DEVELOPMENT AND DEMONSTRATION OF A MULTIPLE MATERIAL

STEREOLITHOGRAPHY SYSTEM

OSWALDO ALONSO LOZOYA

Department of Mechanical and Industrial Engineering

APPROVED:

____
Ryan B. Wicker, Ph.D., Chair

____
Malcolm N. Cooke, Ph.D.

____
Carl W. Dirk, Ph.D.

____
Pablo Arenaz, Ph.D.
Dean of the Graduate School

DEVELOPMENT AND DEMONSTRATION OF A MULTIPLE MATERIAL STEREOLITHOGRAPHY SYSTEM

by

OSWALDO ALONSO LOZOYA, B.S.M.E.

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 and Industrial Engineering

THE UNIVERSITY OF TEXAS AT EL PASO

May 2006

UMI Number: 1435303

UMI Microform 1435303

ProQuest Information and Learning Company
300 North Zeeb Road
P.O. Box 1346
Ann Arbor, MI 48106-1346

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my advisor and mentor, Dr. Ryan B. Wicker, who guided me through this journey and encouraged me to thrive in the achievement of unprecedented goals and visions of my studies. His continuous guidance and the opportunity of becoming his research assistant throughout my graduate studies made all this work possible. I would like to extend my regards to the other committee members, Dr. Malcolm N. Cooke and Dr. Carl W. Dirk, for their patience and support during the writing of this thesis.

My deepest gratitude goes to my family and loved ones, for supporting and believing in me at all times. The faith and love they deposit in me continually is the driving force of my ambitions, and their care and concern for my personal advance at all levels is the strength that keeps me motivated in times of despair and doubt. For all these and many more reasons, this thesis is dedicated to my mother, Verónica Angélica Iñiguez; my father, Luis Raul Lozoya; and my brothers Juan Raul and Luis Gerardo. Thank you for wishing me the best always. Thank you for waiting for my safe return home always. Thank you for being an intrinsic part of me.

This work could have not been completed without the support of Liz Pardo, Carlos Herrera, Rudy Aguilar and the entire faculty and staff members that shared my experiences at the UTEP Mechanical Engineering Department throughout this stage of my life. To Francisco Medina, Karina Arcaute, Hector Sandoval, Luis Ochoa, Yinko Grajeda, Asim Inamdar and everyone directly involved in the activities of the W.M. Keck BBMEL goes my deepest appreciation.

To all the people I met in the extent of my studies here at UTEP, in Ciudad Juárez, El Paso and other places, who gave me the gift of their unconditional friendship and belief in the hardest times and in the lightest. To those who taught me so much when they thought I was the one

teaching, and to those who unconditionally instructed me while they were learning from me. To those who are waiting for me. And to those who remember me fondly for the slightest moments we were able to share a piece of our lives. To every one of them, I extend my heartfelt gratitude.

This support and other research support for the fulfillment of this thesis were provided through the Texas Advanced Research (Advanced Technology / Technology Development and Transfer) Program under Grant #003661-0020-2003. Other research support was also provided through Grant #11804 from the W.M. Keck Foundation; research Contract #28643 from Sandia National Laboratories in the Laboratory Directed Research and Development (LDRD) program, and through the endowed Mr. and Mrs. MacIntosh Murchison Chair I in Engineering.

This thesis was submitted to the Supervising Committee on November 22nd, 2005.

EXECUTIVE SUMMARY

The research described in this thesis addresses the development of a working multiple material stereolithography (MMSL) system by means of a functional retrofit of components into an existing stereolithography (SL) machine as a demonstration of MMSL manufacturing feasibility. A patent filed by Wicker, Medina, and Elkins (2004a) covering the MMSL concept, was used as the primary design reference for the implementation of the retrofit to the existing SL machine. The developed retrofitted MMSL system is installed in the process chamber of a SLA™ 250/50 by the removal of some of the components of the original system (e.g. Zephyr™ blade). Original system laser and optical equipment (laser beam spot size of 0.004-in – 0.008-in from a DPSS laser source) along with the vertical stage (0.0001-in resolution) and computer controls were used in the retrofit.

Using the concept of a rotary multiple vat assembly with diverse resins, multiple material parts were built for testing. The build envelope of the system is 3-in x 3-in x 1-in, using a layer thickness of 0.008-in and resin overfill strategy in order to maintain a constant surface level. The construction of parts follows a stratified strategy, where single material sections in a multiple material part are completed on the platform sequentially, in order to minimize build time and limit the number of intermediate resin washing cycles (used to rinse resin out of parts prior to their submersion in a different resin). Because of the process followed, a sweeping blade cannot be used to control resin surface uniformity. Dip coating and increased wait time between layer construction, inspired in early SL system models, were the techniques used instead for layer surface wetting.

