AFRL-AFOSR-VA-TR-2019-0214

Acquisition of Advanced Cold Metal Transfer GMAW Robotic Additive Manufacturing System

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Final Report

Air Force Research Laboratory
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14. ABSTRACT
Under the DURIP Grant FA9550-17-1-0444, ‘Acquisition of a precision Fronius Cold Metal Transfer-Advanced, CMT-Advanced, Gas Metal Arc wire (GMAW) welding system’, PSU acquired and installed the system with integration of a Fronius CMT-Advanced unit with a Yaskawa Motoman 6-axis robot and a 2 axis coordinated positioner. The final report contains the system installation, performance, and further project plans with the system. The high deposition rate CMT-advanced system will contribute in the area of wire arc additive manufacturing with robotic control, and Cold Metal Transfer (CMT) additive manufacturing (AM). The sync-up with the existing Electrospark (ESD) (micro deposition rate) technology has been tested and the initial results posed mechanically and chemically stable multi-layered structures with localized property variation, which can be applied to multi-scale additive manufacturing applications.

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December 26th, 2018

Tae-Kyu Lee, PhD
Associate Professor
Department of Mechanical and Materials Engineering
Portland State University
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Dear Dr. Jaimie Tiley,

Thank you for your support on the DoD-AFOSR grant (FA9550-17-1-0444) ‘Acquisition of Advanced Cold Metal Transfer GMAW Robotic Additive Manufacturing System’. The attached final report contains the system installation, performance, and further project plans with the system. The high deposition rate CMT-advanced system will contribute in the area of wire arc additive manufacturing with robotic control, and Cold Metal Transfer (CMT) additive manufacturing (AM). The sync-up with the existing electrospark (ESD) (micro deposition rate) technology has been tested and the initial results posed mechanically and chemically stable multi-layered structures with localized property variation, which can be applied to multi-scale additive manufacturing applications.

Sincerely,

Tae-Kyu Lee

Acquisition of Advanced Cold Metal Transfer GMAW Robotic Additive Manufacturing System

Final Report

Tae-Kyu Lee (PI)
Associate Professor

William Wood and **Robert Turpin (co-PI)**
Professor and Senior staff researcher
Department of Mechanical and Materials Engineering
Portland State University

Air Force Office of Scientific Research (AFOSR)
DURIP Grant FA9550-17-1-0444
September 30th, 2017 – September 29th, 2018

Final update December 26th, 2018

Abstract

The attached final report contains the system installation, performance, and further project plans with the system. The high deposition rate CMT-advanced system will contribute in the area of wire arc additive manufacturing with robotic control, and Cold Metal Transfer (CMT) additive manufacturing (AM). The sync-up with the existing Electrospark (ESD) (micro deposition rate) technology has been tested and the initial results posed mechanically and chemically stable multi-layered structures with localized property variation, which can be applied to multi-scale additive manufacturing applications.

Executive Summary

Under the DURIP Grant FA9550-17-1-0444, 'Acquisition of a precision Fronius Cold Metal Transfer-Advanced, CMT-Advanced, Gas Metal Arc wire (GMAW) welding system', PSU acquired and installed the system with integration of a Fronius CMT-Advanced unit with a Yaskawa Motoman 6-axis robot and a 2 axis coordinated positioner. Successfully installed and tested, the system add an important high quality high deposition additive manufacturing (AM) capability to PSU's joining based AM capabilities and further will contribute the complementary AM capabilities supporting the DoD mission on advanced multi-scale and multi-layer AM structures and the U.S. industry competitive manufacturing technology base. The installed CMT-Advanced Wire based system transforms conventional wire based gas metal arc AM and combines highest quality deposition, precision arc control, spatter free, low heat input, microprocessor controlled deposition together with an integrated multi-axis robotic and multi axis coordinated positioner.

