufacturing schedules, deposit quality inspection. The metal deposition system used for this project was the DMD505 machine located at Focus: HOPE. This system has a 5kW CO2 laser, 5-axis CNC motion control, and a four material powder delivery system (see Appendix A).

Technical Results

Hastelloy C276 Deposit Mechanical Tests

- Side bend test – The averaged results of the side bend tests are shown in Table 1 and the respective individual test load-deflection curves are shown in Figure 9. The 100% 4140 steel substrate exhibited the highest ductility with most specimens exceeding 90^o bending with the closest repeatability of the three material combinations. The 50% Hastelloy deposit / 50% 4140 substrate specimens exhibited the lowest ductility however reached loads 22% higher than the 100% substrate material.
- Lap shear test - The averaged results of the lap shear tests are shown in Table 2 and the respective individual test load-deflection curves are shown in Figure 10. The results of these tests are clear evidence of the strength capability of the metallurgical bond created by the DDM process. The 50% Hastelloy deposit / 50% 4140 substrate exhibited an average shear yield stress of 718 MPa (±103) which was 20% and 42% greater than the 100% Hastelloy and 100% substrate materials respectively. The lap shear test specimen design (see Figure 5) is specifically for determining the strength of the bond at the material interface.
- Tensile test - The averaged results of the tensile tests are shown in Table 3 and the respective individual test load-deflection curves are shown in Figure 11. As was expected, the test specimens fabricated partially or wholly of the super alloy Hastelloy 262 exhibited significantly higher strength than the 4140 steel substrate material. However unexpectedly, the 50% Hastelloy deposit / 50% 4140 substrate material was 10-13% stronger than the 100% Hastelloy material. As in the bend test the 100% substrate material was the most ductile, and the % elongation results varied proportionately with the Hastelloy/substrate percentage.
- Corrosion test – Figure 14 shows the final condition of the corrosion test specimens. As expected the all-steel material significantly deteriorated during the 168 hour salt spray test, the Hastelloy exhibited minimal corrosion, and the respective faces (front/back) of 50%/50% specimens mimicked the 100% materials.

Table 1: Side bend test results (averaged) for Hastelloy deposit

Mtrl. Avg.	Fixture Extension @ Break (mm)	Maximum Flex Load (kN)	Calculated Angle (deg)
100% substrate	13.54	8.09	91
100% Hastelloy	12.98	9.12	87
50% / 50%	11.21	9.84	77

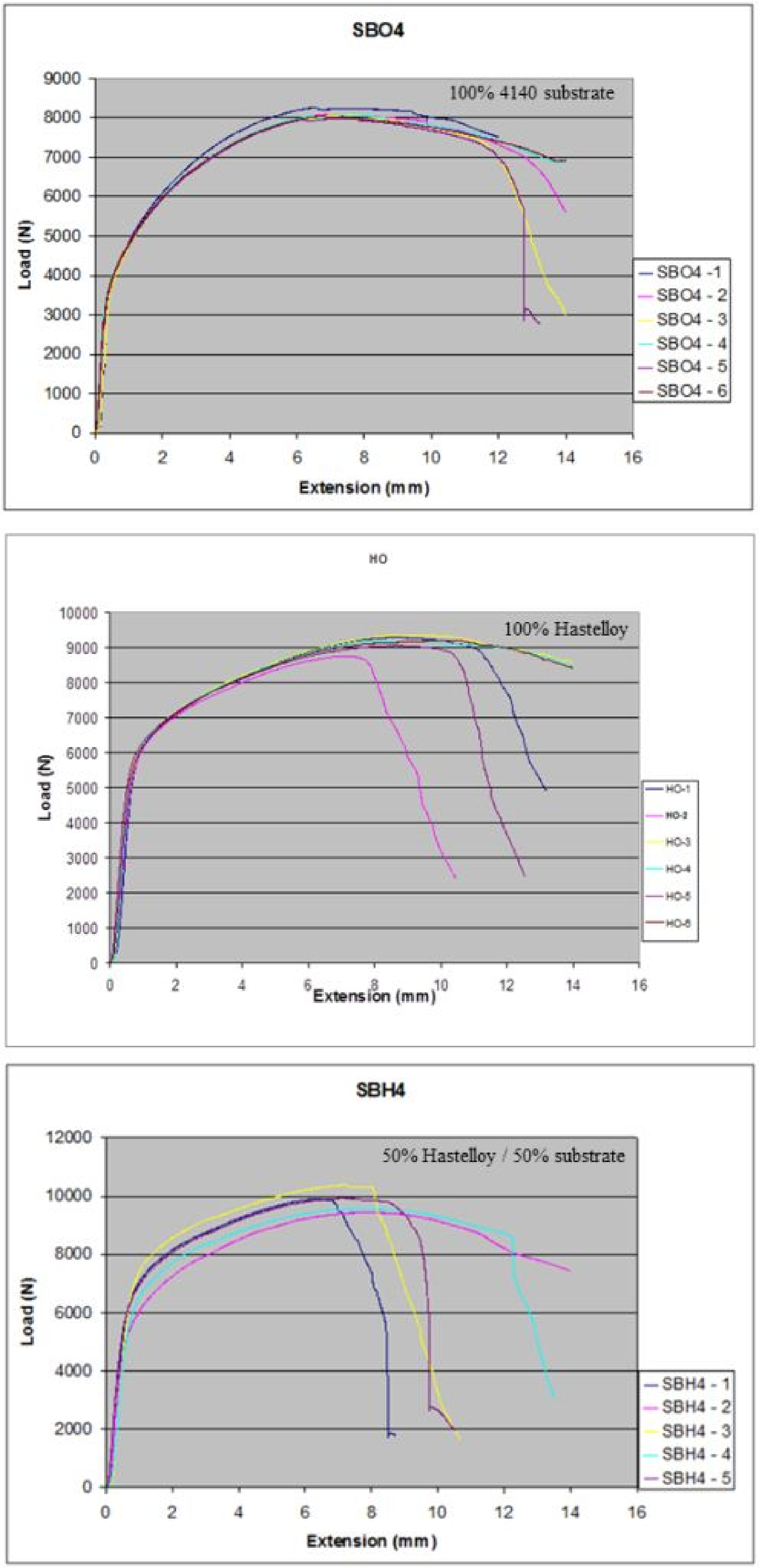


Figure 9: Graph of side bend test results for Hastelloy deposit and substrate

Table 2: Lap shear test results (averaged) for Hastelloy deposit

Material	Shear Yield Stress (MPa)
100% substrate	504
100% Hastelloy	597
50% / 50%	718