The retrofitted MMSL system proves the feasibility of MMSL manufacturing; however, its vertical accuracy requires improvement. During MMSL stratified build, upper plane offset of part surfaces in different material sections, designed to be coincident in the CAD file and in the order of 20 mils (two- to three-layer thicknesses), becomes present; this is affected by surface wetting of each material (i.e. resin mounding) and retrofit assembly dimensional stack-up deviations. This situation can be improved to the order of 3-4 mils (less than one-layer thickness) by performing measurements of resin level height above Mylar® platform surface, originally proposed by Hector Sandoval for platform home location, and calculating differences between multiple vats at a known vertical stage location, using a hexagonal wet film comb coating thickness gage (Elcometer®), as shown by stratified build single material SL manufacturing measurements also presented in this thesis. The accuracy of the system in the planar region remains within the capability of the original SL system, as expected, with resolution within the range of 0.004-in – 0.008-in, as it is the case for the laser beam spot size.

Multiple material shear and normal specimens were used in order to demonstrate the feasibility of MMSL manufacturing and as samples for multiple bonding strength characterization through tensile testing, using three different resins from DSM Somos®: WaterShed™ 11120, ProtoTherm™ 12120 and NanoForm™ 15120. No conclusive result to define the failure limits of shear bonding strength were found, as specimen failure outside of the bonding contact plane occurred, leaving the definition of ultimate shear bonding strength undefined. Nonetheless, since they define an upper shear stress value prior to sample fracture that follows a linear response in the stress-strain curves before any cold-drawing behavior is observable (i.e. polymer yield region), shear stress values recorded at specimen failure were used to determine reference engineering design yield parameters. The reference shear strength values

(95% CI) obtained through testing are the following: 2080 ± 178 psi (3.18 ± 0.58 % elongation) for WaterShed™-NanoForm™; 2673 ± 294 psi (5.33 ± 0.62 % elongation) for WaterShed™-ProtoTherm™; and 1934 ± 465 psi (1.92 ± 0.53 % elongation) for ProtoTherm™-NanoForm™.

Normal bonding strength testing results describe a behavior similar to mechanical testing response of semi-crystalline polymeric structures. In addition, multiple material specimens illustrate different stress-strain responses in the cold drawing and strain hardening regions of the response for each multiple material bonding interface. In ductile-to-brittle multiple material bonding (WaterShed™-ProtoTherm™ and WaterShed™-NanoForm™ multiple material specimens), a mean ultimate normal strength with smaller distribution spread can be determined, in comparison with dispersed data distribution of elongation at break of the specimens; the opposite occurs in the tested brittle-to-brittle multiple material specimens (ProtoTherm™-NanoForm™). The mean yield stress (95% CI) of ductile-to-brittle multiple material specimens is always higher than the brittle-to-brittle multiple material bonding case: 835 ± 295 psi for ProtoTherm™-NanoForm™; 1423 ± 228 psi for WaterShed™-NanoForm™; and 1019 ± 203 psi for WaterShed™-ProtoTherm™. This may suggest the influence of WaterShed™ (ductile resin, 11 – 20 % elongation at break material specification from DSM Somos®) in helping the bonding interface sustain higher loads in ductile-to-brittle interfaces by plastically deforming, as shown by the quasi-cleavage fracture mode SEM image for a WaterShed™-ProtoTherm™ normal sample interface separation surface after testing.

In order to understand shear bonding strength behavior on these SL materials, single material samples optimized for shear fracture using linear elastic FEA were built (gage width 0.125-in, gage thickness 0.240-in, step-notch extension 0.100-in across half the specimen's thichness, shear plane overlap 0.040-in), both in the MMSL retrofit and a standard single material SL

system, with WaterShed™ and an additional resin, DSM Somos® 9120, with a 3:1 ratio between gage region normal cross section (i.e. step-notch section) and shear (i.e. overlap) plane area. Shear fracture was not observed for any sample built with any of these two SL materials; instead, normal fracture modes are found outside of the shear plane, as observed in the samples and described by numerous SEM images portraying cleavage brittle fracture modes in the fracture surfaces of specimens built in various orientations, build runs and stratified builds in both single or multiple vats. In addition, testing results yield different nominal shear stress values along with comparable specimen extension at sample fracture for different sample build orientations, with lower shear stress values for samples built vertically in contrast with any other orthogonal orientations (sample built on edge or built on flat specimen surfaces), which may suggest an effect on the manner the shear plane is built during SL manufacturing on shear bonding strength; for example, in the case of individual build runs of WaterShed™ samples in a single orientation, the testing results for nominal shear stress are the following (95% CI): 6033 ± 114 psi for samples built on edge; 6386 ± 153 psi for samples built on flat; and 4194 ± 242 psi for samples built vertically. On the other hand, for Aluminum Alloy 6061-T6 samples using the same linear elastic FEA optimized geometry (machined from stock by Carlos Herrera, Mechanical and Industrial Engineering Department technical staff associate and machinist), shear fracture is present in all cases, with ultimate shear strength values that match the published properties of this material (30,000 psi) and characteristic shear dimple (microvoid coalescence or MVC) fracture modes on the fracture surface.

Although the total integration of some of the described subsystems of the patent is left for future research, the operation of the manual MMSL system presented here is the first known

demonstration of this technology. Successful demonstration of the system provides a useful tool for future MMSL research.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF EQUATIONS

LIST OF FIGURES