ORNL/TM-2019/1083
CRADA/NFE-17-06826

# Electrochemical Machining Technology for Surface Improvements of Ni-base Superalloy Additively Manufactured Components


Michael Kirka
Daniel Herrington

CRADA FINAL REPORT
NFE-17-06826

**January 4, 2019**

Approved for Public Release.
Distribution is Unlimited.

OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE US DEPARTMENT OF ENERGY

**ORNL/TM-2019/1083**
**CRADA/NFE-17-06826**

Materials Science and Technology Division
Manufacturing Demonstration Facility

# Electrochemical Machining Technology for Surface Improvements of Ni-base Superalloy Additive Manufactured Components

Michael Kirka (ORNL)
Daniel Herrington (Voxel)

Date Published:
January 4, 2019

Prepared by
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, TN 37831-6283
managed by
UT-BATTELLE, LLC
for the
US DEPARTMENT OF ENERGY
under contract DE-AC05-00OR22725

## CONTENTS

# ACKNOWLEDGEMENTS

This CRADA NFE-17-06826 was conducted as a Technical Collaboration project within the Oak Ridge National Laboratory (ORNL) Manufacturing Demonstration Facility (MDF) sponsored by the US Department of Energy Advanced Manufacturing Office (CPS Agreement Number 24761). Opportunities for MDF technical collaborations are listed in the announcement "Manufacturing Demonstration Facility Technology Collaborations for US Manufacturers in Advanced Manufacturing and Materials Technologies" posted at http://web.ornl.gov/sci/manufacturing/docs/FBO-ORNL-MDF-2013-2.pdf. The goal of technical collaborations is to engage industry partners to participate in short-term, collaborative projects within the Manufacturing Demonstration Facility (MDF) to assess applicability and of new energy efficient manufacturing technologies. Research sponsored by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Advanced Manufacturing Office, under contract DE-AC05-00OR22725 with UT-Battelle, LLC.

## ABSTRACT

Additive Manufacturing's (AM) promise and potential is of growing interest to US industries such as the energy sector. However, to move AM from prototyping to full-scale production a number of key risk areas must still be overcome, particularly the enhancing the surface finish of AM parts. Due to the industry's desire for components fabricated from difficult to machine alloys and highly complex geometries, advanced finishing technologies are needed. This project focused on the ability to enhance the surface finish of material from the crack prone Ni-base superalloy Inconel 738 fabricated using the Arcam electron beam melting (EBM) process using the Pulsed Electrochemical Machining (PECM) process for surface enhancements. To evaluate the suitability of the PECM process, several artifacts were experimented with, each of which had increasing levels of complexity and relevancy to the industrial gas turbine sector. Ultimately, it was shown that the finish of as-built relevant EBM gas turbine airfoil surfaces could be enhanced by an average of 4x to approach an average roughness of a surface (Ra) equivalent of 1 um.


## 1. ELECTRON BEAM MELTING BUILDS

This phase 2 technical collaboration project (MDF-TC-2017-39) was begun on July 5, 2017 and was completed on September 30, 2018. The collaboration partner Voxel Innovations is a small business. Based on this project, the team of Oak Ridge National Lab and Voxel Innovations has demonstrated that Pulsed Electrochemical Machining is a valuable finishing process for electron beam melting produced parts

For surface finishing trials, four types of geometries and build layouts, that each exhibited increasing levels of complexity from a surface finishing standpoint and move towards realistic airfoil topology were utilized. All builds were fabricated using the electron beam melting (EBM) process, from the traditionally non-weldable Ni-base superalloy Inconel 738. Inconel 738 is a material of high interest due to its ability to be used in the prototyping of high value, critical rotating components. In all instances, a Arcam Q10+ system was utilized for the build fabrication.

### 1.1 ARTIFACTS

For initial process development, cubic artifacts were fabricated with differing contour parameters, to yield different levels of surface roughness. The intent being to use the cubes as both the cathode and anode in the PECM process. With the open question to be addressed, to what degree does the additively manufactured cathode pass its roughness into the anode, and to what extent can this be mitigated electrochemically. The layout of the cubic artifacts printed are shown in Figure 1.

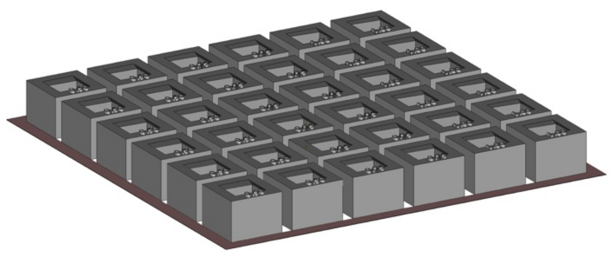

*Figure 1:Cube artifacts fabricated using the Arcam process from Inconel 738.*

## 1.2 AIRFOIL ARTIFACTS

Illustrated in Figure 2 are airfoil artifacts designed to capture features relevant to airfoils of interest, i.e. curvature of the low and high pressure faces and the critical high stress platform to airfoil transition, and airfoil to shroud transition. Additionally, blades representing the geometry of interest to an industrial partner for a gas turbine engine demonstration test were fabricated for trial finishing through the PECM process.

