UNIVERSITI PUTRA MALAYSIA

FRICTION-STIR INCREMENTAL SHEET FORMING OF ALUMINUM ALLOY AND METAL MATRIX COMPOSITE

QASIM MHALHAL AZPEN

FRICTION-STIR INCREMENTAL SHEET FORMING OF ALUMINUM ALLOY AND METAL MATRIX COMPOSITE

By

QASIM MHALHAL AZPEN

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

April 2018

DEDICATION

To my lovely homeland Iraq, soul of my father may Allah SWT blesses his soul and put him in Wide paradises, my beloved mother, Allah bless her, and finally my marvelous family

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

FRICTION-STIR INCREMENTAL SHEET FORMING OF ALUMINUM ALLOY AND METAL MATRIX COMPOSITE

By

QASIM MHALHAL AZPEN

April 2018

Chairman : Associate Professor B.T. Hang Tuah Bin Baharudin, PhD
Faculty : Engineering

Currently, there is a growing market for manufacturing customized, rapid prototyping and low-cost sheet parts with small to medium batches (particularly in transportation, artificial medical alternatives, and aerospace industries). Incremental Sheet Forming (ISF) was born as an advanced sheet forming process to perfectly fit previous requirements. ISF is described to have inherent flexibility, high formability, and low-cost and forming forces compared to traditional sheet metal forming processes. Nevertheless, increasing demands to utilize the lightweight materials in various applications has placed this developed process in a critical challenge to deal with low formability materials at room temperature. Among all heat-assisted ISF processes, frictional stir-assisted Single Point Incremental Forming (SPIF) was presented in this study. Besides the mentioned advantages of ISF, frictional stir-assisted SPIF displays superior benefits as it does not require an external heating source and has a better final surface finish than the other types. Accordingly, this technique was used to improve the formability of two lightweight materials: aluminum alloy AA60601-T6 and metal matrix composite AA6061/20%SiCp-T1 sheets. The study focuses on the investigation of the process aspects, which include process formability indicators, forming forces, and surface roughness. Tool rotation speed, feed rate, step size, and tool diameter are proposed as process parameters to evaluate their impact on the output responses. In this regard, Taguchi Design of Experiment (DoE) technique and the analysis of variance (ANOVA) were employed to design the experimental work and statistically evaluate the

impact of each parameter. For AA6061-T6 experiments, the rotation spindle speed was the most dominant parameter that affects formability and forming forces where the percentage contributions of this parameter are 90% and 73%, respectively. On the other hand, the tool diameter has a significant impact on the internal surface roughness with a percentage contribution of 93%. The values of the determination coefficients R2 are 95, and 98% for the formability and surface roughness, respectively. From the results comparison of the two materials, maximum angles, maximum height, minimum forming force, minimum surface roughness are 66.15^{o}and 48^{o}; 27.46 mm and 11.55 mm; 2.4478 KN and 2.1273 KN; 0.3 µm and 1.741 µm, for AA606-T6 and AA6061/20%SiCp-T1, respectively.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperlun untuk ijazah Doktor Falsafah

PEMBENTUKAN TOKOKAN GESERAN ADUKAN ALOI ALUMINUM DAN KOMPOSIT MATRIKS LOGAN

Oleh

QASIM MHALHAL AZPEN

April 2018

Pengerusi : Profesor Madya B.T. Hang Tuah Bin Baharudin, PhD
Fakulti : Kejuruteraan

