UNIVERSITI PUTRA MALAYSIA

DEVELOPMENT OF INCONEL 718 PARTS PRODUCED BY METAL INJECTION MOLDING TECHNIQUE FOR AEROSPACE APPLICATION

MUHAMMAD JABIR BIN SULEIMAN @ AHMAD

FK 2019 86

DEVELOPMENT OF INCONEL 718 PARTS PRODUCED BY METAL INJECTION MOLDING TECHNIQUE FOR AEROSPACE APPLICATION

By

MUHAMMAD JABIR BIN SULEIMAN @ AHMAD

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Master of Science

May 2019

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Master of Science

DEVELOPMENT OF INCONEL 718 PARTS PRODUCED BY METAL INJECTION MOLDING TECHNIQUE FOR AEROSPACE APPLICATION

By

MUHAMMAD JABIR BIN SULEIMAN @ AHMAD

May 2019

Chair : Assoc. Prof. Ir. Ts. Abd. Rahim bin Abu Talib, PhD
Faculty : Engineering

The thesis presents the results of the investigation carried out to determine the effect of composition of the binder system and sintering cycle of metal powder binder mixture on the properties of inconel 718 sintered specimens produced by the Metal Injection Molding (MIM) technique.

In this study, Inconel 718 are the nickel-based superalloys with superior materials properties range from high temperature mechanical strength, toughness to resistance to degradation in oxidizing and corrosive environment. Metal Injection Molding (MIM) is a process that has the capability to produce a component with complex shaped in high production capacity. Commonly the process requires the combination of two different types of materials; metal power and several thermoplastic materials which act as a binder system.

Based on previous studies on Palm Stearin (PS), it has already classified as an alternative material for the existing binder material. PS is derived from palm oil and it has been formulated for suitability for use in the MIM process. The main advantageous of using PS in MIM process is it has various elements with differences in the weight composition and temperature. It can benefit greatly during debinding process as it can be removed gradually, thus indirectly helps in maintaining the original structure and shape of the debound part. The earlier removal of PS, helps to form capillary holes for the removal of the remaining binder. To determine the properties of sintered part using these palm oil derivative binder, a PE-PS binder system are developed with the combination of PS and Polyethylene (PE), and it is compared with conventional binder material named PE-PW-SA, combination of PE, Paraffin Wax (PW) and Stearic Acid (SA).

The Inconel 718 and binder system are mixed together at 160 °C for 2 hours. The mixture of both materials is considered as feedstock were then injected molded into a tensile test shape. The binder system then was removed through the debinding process and sintered in vacuum atmosphere at 1260 °C for 6 hours with 3 different sintering cycles. The comparison are made between these specimens contain of two different binder system based on the physical and mechanical properties of Inconel 718 (IN718) sintered parts and micrograph observation.

This study has discussed the effect of palm oil derivative, as compared with conventional binder systems, on the physical and mechanical properties of the injection molded Inconel 718 sintered parts sample. As an alternative binder system in MIM, the results showed that combinations of palm stearin and inconel 718 can produce sintered parts that able to meet Metal Powder Industries Federation Standard (MPIF) 35 in terms of physical and mechanical properties of the sintered MIM part and supported by good results of microstructure behavior. This has proved that palm stearin can be applied with metallic material; Inconel 718 in the production of aerospace components using metal injection molding.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Sarjana Sains

PEMBANGUNAN BAHAGIAN INCONEL 718 YANG DIHASILKAN MENGGUNAKAN TEKNIK PENGACUAN SUNTIKAN LOGAM UNTUK APLIKASI AEROANGKASA

Oleh

MUHAMMAD JABIR BIN SULEIMAN @ AHMAD

Mei 2019

Pengerusi : Prof. Madya Ir. Ts. Abd. Rahim bin Abu Talib, PhD
Fakulti : Kejuruteraan

Tesis ini membentangkan hasil kajian yang dijalankan untuk menentukan kesan komposisi sistem pengikat dan kitaran sintering ke atas gabungan serbuk logam dan bahan pengikat dan sifat-sifat spesimen Inconel 718 yang telah disinter setelah ianya dihasilkan menggunakan teknik Pengacuan Suntikan Logam (MIM).

Dalam kajian ini, Inconel 718 adalah superaloi berasaskan nikel dengan ciri-ciri bahan yang unggul berkisar dari kekuatan mekanikalnya yang berkebolehan dari segi suhu yang tinggi, ketahanan terhadap terhadap pengoksidaan dan persekitaran yang mengakis. Pengacuan Suntikan Logam (MIM) adalah proses yang mempunyai keupayaan untuk menghasilkan komponen yang kompleks dalam kadar tinggi dari segi kapasiti pengeluaran. Kebiasaannya proses ini memerlukan kombinasi dua jenis bahan; serbuk logam dan beberapa bahan termoplastik yang bergabung dan berfungsi sebagai sistem pengikat.

Berdasarkan kajian terdahulu mengenai Palm Stearin (PS), ianya telah diklasifikasikan sebagai bahan alternatif untuk bahan pengikat yang sedia ada. PS berasal daripada minyak kelapa sawit dan ia telah dirumuskan bersesuaian untuk digunakan dalam proses MIM. Kelebihan utama menggunakan PS dalam proses MIM adalah ia mempunyai pelbagai elemen dengan perbezaan dari segi komposisi berat dan suhu. Ia dapat memberi manfaat yang sangat besar semasa proses penyahikatan kerana ia boleh diekstrak secara beransur-ansur dan berperingkat-peringkat, oleh itu ianya secara tidak langsung membantu dalam mengekalkan struktur asal dan bentuk bahagian yang telah diyahikatkan. Penyingkiran awal PS, membantu membentuk lubang kapilari untuk penyingkiran bahan pengikat yang selebihnya. Untuk menentukan hasil ciri-ciri spesimen yang menggunakan pengikat turunan minyak sawit ini yang

telah dibakar pada suhu tinggi, sistem pengikat PE-PS dikembangkan dengan gabungan PS dan Polyethylene (PE), dan ianya dibandingkan dengan bahan pengikat konvensional yang dinamakan PE-PW-SA, kombinasi PE, Paraffin Wax (PW) dan Stearic Acid (SA).