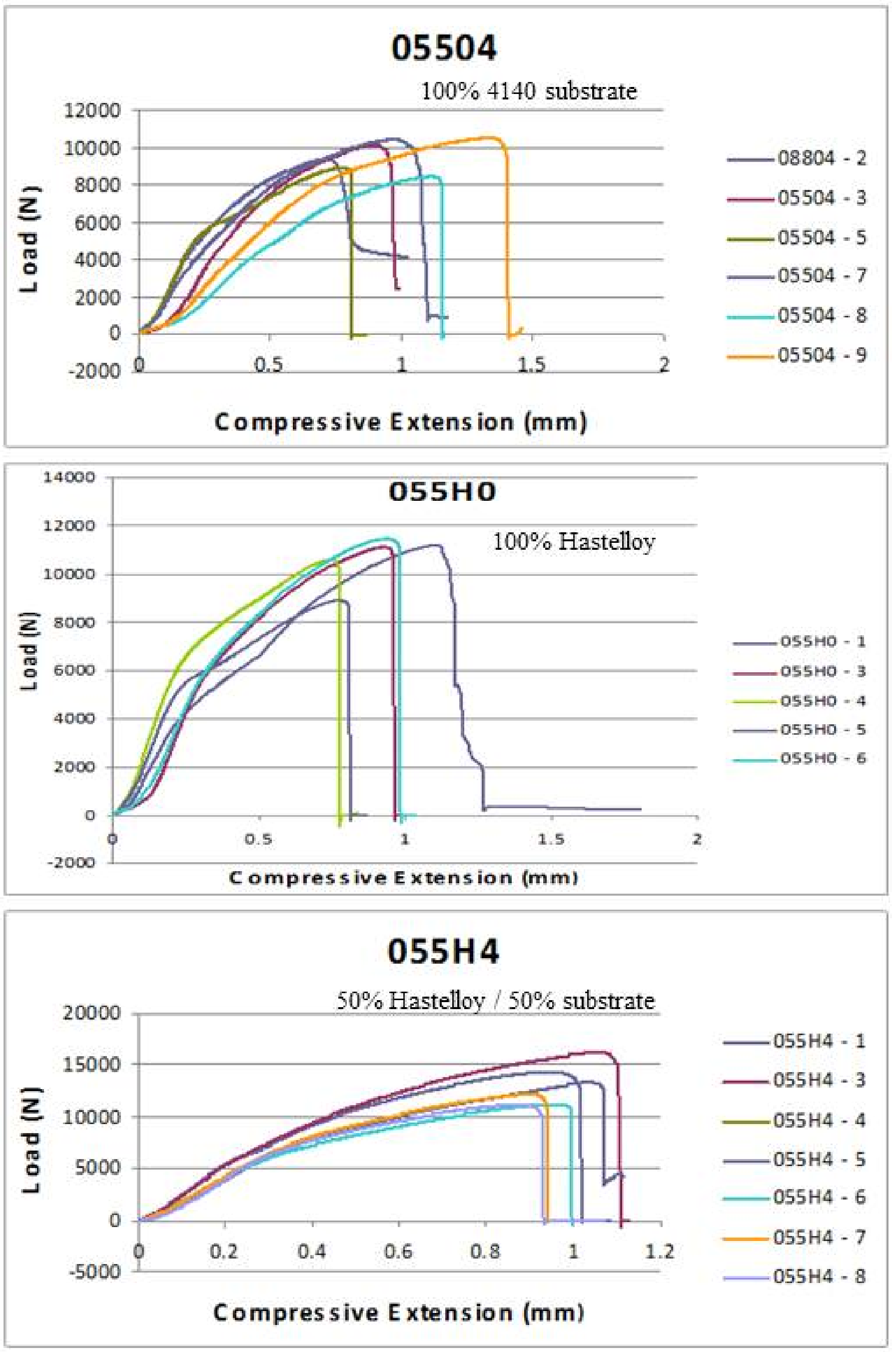


Figure 10: Graph of lap shear test results for Hastelloy deposit and substrate

Table 3: Tensile test results (averaged) for Hastelloy deposit

Material	Yield Stress (MPa)	Ultimate Tensile (MPa)	Elongation (%)
100% substrate	431.00	724.00	22
100% Hastelloy	661.00	908.00	16
50% / 50%	749.00	996.00	19