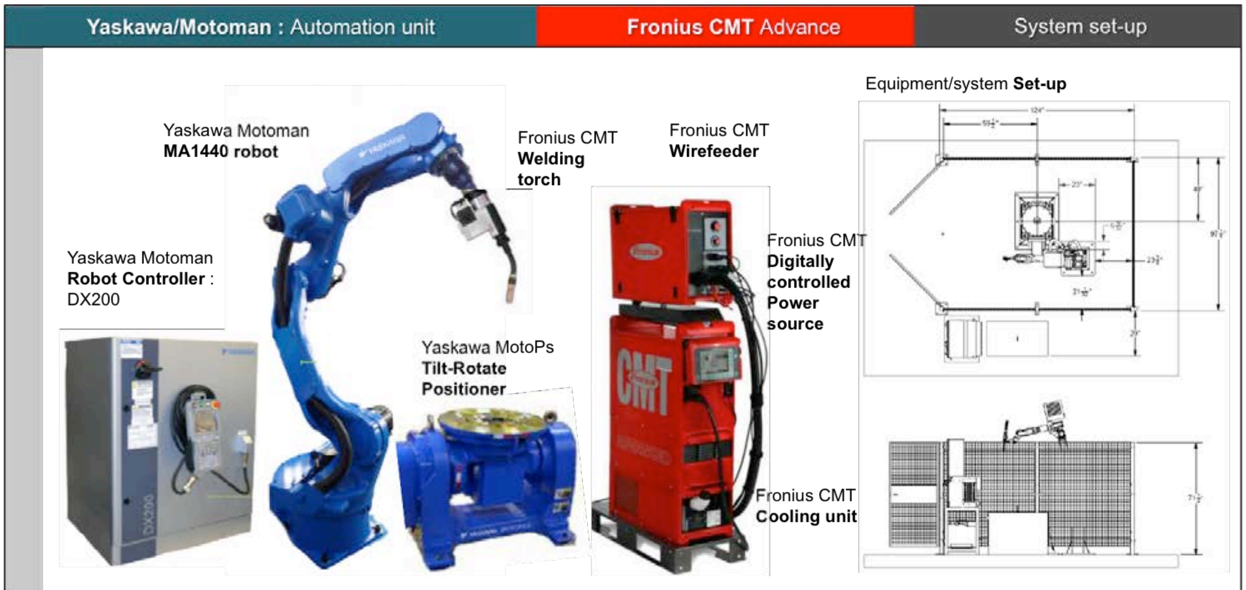
Addition to this system, PSU currently has existing low deposition rate micro-scale electrospark deposition (ESD) capability and comprehensive expertise in multi-layer deposition technology. Combining the high deposition rate AM capability and the interlayer modification capability using ESD, localized property variation was possible, which can be adapted to implement AM technologies in defense systems for both new and in-service repair for affordable life extension and high-level performance, process optimization and reliability enhancement.

Development of these technology items was performed along with the acquisition of the system and installation. The final report contains some of the initial test results, which will develop to further projects. Sync-up of multiple AM technology methodology including ESD and the installed CMT-Advanced system, will enable high productivity AM component design incorporating advanced materials science principles integrated into functionally designed and engineered multilayered alloy components. This will enable advanced structural repairs to and joining of near net shaped AM and conventional subassemblies.

System description

The acquired and installed system's, Fronius Cold Metal Transfer-Advanced (CMT-Advanced) robotic wire based system components are shown in Figure 1. The proposed and executed budget summary is attached in Appendix A. The system has two major system components: Automation/Robotic system (Yaskawa Motoman) and the CMT-advanced (Fronius) system. The Fronius system main components are the digitally controlled power supply, the

CMT wirefeeder, CMT welding torch with embedded servo-motor for precision wire feed control, and the CMT cooling unit. Gas shielding is integrated through the robot into the CMT torch. The Yaskawa Motoman robot motion controller controls both the Yaskawa Motoman MA 1440 robot and the MotoPs tilt-rotate positioner. The robot motion and coordinated positioner and the Fronius CMT-Advanced are controlled by a programmable single pendent.



Robot: Yasgawa Motoman MA1440 Robot and 2 axis positioner	Weld Package: Fronius CMT Advanced Package	Mechanical Hardware and Engineering Design: Robot riser/mounting, 2-axis positioner riser, controller skid	Electrical Hardware, controls and engineering design: Electrical/controls Cabinet, HMI, Power distribution, electrical engineering design and controls programming	Safety Hardware and engineering design: Perimeter safety fence, safety controller, RIA 15.06 safety compliance, design and safety programming	Installation assistance labor
$116,456	$54,052	$24,305	$11,470	$18,713	$3,680

Subtotal system : $228,676, Educational institution discount : $ (22,868) Total system : $205,808