Inconel 718 dan sistem pengikat telah dicampur bersama-sama pada suhu 160 °C selama 2 jam. Campuran kedua-dua bahan itu dipertimbangkan sebagai bahan suapan kemudian disuntik dan dibentuk menjadi spesimen ujian tegangan. Sistem pengikat kemudian dikeluarkan melalui proses penyahikatan dan dibakar dalam keadaan vakum pada suhu 1260 °C selama 6 jam dengan tiga kitaran sintering yang berbeza. Perbandingan dibuat ke atas spesimen-spesimen ini yang mengandungi dua sistem pengikat yang berlainan berdasarkan sifat-sifat fizikal dan mekanikal Inconel 718 (IN718) bahagian yang telah dibakar pada suhu tinggi dan pemerhatian mikrograf.

Kajian ini telah membincangkan kesan turunan minyak kelapa sawit, berbanding dengan sistem pengikat konvensional, pada sifat fizikal dan mekanikal suntikan yang dibentuk sampel Inconel 718 yang telah dibakar. Sebagai sistem pengikat alternatif untuk MIM, keputusan menunjukkan bahawa gabungan stearin sawit dan Inconel 718 dapat menghasilkan bahagian dibakar yang mampu memenuhi Standard Persekutuan Serbuk Industri (MPIF) 35 dari segi sifat fizikal dan mekanik bahagian MIM tersebut dan disokong dengan hasil yang baik dari keadaan mikrostrukturnya. Ini telah membuktikan bahawa stearin sawit boleh digunakan dengan bahan logam; Inconel 718 dalam pengeluaran komponen aeroangkasa menggunakan acuan suntikan logam.

ACKNOWLEDGEMENTS

The author is very grateful to Allah S.W.T. because of the blessings, the grace, the inspiration and the chances given by the Almighty, so that he could write this thesis and complete his Master of Science in Aerospace Engineering at Universiti Putra Malaysia.

With boundless love and appreciation, the author would like to extend his heartfelt gratitude and appreciation to the people who helped him bring this study into reality. The author would like to extend his profound gratitude to the following:

To his parent, wife and children; Hj. Suleiman @ Ahmad bin Hj. Ghazali, Hjh. Sutinah binti Abdullah, Liyana binti Jamaludin, Muhammad Qausar bin Muhammad Jabir and Ainnur Humaira binti Muhammad Jabir for their neverending love, support and encouragement to make this study possible.

To the supervisor, Assoc. Prof. Ir. Dr. Ts. Abd. Rahim bin Abu Talib whose consistent guidance, ample time spent and consistent believe in him throughout these years has truly help him bring this study into success. To the supervisor committee; Dr. Mohammad Yazdi bin Harmin, the author truly appreciates his favourable response regarding the study.

To the external supervisor and senior researcher in SIRIM Berhad, Dr. Rosdi bin Ibrahim whose expertise, experience and fully trust in the author to turn the study from a MESTECC’s Sciencefund Grant, R & D project to this Master study has become a reality.

The author would like to express his special gratitude and thanks to his friend, Ahmad Nizam bin Abdullah from SIRIM Berhad and Mohamad Azmeer from Photonic Department, UPM for their continuous support for their friend whenever and wherever needed. Only Allah SWT can repay them and may their life be fully blessed by the Almighty.

This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Master of Science. The members of the Supervisory Committee were as follows:

Abd. Rahim bin Abu Talib, PhD
Associate Professor Ir. Ts.
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Mohammad Yazdi bin Harmin, PhD
Senior Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Rosdi bin Ibrahim, PhD
Industrial Centre of Innovation (ICI) in Biomedical,
SIRIM Industrial Research (SIR), SIRIM Berhad,
Malaysia
(Member)

____
ROBIAH BINTI YUNUS, PhD
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date:

Declaration by graduate student

I hereby confirm that:

- this thesis is my original work;
- quotations, illustrations and citations have been duly referenced;
- this thesis has not been submitted previously or concurrently for any other degree at any other institutions;
- intellectual property from the thesis and copyright of thesis are fully-owned by Universiti Putra Malaysia, as according to the Universiti Putra Malaysia (Research) Rules 2012;
- written permission must be obtained from supervisor and the office of Deputy Vice-Chancellor (Research and Innovation) before thesis is published (in the form of written, printed or in electronic form) including books, journals, modules, proceedings, popular writings, seminar papers, manuscripts, posters, reports, lecture notes, learning modules or any other materials as stated in the Universiti Putra Malaysia (Research) Rules 2012;
- there is no plagiarism or data falsification/fabrication in the thesis, and scholarly integrity is upheld as according to the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) and the Universiti Putra Malaysia (Research) Rules 2012. The thesis has undergone plagiarism detection software.

Signature: ________________________ Date: __________________

Name and Matric No.: _______________________________________

Declaration by Members of Supervisory Committee

This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) are adhered to.