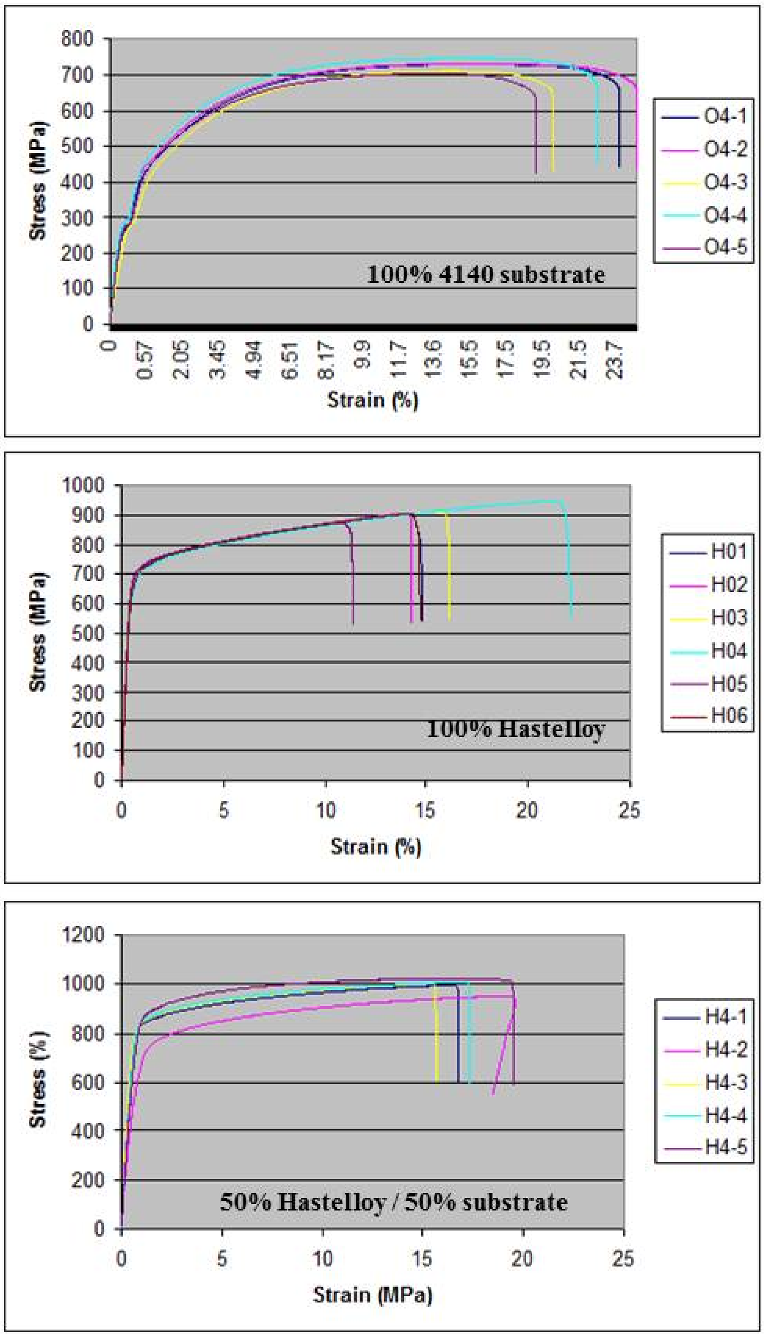


Figure 11: Graphs of tensile test results for Hastelloy deposit and substrate

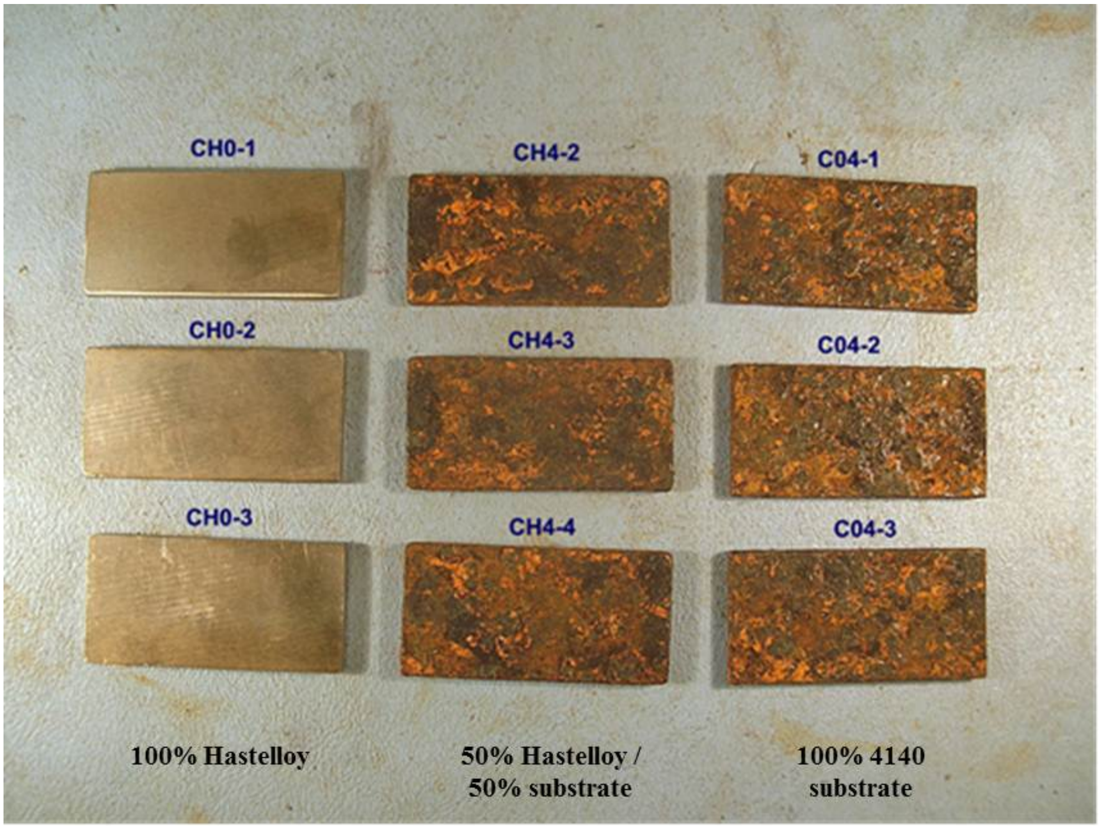


Figure 12: Samples after 168 hours salt spray corrosion test

Stellite 6 Deposit Mechanical Tests

- Specimen machining issue – Throughout the preparation of Stellite deposit/4140 steel substrate test specimens, the machinists found some machining processes of these bimetallic samples difficult with the in-process or final specimens exhibiting varying amounts of bending and distortion. Because of this issue with the side bend and tensile test specimens, those tests could not be completed.
- Side bend test – While a full set of test specimens was unavailable for side bend testing (see above), a small experiment comparing the bend performance of 50% Stellite/50% 4140 steel substrate with the deposit in the up or down fixture position was conducted. Figure 13 compares the resulting load/deflection curves. The specimen with the Stellite deposit facing downward in the 3-point test fixture, and thus in tension, was significantly weaker than the opposing orientation, which placed the deposit material in compression. This result clearly demonstrates the brittle nature of Stellite 6.
- Lap shear test - The averaged results of the lap shear tests are shown in Table 4 and the respective individual test load-deflection curves are shown in Figure 14. Both the 100% Stellite deposit and the 50% Stellite/50% substrate materials were significantly stronger than the 100% substrate material. Like the Hastelloy material, the metallurgically bonded material at the 50% Stellite deposit/50% substrate interface was stronger than the 100% Stellite deposit material, 19% in this case.
- Tensile test – Unavailable (see above). For reference. the standard material properties for Stellite 6 are: 897 MPa ultimate tensile strength with less than 1% elongation (from www.matweb.com)
- Corrosion test – Stellite material was not subjected to corrosion testing.

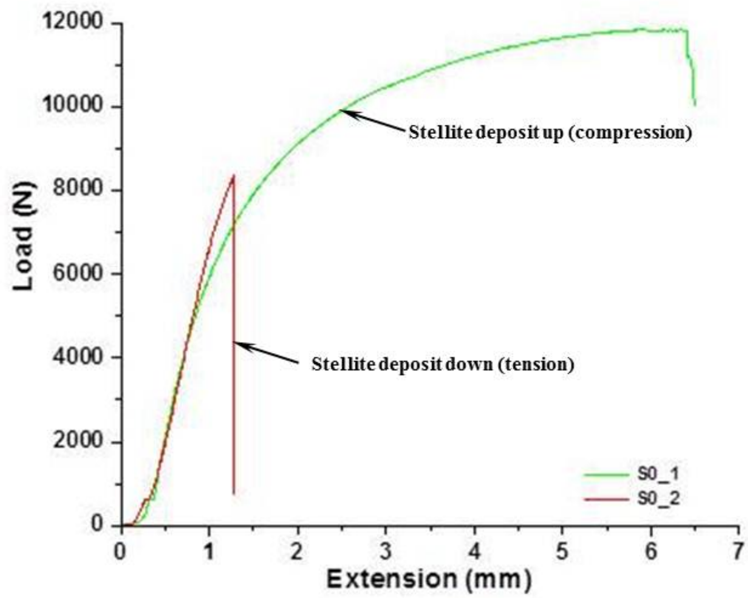


Figure 13 – Comparison of side bend test results for 50% Stellite/50% 4140 steel orientation

Table 4: Lap shear test results (averaged) for Stellite deposit

Material	Shear Yield Stress (MPa)
100% substrate	504
100% Stellite	1140
50% / 50%	1360

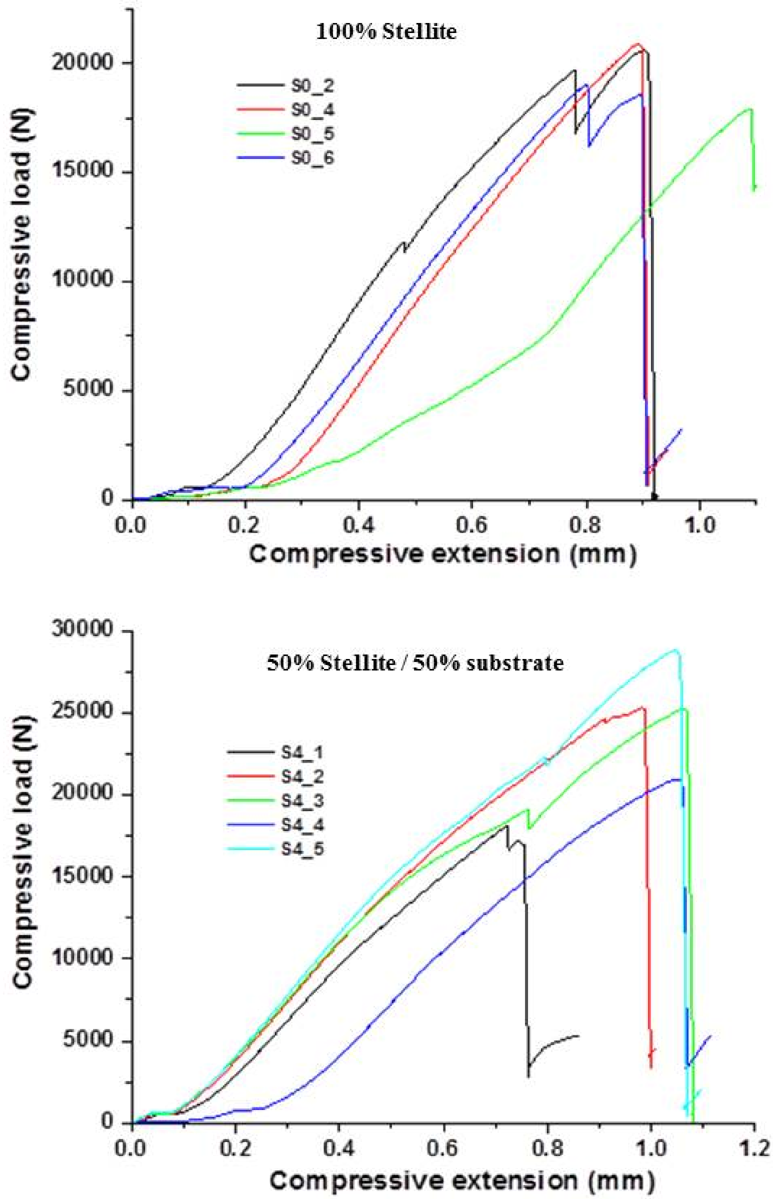


Figure 14: Graph of lap shear test results for Stellite deposit and substrate

4340 Steel Deposit Mechanical Tests

- Side bend test – Similar to the side bend testing of Stellite material, the bimetallic 4340 steel deposit/4140 steel substrate specimens were tested with the deposit facing up and down. The averaged results of these side bend tests are shown in Table 5 and the respective individual test load-deflection curves are shown in Figure 15. The specimens with the 4340 steel deposit facing downward in the 3-point test fixture, and thus in tension, were significantly weaker than the opposing orientation, which placed the deposit material in compression. This was an unexpected result because the two steels have similar ductility properties with the tensile % reduction of area being 56.9% and 50% for 4140 and 4340 respectively (from www.matweb.com). The specimen fracture points were inspected using a scanning electron microscope (SEM) and the views are shown in Figure 16. These photos show that the fracture surfaces are different and that a crack is present at the interface of the bimetallic interface of the two steel materials.
- Lap shear test - The averaged results of the lap shear tests are shown in Table 6 and the respective individual test load-deflection curves are shown in Figure 17. The 50% 4340 deposit/50% 4140 substrate material and the 100% 4140 substrate material were nearly equal and 28% weaker than the all-4340 deposit material.
- Tensile test – As described in the previous section, the tensile test specimens exhibited bending and distortion which affected their apparatus mounting and thus test results. Because of this issue, tensile testing of 4340 deposit specimens could not be completed.
- Corrosion test – 4340 steel material was not subjected to corrosion testing.