Figure 1. Acquired System configuration

System delivery and set-up

The Yaskawa MA1440 unit, Yaskawa Tilt-rotate positioner and the Fronius CMT-Advanced unit were purchased and system integrated by Pre-Tec, a division of Willamette Valley Company (675 McKinley street, Eugene, OR). The Robot riser/mounting unit and 2 axis positioner riser was manufactured in PSU and delivered to Pre-Tec for the system integration. After integration, the whole completed system was delivered to the final location in PSU PEPCO building on September 26th. Figure 2 presents the PSU manufactured riser unit and the delivered mounted Yaskawa MA1440 robot and Tilt rotate positioner integrated with the Fronius CMT system.

Figure 2. Robot riser unit and mounted Yaskawa MA1440 robot with Tilt rotate positioner, integrated with the Fronius CMT system, delivered to PSU PEPCO lab (1927 SE Water ave, Portland, OR 97214), which is a local laboratory site specialized in Additive manufacturing and macro-joining facility near PSU main campus. (Figure 3) The Material Research laboratory have three locations; Ondine lab for Metallography and mechanical testing, Advanced material and manufacturing research lab for thermal and reliability testing, and the PEPCO lab.

Figure 3. Location map of the PEPCO lab. The Material Research laboratory have three locations; Ondine lab, Advanced material and manufacturing research lab, and PEPCO lab.

Installation and Unit test

As shown in Figure 4, the system was installed in the PEPCO building with the safety fence and welding ray protection shield film. System check-up by Pre-Tec engineers was performed with re-assembling and connecting the Yaskawa control unit and Fronius power supply with the wire feeding system. Each unit is indicated in Figure 5.

Figure 4. Safety fence and acquired system final configuration in PEPCO lab.

Figure 5. Completed system set-up after installation and test run.

The control unit for the Yaskawa MA1440 and the Fronius CMT-Advanced power supply and wire feeding system is shown in Figure 6. Addition to the listed system, a Universal sensor unit was installed to the Yaskawa Robot MA1440 for position control and a Fluke IR imager (Ti300) was purchased for temperature measurement and control feed during CMT multi-layer deposition. After installation, the system went through the test run and all system features were tested with a 308 stainless steel wire (1.2mm diameter wire) on a 308 stainless steel substrate.

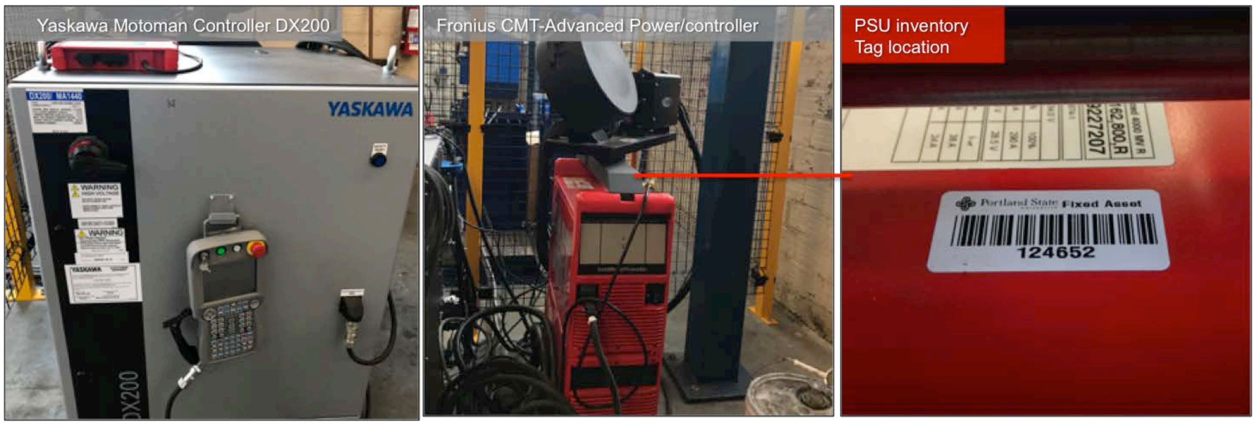


Figure 6. Control unit for the Yaskawa MA1440 and the Fronius CMT-Advanced power supply and wire feeding system. PSU inventory tag is placed on the Fronius Power supply unit.