Signature: ______________________________
Name of Chairman of Supervisory Committee: ______________________________

Signature: ______________________________
Name of Member of Supervisory Committee: ______________________________

Signature: ______________________________
Name of Member of Supervisory Committee: ______________________________

TABLE OF CONTENTS

		Page
ABSTRACT		i
ABSTRAK		iii
ACKNOWLEDGEMENTS		v
APPROVAL		vi
DECLARATION		viii
LIST OF TABLES		xii
LIST OF FIGURES		xiii
LIST OF ABBREVIATIONS		xiv
CHAPTER		
1	**INTRODUCTION**	1
	1.1 Overview	1
	1.2 Problem Statement	2
	1.3 Objectives	3
	1.4 Scope of Research	4
	1.5 Research Questions	4
	1.6 Hypothesis	4
	1.7 Thesis Organization	4
2	**LITERATURE REVIEW**	6
	2.1 Overview	6
	2.2 Powder Material	6
	2.2.1 Superalloy Inconel 718	8
	2.3 Binder Material	9
	2.4 Metal Injection Molding (MIM)	12
	2.4.1 Mixing Process	13
	2.4.2 Injection Molding Process	13
	2.4.3 Debinding Process	14
	2.4.4 Sintering Process	15
	2.5 Summary	16
3	**METHODOLOGY**	17
	3.1 Overview	17
	3.2 Characterization of Metal Powder and Binder Material	19
	3.3 Mixing Process	21
	3.3.1 Measurement of Solid Loading	21
	3.3.2 Mixing Process	22
	3.4 Injection Molding Process	23
	3.5 Debinding Process	23
	3.5.1 Solvent Extraction Process	23
	3.5.2 Thermal Pyrolisis Process	24
	3.6 Sintering Process	24

	3.7	Measurement of Physical and Mechanical Properties	25
		3.7.1 Density	25
		3.7.2 Hardness	25
		3.7.3 Porosity	26
		3.7.4 Tensile Strength	26
		3.7.5 Dimensional	26
		3.7.6 Weight Loss	27
		3.7.7 Shrinkage	27
		3.7.8 Elongation	28
	3.8	Microstructure Observation of Sintered Specimens	28
		3.8.1 Sample Preparation	28
		3.8.2 Microstructure Observation	29
4	**RESULTS AND DISCUSSION**		30
	4.1	Injection Molding and Debinding Process	30
	4.2	Physical and Mechanical Properties of Sintered Specimens	33
		4.2.1 Density	33
		4.2.2 Porosity	35
		4.2.3 Shrinkage and Weight Loss	36
		4.2.4 Hardness	37
		4.2.5 Tensile Strength and Elongation	38
	4.3	Microstructure Observation of Sintered Specimens	40
5	**CONCLUSION**		46
	5.1	Overview	46
	5.2	Concluding Remarks	46
	5.3	Recommendations for Future Research	47
REFERENCES			48
APPENDICES			51
BIODATA OF STUDENT			60
LIST OF PUBLICATIONS			62

LIST OF TABLES

Table		Page
2.1	MIM Materials	7
2.2	Types of Binder System	10
2.3	Content of Palm Stearin with Melting Temperature	11
3.1	Chemical Composition of Inconel 718 Powder	19
3.2	Content and Melting Temperature of PS	20
3.3	Melting and Evaporation Temperature of PE, PW, SA and PS	21

LIST OF FIGURES

Table		Page
3.1	Flow Chart	18
3.2	Scanning Electron Micrograph of Inconel 718 Spherical Powder	20
3.3	Inconel 718 Feedstock	22
4.1	Inconel 718 Green Samples	30
4.2	Scanning Electron Micrograph of Inconel 718 Green Samples (a) 200 magnification and (b) 1000 magnification	31
4.3	Scanning Electron Micrograph of Inconel 718 Brown Samples (a) 200 magnification and (b) 1000 magnification	32
4.4	Density of Sintered Inconel 718	33
4.5	Sintered Inconel 718 Samples of 70-30 Powder/Binder Ratio (a) Sintering Cycle 1, (b) Sintering Cycle 2 and (c) Sintering Cycle 3	34
4.6	Porosity of Sintered Inconel 718	35
4.7	Shrinkage of Sintered Inconel 718	36
4.8	Weight Loss of Sintered Inconel 718	37
4.9	Hardness of Sintered Inconel 718	38
4.10	Ultimate Tensile Strength of Sintered Inconel 718	39
4.11	Elongation of Sintered Inconel 718	40
4.12	Optical Micrograph of Sintered Inconel 718 at 100 magnification of (a) PE-PS Powder/Binder Ratio 66-34 and (b) PE-PW-SA Powder/Binder Ratio 66-34	42
4.13	Optical Micrograph of Sintered Inconel 718 at 500 magnification of (a) PE-PS Powder/Binder Ratio 66-34 and (b) PE-PW-SA Powder/Binder Ratio 66-34	43
4.14	Scanning Electron Micrograph of Sintered Inconel 718 at 200 magnification of (a) PE-PS Powder/Binder Ratio 66-34 and (b) PE-PW-SA Powder/Binder Ratio 66-34	44
4.15	Scanning Electron Micrograph of Sintered Inconel 718 at 1000 magnification of (a) PE-PS Powder/Binder Ratio 66-34 and (b) PE-PW-SA Powder/Binder Ratio 66-34	45