Saat ini, ada pasar yang berkembang untuk pembuatan komponen prototyping yang disesuaikan, cepat dan murah dengan batch kecil hingga menengah (terutama dalam transportasi, alternatif medis buatan, dan industri kedirgantaraan). Incremental Sheet Forming (ISF) lahir sebagai proses pembentukan lembaran lanjutan untuk memenuhi persyaratan sebelumnya dengan sempurna. ISF digambarkan memiliki fleksibilitas yang melekat, formabilitas tinggi, dan kekuatan biaya rendah dan membentuk dibandingkan dengan proses pembentukan lembaran logam tradisional. Namun demikian, meningkatnya tuntutan untuk memanfaatkan bahan ringan dalam berbagai aplikasi telah menempatkan proses yang dikembangkan ini dalam tantangan kritis untuk menangani bahan formability rendah pada suhu kamar. Di antara semua proses ISF panas yang dibantu, Frictional Stir-assisted Single Point Incremental Forming (SPIF) disajikan dalam penelitian ini. Selain keuntungan ISF yang disebutkan di atas, bantuan gesekan gesekan (SPIF) menampilkan manfaat unggul karena tidak memerlukan sumber pemanasan eksternal dan memiliki akhir permukaan akhir yang lebih baik daripada jenis lainnya. Dengan demikian, teknik ini digunakan untuk meningkatkan kemampuan formability dari dua bahan ringan: paduan aluminium AA60601-T6 dan matriks logam komposit AA6061 / 20% SiCp-T1 lembar. Studi ini berfokus pada penyelidikan aspek proses yang meliputi indikator formability proses, kekuatan pembentukan, dan kekasaran permukaan. Kecepatan putaran alat, laju umpan, ukuran langkah, dan diameter pahat diusulkan sebagai parameter proses untuk mengevaluasi

dampaknya terhadap tanggapan output. Dalam hal ini, teknik Taguchi Design of Experiment (DoE) dan analisis varians (ANOVA) digunakan untuk merancang pekerjaan eksperimental dan secara statistik mengevaluasi dampak dari setiap parameter. Untuk eksperimen AA6061-T6, kecepatan putaran spindle adalah parameter yang paling dominan yang mempengaruhi formability dan kekuatan pembentukan di mana kontribusi persentase dari parameter ini adalah 90% dan 73%, masing-masing. Di sisi lain, diameter alat memiliki dampak yang signifikan terhadap kekasaran permukaan internal dengan persentase kontribusi 93%. Nilai koefisien determinasi R2 adalah 95, dan 98% untuk sifat mampu bentuk dan kekasaran permukaan, masing-masing. Dari hasil perbandingan dua bahan, sudut maksimum, ketinggian maksimum, gaya pembentuk minimum, kekasaran permukaan minimum adalah 66,15^{o} dan 48^{o}; 27.46 mm dan 11.55 mm; 2.4478 KN dan 2.1273 KN; 0.3 µm dan 1.741 µm, untuk AA606-T6 dan AA6061 / 20% SiCp-T1, masing-masing.

ACKNOWLEDGEMENTS

بسم الله الرحمن الرحيم

"In the name of Allah, most Gracious, most Compassionate"

Although it is impossible to acknowledge every individual's contribution. I owe my gratitude to all those people who have made this thesis possible. I am deeply indebted to my supervisor Associate Professor Dr. B.T. Hang Tuah Bin Baharudin for his unconditional support and encouragement to finish this study. I would like to thank my advisors, Professor Dr. Shamsuddin Bin Sulaiman and Associate Professor Dr. Faizal Mustapha for the many valuable discussions that helped me to understand my research area better.

I would like to thank my supportive and loving wife, who has made this life journey to Malaysia and with the PhD dissertation much more pleasant. Her love and helpful spirit have motivated me to achievements beyond my own expectations.

To my lovely daughters Adian, Tabarek, Dawalqamar, Fatimah and Baneen, and my gentle son, Musa .This is meant for you and I wish to see you all in this position in the future. Thank you for your patience and support I shall always be proud of you.

Thanks go to my employer the Ministry of Higher Education and Scientific Research , Middle Technical University- Institute of Technology-Baghdad-Iraq, who given me the opportunity to gain higher education standard.

I am truly grateful to all colleagues and the workshop teams at the Department of Mechanical Engineering and Manufacturing / Universiti Putra Malaysia for their advice and support. Also, my thanks to German-Malaysian- Institute for their help.

I certify that a Thesis Examination Committee has met on 12 April 2018 to conduct the final examination of Qasim Mhalhal Azpen on his thesis entitled "Friction-Stir Incremental Sheet Forming of Aluminum Alloy and Metal Matrix Composite" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

Members of the Thesis Examination Committee were as follows:

Tang Sai Hong, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Mohd Khairol Anuar bin Mohd Ariffin, PhD
Professor Ir.
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

Zulkiflle bin Leman, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

I.S. Jawahir, PhD
Professor
University of Kentucky
United States
(External Examiner)

NOR AINI AB. SHUKOR, PhD
Professor and Deputy Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 28 June 2018

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

B.T. Hang Tuah Bin Baharudin, PhD
Associate Professor, Ir
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Shamsuddin Bin Sulaiman, PhD
Professor
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Faizal bin Mustapha, PhD
Professor, Ir
Faculty of Engineering
Universiti Putra 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.: Qasim Mhalhal Azpen, GS39560

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) were adhered to.