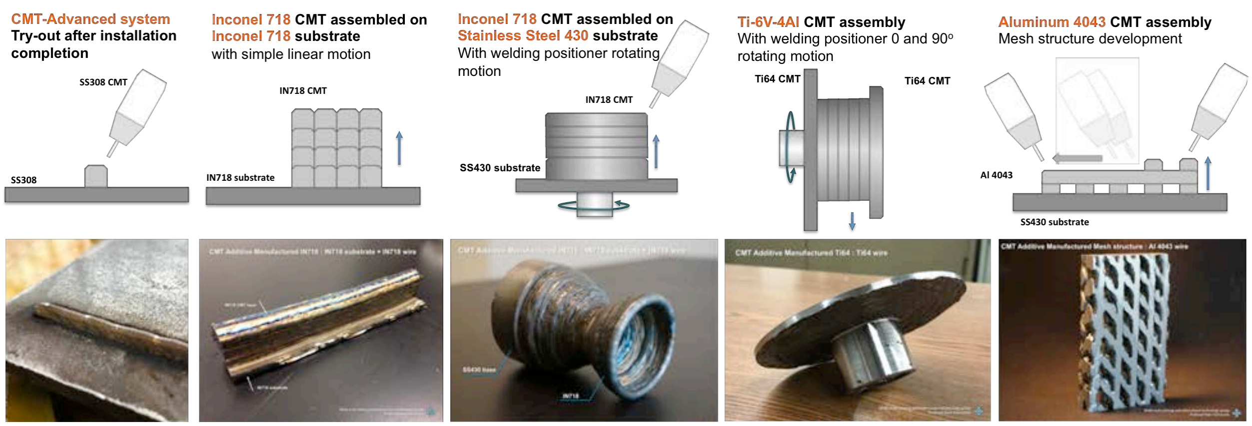


Figure 7. CMT test build-up structures. From right to left, CMT-Advanced try-out, Inconel 718 CMT with simple stack-up, Inconel 718 on Ferritic Stainless steel 430 with turn-table positioner. Ti64 with 90degree tilt rotation, and mesh structure build with Aluminum 4043.

The test deposition layer was clean and as expected using the Fronius pre-program for CMT-Advance unit. The mono-layer deposition can be seen in Figure 7, on the right subset picture. Since the system delivery and installation was completed late September 2018, a parallel development using the existing CMT (First generation) was performed during the year 2018 on multi-layer deposition AM. Figure 7 shows the examples of the initial process developments including Inconel 718, Ferritic Stainless steel 430, Ti-6V-4Al and Aluminum 4043 high deposition rate AM. These process try-outs are targeting to optimize the CMT process parameters, which will be used in the CMT-Advanced process. As presented in Figure 7, simple stack-up process and build-up with turn table positioner were performed to optimize the interface stability, which was analyzed with Electro backscattered diffraction (EBSD) and mechanical testing.

Localized property tuning using Electro spark deposition (ESD) and CMT integration

As stated in the submitted DURIP Grant proposal, the core research and applied development goals that acquisition of the equipment enabled, are to establish at the fundamental level, the evolution of multi-pass, multi-layered complex microstructures in advanced alloy systems and the relationships between process parameters, electrode chemistry, and resulting structure. Knowing these parameters and items will allow multi-directional application by combining existing AM technologies. One of the goals is to integrate CMT-advance and electrospark deposition (ESD), CMT as a building process and ESD as an interface modifier.

Cold metal transfer (CMT) is a short circuit process, in which droplets detach from the wire in a new way. In the conventional short-circuit process, the wire advances until a short circuit occurs. At this moment the welding current rises, which allows the short circuit to open and ignite the arc again. In CMT, the torch's servomotor wire drive mechanism momentarily retracts the electrode wire during each cycle. This subtle retraction, forward and back wire motion, provides the foundation for precision arc control and reduced heat input. In CMT, high current is not responsible for opening the short and initiating molten droplet transfer. Instead, the electrode retraction initiates molten drop transfer. Surface tension holds the molten droplet onto the end of the wire. Therefore, current and heat input are extremely low during the short circuit. Figure 8 shows the major difference between First generation CMT and CMT advanced system.