LIST OF ABBREVIATIONS

AMREC	Advanced Materials Research Centre
ASTM	American Society for Testing and Materials
FCC	Face Centered Cubic
PE-PS	Binder system; Polyethylene – Palm Stearin
PE-PW-SA	Binder system; Polyethylene – Paraffin Wax – Stearic Acid
°C	degree Celcius
°C/min	degree Celcius per minute
g	gram
g/cm^3	gram per cubic centimetre
HTCAF	high temperature control atmosphere furnace
h	hour
HCl	Hydrochloric Acid
HIP	Hot Isostatic Press
IN718	Inconel 718
ICP	Induced Couple Plasma
kN	kilonewton
MESTECC	Malaysian Ministry of Energy, Science, Technology, Environment and Climate Change
MPOB	Malaysian Palm Oil Board
MPa	megapascal
MIM	Metal Injection Molding
MPIF	Metal Powder Industries Federation
μm	micrometre
mm/min	millimetre per minute
ml	millilitre
N	newton
Nm	newton metre
HNO_3	Nitric Acid
PM	Powder Metallurgy
PS	Palm Stearin
PW	Paraffin Wax
ppm	parts per million
%	percentage
PE	Polyethylene
66-34	Powder-binder ratio; 66 vol.% powder and 34 vol.% binder
68-32	Powder-binder ratio; 68 vol.% powder and 32 vol.% binder
70-30	Powder-binder ratio; 70 vol.% powder and 30 vol.% binder
STA	Simultaneous Thermal Analysis
SIRIM	Standard and Industrial Research Institute of Malaysia
SA	Stearic Acid
UTS	Ultimate Tensile Strength
USA	United States of America
HV	vickers hardness
vol.%	volume percentage
wt.%	weight percentage

CHAPTER 1

INTRODUCTION

1.1 Overview

Advancements on the aviation and flying machine industry have been quickly growing after some time, and stay up to date with the most recent innovation has moved toward becoming piece of regular day to day existence for the fulfilment of human needs. Based on flight segment, the enhancements of materials utilized as a part of airplane gas turbine motors which constitute 50 % of aggregate aircraft weight must ensure its reality persistently. Aircraft gas turbine motors make brutal situations for materials because of the high working temperatures and high stress level (Furrer and Fech, 1999). Superalloys are the type of materials that can adapt to the most astounding temperature and able to withstand serious mechanical burdens and strains in oxidizing conditions. Generally, in light of Ni, Fe or Co, these are the type of superalloys with unrivalled materials properties as the materials can go into high temperature with good mechanical quality and good in strength for protection from corrosion in oxidizing and destructive condition. Accordingly, these materials are utilized as a part of aviation and aircraft industry, as well as in ship, train, petro-chemistry and nuclear reactor ventures (Kushan *et al*., 2012).

Until now, costly manufacturing processes such as machining, investment casting, and hot isostatic pressing have been used for the fabrication of small complex shape of aeronautic parts. In the current industry, casting is often used to process superalloys. However, their products usually combine low dimensional tolerance, rough surface finish and element segregation. Recent material shortages and increases in raw material costs have justified the development of a novel processing route for the fabrication of aeronautic parts (Julien and Després, 2006). An alternative process is metal injection molding (MIM), which offers improved cleanliness, better element homogeneity, finer grain size and a more uniform distribution of precipitating phases. IN-100 and Udimet-700 made by Lange indicated that MIM is a viable method in providing the products which can meet the requirements of geometry and property at low cost (Youhua *et al*., 2010).

An innovation known as Metal Injection Molding (MIM) utilizes the forming advantage of injection molding yet is appropriate to metal and ceramics. This procedure requires a little amount of polymer with an inorganic powder to form a feedstock that can be put into mold. In the wake of forming, the polymeric folio is extracted and the remaining shaped powder is sintered, regularly to close hypothetical densities (German and Bose, 1997). Materials handled through MIM incorporate most common ceramics and alloys – steel, stainless steel, tool steel, silicon nitride, cemented carbide, silicon carbide, copper, tungsten heavy alloys, nickel-base alloys, alumina, cobalt-base alloys, and composite that include tungsten-copper and molybdenum-copper. Other than these customary materials, MIM can likewise deliver claim to fame materials, for example, silicon carbide, nickel superalloys, intermetallics, precious metals, and ceramic-fiber reinforced ceramic composites.

Several studies shown that Inconel 718 can be fabricated using MIM. However, most of these studies use the conventional binder material, for instance; Polyethylene, Paraffin Wax and Stearic Acid in their MIM process. In this study, the Inconel 718 samples have been fabricated using Metal Injection Moulding technique at Metal Injection Molding (MIM) lab, Advanced Materials Research Centre (AMREC), SIRIM Berhad. The sintered samples have been examined based on its physical and mechanical properties, fire test evaluation and microstructure observation.

In recent years, several research studies were conducted at Metal Injection Moulding (MIM) lab, Advanced Materials Research Centre (AMREC), SIRIM Berhad purposely to evaluate palm stearin which derived from palm oil, as a potential binder material. The research work on this new binder material are varies on metallic material such as titanium alloy and stainless steel. Ibrahim *et al*., (2010) has studied the potential of applying palm stearin on the injection moulding of Oral Maxillofacial (OMF) titanium alloy implants and work has continued until pre-clinical study and it was reported by Ibrahim *et al*., (2014).

The findings of this study are also supported by several other studies on the physical, mechanical properties and microstructure evaluation of the injection molded titanium alloy sintered part fabricated with palm stearin by Suleiman @ Ahmad *et al*., (2008), Suleiman @ Ahmad *et al*., (2013) and Suleiman @ Ahmad *et al*. (2014). Sulaiman @ Ahmad *et al*., (2011) have focused on the influence of palm stearin on the metal injection molding of stainless steel 316l sintered parts and it applied on fabrication of orthopaedic and maxillofacial implants.