Table 5: Side bend test results (averaged) for 4340 steel deposit

Material	Fixture Extension @ Break (mm)	Maximum Flex Load (kN)	Calculated Angle (deg)
100% 4140 steel	13.54	8.09	91
100% 4340 steel	1.85	14.75	13
50%/50% 4340 ↓	2.96	9.48	21
50%/50% 4340 ↑	12.34	11.02	84

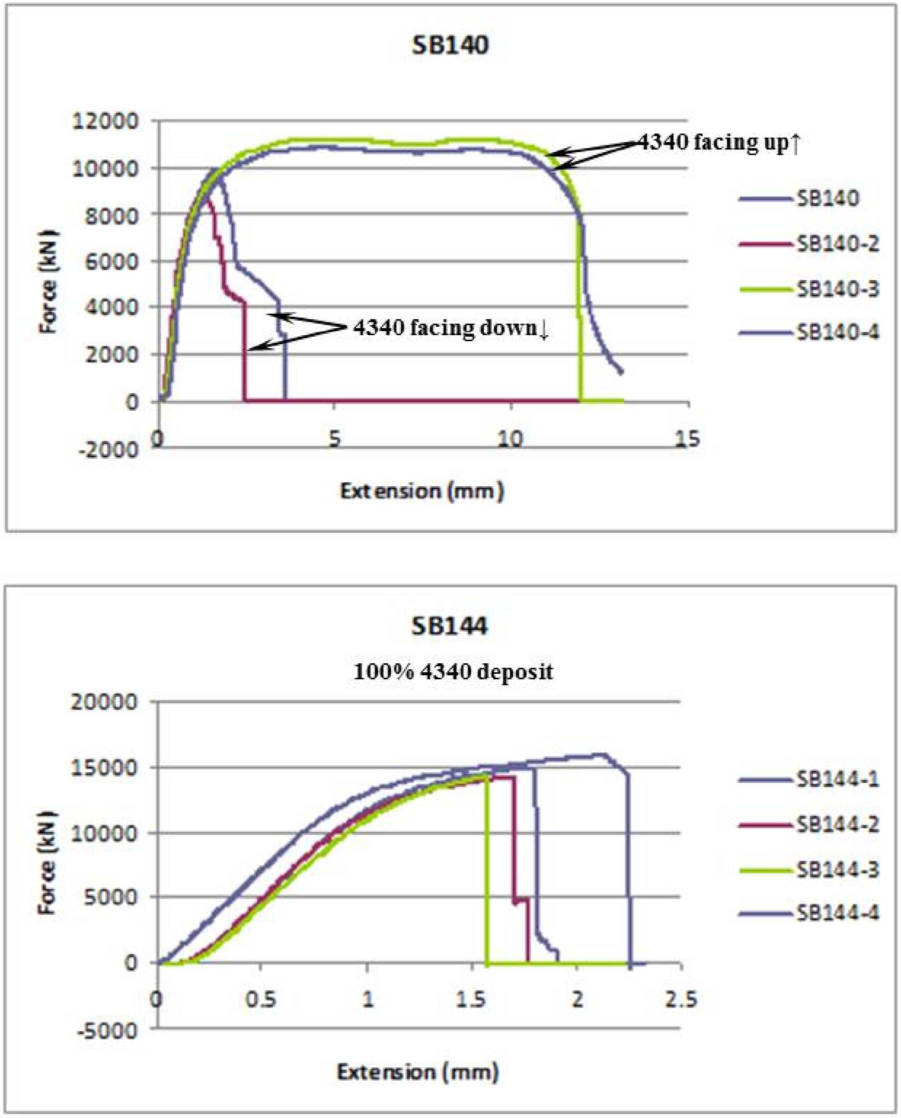


Figure 15: Graph of side bend test results for 4340 steel deposit and 4140 steel substrate

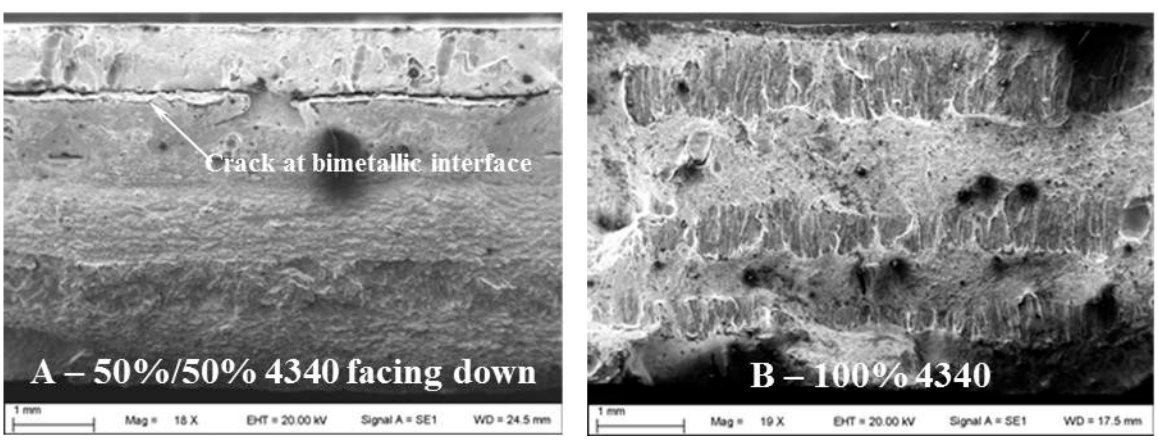


Figure 16: SEM view of side bend test fractures (4340 steel deposit)

Table 6: Lap shear test results (averaged) for 4340 steel deposit

Material	Shear Yield Stress (MPa)
100% 4140 substrate	504
100% 4340 deposit	694
50% / 50%	498

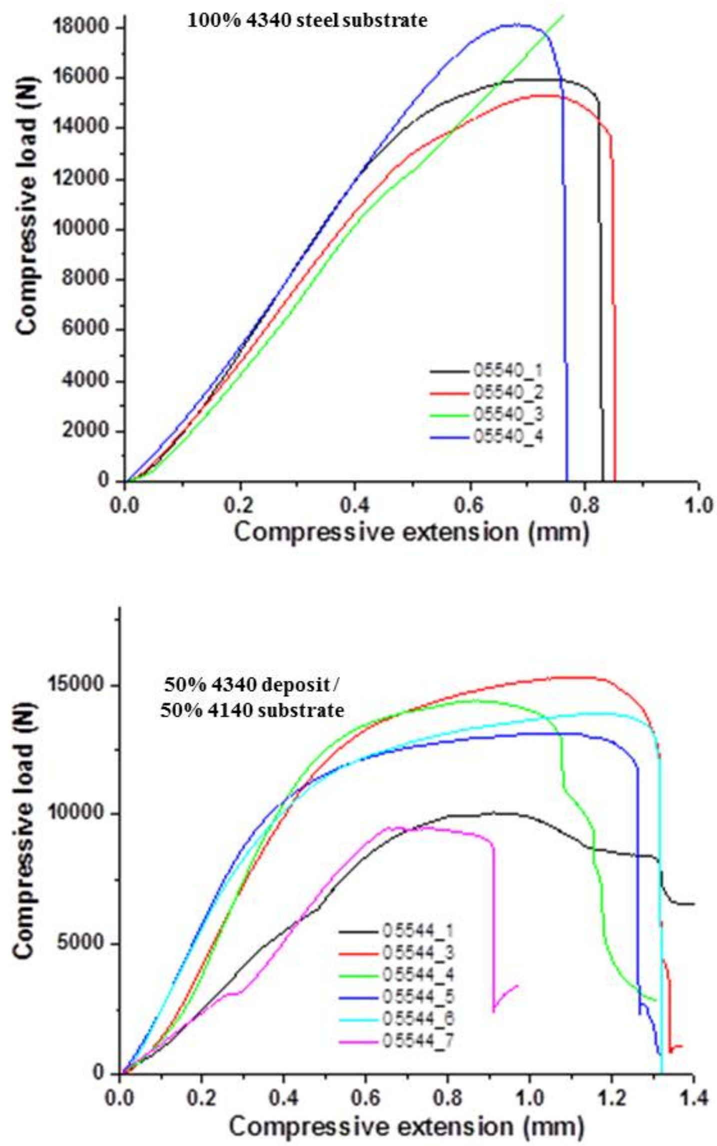


Figure 17: Graph of lap shear test results for 4340 steel deposit and 4140 steel substrate