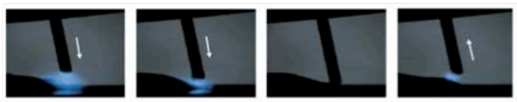
CMT Process First Generation	**CMT Advanced Process** System awarded by DoD-DURIP
- **Wire movement** incorporated into process control - Controlled, **low heat** input - Stable arc - High **welding speed** - Designed for **hand-held application** - **Not adaptable** for robot deposition system - **Initial data** generated using this system	- **Polarity of the welding current** incorporated into process control - **Polarity reversal** takes place in the short-circuit phase - Allows a more **precisely controlled heat input** - Extremely high gap-bridging-ability due to an **increased deposition rate** - Developed For **Additive manufacturing** process
 Wire movement	 CMT negative Initialisation and CMT positive
- PSU has **in-depth experience in the CMT additive layer build process** including per pass thermal history analysis, dilution and layer height optimization - PSU is equipped with **the first generation CMT**, with a manual torch configured for single axis constant speed motion - Most CMT publications are **based on this first generation** process	- **Awarded system** with advanced microprocessor controlled power source - Multi axis robot and coordinated 2 axis position coupled **with CMT-Advanced** provides the **highest level advanced GMA wire based AM in a U.S. university**

Figure 8. Comparison between CMT first generation and the installed CMT-Advanced system.

Due to the open surface and space configuration during CMT process, additional AM methods can be applied simultaneously. This provides the opportunity to modify the surface in between each additive manufactured layer during the CMT process, which enables the potential Mechanical property to be modified during the process simultaneously. One of the surface modifiers can be implemented via Electro spark deposition (ESD). Per processing pass, ESD deposits are on the order of 10-15μm thick and 2mm wide. The target deposition material can be easily changed by switching the electrodes in ESD. Figure 9 shows the ESD system set-up in PSU.

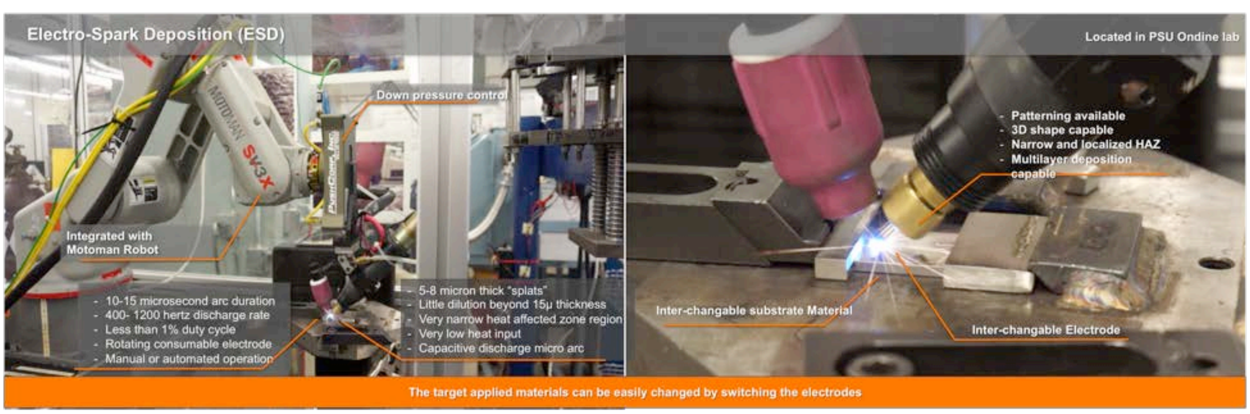


Figure 9. Electro Spark Deposition system (ESD)

The integration of CMT and ESD can be directly applied to legacy and Additive manufactured component repair. Powder-base AM components contains a higher risk of localized defects during the long processing time. A repair procedure for localized defects will be crucial. Simply adding additional material will further mask defects, where CMT-Advanced and ESD each can be used for local repair. In addition for local repairs requiring exacting repair interface and HAZ restrictions, initial AM repair layers using ESD can be used followed by CMT for repair productivity. ESD AM HAZ depth can be as small as 10µm for HAZ sensitive substrates. ESD buildup followed by CMT-Advanced can result in an engineered repair maximizing properties and productivity. Importantly, both AM technologies can also be applied manually, are portable and can be field applied. Figure 10 schematically shows schematically the application of sync-up process, an ESD layer deposition then CMT, to engineer interface repair sites. To enable this concept a series of experiments were performed along with the equipment system acquire and installation. Figure 11, is an initial result of an Aluminum 4043 CMT AM structure with Mg interlayer deposition via ESD process. The outcome structure of this process is an Al4043+1%Mg alloy structure, which can mechanically perform similar to Al4943 alloy. Experiments are in progress on Al-Mg alloy CMT and Mg alloy structures, which already demonstrate a significant mechanical performance enhancement with this CMT+ESD integration. A proposal containing this topic is under preparation for further investigation in this area.