1.2 Problem Statement

The increasing demand makes the industries looking for a better option to cope with the continuous increased cost of the material and manufacturing process, besides being able to improve the surface finish, properties, and shorten the manufacturing time. The manufacturing of Inconel 718 parts that were good in terms of its physical and mechanical properties, and have the capabilities to withstand destructive condition specifically for aerospace parts is a major concern. The common method to produce Inconel 718 parts such as machining is a costly process, parts made using casting usually has low dimensional tolerance, rough surface finish and element segregation. Metal injection molding (MIM) is the method that can be used to overcome this issue. Early studies by Valencia *et al*., (1994) and Valencia *et al*., (1997) has shown the capabilities of

MIM to produce Inconel 718 parts, however the use of hydrogen during sintering and additional of second process; hot isostatic pressing that has causing a lot more cost in the manufacturing process. The choices of binder material are also crucial to health and environment aspect as some conventional binder system such as Stearic Acid (SA), Paraffin Wax (PW), Palmitic Acid (PA), and several other binders, made of petroleum wax and natural acid that can cause several side effects in humans and natural environment. Inhomogeneity of binder in a feedstock due to the unbalanced and immiscibility between binders in the binder system has cause induces in powder segregation during injection process and affects the final properties of injected samples (Royer *et al*., (2015) and (Royer *et al*., (2016)).

1.3 Objectives

In response to the issues, the overall objective of the study were focus on applying the MIM process to produce sintered Inconel 718 parts that meet the Metal Powder Industrial Federation (MPIF) standard. The development of feedstock of Inconel 718 is necessary to ensure that the early stages of mixing, injection and debinding can be established. The Palm Stearin (PS) as an environmentally friendly binder are applied as part of the components in a binder system and this system are compared with another binder system that used conventional binder materials. Powder loading were determined in earlier stages in order to find the most homogenous powder-binder ratio of a feedstock. In order to produce the optimized sintered properties of Inconel 718 parts, three sintering cycle were design to be run in vacuum condition by referring to several steps in the sintering cycle from the journals and combine with the existing thermal pyrolysis debinding - sintering cycle. The intention is the physical and mechanical properties of the sintered part can be obtained without using hydrogen and also without the need to add a second process to the sintering process.

The specific objectives of this study are:

1) To investigate the compatibility of a novel binder system based on palm oil derivatives; palm stearin use to fabricate Inconel 718 tensile test sintered parts by Metal Injection Molding (MIM) technique as compared to a conventional binder system.

2) To analyse suitable sintering cycles on Inconel 718 tensile test sintered parts based on its physical and mechanical properties, and microstructure observation of Inconel 718 tensile test sintered parts.

3) To identify the optimum solid loading with different powder/binder ratio by comparing the physical and mechanical properties, and microstructure observation of Inconel 718 tensile test sintered parts.

1.4 Scope of Research

Therefore, the scope of this master research is optimizing the parameter from the previous study in order to improved physical and mechanical properties and acquired good microstructure behaviour. The Inconel 718 samples with fabricated using feedstock within range of 66 vol.%, 68 vol.% and 70 vol.% of solid loading, two types of binder system; palm stearin; PE-PS and conventional; PE-PW-SA were fabricated using MIM technique and sintered at 3 different cycle with high temperature set equally at 1260 °C for 6 hours.

1.5 Research Questions

The listed research questions were raised in order to prove or disprove the accepted hypothesis:

1) How the differences in the manufacturing methods of producing Inconel 718 aerospace parts from the conventional method can affect the physical and mechanical properties, and microstructure behaviour?

2) Are the injection moulded Inconel 718 parts being able to meet the required aerospace standard?

3) Is the MIM process able to proof its capability as compared to the conventional process in terms of the physical condition of the sample?

1.6 Hypothesis

The objective of this study is driven based on the accepted hypothesis that fabricated Inconel 718 aerospace parts using the MIM process will indicate similarity in terms of physical and mechanical properties to the parts manufactured using the conventional process which includes machining, casting and hot isostatic pressing.

1.7 Thesis Organization

Before the experiment take place, a literature review of this topic has been conducted in order to provide more understanding and clear view of the study. The reading that relates to this study covers on the materials and binder properties, the process of fabrication the tensile test shape samples using MIM technique and analysis on the physical and mechanical properties and micrograph observation of sintered specimen. All of this information is including in Chapter 1.

Chapter 2 covers on the basic principles of MIM process, the main process that involves in MIM and all the parameters that involved in producing the tensile test shape samples. Explanation and description of the testing process on the fabricated specimen were elaborated in Chapter 3. This includes characterization of the specimen according to MPIF Standard 35 that related to physical and mechanical properties of sintered specimen. Micrograph observation and analysis of the materials in powder and specimen form that produced from every process of MIM is also described in this chapter.

All the results of the samples are discussed in Chapter 4, where this clearly shows the results on determining the ratio between Inconel powder and binder system to form a feedstock, measurement of dimension and weight of injection molded tensile test shape samples before and after the debinding process and lastly the sintered samples. The micrograph observations are focused in identify the microstructure behaviour of all sintered samples based on their condition after it was etched using chemical etchant. Comparison are made based on the physical and mechanical properties between each parameter, type of binder system and powder-binder ratio. Chapter 5 concludes the findings and final discussion of overall experiments, additional information on improvements and future plans for this topic.

REFERENCES

A. D. Russell. (2015). *The Manufacture of Gas Turbine Compressor Components by Metal Injection Moulding*. Doctor of Philosophy thesis, Edinburgh Napier University, Scotland.

A. Royer, T. Barriere and J.C. Gelin. (2015). The degradation of poly(ethylene glycol) in an Inconel 718 feedstock in the metal injection moulding process. *Powder Technology* 284: 467-474.

A. Royer, T. Barrière and J.C Gelin. (2016). Development and Characterization of a Metal Injection Molding Bio Sourced Inconel 718 Feedstock Based on Polyhydroxyalkanoates. *Metals* 6(89): 1-10.

A. Royer, T. Barriere and Y. Bienvenu. (2017). Influence of supercritical debinding and processing parameters on final properties of injection-moulded Inconel 718. *Powder Technology* 336: 311–317.

A. R. A. Talib, M. J. Suleiman @ Ahmad, R. Ibrahim, and M. Y. H. (2017). Evaluation of hardness and density properties of sintered Inconel 718 using palm oil-based binder. *International Journal of Sustainable Aviation*, Vol. 3, No. 1: 18-28.