DDM Repair Process Development

CTIS Spindle

The Central Tire Inflation System (CTIS) front spindle from the M939 heavy duty military truck was selected for repair using the DDM processes. The CTIS spindle is a hollow cylindrical part made of 4140 steel. Figure 18 includes a photograph of a damaged spindle before repair and an overall part design print indicating the commonly damaged area of these parts. The typical damage occurs on the outer bearing/sealing surface by pitting corrosion. Metallurgical analysis of the cross-section of the part was carried out to study the microstructure and hardness of the part. Metallurgical analysis revealed that the microstructure of the parts is tempered martensitic 4140 steel with the hardness varying from 25 HRC at the center of the wall to 30 HRC at the outer surface. Due to limited availability of original manufacturing design prints, a small lot of these parts were also reversed engineered to create a dimensional print of the relevant areas of the part. Since the common damage mode of this part was corrosion. The corrosion-resistant nickel-based super alloy Hastelloy C276 was selected as the DDM deposit material. Along with its high strength and wear resistance, this deposit material will provide the added benefit of extending the service life of these parts.

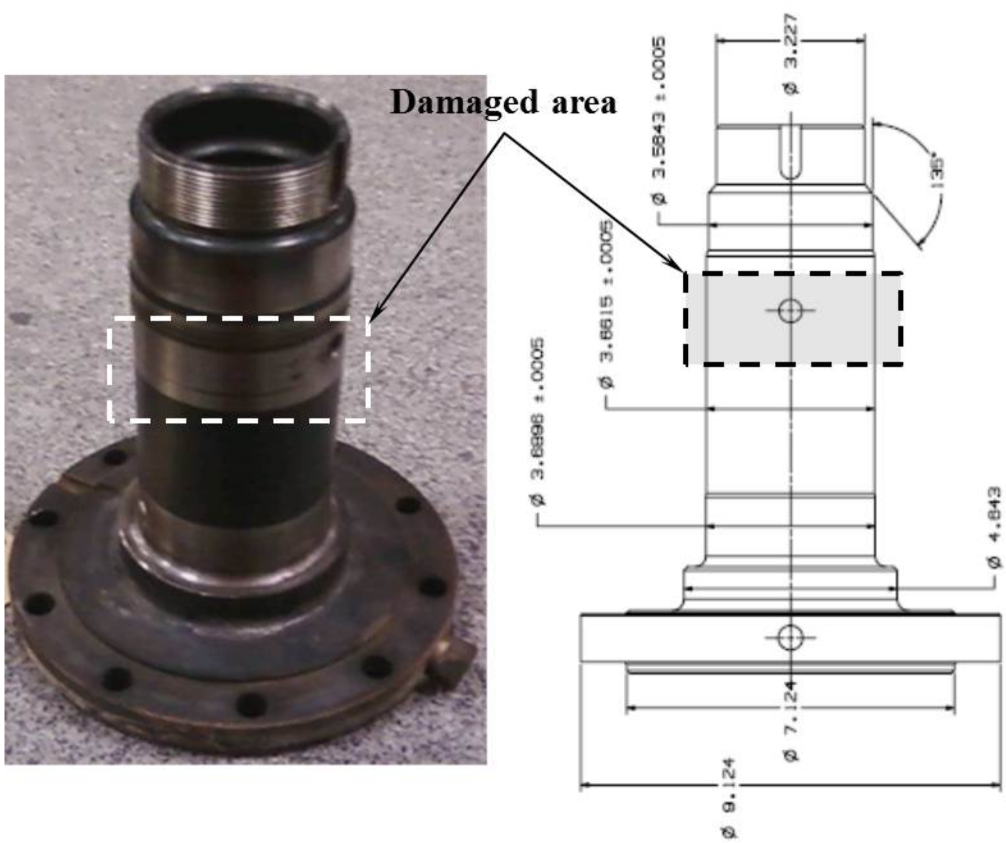


Figure 18: Photo and design print of corrosion-damaged CTIS truck spindle

DDM Remanufacturing Process for CTIS Spindle

The repair process that was developed is based on the scenario of receiving small lots of 100 pieces or less and includes pre and post inspections, damage removal machining, metal deposition, final machining to print, and preparing for shipment. The complete remanufacturing process that was developed for the CTIS spindle, and would also be applicable to similar rotational bearing/seal components, is as follows:

1. **Inspect the part**: Visually inspect the damaged part noting any noticeable defects (Figure 19-A).
2. **Baseline dimensioning**: Populate the pre-process inspection check sheet.
3. **Removal machining**: Using a Mazak 300 CNC machining center in a turning lathe configuration, remove the material from the damage area to a pre-determined diameter (Figure 19-B).
4. **Clean the part**: Visually inspect for inconsistencies, deburr, and thoroughly degrease and clean.
5. **Dye penetrant test #1**: After the cleaning operation, a standard liquid dye penetrant test is used. Once the surface is found to be free of major cracks and/or pores, DDM can start.
6. **Prepare the substrate material**: The surface of the DDM target area is sand-blasted. The part is then loaded onto the rotary axis of the DDM machine (Figure 20).
7. **Direct Deposition of Metal**: Using a pre-programmed tool path and DDM process parameters, the Hastelloy C276 is circumferentially deposited onto the prepared target surface in a layer-by-layer fashion (Figure 19-C).
8. **Final machining**: The part is loaded into a CNC machining center and the deposit surface is machined to final print dimensions including re-drilling the CTIS air hole.
9. **Dye penetrant test #2**: The completed part is dye penetrant tested again to ensure that it is free of flaws, cracks and pores (Figure 19-D).
10. **Final cleaning**: The part is completely cleaned and dried following the dye penetrant test.
11. **Final Inspection:** Populate the final inspection check sheet.
12. **Packaging**: Wrap the part in VCI paper and prepare for return shipping.