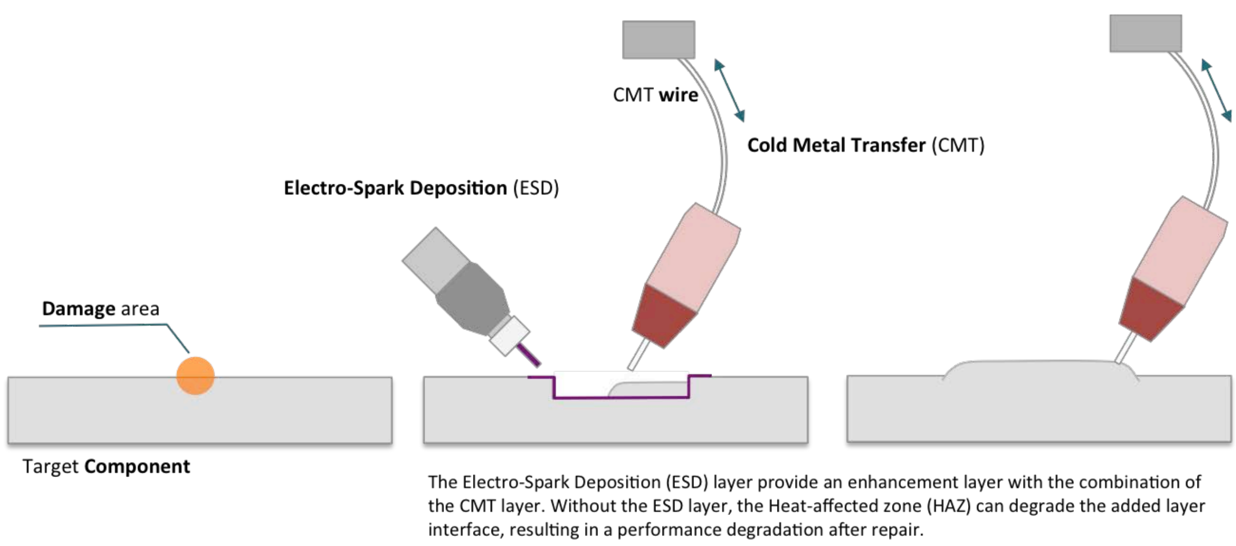


Figure 10. Combination of ESD and CMT for defect repair

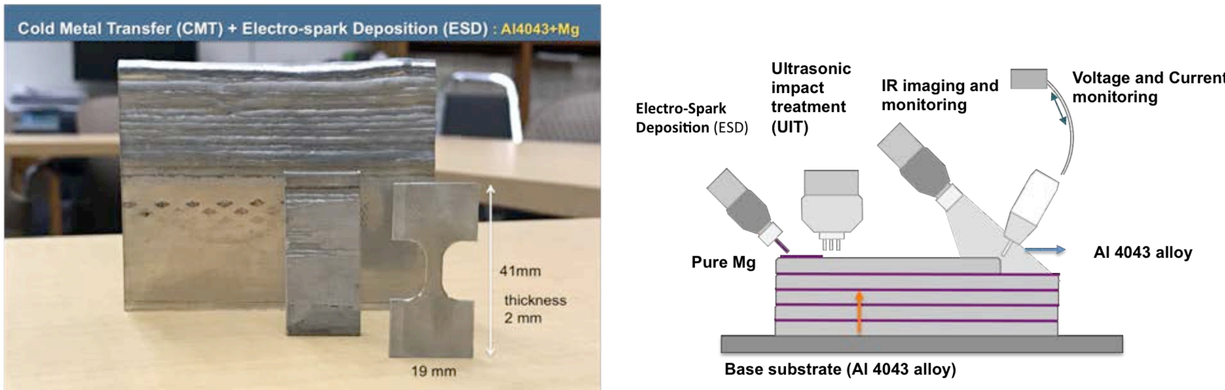


Figure 11. Aluminum 4043 CMT multi-layer structure with Mg ESD interlayer deposition

