

DEVELOPMENT OF AN AUTOMATED ULTRASONIC WIRE EMBEDDING
PROCESS FOR USE WITH MATERIAL EXTRUSION ADDITIVE
MANUFACTURING AND RAPID ELECTRONICS
FABRICATION

NIKKI LEE MARTINEZ

Master's Program in Mechanical Engineering

APPROVED:

David Espalin Ph.D., Chair

Eric MacDonald Ph.D.

Amit J. Lopes Ph.D.

Stephen L. Crites, Jr., Ph.D.
Dean of the Graduate School

Copyright ©

by

Nikki Lee Martinez

2020

Dedication

This thesis is dedicated to my family, friends, and colleagues who supported me.

PREVIEW

DEVELOPMENT OF AN AUTOMATED ULTRASONIC WIRE EMBEDDING
PROCESS FOR USE WITH MATERIAL EXTRUSION ADDITIVE
MANUFACTURING AND RAPID ELECTRONICS
FABRICATION

by

NIKKI LEE MARTINEZ., B.Sc.

THESIS

Presented to the Faculty of the Graduate School of
The University of Texas at El Paso
in Partial Fulfillment
of the Requirements
for the Degree of

MASTER OF SCIENCE

Department of Mechanical Engineering
THE UNIVERSITY OF TEXAS AT EL PASO

December 2020

Acknowledgments

I would like to first acknowledge Dr. Ryan Wicker, Director of the W.M. Keck Center for 3D Innovation and especially my advisor Dr. David Espalin for the opportunity given to me to conduct this research and learn so many valuable skills. I give Dr. Espalin my sincerest gratitude for his constant support and guidance as my advisor.

I want to thank the staff and my colleagues at the W.M. Keck Center who have also provided so much help and encouragement along the way. Jose Coronel as was my manager was both a teacher and example of professionalism. Kazi Billah for his unbiased teaching, being a great teacher even from my first day. Emerson Armendariz who aided me in much of the trouble shooting and improvement of this work. Sol Barraza and Christina Pickett, dear friends, whose companionship made hard days of work less of a burden. I give my utmost gratitude to my colleague Angel Vega whom this project would not be possible without, his contributions from the earliest stages of this research to the last were integral to its completion. And lastly, Jennifer Wilhite whose is to thank for guiding me along the writing process from start to finish and always encouraging and pushing me to do better.

Another acknowledgement I would like to give is to the companies who supported this work with their interest in it, offering projects that challenged myself and my colleagues to improve our work and aided us by example of what it meant to be engineers and work as a team with others. Among them I would like to thank Tom Place from Aura Technologies, John Blum from Triton Systems, Kyle Ferguson from Los Alamos National Laboratory, and Jacob Rome from Aerospace Corporation.

Lastly, I would like to thank my parents Laura and Dennis Martinez, who supported and encouraged me to great lengths on my path to become an engineer.

Abstract

Polymers have been used in Additive Manufacturing (AM) by many industries for rapid prototyping. Parts created using polymer AM however are known to be relatively expensive thus limiting them to small volume production and making them inapplicable for mass production, while their inherent porous and anisotropic properties make them mechanically inferior to parts made using traditional methods such as injection molding. As projects demand more efficient designs, and at the same time ask for more complex features, AM, combined with other manufacturing processes, like Ultrasonic Wire embedding, can streamline and consolidate assemblies. In the realm of composite and multifunctional assemblies, the layer-by-layer construction of AM parts allows components to be embedded within assemblies simplifying them and making them compact; thus, overcoming design constraints, and reducing weight and space in aeronautical and aerospace applications. Wire embedding, in particular, allows parts to not only be structural but also utilizes the substrates material properties to insulate wiring away from the environment while also retaining the wire and allowing the integration of bulkheads. Inserting wires however can be a challenge as they must be placed securely, accurately, and below the top layer so as not to interfere with subsequent layers atop them. The tool developed in this research makes use of ultrasonic energy to deform the channel around the wire and ensure consistent attachment. The system developed here makes use of a specially designed ultrasonic horn and mounting system to lay wire within polymer surfaces. The tool integrated into our multi-3d system which allows parts to be removed from a Stratasys Fortus 400mc printer, placed on a CNC on which the ultrasonic wire embedder is mounted, and redeposited in the printer after embedding so that printing can be finished, completely encapsulating the wire and any components placed within the part.