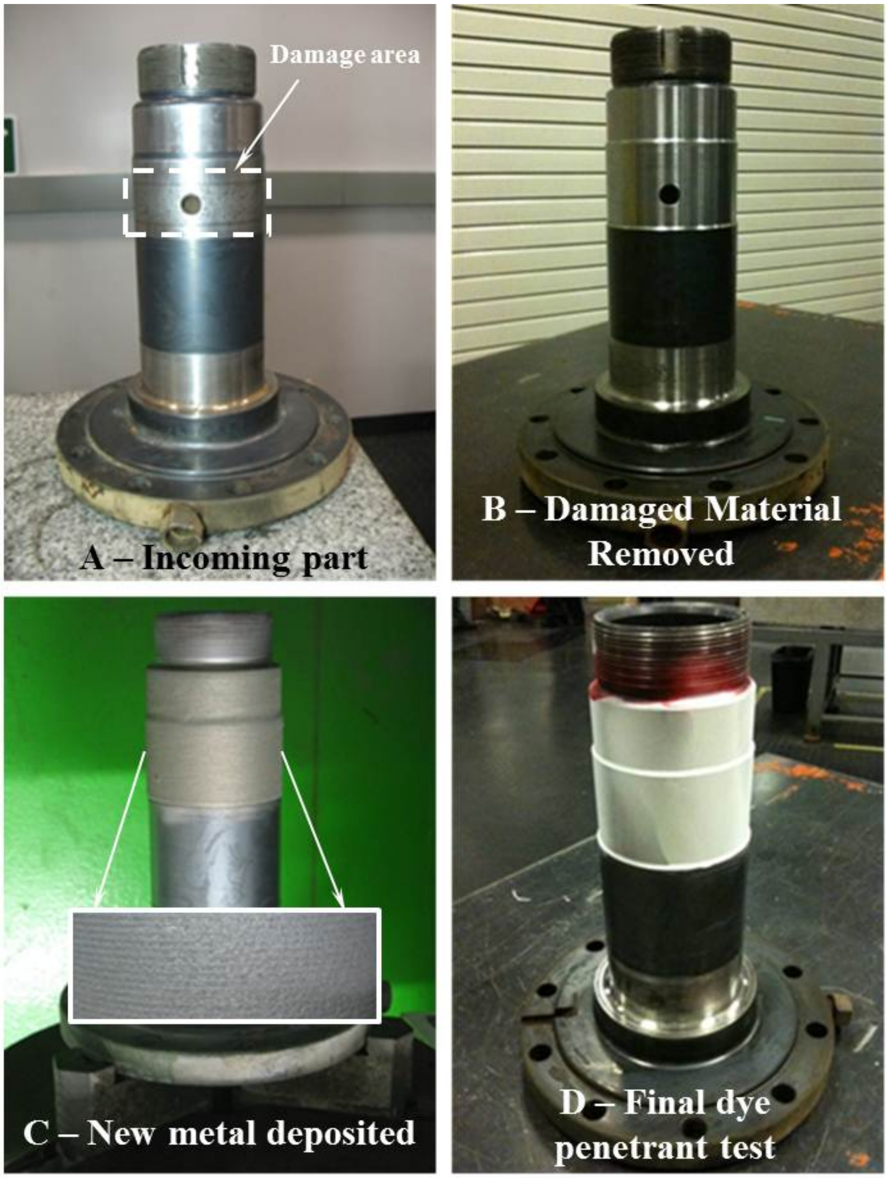


Figure 19: DDM repair process of M939 truck CTIS spindle

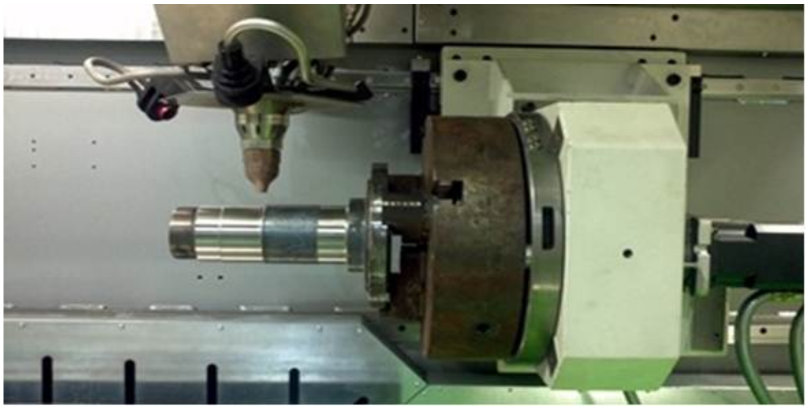
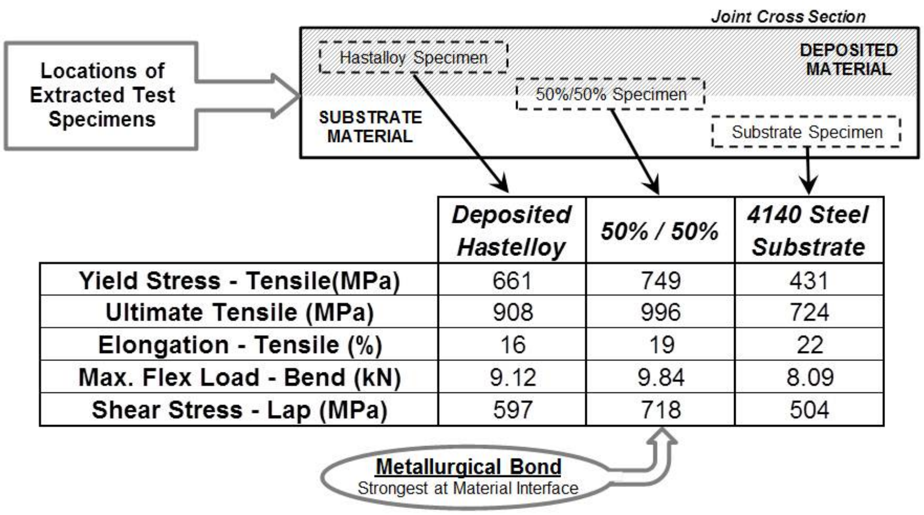


Figure 20: CTIS spindle loaded onto rotary axis of DDM machine

Important Findings and Conclusions

- The DDM is well suited to repair the surface damage on mechanical components and depending on the deposit/substrate material combination can provide a deposit to substrate bond that is greater than each of the separate metals (see Figure21). The different NSN components that were issued to us for investigation were of different geometries and required extensive studies and Statistical Process Control (SPC) to reverse engineer the components which were selected for investigation. Focus: HOPE designed, implemented, and fabricated fixtures to use our machinery for remanufacturing these parts to military standards. A limitation that we found for using DDM as a repair process of components requiring significant differences in material hardness and ductility, such as case hardening on medium steel castings, requires additional study. Funds were not available in this contract effort to develop the stress relieving processes which will be required to eliminate the cracking that appears when depositing material on case hardened surfaces.



	Deposited Hastelloy	50% / 50%	4140 Steel Substrate
Yield Stress - Tensile(MPa)	661	749	431
Ultimate Tensile (MPa)	908	996	724
Elongation - Tensile (%)	16	19	22
Max. Flex Load - Bend (kN)	9.12	9.84	8.09
Shear Stress - Lap (MPa)	597	718	504

Figure 21: Hastelloy DDM deposit metallurgical bond strength

- The DDM process is superior to the flame spray method (see Table 7). For mechanical repairs, the flame spray method provides a protective coating between grit blast and a sealing process. The DDM bond is a process of melting materials in a heating zone and accelerating them into a molten state onto a target to form a contiguous material blend from the initial substrate through alloy layer(s) to deposited material. The flame spray method is a coating whereas DDM application is a bonding.

Table 7: Comparison of DDM vs. Flame Spray

	Direct Metal Deposition[1]	Flame Spray[2]
Metallurgical Bond	Yes	No
Porosity	less than 0.2%	less than 10%
Tensile Strength	80-100% of base material	83 MPa[3]
Deposition Thickness (in.)	0.441 + (0.0315 x 14 layers)	0.002 - 0.25

[1] *FH-CAT testing and analysis*
[2] *Handbook of Thermal SprayTechnology, ASM International, 2004*
[3] *Limited by structural adhesive*

- The DDM process of laser cladding proves to be very effective for material build up. The weldability of metallurgically similar alloys is very high. The alloys that are easily welded are low carbon steel, nickel, titanium, and copper. Aluminum and cast iron alloys cannot be easily welded but altering the microstructure characteristic may be an alternative solution.

- Another advantage of DDM is the enhanced wear characteristics due to the fine microstructure capability of the process. The cladding layer produced from DDM yields very fine particulate structure with a complicated microstructure that increases the hardness and strength of the material. To achieve a different microstructure, a change in the process and parameter would adjust the microstructure. The very fine cast microstructure can sometimes result in reduced ductility which may be a limitation with the DDM process in some applications.

- DDM also provides the ability to solve corrosion issues. For repair applications, corrosion-damaged material can be metallurgically replaced with a similar non-corrosive alloy. For new production parts, a relatively low cost metal can be clad with a corrosion resistant alloy. This bimetallic method provides the ability of attaining part performance requirements with less costly corrosion prone materials but increase the corrosive life of the overall component by selectively applying corrosion material where needed.

- The life cycle cost of component parts can be reduced by implementing a DDM remanufacturing program. Based on seven Navy and Army system components that Focus: HOPE has successfully repaired throughout this contract, potential cost savings of DDM remanufactured parts could be 10-30% compared to new replacement parts.