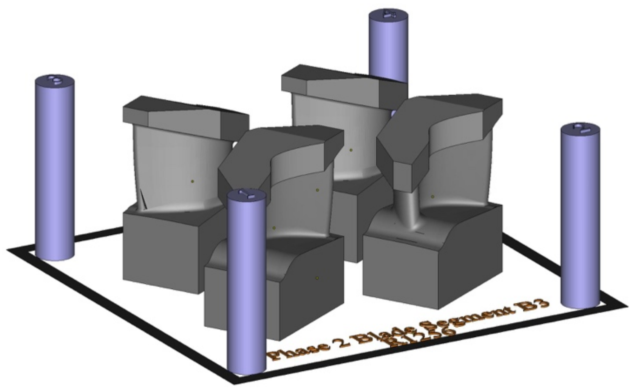


*Figure 2: Airfoil artifact layout fabricated from Inconel 738 for experimenting with the PECM process.*

# 2. PULSED ELECTROCHEMICAL MACHINING

The Pulsed Electrochemical Machining (PECM) process uses electrolysis to dissolve metal materials by creating an electrode in the inverse shape of the desired part. By maintaining a small gap between the electrode and the desired workpiece, PECM uses the localization of current density to copy the electrode shape into the end part in a non-contact operation.

## 2.1 PECM PROCESS DEVELOPMENT

The PECM process development was focused on three key areas: electrolyte type, pulsed power parameters, and cathode/fixture geometry. Given the chemical make-up of Inconel 738, Voxel was able to use its standard electrolyte solution of a neutral pH salt electrolyte. Therefore, Voxel was able to validate that a known electrolyte solution produced acceptable results and did not have to tune any electrolyte parameters. During early tests, Voxel recognized that the pulse parameters could have a significant effect the naturally occurring nickel-oxide layer and that effective removal is necessary to ensure quality surface finishes in this material. Furthermore, the pulse parameters were shown to have a significant effect on the removal of as-printed build lines inherent in the AM process. By adjusting the pulse parameters, Voxel could tune the process to remove either the macro roughness or the micro roughness. Finally, multiple cathode shapes and flow fixtures were trialed to investigate the effect of flow direction specific to this geometry.

## 2.2 PECM TEST RESULTS

Shown in Figure 3 are the before and after cube test artifacts (Figure 1) that underwent PECM to understand the critical process variables for EBM Inconel 738 material. These results showed the importance of small gap to maintain efficient removal of the peaks vs. the valleys. In addition, although the black nickel oxide layer could be maintained or removed via in-process conditions, its presence did not prevent further PECM removal but did affect the removal efficiency.

*Figure 3: Comparison of cube artifacts showing the ability to enhance the surfaces to 1 um Ra. The post-processed surfaces are shown on the left and initial surfaces on the right.*

In increasing the complexity of the representative artifacts towards that of an airfoil, trials were conducted on the artifacts with the intent of enhancing the surface finish of both the high and low pressure sides of the airfoil, in addition to the critical root of the airfoil into the platform. Illustrated in Figure 4 are two attempts with different PECM parameters. As can be seen the surfaces have been enhanced and shown to be close to that of cast material based on laser profilometry, with surface roughness measurements shown for representative locations on the artifact before and after PECM in Figure 5 and 6. Summarized in Table 1 are Ra and Rz values for additional locations over the airfoil artifact. As a note, Ra is the average roughness of a surface. Rz is the difference between the tallest "peak" and the deepest "valley" in the surface. Overall, a minimum decrease of 4x in the surface roughness was achieved.

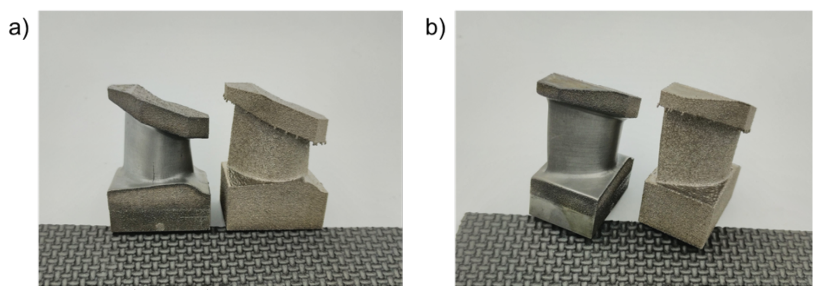


*Figure 4: Airfoil artifacts with PECM a) PECM conditions 1 b) PECM conditions 2.*