A. R. A. Talib, I. Mohammed, N. M. Damshal, M. J. Suleiman @ Ahmad. (2019). Physical and Mechanical Properties of Fireproof Inconel 718 with Palm Stearin and Stearic Acid Binder. *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences*, Vol. 54, Issue 1: 112-123.

A. Simchi. (2006). Densification and Microstructural Evolution during Co-sintering of Ni-Base Superalloy Powders. *Metallurgical and Materials Transactions A 37A*: 2549-2557.

A. S. T. M. American Society for Testing and Materials International. (2017). ASTM B311-17. Standard Test Method for Density of Powder Metallurgy (PM) Materials Containing Less Than Two Percent Porosity.

A. S. T. M. American Society for Testing and Materials International. (2016). ASTM E8/E8M-16a. Standard Test Method for Tension Testing of Metallic Materials.

A. S. T. M. American Society for Testing and Materials International. (2009). ASTM B933-16. Standard Test Method for Microindentation Hardness of Powder Metallurgy (PM) Materials.

B. Julien and M. Després, (2006). Metal Injection Moulding: A Near Net Shape Fabrication Method for the Manufacture of Turbine Engine Component. *Cost Effective Manufacture via Net-Shape Processing. Meeting Proceedings RTO-MP-AVT*-139(8): 8-1 – 8-16.

D. Furrer and H. Fecht. (1999). Ni-Based Superalloys for Turbine Discs. *JOM* January 1999: 14-17.

E. A Ott and M.W Peretti. (2012). Metal Injection Molding of Alloy 718 for Aerospace Application. *JOM* 64(2): 252-256.

E. Hnatkova, B. Hausnerova, A. Hales, L. Jiranek, F. Derguti and I. Todd. (2017). Processing of MIM feedstocks based on Inconel 718 powder and partially water-soluble binder varying in PEG molecular weight. Powder Technology 322: 439–446.

G. C. Wei. (2006). *Pengacuan Suntikan Keluli Kalis Karat 316L dengan Menggunakan Sistem Pengikat*. Master Thesis, Universiti Kebangsaan Malaysia, Malaysia.

H. Youhua, L. Yimin, H. Hao, L. Jia and T. Xiao. (2010). Preparation and Mechanical Properties of Inconel 718 Alloy by Metal Injection Molding. *Rare Metal Materials and Engineering* 39(5): 775-780.

J. J. Valencia, J. Spirko and R. Schmees. (1997). Sintering Effect on the Microstructure and Mechanical Properties of Alloy 718 Processed by Powder Injection Molding. *Proceeding of The 4th International Symposium on Superalloys 718, 625, 706 and Various Derivatives, E. A. Loria ed., Pittsburgh, 1997, The Minerals, Metals & Society*: 753-762.

J. J. Valencia, T. McCabe, K. Hens, J. 0. Hansen and A. Bose. (1994). Microstructure and Mechanical Properties of Alloy 625 and 718 Process by Powder Injection Molding. *Proceeding of The 4th International Symposium* on Superalloys 718, 625, 706, and Various Derivatives Symposium, *E. A. Loria ed., Pittsburgh, 1994, The Minerals, Metals & Society*: 935-945.

M. A. Porter. (2003). *Effects of Binder Systems for Metal Injection Moulding*. Master Thesis, Lulea University of Technology, Sweden.

M. A. Ahmad, N. Johari, M. J. Sulaiman @ Ahmad, R. Ibrahim and A. R. A. Talib. (2014). Analysis of the Rheological Behavior and Stability of Inconel 718 Powder Injection Molding (PIM) Feedstock. *Advanced Materials Research* 879: 63-72.

M. C Kushan, S.C Uzgur, Y. Uzunonat and F. Diltemiz. (2012). ALLVAC 718 Plus™ Superalloy for Aircraft Engine Applications. In Dr. Ramesh Agarwal. *Recent Advances in Aircraft Technology* (pp. 75-96). Croatia: InTech.

M. Jabir, M. A. Ahmad, R. Ibrahim, M. Muhamad, A. Shaaban, R. Awang and S. Muhamad. (2011). Influence of palm stearin on powder injection moulding of stainless steel 316L. Materials Research Innovations 15: 30-33

M. J. Suleiman @ Ahmad, M. A. Ahmad, N. Mohamed, Y. Mohamad Junus, R. Ibrahim, M. Mohamad, M. R. Abdul Kadir, N. Abu Kassim, R. Awang and S. Muhammad. (2013). Effect of Atmosphere on the Sintered Titanium Alloy Produced by Metal Injection Molding (MIM) Technique. *Journal of Industrial Technology 21*: 9-17.

M. J. Suleiman @ Ahmad, M. A. Ahmad, R. Ibrahim, M. Mohamad, N. Abu Kasim, M.R Abdul Kadir, S. Muhamad, Y. Itoh, K. Hanada and T. Shimizu. (2013). Effect of Sintering Conditions on Mechanical Properties and Microstructure of Titanium Alloy Produced by Metal Injection Moulding (MIM). *Advanced Materials Research 686*: 164-169.

M. J. Suleiman @ Ahmad, M.A Ahmad, R. Ibrahim, M. Mohamad, N. Abu Kasim, M.R Abdul Kadir, S. Muhamad, Y. Itoh, K. Hanada and T. Shimizu. (2014). Physical and Mechanical Properties of Sintered Titanium Alloy Produced Through Metal Injection Molding (MIM) Process for Craniofacial Application. *Advanced Materials Research 879*: 85-89.