Signature: ______________________________

Name of Chairman of Supervisory Committee: Associate Professor Ir. Dr. B.T. Hang Tuah Bin Baharudin

Signature: ______________________________

Name of Member of Supervisory Committee: Professor Dr. Shamsuddin Bin Sulaiman

Signature: ______________________________

Name of Member of Supervisory Committee: Professor Ir. Dr. Faizal Bin Mustapha

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

t0	Initial sheet thickness
t	Instantaneous part wall thickness
θ	Forming wall angle
δ	Thinning limit
σϕ	Meridian stress
σm	Hydrostatic stress
σθ	Circumferential stress
σt	Thickness stress
$\boldsymbol{\varepsilon_{\varphi}}$	Meridian strain
$\boldsymbol{\epsilon_{\theta}}$	Circumferential strain
$\boldsymbol{\varepsilon_{t}}$	Thickness strain
$\boldsymbol{\varepsilon_{1}}$	Major strain
$\boldsymbol{\varepsilon_{2}}$	Minor strain
Fx	Forming force in X-direction
Fy	Forming force in y-direction
Fz	Forming force in z-direction
Fxy	The in-plane reaction force
Fz_p	Peak forming force in Z-direction
Fz_s	Steady state force in Z-direction
Fr	Radial force
Ft	Tangential force
ω	Spindle speed
f	Feed rate
z	Step size
D	Tool diameter
h	Height of the sample
Fz-max.	Maximum axil force
Ra	Surface roughness
F	Friction force

Vi	Relative velocity between the forming tool and the sheet metal
Tmax	Maximum tool-sheet interface temperature
µ	Coefficient of friction
Po	Mean pressure
H	Hardness
l	Effective contact length of the tooltip with the sheet metal at instant forming angle
U1	Sliding velocity of the forming tool
U2	Sliding velocity of the sheet metal
K_1	Thermal conductivity
ρ_1	Density
C_1	Specific heat
R2	Regression coefficient
Pred.R2	predicted R2
Adj.R2	Adjusted R2

LIST OF ABBREVIATIONS

ISF	Incremental sheet forming
SPIF	Single point incremental forming
MMC	Metal matrix composite
DoE	Taguchi design of experiment
S/N	Signal to noise ratio
ANOVA	Analysis of variance
AMCs	Aluminum matrix composites
SiCp	Silicon carbide particles
VWACF	Varying wall angle conical frustum
CNC	Control numerical computer
CAD	Computer added design
CAM	Computer added manufacturing
TPIF	Two points incremental forming
FLDs	Forming limit diagrams
FLCs	Forming limit curves
FFLDs	Fracture forming limit curves
LST	laser surface texture
FEM	Finite element method
ORB	oblique roller-ball tool
EHIF	Electric hot incremental forming
EAIF	Electropulse-assisted incremental forming
EP	Elastoplastic
HSS	High speed steel

CHAPTER 1

INTRODUCTION

1.1 Overview

In recent decades, most world governments and organizations have been pushed to decrease the classical energy consumption, while simultaneously restrict using resources that cause environmental pollution. Thus, utilizing lightweight materials and innovative production techniques, in many industrial sectors, are the key factors to reach these valuable goals (Kleiner *et al.*, 2003).

The Incremental Sheet Forming (ISF) process is an emerged flexible forming process (Hussain *et al.*, 2013), whereby, complex three-dimensional shapes can be manufactured by simple jig and with the use of simple forming tools that move over a controlled tool path. Therefore, the lead-time and production cost will be less. The sheet is deformed into the final required shape by a sequence of small, localized, and incremental deformations; consequently, avoiding necking in sheet metals. As a result, the formability of sheets is extremely high compared to the conventional sheet metal forming processes (Cao *et al.*, 2015; Ingarao *et al.*, 2011; Zhang *et al.*, 2010). Moreover, the forming forces in this process are less than that in conventional ones because of localized deformation. This contributes, to a great extent, in reducing the capacity and size of the machines employed in this process. All these advantages make ISF an alternative to traditional sheet forming processes for producing intricate components in small batches like customized and prototype parts; especially in aerospace, automotive, and biomedical applications (Cao *et al.*, 2015). Figures 1.1-1.3 present the applications of ISF in the transportation and medical fields, respectively.