Table of Contents

Acknowledgments	v
Abstract	vi
Table of Contents.....	vii
List of Figures	x
List of Tables	xii
Chapter 1	1
Introduction.....	1
1.1 Background	1
1.2 Motivation	4
1.3 Thesis Objectives.....	5
1.4 Thesis Outline.....	6
Chapter 2	7
Literature Review	7
2.1 Introduction	7
2.2 End-Use Applications	7
2.3 Electronic Implementation	9
2.4 Materials for Electrical Transmission	10
2.5 Connecting Traces	14
Chapter 3	16

Exploratory Work.....	16
3.1 Wire Embedding Tests.....	16
3.2 Wire Placement Tool	18
Chapter 4	21
Tool Design.....	21
Overview.....	21
4.1 Ultrasonic horn and Power Supply	22
4.2 Gantry Mount	24
4.3 Load cell.....	25
4.4 Wire feeder	26
4.5 Tool Control	29
Chapter 5	30
Methodology.....	30
5.1 Experimental Setup.....	30
5.2 Parallelism	31
5.3 Dynamic Loading	31
5.4 Power Amplitude.....	32
5.5 Preload and Air Cylinder Pressure.....	32
5.6 Embedding PC.....	32
5.7 Channel Dimensions and Peak Force	32

5.8	Variable Pulse Length.....	33
5.9	Embedding ULTEM 9085.....	33
5.10	RC Demonstration Circuit.....	33
Chapter 6	.....	35
Results	.....	35
6.1	Parallelism Test	35
6.2	Dynamic Loading Test.....	36
6.3	Power Amplitude Test	38
6.4	Preload and Air Cylinder Pressure Test.....	39
6.5	Embedding PC Test	40
6.6	Dynamic vs. Embedding Forces.....	42
6.7	Channel Dimensions and Peak Force	43
6.8	Variable Pulse Length.....	44
6.9	Embedding PC vs. ULTEM 9085.....	46
6.10	PC and ULTEM 9085 Embedding Statistics.....	49
6.11	RC Demonstration Circuit.....	56
Chapter 7	.....	58
Discussion	.....	58
References	.....	60
Vita	.....	63

List of Figures

Figure 1: Dog bones inside Fortus 400mc(left), CAD representation (right)	16
Figure 2: Wire Placement Tool.....	18
Figure 3: Wire placement tool tips (left), 6061-aluminum ultrasonic horn (right).....	19
Figure 4: Large radius where press-fit failed (left), wire slipping in channel causing it to be drawn into the part (right).....	20
Figure 5: CAD of complete gantry assembly	21
Figure 6: Finished ultrasonic embedding tool mounted on CNC gantry	22
Figure 7: Copper wire path.....	23
Figure 8: Gantry assembly.....	24
Figure 9: load cell CAD	25
Figure 10: Forces transfer through assembly	26
Figure 11: Wire feeder assembly	27
Figure 12: Wire Cutter Assembly	28
Figure 13: Arduino and H-bridge mount.....	29
Figure 14: Testing Setup	30
Figure 15: Force recorded at each corner of the sample	35
Figure 16: Dynamic Force Test	36
Figure 17: Representation of tool flexing while embedding	37
Figure 18: Amplitude Comparison	38

Figure 19: Cylinder Pressure Comparison	39
Figure 20: First Pulse of Embedding on PC	40
Figure 21: Embedding Pulse at Center of Trace on PC	41
Figure 22: Comparison of first and center pulse on PC	41
Figure 23: Dynamic Movement Test vs. Embedding on PC	42
Figure 24: Average Force vs. Average Channel Width	43
Figure 25: Variable Pulse length Tests	44
Figure 26: 0.5 second pulse vs. 0.3 second pulse	45
Figure 27: 0.5 second pulse at start.....	46
Figure 28: 0.5 second pulse at middle.....	47
Figure 29: PC embedding sample (left), ULTEM 9085 embedding sample (right).....	48
Figure 30: Stages of Embedding.....	49
Figure 31: Force deltas during embedding.....	52
Figure 32: Machining cavities	56
Figure 33: Laser Soldering	57
Figure 34: Finished samples	57

List of Tables

Table 1: Time to Embed Statistics	50
Table 2: Delta 1 Statistics	52
Table 3: Delta 2 Statistics	53
Table 4: Delta 3 Statistics	54

PREVIEW

Chapter 1

Introduction

1.1 Background

Additive manufacturing (AM), often referred to as 3D printing, is used to describe a process in which a part is constructed by depositing material in a layer-by-layer fashion based on data interpreted from a computer aided design file (CAD). AM stands out from traditional casting and machining processes in that it creates less waste, requires less tooling and setup, and produces parts with complex features and internal geometries that are not possible through other traditional methods. Within the realm of AM, there are multiple unique methods of production that all use a myriad of different materials ranging from the hardest of metals, such as tungsten, to the softest of plastics like thermoplastic polyurethane. This paper revolves specifically around the uses of Material Extrusion (ME) and the production of plastic parts. In ME, a polymer already extruded into a long wire is fed into a heated nozzle where it is softened into a semi liquid state and then precisely deposited on a flat build platform to build individual layers of a part. Each layer self-hardens in the environment of the build plate and the subsequent layer is then built atop it. The part's geometry and placement are optimized for each case to fit within the build envelope, limit defects, shorten print time, and consider the asymptotic nature parts will always have when produced using the ME process.