M. J. Suleiman @ Ahmad, N. Johari, M.A Ahmad, R. Ibrahim, A.R Abu Talib and M.Y Harmin. (2016). Solvent Debinding of Inconel 718 Fabricated via Metal Injection Molding. *Advanced Materials Research 1133*: 275-279.

M. P. I. F. Metal Powder Industries Federation. (2016). MPIF Standard 35. Materials Standards for Metal Injection Molded Parts.

N. Johari, R. Ibrahim, M.A Ahmad, M.J Suleiman @ Ahmad, A.R Abu Talib. (2014). The Effect of Sintering Temperature on Physical Properties of

Sintered Inconel 718 for Potential Aerospace Industry Application. *Advanced Materials Research* 879: 139-143.

Ö. Özgün, H.Ö Gülsoy, R. Yilmaz and F. Findik. (2013). Injection molding of nickel based 625 superalloy: Sintering, heat treatment, microstructure and mechanical properties. *Journal of Alloys and Compounds* 546: 192-207.

Ö. Özgün, H.Ö Gülsoy, R. Yılmaz and F. Fındık. (2013). Microstructural and mechanical characterization of injection molded 718 superalloy powders. *Journal of Alloys and Compounds 576*: 140-153.

R. Ibrahim, M. A. Ahmad, M. J. Sulaiman @ Ahmad, Ismail, M.R., Mohamad, M., Awang, R., and Muhamad, S. (2010). Injection Molding of Titanium Alloy Implant For Biomedical Application Using Novel Binder System Based On Palm Oil Derivatives. *American Journal of Applied Sciences 7(6)*: 811-814.

R. Ibrahim, M. A. Ahmad, M. J. Sulaiman @ Ahmad, N. Johari, M. Muhamad and A. R. A. Talib. (2012). Injection Molding of Inconel 718 Parts for Aerospace Application Using Novel Binder System Based on Palm Oil Derivatives. *Journal of World Academy of Science Engineering and Technology* 70: 526-530.

R. Ibrahim, M. A Ahmad, M. J. Sulaiman @ Ahmad, N. Johari, M. Muhamad and A. R. A. Talib. (2014). Effect of Solid Loading on the Physical Properties of the Sintered Inconel 718 using Metal Injection Moulding (MIM). *Advanced Materials Research* 879: 164-16.

R. M. German and A. Bose. (1997). *Injection Molding of Metal and Ceramics*. Princeton, New Jersey: Metal Powder Industries Federation.

R. M. German. (1994*). Powder Metallurgy Science 2nd Edition*. Princeton, New Jersey: Metal Powder Industries Federation.

R. C. Reed. (2006). The Superalloys Fundamentals and Applications. Cambridge University Press, New York, USA.

U. Gökmen and M. Türker. (2017). An Analysis of Rheological Properties of Inconel 625 Superalloy Feedstocks Formulated with Backbone Binder Polypropylene System for Powder Injection Molding. *Arch. Metall. Mater.* 62(4): 1937-1944.

V. Demers, F. Fareh, S. Turenne, N.R. Demarquette and O. Scalzo. (2018). Experimental study on moldability and segregation of Inconel 718 feedstocks used in low-pressure powder injection molding. *Advanced Powder Technology* 29: 180-190.

BIODATA OF STUDENT

Muhammad Jabir bin Suleiman @ Ahmad holds a Bachelor of Manufacturing Engineering (Manufacturing Design) from Universiti Teknikal Malaysia Melaka (UTeM), Melaka in 2007. He comes from a manufacturing background where he spend 7 month as an industrial trainer at Fujitsu Component (M) Sdn Bhd, Pontian, Johor in 2006 and manage to acquire a Final Year Project of his Bachelor's degree by conducting a study of wear mechanism on electrode parts and cutting tools using their CNC machines under supervision of Assoc. Prof. Ir. Dr. Mohd Hadzley bin Abu Bakar, Head of Manufacturing Process Department from Faculty of Manufacturing Engineering, UTeM and support of Mr. Azizan Ahmad, Head of Tooling Section. The result of the study were then applied in their production process and improved their quality and capabilities in CNC machining process. During that time, he also totally involved in conducting a project of applying a CWorks, a computer management program of integrating the whole process involved in their Tooling Section.

His career started as soon as he graduated. He was appointed as a research assistant and he works in the field of manufacturing a magnetic material under supervision of Prof. Dr. Azizah binti Shaaban from Faculty of Manufacturing Engineering, UTeM. He pursues his career to become a researcher at Structural Materials Program (SMP) at Advanced Materials Research Centre (AMREC), SIRIM Berhad in 2008 and until now he become actively involved as a member in 11 research and development projects within the field of advanced materials and manufacturing of products using metal injection molding (MIM) process. Most of the project were funded by the Malaysia Government under Ministry of Energy, Science, Technology, Environment and Climate Change (MESTECC), Ministry of Higher Education (MOHE) and Ministry of Finance (MOF). The projects has involvement with various parties from universities, research institutions, government-linked companies and government departments.

Out of these numbers; one of them is Technofund project, six are Sciencefund projects, one is Prototype Research Grant Scheme (PRGS) a project collaboration with University of Malaya (UM), one is a Contract Research Service Project between Universiti Teknologi PETRONAS (UTP), Nanomalaysia Berhad (NMB) and SIRIM Berhad, one is a development fund for a setup of ISO 17025 accredited lab focus on testing of medical devices product and the remaining project is a Socio-Economy project collaboration with Jabatan Kesihatan Negeri Kedah focus on developing and delivering several numbers of Portable Procedure Station (PPS) to be use at Emergency Unit in all general hospital in Kedah state.