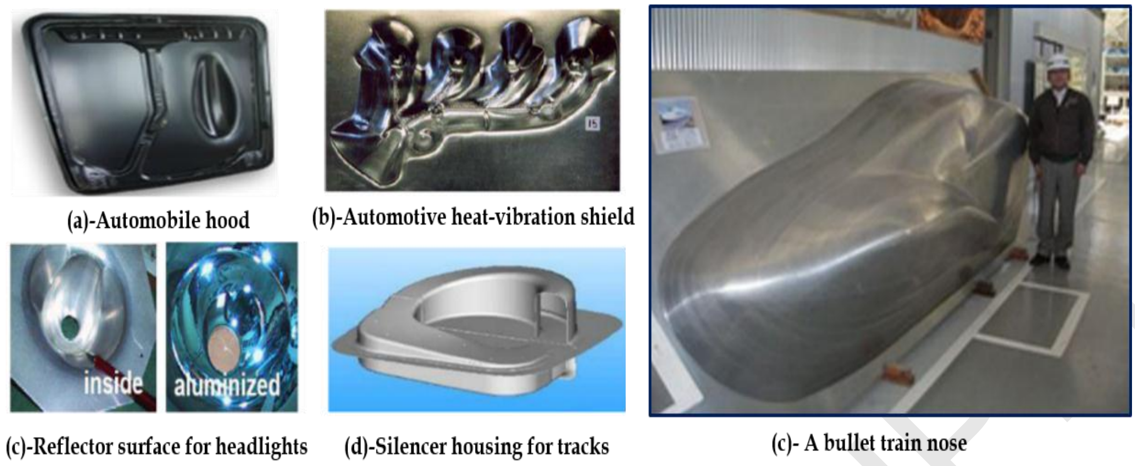

Figure 1.1 : Some of the transportation sector parts produced by ISF: a) [Amino website], b) and c) (Jeswiet *et al.*, 2005c), d) (Jeswiet *et al.*, 2005b) **and e)-[Amino website]**

Figure 1.2 : Some of the medical parts manufactured by ISF: a) (Bagudanch *et al.*, 2015b) **, b)** (Ambrogio *et al.*, 2005) **and c)**

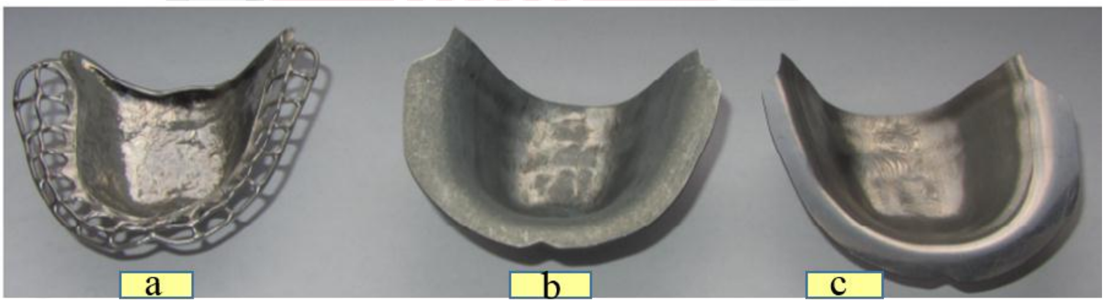

Figure 1.3 : Some of the medical parts produced by ISF: a) Cobalt-chrome alloy (cast) b) EN DCO4 (ISF) and c) EN X6r17(ISF) (Milutinovića *et al.*, 2014)

While Figure 1.4 displays the different intricate shapes that can be achieved by incremental sheet forming.

