PH.D THESIS

WORKING

TITLE

by

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A thesis submitted to the Faculty and the Board of Trustees of the Colorado School of Mines in partial fulfillment of the requirements for the degree of Doctor of Philosophy (Materials Science and Engineering).

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ABSTRACT

This thesis focused on the characterization of additively manufactured titanium alloys using high energy X-ray diffraction.

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LIST OF FIGURES AND TABLES

LIST OF SYMBOLS

alpha . . . . . α

LIST OF ABBREVIATIONS

high energy X-ray diffraction . . . . . HEXRD

ACKNOWLEDGMENTS

Mom & Dad & Noelle & Zack

Thomas & Marcella

To be determined.

CHAPTER 1

OUTLINE

This is an outline of all the sections of my Ph.D thesis that I think should be present. It will also help me in organizing all of the work I've done in graduate school.

Let's start with just a list dating back to the beginning

- Review paper on machine learning in additive manufacturing
- This is a maybe to include Matrix Completion with Dr. Wang
- This is a maybe to include Lockheed Martin Ti-6Al-4V project
  - Laboratory X-ray Diffraction characterization of β phase
  - Metallography
  - Hardness testing of antler sample
  - Metallograpy and microscopy of Ti-6Al-4V build wall
- In Situ High Energy X-ray Diffraction of Cold Metal Transfer Welded SS308L and Ti-6Al-4V
- High Energy X-ray Diffraction Characterization of Additively Manufactured Ti-5553 Octet Truss Lattices

CHAPTER 2

SCIENTIFIC APPROACHES TO RESEARCHING, MODELING, AND ENGINEERING ADDITIVELY MANUFACTURED MATERIALS

This section probably needs to come first because (at least at the moment) it contains a lot of literature review that is relevant to the later chapters.

CHAPTER 3

IN SITU HIGH ENERGY X-RAY DIFFRACTION OF COLD METAL TRANSFER WELDED SS308L AND TI-6AL-4V

Highlights of this chapter:

- Characterization technique
- Equilibrium phase diagrams, continuous cooling curves, TTT diagrams for each alloy
- Results obtained
- SS308L – measurement of temperature, cooling rate, difficulty in calculating temperature gradient
- Ti-6Al-4V – measurement of phases, attempts at fitting temperature
- Ti-6Al-4V – observation of α unit cell shift during $\beta \rightarrow \alpha$ transition
- Ti-6Al-4V – differences in cooling rate, phase fraction observed between point depositions and line welds

3.1 Characterization Technique

There is a lot of information to cover here and a lot of it is going to overlap/relate to the lattices section as well. I want to get the in situ stuff figured out first, then the lattices characterization, and then find a way to make them into one section.

3.1.1 High Energy X-ray Diffraction

3.1.2 Scattering Through Amorphous Materials

3.1.3 Scattering Through a Rapidly Cooling Material

Debye-Waller Factor, Preferred Orientation of Samples, Detector Acquisition Speed, Detector Coverage

3.1.4 Diffraction Information Specific to $\alpha + \beta$ Ti alloys

3.1.5 The various sources of broadening and intensity drops

Residual stress, dislocation density, alloy partitioning, the Lorentz factor

3.2 Material Properties of Ti-6Al-4V

This is where we include important background information on Ti-6Al-4V including things like:

- Composition
- Phase diagram
- Thermomechanical properties including CTEs and moduli
- Microstructural characteristics, both the possible microstructures and the ones we observe
- Deviations in material properties between traditional manufacturing and wire feed DED

3.3 Calculation of Temperature

Write up Don and Adrian's idea of calculating temperature using lattice thermal strains. Show their applicability to SS but inapplicability to Ti-6Al-4V. Discuss possible reasons why Ti-6Al-4V did not work out.

3.4 Phase transformations during solidification/cooling of the material

Discuss what you observed in your diffraction results. Talk about whether or not the observed results can be interpreted to be 'true' or if something else (like preferred orientation) is skewing the results. Talk about what useful information you got out of it.

3.5 The martensitic phase transformation in Ti-6Al-4V

This is where the letter on unit cell shifts observed will go. Of course, you need to tweak it to flow with the rest of the chapter.

3.6 Differences between point depositions and line welds

Talk about the observed differences in results between the two deposition geometries. What does this indicate about differences in the processes? Why are they different? What implications does this have for the modeling/research of AM Ti-6Al-4V?

3.7 CHESS samples

This research is not quite yet resolved – how do the results of your experiment at CHESS, coupled with Behnam's TEM of the same wall, relate to the results obtained in situ?

CHAPTER 4

HIGH ENERGY X-RAY DIFFRACTION CHARACTERIZATION OF ADDITIVELY MANUFACTURED TI-5553 OCTET TRUSS LATTICES

- Characterization technique
- Sample manufacturing
- Loading conditions
- Ashby and Deshpande's theory of octet trusses
- Calculation of strain
- Calculation of stress
- Metallography/microscopy of sample microstructures
- fractography of samples
- tomography of samples before and after
- ex situ loading of samples
- Results from HEXRD calculations
- FEA models for comparison with HEXRD
- spatial statistical regression of strain/stress response in samples

APPENDIX

ANALYSIS OF DIFFRACTION RESULTS USING NUMPY AND MATPLOTLIB