Since the resurgence of AM in recent years, many improvements have been made to ward off previous frustrations associated with the processes. As a result, AM has expanded into multiple industries and been applied to several projects, mostly as a method of rapid prototyping, but more recently as a means for complex final parts that cannot be constructed by any other means. By themselves, AM parts have limited functionality and can only fulfil a limited number

of applications due to their lower strength compared to solid injection model parts and subsequent limitations in production numbers due to the steep cost curve. But when combined with other technologies, the range of suitable applications opens greatly especially in the aerospace and aeronautical industry where often low numbers of custom-tailored parts are needed for specialized applications. Work previously done by Espalin et al. (2014) at the W.M. Keck Center for 3D Innovation at the University of Texas at El Paso demonstrated the possibilities of multi-functionality in 3D printed parts and methods to implement electrical components into polymer substrates. The introduction of wiring and components such as bulkheads or sensors means that assemblies can be compacted and serve multiple roles while also incorporating the advantages in rapid prototyping offered by AM allowing designs to be modified throughout the process. Small adjustments from one design to the next that would ordinarily cost weeks and thousands of dollars to rework a production line can be bypassed by at any point at the press of a few buttons.

This work demonstrates methods for implementing copper wires for component connections in multifunctional parts. While embedding copper wire into the substrate does come with challenges, the merits of copper outweigh both inks and filaments. The high resistivity of conductive filaments and short lifespan of conductive inks severely limits the number of applications in which parts fabricated using these methods can be used. Though difficult to accurately place and conceal, a solid copper wire is inexpensive, readily available, and has a higher conductivity; all traits that that will lead to more reliable and longer lasting parts.

This research is focused on overcoming the issues previously found with the implementation of solid copper wires into AM parts and creating tooling alongside a manufacturing process to expedite the manufacturing of unique multifunctional parts. In this

multilayered process, the print is interrupted at a predetermined layer so that components can be embedded into preprinted channels using ultrasonic energy. The deformation of these channels by the ultrasonic energy securely holds the wires in place below the highest layer so they do not interfere with the print when it is resumed. Since this system is separate from the FDM printer itself, our multi 3D system is used to transfer the printed part to the wire embedding station and then back so the print can be resumed in order to encapsulate the wires and components within the substrate (Coronel, 2015). The Multi3D System includes two Stratasys Fortus 400mc FDM machines, a CNC router on which the ultrasonic horn is mounted with a variety of other tools, and a Yaskawa robotic arm that is used to transfer the build plate between machines. This complex system is what makes it possible to construct these multifunctional and multi composite parts. The ultrasonic system is made up of 3 main components that were all selected and modified for this application. The ultrasonic horn was modified to be integrated with the wire feeding system. Both are mounted to a custom chassis that was designed in house to accommodate a load cell to measure the forces being applied. The wire feeding system was developed based on previous experiences and literature review from similar mechanisms.

1.2 Motivation

Engineers and scientists are not only the people who ask “Why?” They are the ones who cannot rest until they solve the problem. As technology evolves, the problems engineers and scientists must solve have only become more complex. In many cases, assemblies and designs have become cumbersome as design and manufacturer engineers must accommodate far too many criteria, forcing them to make compromises in design or available features.

The consolidation of assemblies into single parts and ease of redesign and specialization offered by advanced manufacturing methods leads to more efficient systems, faster manufacturing, and weight savings which are vital because every ounce counts in aeronautical and aerospace engineering applications. Ultrasonic embedding is just one of many methods paving the way towards significant strides in the development and improvement of future manufacturing methods. Advanced manufacturing methods lead to more efficient systems and manufacturing processes. Even more important to the aeronautical and aerospace engineering applications is ultrasonic embedding’s potential to make significant weight savings through the consolidation of assemblies into single parts.

The use of ultrasonic embedding in composite multifunctional parts is one of the building blocks the W.M. Keck center is developing in its goal of completely automated manufacturing of electromechanical assemblies. Now more than ever, there is an emphasis in industry on consolidating designs and expediting the design process. The rapid prototyping offered by AM when combined with other processes, such as pick and placement systems and laser soldering, can lead to products that can be designed and build on a case-by-case basis. Perfecting the ultrasonic embedding process is a bridge that must be crossed before all these processes can be combined into one machine to even further the capabilities of these process. The W.M. Keck