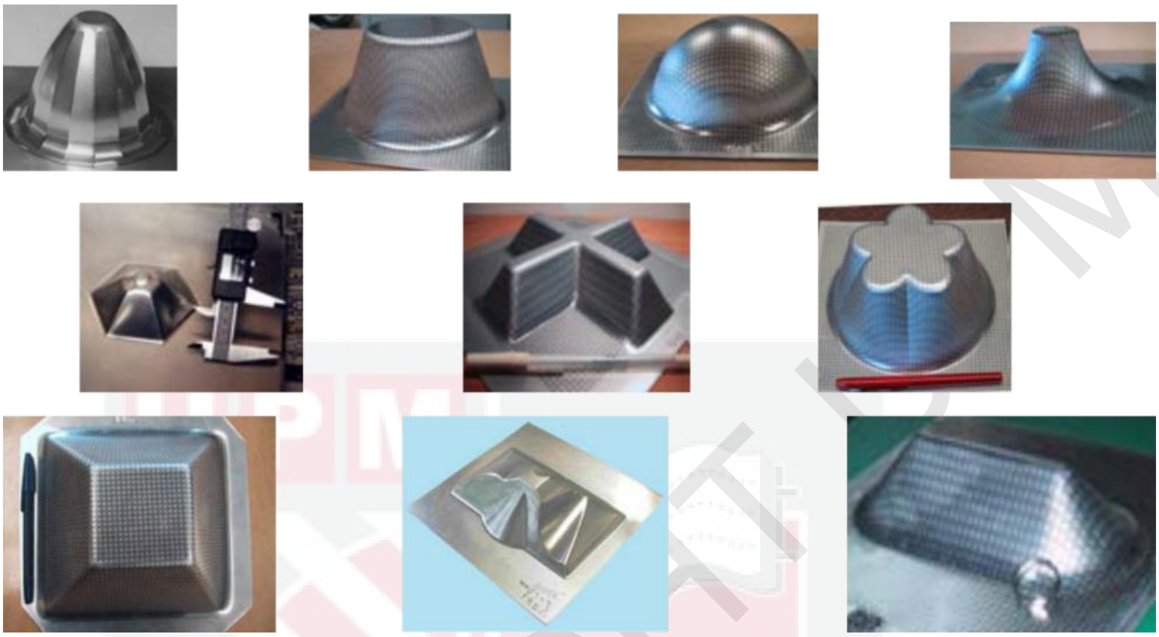

Figure 1.4 : Some of the intricate parts produced by ISF
(Jeswiet et al., 2005c)

In the beginning of the last century, high interest appeared to improve and employ lightweight materials in various industrial applications such as aerospace, marine, and automobile sectors (Ambrogio *et al.*, 2012a; Bao *et al.*, 2015). In general, lightweight materials include aluminium, magnesium, titanium, and their alloys: plastic, polymer, ceramic, and metal matrix composites (Campbell, 2012). These materials are known for their high strength-to-weight ratio, and characterized by their low formability at room temperature (Ambrogio *et al.*, 2012a; Ambrogio and Gagliardi, 2015; Jeswiet *et al.*, 2008). With the growth of lightweight material applications, dealing with the challenges in forming these low formability materials have become inevitable (Ambrogio *et al.*, 2012a; Ambrogio and Gagliardi, 2015; Hussain *et al.*, 2012).

According to the excellent ability of ISF, this technique can be utilized for manufacturing intricate parts; and simultaneously, is an appropriate process to enhance the formability of lightweight materials (Bambach *et al.*, 2007; Fratini *et al.*, 2004; Silva *et al.*, 2009b).

1.2 Problem Statement

In the past few decades, high interest has focused on utilizing lightweight materials in various industrial applications such as aerospace, marine, and automobile sectors due to their superior properties (Ambrogio et al., 2012a). For instance, aerospace ingredients and aircraft bodies are manufactured from aluminum, magnesium, and titanium alloys (Bao et al., 2015). These materials are known for their high strength-to-weight ratio and characterized by low formability at room temperature (Jeswiet et al., 2008). Moreover, research and development has shifted from plain to composite materials. Among the numerous types of MMCs, aluminum matrix composites (AMCs) are gaining importance; particularly in applications where strength-to-weight ratio is of major interest (Swamy et al., 2010). The main benefits of AMCs comprise of enhanced stiffness, controlled thermal expansion coefficient, improved damping capability, enhanced high-temperature properties, and thermal/heat management (Christy et al., 2010). Consequently, these composites are widely employed in many industrial applications such as aerospace, marine, automotive, sports, electronics, and welding electrodes (Anandakrishnan and Mahamani, 2011; Yuan et al., 2012). With the growth in the applications of lightweight materials, including AMCs, dealing with the challenges in forming these low formability materials have become inevitable (Ambrogio et al., 2012a; Ambrogio and Gagliardi, 2015; Hussain et al., 2012). Conventional manufacturing processes such as deep drawing and stamping require expensive equipment and long lead-time (Ambrogio et al., 2012a; Neugebauer et al., 2011).