Implications for Further Research

Direct Deposition of Metal (DDM) on Hard Surfaces and Alloy Castings

A cost effective process needs to be developed to permit effective performing DDM on materials having extreme differences in hardness between the core material and the surface such as spindles with very hard journal surfaces. DDM of these categories of parts is problematic. Since design specifications for legacy systems is seldom available, a process needs to be developed to estimate design specifications to ensure they can be replicated in DDM repaired components.

DDM of Aluminum

There are many possibilities for DDM fabrication with aluminum alloys and perhaps aluminum metal matrix composite materials

FSW Tool Manufacturing Methods

Related to another task of the current work directive, Friction Stir Welding (FSW) offers significant opportunities to manufacture light weight durable structures. However the high cost and manufacturing difficulty of tooling suitable for application to extremely hard materials such as titanium and high hard armor, limits the breadth at which FSW can be used in the production of military structures. A DDM process to apply ultra-hard material to the surface of a tungsten FSW tooling substrate may reduce FSW costs.

Special Comments

The state of the art Focus: HOPE Metallurgy Laboratory was actively used for analysis of the DDM samples produced throughout this project. The ability to quickly perform material analysis expedited the research undertaken and by exposing Focus: HOPE students to these analytical tools they obtain valuable experience.

The following lab capabilities were used for DDM analysis:

- The Instron Universal Tester is used for three types of tests in our lab. Tensile testing, lap sheer testing, and three-point bend testing. These tests allow us to collect data on the material properties under load of both DDM and FSW samples.

- The Micro Hardness tester is used to test the hardness of points on DDM and FSW samples. These tests can be of a single point, multiple points, or a grid of points taken over the entire surface of the sample. A multiple point test is preferred over a single point test, because the multiple point tests allows for more certainty in the accuracy of the tests, A grid test is typically used to develop a profile of the hardness across a specimen cross-section. This is important since the hardness of the DDM and FSW samples is not uniform.

- The Optical Microscope is used for visually inspecting samples. The microscope has a range of magnification from 50x-1000x. The microscope is equipped with a digital camera, and connected to a computer with specialized software that allows the processing of the microscopes images for useful data, like grain size, and porosity percentage.

- Grinder/Polisher is used for developing a polished sample. These samples are then used in the micro hardness tester, optical microscope, and scanning electron microscope.

- The Mounting Press A limitation of the Grinder/polisher is that samples must fit in one of two part holders. The primary part holder is configured for 1.25" round samples. The mounting press produces mounted samples in five minutes that fit this holder. The only other option currently available is to use epoxy to cold mount the samples, but this takes several hours.

- The Precision Saw and Abrasive Cutter are used to separate samples from a larger section. Currently the maximum sample size that can be polished in the grinder/polisher is slightly less than 2" in size since many samples are larger then this when brought to the lab some form of auxiliary cutting is often needed. The abrasive saw is used for sectioning when precision is not required and/or the donor sample is too large for the precision saw. The precision saw is limited to processing smaller samples, but does so with less loss of material, increased precision, and less surface deformation then the abrasive cutter.

- Zeiss Scanning Electron Microscope (SEM) is used for visual analysis of samples. It has a much greater maximum magnification and depth of field then the optical microscope. This allows for better viewing of samples with fine details and non planar surfaces. The SEM is also currently equipped with both an Energy Dispersive Spectroscopy (EDS), and Electron Back Scatter Diffraction (EBSD) detector. The EDS detector is used for elemental analysis of samples, and the EBSD detector allows examination of grain orientation.

Appendix A:
DMD 505 Machine Information

Figure A1: DMD 505 machine at Focus: HOPE Center for Advanced Technology

The POM DMD 505 machine is developed by POM Group based in Auburn Hills MI in collaboration with Trumpf Inc. The machine is designed to provide solutions for a multitude of material deposition tasks in the field of DDM application. The machine body is a torsion-resistant welded steel construction and designed for highest loads. The inherent rigidity of the machine body effectively prevents vibrations when changing directions.   The use of weight-optimized laser-welded machine components, coupled with maintenance-free, digital three-phase servo motors, ensures optimal machine dynamics at high precision. Five NC controlled axes for 2D and 3D machining are located in the "flying optics" assembly. All guide ways are designed for the highest precision and protected against contamination and laser reflections. This ensures excellent machining quality and unsurpassed long-term reliability of the machine. The machine has a built in Trumpf CO_2 laser. The laser beam delivery system is purged with purified compressed air to ensure system reliability and uptime. The CO_2 lasers are mounted on a steel bracket attached to the machine body, thereby guaranteeing stable alignment between beam source and machine tool. Water-cooled telescope and bending mirrors ensure reliable continuous machine operation. A mirror telescope provides for the best possible adaptation of the CO_2 lasers to the variable beam path lengths of the beam guidance machine. AutoLas Plus is a system for automatic focus adjustment and programmable focus position during laser cladding.
An alignment laser (pilot laser) of highest point stability is coupled into the beam guide way as a setup aid for the operator and for beam alignment. The laser beam is focused by means of copper mirror optics when cladding. The POM DMD SYSTEM is equipped with CO_2 lasers of the TRUMPF TLF series. TRUMPF TLF lasers are radio-frequency excited gas lasers. The laser power is infinitely adjustable. The excellent beam quality of the lasers ensures precise and dependable deposition results throughout the working range. The utilization of a radial turbine blower on magnetic bearings and an oil-free diaphragm vacuum pump reduces CO_2 laser maintenance to a minimum and ensures maximum availability. The integrated gas mixer unit

allows the use of conventional standard gases (helium, nitrogen, carbon dioxide) available on the market. The machine complies with the essential safety and health provisions as stipulated in EC Machinery Directive 98/37/EC and is delivered with “CE marking or a manufacturer's declaration. Besides other measures, this requires that the machine also be equipped with an enclosed safety cabin and a powerful extraction system.

Technical Data

Travel range of linear axis X, Y, Z	
X axis	2000 mm
Y axis	1000 mm
Z axis	750 mm
Movement of rotary axis B, C	
Swivel range of B axis	± 45°
Rotation range of C axis	± 190°
Swivel radius B axis	300 mm
Axis offset C/B-90° deflection	140 mm
Rotary A axis (optional)	
Rotation range of A axis	n x 360°
Table diameter (with bore and thread pattern)	400 mm
Payload	300 kg
Work diameter in horizontal orientation (default)	1000 mm
Work diameter in vertical orientation	500 mm
Axis travel speeds	
X direction	10 m/min
Y direction	10 m/min
Z direction	10 m/min
B axis	120°/sec
C axis	180°/sec
Machine accuracy *	
Smallest programmable increment	0.001 mm / 0.001°
Positioning accuracy (Pa)	0.08 mm/m, 0.015°
Repeatability (Ps)	0.04 mm/m / 0.005°

Work table

Table plate interface	2 pins for precise positioning of a fixture plate
Working height (support height) spacer)	300 mm, 500 mm (with
Repeating accuracy in X,Y,Z	± 0.10 mm
Travel speed	10 m/min
Payload (max.)	7000 kg
Laser power	5000 or 10,000 watts
Chiller - Standard water-to-air unit with closed Al and Cu primary circuit	Ambient temperature 10°-35° C (43° on request)

DMD Powder Feeder Unit

Powder feed rate	1 – 30 g / min
Deviation from nominal flow rate, constancy of powder stream	+/- 1% of preset value
Max. no. of integrated powder feeders	4
Powder grain size (Standard)	44 - 120 micron
Low density powder (Optional)	≥ 10 micron
Ability to generate graded structures by mixture of different powders structures)	given (multi material
Change over time of powder hoppers	20 sec (quick disconnects)
Flow rate of DMD process gas (Argon, Helium)	0 - 30 l/min (programmable)

DMD Optics and Nozzle

Focusing optics	water-cooled copper mirror 300 mm focal length
Nozzle build	coaxial powder delivery
Deposition rate - Iron-based alloys	20 cm³/h (1,00 inch³/h)
Powder efficiency	39 %
Max. inclination of DMD nozzle	± 45°
Adjustable beam spot size	Range #1:0.425mm – 2.3mm Range #2:2.3mm – 4.250mm
Concentricity through adjustment range	0.10mm