Conclusion

With the important and crucial support from the AFOSR, the precision Cold Metal Transfer-Advanced, CMT-Advanced, Gas Metal Arc wire (GMAW) welding system is acquired, installed and tested succesfully. This final report explains the system installation, performance, and further project plans with the system. The high deposition rate CMT-advanced system will contribute in the area of wire arc additive manufacturing with robotic control, and Cold Metal Transfer (CMT) additive manufacturing (AM). The sync-up with the existing electrospark (ESD) (micro deposition rate) technology has been tested and the initial results posed mechanically and chemically stable multi-layered structures with localized property variation, which can be applied to multi-scale additive manufacturing applications. Further development using this equipment and system will resulting in identification of fundamental mechanism and experimental validation, integration of various AM processes, and will bring significant intellectual benefit to greatly expanded AM and advanced joining research. This will made possible for further applications to researchers in University, DoD and industry.

Appendix A

PRETEC

675 McKinley Street, Eugene, OR 97402
(541) 484.2368 - (800) 205.9826
www.pre-tec.com

BUDGETARY AUTOMATION PROPOSAL — **NO. A160707MB-RB2** — **7/07/2016**

CUSTOMER NAME:	Portland State University	PHONE NUMBER:	(503) 725-2984
CONTACTS:	William Wood	EMAIL ADDRESS:	woodw@cecs.pdx.edu
ADDRESS:	520 SW Hall Street		
CITY/ST/ZIP:	Portland, OR 97207		
SHIPPING ADDRESS:	SAME	FREIGHT:	FOB Eugene, OR

Additive Machining Development Cell

Item	Description	Each	QTY	Selling Price
1	**Robot: Yaskawa Motoman MA1440 Robot & 2 Axis Positioner** See Enclosed Yaskawa Product Information	$ 116,456	1	$ 116,456
2	**Weld Package: Fronius CMT Advanced Package**	$ 54,052	1	$ 54,052
3	**Mechanical Hardware and Engineering Design** Robot Riser / Mounting, 2-Axis Positioner Riser, Controller Skid	$ 24,305	1	$ 24,305
4	**Electrical Hardware, Controls and Engineering Design** Electrical/Controls Cabinet, HMI, Power Distribution, Electrical Engineering Design & Controls Programming	$ 11,470	1	$ 11,470
5	**Safety Hardware and Engineering Design** Perimeter Safety Fence, Safety Controller, RIA 15.06 Safety Compliance, Design and Safety Programming	$ 18,713	1	$ 18,713
6	**Process Development & Integration** Integratation of the Controls Package, Material Handling Harware, Robot Motion with Process Parameter Development, Programming, System Testing and FAT Labor	N/A	0	N/A
7	**Installation Assistance Labor (Estimate):** (2) technicians ((2) Days Planned)	$ 1,840	2	$ 3,680
	Subtotal System			$ 228,676

Item	Additional Items	Each	QTY	Selling Price
8	**Educational Institution Discount, 10%**	$ (22,868)	1	$ (22,868)
9				$ -
	Total System Investment with Options			$ 205,808

Notes

- Terms: **30%** with PO / **30%** after Design Review, upon receipt of invoice / **30%** After FAT, prior to Shipping / **10%** Due Net 30 Days after date of Installation.
- Delivery of the Systems is estimated at **12-14** weeks, after receipt of a purchase order and down payment.
- Delivery dates are subject to backlog and will be established after acceptance of purchase order.
- Prices indicated are estimates based on the information provided to date.
- Specification details need to be mutually agreed to before work on the project commences.
- Modification to the project scope may result in a new Quote, or are subject to Engineering Change Orders.
- The quote is valid for **45** days from the date indicated.
- A separate PO is required for PRE-TEC personnel to be onsite assisting with equipment installation.

Thank you for the opportunity to quote.

Rufus Burton
Sales Manager

A Division of Willamette Valley Company