ISF is a promising sheet forming process and becomes a worthy alternative to the traditional sheet forming processes. ISF has been used in manufacturing small batch or customized sheet components in various sectors. These sectors comprise transportation (automobile hood, automotive heat-vibration shield, reflector surface for headlights, silencer housing for tracks and a nose of bullet train), biomedical (cranial plate, ankle support, knee implant and dental—custom-made dental crowns), aerospace (Housings and fairings) and architectural (custom-made formwork, panels).

Heat-assisted ISF processes have been suggested to improve the formability at warm or hot conditions. These methods include electric-assisted ISF, laser-assisted ISF, and frictional stir-assisted ISF Among all heat-assisted ISF processes, frictional stir-assisted Single Point Incremental Forming (SPIF) was presented in this study. This process depends on the frictional heating generated by increasing the tool rotation speed, which causes a significant rise in sheet metal temperature, thereby, increasing the material's formability.

Besides the advantages of heat-assisted ISF, frictional stir-assisted SPIF displays superior benefits as it does not require an external heating source and has a better final surface finish compared to other heat-assisted SPIF approaches. One of the limitations of this process is the probability for getting an adequate combination of the main process parameters values to attain a high formability, low forming forces and high quality of the surface finish of the part formed. Accordingly, this technique was used to improve the formability of lightweight materials AA60601-T6 and AA6061/20%SiC_p-T1 sheets. These two materials are widely used in aerospace and transportation industries. For example- the percentage weight of the composites materials and aluminum alloys in Boeing 787 are 50% and 20%, respectively.

From the above discussion, the following advantages of frictional stir-assisted SPIF implemented on AA60601-T6 and AA6061/20%SiC_p sheets are presented as follows:

1. These two materials are attractive to use in many industrial sectors, but their employment is limited by material and production costs.
2. There is an increasing demand to customize components and rapid prototyping techniques in the forming of sheet parts.
3. According to the requests mentioned, SPIF can be proposed as a promising process that can achieve the above-mentioned demands.

1.3 Thesis Objectives

Based on the problem statement, the main study objectives can be expounded as follows:

1. To investigate experimentally the formability of two lightweight materials, which are aluminium alloy and aluminum matrix composite sheets, by using frictional stir incremental forming. The formability is evaluated in regard to the maximum wall angle, maximum height, and thinning limit.
2. To analyse the impact of the parameters (tool rotational speed, feed rate, step size, and tool diameter) on forming forces via the forming process.
3. To determine the effect of studied parameters on the surface roughness of the samples produced.

Design of the experiment (Taguchi method) and analysis of variance (ANOVA) approaches were employed to determine the qualitative correlation that characterizes the relationship between the main single point incremental parameters and the different process responses.

The novelty of this work comes from that two lightweight materials were first successfully formed with friction-stir assisted SPIF process. While the significant difference with the previous studies is building empirical models for formability indicators and surface roughness for the AA6061-T6 with an optimization of the final surface roughness. In addition, the present study develops an effective mathematical equation to estimate the maximum flash temperature at the tool-sheet interface. Estimation of the interface temperature is quite important to know the range at which the materials reach their maximum elongations. This can be achieved by a proper combination of the process parameters values during incremental sheet forming process.