Closed loop feedback system

Type	Optical, 3 x CCD cameras
Wanted signal	3D layer geometry
Control variables	laser power, travel speed, powder feed rate

Data transmission network card

Ethernet adapter	10 Mbit/s
Supported network protocols	NetBeui, TCP/IP, Novell-Server NFS file system
BNC connection, max. cable length	170 m
RJ45 connection, max. cable length	100 m

Miscellaneous

Space requirements (D x W x H)	approx. 5m x 7m x 3,3 m
Total weight	see installation conditions
Electrical connection	230 / 400 V, 50 Hz (EU) 115 / 460 V, 60 Hz (US)

Appendix B:
4340 Steel Powder Specification

CARPENTER
Powder Products

Carpenter Powder Products Inc.
600 Mayer Street
Bridgeville, PA 15017

Phone 412.257.5102
Fax 412.257.5154

PRODUCT CERTIFICATION

WORK ORDER

LOT NUMBER
B3559

SALES ORDER / RLS
015646 / 1

SOLD TO

Focus: HOPE
Shipping & Receiving
1400 Oakman Blvd
Detroit, MI 48238
USA

Quality system of Carpenter Powder Products Inc. is registered in accordance to the quality system standards of ISO9001 and AS9100.

CUSTOMER P.O.	CUSTOMER PART	QUANTITY	LADING NO	SHIPMENT DATE
40185		100 Lbs	00021838	03/12/2009

CPP PART NUMBER: **2824103-0002**
Micro-Melt® 4340
CPP 4340 (-140+325M)

REMARKS

Chemical Analysis - Wt %

C	Mn	P	S	Si	Ni	Cr	Mo	Fe
0.43	0.75	0.017	0.009	0.18	1.90	1.0	0.46	Bal

Test Results

TEST	UNITS	RESULT
Mesh +140	w/o	1
Mesh -325	w/o	1

End of Certification

Inspection certificate EN 10204-3.1B. The requirements stipulated are fulfilled. The test report shall not be reproduced except in full, without the written approval of the laboratory. I certify that this is a true and correct copy of the tests shown on our laboratory records. The recording of false, fictitious or fraudulent statements or entries on this document may be punished as a felony under Federal statutes including Federal Law, Title 18, Chapter 47.

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Appendix C:
Stellite 6 Powder Specification

Page 1 of 2

Deloro Stellite

Deloro Stellite
1201 Eisenhower Drive N
Goshen, IN 46526 USA
Tel: 574-534-2585
Fax: 574-534-3417
www.Stellite.com

Material
Certified Report of Testing

Certification Date: 11/03/2011
Certification No.: 111103050
Sampling Date: 09/16/2011

Bill To: FOCUS HOPE
1400 OAKMAN BLVD

DETROIT, MI 48238
USA

Ship To: FOCUS HOPE
1400 OAKMAN BLVD

DETROIT, MI 48238
USA

Product Code: 510608D012
Alloy No.: 1060
Heat/Lot No.: 5110918-1
Stellite Order No.: 05110211-01
Customer PO No.: 11R&D000010

Product Description: Stellite 6
Customer Spec: SCD-W
Quantity Ordered: 60 lbs
Quantity Shipped: 60 lbs
Customer ID No.: 101525

Chemical Analysis

Element	Results	Units
ASTM E1019-08 by Combustion		
Carbon	1.2	%
Sulfur	0.004	%
Analytical Calculation		
TAO_Contents	0.10	%
ISO 14707:2000 - GD-OES		
Cr	28.4	%
Fe	1.8	%
Mn	0.4	%
Mo	0.1	%
Ni	2.0	%
P	0.003	%
Si	1.3	%
W	4.7	%
Analytical Calculation		
Material Balance	Co	

Sieve Analysis

Sieve Size	Results	Units
80 mesh / 180 µm	0	%
100 mesh / 150 µm	3.4	%
140 mesh / 106 µm	36.7	%
200 mesh / 75 µm	35.1	%
270 mesh / 53 µm	22.2	%
325 mesh / 45 µm	2.4	%
400 mesh / 38 µm	0.2	%
Pan	0	%

Physical Properties

Parameter	Results	Units
Apparent Density	4.5	g/cm³
Flow Rate	17	sec/50g
PTA Hardness test	46	HRC

Signed: Brad Belcher For and on behalf of Deloro Stellite.
Bradley S. Belcher, Acting Quality Manager

Reference: Stellite

Disclosure: All laboratory testing contained within this report has been performed within ASTM standards (B212, B213, B214, B215, E11, B922, B29, and E1019) or other commercially recognized standards and are traceable to NIST Standards where applicable. Certification in accordance with EN 10204:2004 Type 3.1. All results are actual measured values of either internal testing or certified external testing. Deloro Stellite uses the following Nadcap Certified Labs for External Chemistries; Sherry Labs (Cert # 122524), Dirats Labs (Cert # 117584) or NSL (Cert # 117439). External Lab Reports available on request. The test report shall not be reproduced except in full, without the written approval of the laboratory. NOTE: The recording of false, fictitious or fraudulent statements or entries on this document may be punishable as a felony under Federal Statutes.

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Revision 6/20/2011 GKM

Appendix D:
Hastelloy C276 Powder Specification

Deloro Stellite

Deloro Stellite
1201 Eisenhower Drive N
Goshen, IN 46526 USA
Tel: 574-534-2585
Fax: 574-534-3417
www.Stellite.com

Material
Certified Report of Testing

Certification Date: 11/15/2011
Certification No.: 111110067
Sampling Date: 11/10/2011

Bill To:	Ship To:
FOCUS HOPE 1400 OAKMAN BLVD DETROIT, MI 48238 USA	FOCUS HOPE 1400 OAKMAN BLVD DETROIT, MI 48238 USA

Product Code:	527608D005	**Product Description:**	Nistelle C-276
Alloy No.:	2760	**Customer Spec:**	SCD-W
Heat/Lot No.:	3111155-1	**Quantity Ordered:**	50 lbs
Stellite Order No.:	05110211-01	**Quantity Shipped:**	50 lbs
Customer PO No.:	44R&D000010	**Customer ID No.:**	101525

Chemical Analysis

Element	Results	Units
ASTM E1019-08 by Combustion		
Carbon	0.01	%
Sulfur	0.003	%
ISO 14707:2000 - GD-OES		
Co	0.1	%
Cr	15.4	%
Fe	5.7	%
Mn	0.7	%
Mo	15.7	%
P	0.008	%
Si	0.5	%
V	0.15	%
W	3.5	%
Analytical Calculation		
Material Balance	Ni	

Sieve Analysis

Sieve Size	Results	Units
80 mesh / 180 µm	0.0	%
100 mesh / 150 µm	3.2	%
140 mesh / 106 µm	21.7	%
200 mesh / 75 µm	30.9	%
270 mesh / 53 µm	34.5	%
325 mesh / 45 µm	9.1	%
400 mesh / 38 µm	0.6	%
Pan	0.0	%

Physical Properties

Parameter	Results	Units
Apparent Density	4.8	g/cm^3
Flow Rate	16	sec/50g
PTA Hardness test	90	HRB

Signed: Brad Belcher For and on behalf of Deloro Stellite.
Bradley S. Belcher, Acting Quality Manager

Reference: Stellite

Disclosure: All laboratory testing contained within this report has been performed within ASTM standards (B212, B213, B214, B215, E11, B822, E29, and E1019) or other commercially recognized standards and are traceable to NIST Standards where applicable. Certification in accordance with EN 10204:2004 Type 3.1. All results are actual measured values of either internal testing or certified external testing. Deloro Stellite uses the following Nadcap Certified Labs for External Chemistries; Sherry Labs (Cert # 122524), Dirats Labs (Cert # 117584) or NSL (Cert # 117439). External Lab Reports available on request. The test report shall not be reproduced except in full, without the written approval of the laboratory. NOTE: The recording of false, fictitious or fraudulent statements or entries on this document may be punishable as a felony under Federal Statutes.

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