Muhammad Jabir has published over 20 papers in the field of manufacturing engineering and most of it are related to the research and development works on MIM of Biomedical Metal Implant, Electronic and Aerospace parts, Degradation of Biomedical Ceramic Implant and Plasma Spray Biomedical Coating. He has won 1st Place in the Best Paper Award (Life Science Category) for his study on Degradation of Biomedical Ceramic Implant during the 23rd Scientific Conference of Microscopy Society Malaysia 2014 (SCMSM2014) at Universiti Teknologi PETRONAS (UTP), Perak.

Other recognition he received during his involvement in these various projects are Bronze Medal in BioMalaysia 2008, Gold Medal & Best Award in Malaysia Technology Expo (MTE2012), Gold Medal, Best Invention, Best Green Invention and IFIA Laureate for Excellent Invention in International Invention, Innovation & Technology Exhibition (ITEX2012) and Bronze Medal in International Invention, Innovation & Technology Exhibition (ITEX2014). He also has been appointed as a reviewer in International Conference on Advanced Materials Engineering and Technology (ICAMET2013) and Chairperson of Oral Session at Conference on Biomedical and Advanced Materials (Bio-CAM2017).

Muhammad Jabir are also appointed as a secretary in several event organized by SIRIM Berhad and he actively involved in the organizing committee for Advanced Materials Conference (AMC) of 2012, 2014, 2016 and 2018 edition. Other conference and event that he involved are Advanced Powder Metallurgy Symposium (APMS) of 2015 and 2017 edition, 1st Symposium and Exhibition on Additive Manufacturing (SEAM2016), 1st Conference on Biomedical and Advanced Materials (Bio-CAM2017), SIRIM Invention, Innovation and Technology Expo (SI2TE) of 2017 and 2018 edition and recently, SIRIM-WAITRO International Conference (SWIC2018).

He also involved as an officer who responsible in conducting any test related to biomedical materials at the Carbon & Sulfur Characterization 17025 Accredited Lab in Industrial Centre of Innovation (ICI) of Biomedical facilities. Other labs that he fully involved are Biomechanic Characterization Lab and Metal Degradation Lab which heading towards a recognition as a 17025 Accredited Lab.

Currently Muhammad Jabir pursuing a Master of Science in Aerospace Engineering based on research work under supervision of Assoc. Prof. Ir. Ts. Dr. Abd. Rahim bin Abu Talib, Head of Aerospace Engineering Department from Faculty of Engineering, Universiti Putra Malaysia (UPM). The research work of this study is a continuous work based on a research projects in collaboration between SIRIM Berhad and UPM entitled “Development of Inconel 718 Parts using Super Critical Carbon Dioxide (CO_2) Debinding Technique for Potential Aerospace Industry Application” under a ScienceFund grant approved in 2011 and completed in 2013.

LIST OF PUBLICATIONS

R. Ibrahim, M. Azmirruddin, M. Jabir, N. Johari, M. Muhamad and A. R. A. Talib. (2014). Effect of Solid Loading on the Physical Properties of the Sintered Inconel 718 using Metal Injection Moulding (MIM). *Advanced Materials Research* 879: 164-168.

M. Azmirruddin, N. Johari, M. Jabir, R. Ibrahim and A.R.A. Talib. (2014). Analysis of the Rheological Behavior and Stability of Inconel 718 Powder Injection Molding (PIM) Feedstock. *Advanced Materials Research* 879: 63-72.

Nurhaslina Johari, Rosdi Ibrahim, Mohamad Azmirruddin Ahmad, Muhammad Jabir Suleiman @ Ahmad, Abdul Rahim Abu Talib. (2014). The Effect of Sintering Temperature on Physical Properties of Sintered Inconel 718 for Potential Aerospace Industry Application. *Advanced Materials Research* 879: 139-143.

Muhammad Jabir bin Suleiman @ Ahmad, Nurhaslina binti Johari, Mohamad Azmirruddin bin Ahmad, Rosdi bin Ibrahim, Abd. Rahim bin Abu Talib and Mohammad Yazdi bin Harmin. (2015). Solvent Debinding of Inconel 718 Fabricated via Metal Injection Molding. *Advanced Materials Research* 1133: 275-279.

Abd. Rahim Abu Talib, Muhammad Jabir Suleiman @ Ahmad, Rosdi Ibrahim, and Mohammad Yazdi Harmin. (2017). Evaluation of hardness and density properties of sintered Inconel 718 using palm oil-based binder. *International Journal of Sustainable Aviation*, Vol. 3, No. 1: 18-28.

Abd. Rahim Abu Talib, Ibrahim Mohammed, Nadia Mohamad Damshal, Muhammad Jabir Suleiman @ Ahmad. (2019). Physical and Mechanical Properties of Fireproof Inconel 718 with Palm Stearin and Stearic Acid Binder. *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences*, Vol. 54, Issue 1: 112-123.

UNIVERSITI PUTRA MALAYSIA

STATUS CONFIRMATION FOR THESIS / PROJECT REPORT AND COPYRIGHT

ACADEMIC SESSION : _______________

TITLE OF THESIS / PROJECT REPORT :

____

____

____

NAME OF STUDENT :

____

I acknowledge that the copyright and other intellectual property in the thesis/project report belonged to Universiti Putra Malaysia and I agree to allow this thesis/project report to be placed at the library under the following terms:

1. This thesis/project report is the property of Universiti Putra Malaysia.
2. The library of Universiti Putra Malaysia has the right to make copies for educational purposes only.
3. The library of Universiti Putra Malaysia is allowed to make copies of this thesis for academic exchange.

I declare that this thesis is classified as:

*Please tick (√)

☐	**CONFIDENTIAL**	(Contain confidential information under Official Secret Act 1972).
☐	**RESTRICTED**	(Contains restricted information as specified by the organization/institution where research was done).
☐	**OPEN ACCESS**	I agree that my thesis/project report to be published as hard copy or online open access.