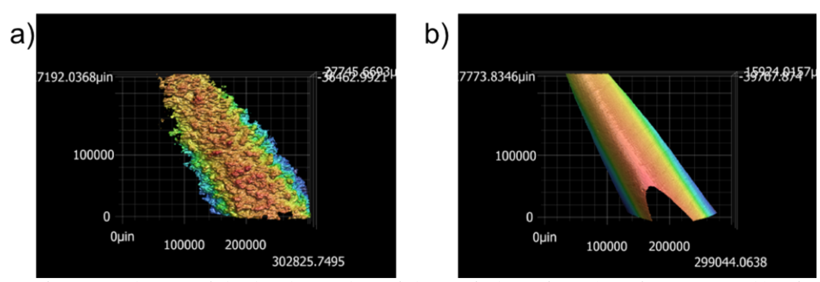


*Figure 5: Surface roughness of the leading edge of the airfoil artifact a) Before PECM b) After PECM.*

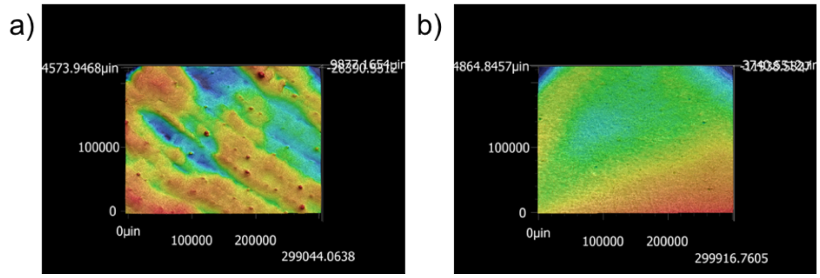


*Figure 6: Surface roughness of the platform of the airfoil artifact a) Before PECM b) After PECM.*

*Table 1: Roughness values before and after PECM for a representative airfoil artifact.*

| | *all values in µin* | | | |
|---|---|---|---|---|
| | **$R_a$ Before** | **$R_z$ Before** | **$R_a$ After** | **$R_z$ After** |
| Platform | 145.6 | 709.2 | 33.8 | 188.2 |
| Shroud | 1295.9 | 5687.2 | 38.6 | 195.7 |
| L Edge | 1440.6 | 6492.6 | 49.0 | 257.1 |
| T Edge | 1065.4 | 4786.4 | 47.6 | 241.1 |
| P Surface | 2502.8 | 2422.3 | 47.6 | 262.1 |
| S Surface | 3139.9 | 3527.9 | 50.1 | 282.0 |

The final effort of this program has focused on the ability to fabricate near-net shaped airfoils and utilize the PECM process for full surface finishing of the critical surfaces. Shown in Figure 7 is a non-proprietary blade that was finished using the PECM process in place of a proprietary design of a real industrial gas turbine engine airfoil that has been surfaced finished. As should be noted, microstructural evaluation of the area surrounding the surfaces electrochemically machined did not indicate any changes in microstructure from that of the as-built material.

*Figure 7: Non-proprietary blade with the surface finished by PECM.*

## 3. IMPACTS

Based on these test results, the team of Oak Ridge National Lab and Voxel Innovations have demonstrated that PECM is a valuable finishing process for EBM produced parts. The PECM process localization for removing large scale roughness while maintaining geometric accuracy means that large roughness or asperities due to support structures or attached powder re-melt areas are easily managed with PECM. In addition, it is expected that the demonstrated PECM finished surface roughness can be further improved with continued process development however these results already exceed the needs of turbine engine OEMs. Finally, the PECM processing speed demonstrated during these tests lends itself to higher volumes and can help enable the use of additive manufacturing and EBM for production part applications.

### 3.1 Subject Inventions

There are no subject inventions associated with this CRADA .

## 4. CONCLUSIONS

To date a critical drawback to industrial use of parts fabricated using the EBM process has been the surface roughness of the as-fabricated parts. Through the PECM process, critical surfaces on representative non-proprietary blade geometries fabricated from the crack prone Ni-base superalloy Inconel 738 were successfully finished and resulted in a 4x surface roughness enhancement. As a result, the finished surfaces were on-par with that of cast surfaces, making EBM processed Inconel 738 feasible for advanced gas turbine designs and enabling a new design space for the gas turbine industry that takes advantage of the geometric complexities of additive manufacturing.

## 5. VOXEL BACKGROUND

Voxel Innovations is an advanced manufacturing company specializing in advanced manufacturing process and services related to Pulsed Electrochemical Machining (PECM). Voxel was incorporated in Raleigh, NC in late 2015 after three years of business plan development, customer networking, discussions with suppliers and domain experts, and in-depth process research. The PECM process being pioneered by Voxel Innovations is unrivaled in its ability to quickly and accurately machine specialty metal alloys found in jet engines, industrial gas turbines, and turbochargers. Their mission is to use PECM and related manufacturing technologies to supply critical, high-value components to the energy industry.