1.4 Significant of Study

In the last decade, there has been an increasing demand for using lightweight materials in different industrial applications; they include magnesium, titanium, aluminum alloys, and compound materials. These materials are preferred due to their low weight and extraordinary strength-to-weight ratio. On the other hand, metal matrix composites (MMCs) are compound materials that provide the means for ultra-lightweight components. Currently, MMCs are employed in a wide range of applications pertaining to aircrafts, the automobile industry, in cutting tools, and sporting products. The application of MMCs is limited by its low formability at room temperature, low machining efficiency, and poor machinability which is the result of their highly abrasive-nature. These factors cause excessive tool wear in cutting processes.

Besides the advantages of incremental sheet forming, the use of frictional stir incremental forming presents superior advantages because it does not require additional heating equipment compared to other heat-assisted SPIF. In this work, this technique was used to improve the formability of two important lightweight materials (AA60601-T6 and AA6061/SiC_p sheets) that can be employed in the automotive, aerospace, and space structural sections. Furthermore, this study encourages the continuation of this research to develop incremental sheet forming that deals with hard-to-form materials. Thus, it will contribute to the increasing probability of applying this technique with such materials to manufacture components in vital applications in future. Moreover, no previous study had focused on ISF to produce components made from AA6061-T6 or AA6061/SiC_p metal matrix composites by frictional stir-assisted Single Point Incremental Forming (SPIF).

1.5 Scope and Limitations of the Study

1.5.1 Scope

The scope of this work is limited to studying of process demands of SPIF at room temperature within three parts:

1- Obtaining the mechanical properties and chemical composition of the two studied materials (AA6061-T6 and AA6061/SiC_p composites) using tensile test and chemical composition test, respectively.
2- Utilizing the single point incremental forming to investigate the formability for both materials using varying wall angle conical frustum (VWACF) test.
3- Studying the effect of different parameters (tool rotational speed, feed rate, step size, tool diameter, and material type) on:

- Formability indicators (wall angle, height, and thinning limit)
- Forming forces
- Surface roughness
- Tool-sheet interface temperature

1.5.2 Limitations

As known, the recognized limitations in SPIF are wall angle, surface quality, geometric accuracy, and material thinning. Moreover, hard-to-form materials, such as lightweight materials, are characterized with high yield stress, spring back, and surface properties which increase the friction between the forming tool and the sheet surface. Usually, to deal with these hard materials, it will require high forming forces that result in high friction, dimensional deviation, and tool degradation. Consequently, utilizing one of the heating resources is essential to solving this issue.

1.6 Thesis outline

The present thesis consists of five chapters. Chapter 1 is the introductory chapter that offers the basic information and applications of incremental sheet forming in various industrial sectors. Chapter 2 is the literature review of the single point incremental forming process. It includes an enumeration of previous works, which deal with the forming of hard-to-form materials according to the heating resource. It extensively provides the influence of important parameters on the performance of the frictional stir incremental forming process. Chapter 3 discusses the main methodologies applied in this work. It includes the testing of the materials used, and the design of the experiments. The experimental equipment employed in the single point incremental forming experiments include CNC milling machine, jig and forming tools, dynamometer, as well as measuring devices and instruments. Moreover, CAD/CAM software was applied to design and generate the tool path of the final product shape. Chapter 4 provides the obtained results of the frictional stir incremental forming experiments. Some of the important relationships between the results of both studied materials were specified. Chapter 5 presents the overall conclusions of this project and the directions for future work.

REFERENCES

Adams, D. (2013). Improvements on single point incremental forming through electrically assisted forming, contact area prediction and tool development.

Adams, D. W. (2014). *Improvements on single point incremental forming through electrically assisted forming, contact area prediction and tool development*: Queen's University (Canada).

Aerens, R., Eyckens, P., Van Bael, A., and Duflou, J. (2010). Force prediction for single point incremental forming deduced from experimental and FEM observations. *The International Journal of Advanced Manufacturing Technology, 46* (9), 969-982.

Al-Ghamdi, K. A., and Hussain, G. (2015). Forming forces in incremental forming of a geometry with corner feature: investigation into the effect of forming parameters using response surface approach. *The International Journal of Advanced Manufacturing Technology, 76* (9-12), 2185-2197.

Al-Obaidi, A., Kräusel, V., and Landgrebe, D. (2015). Improvement of formability in single point incremental forming of DP1000 steel aided by induction heating. *Applied Mechanics & Materials, 794*

Al-Obaidi, A., Kräusel, V., and Landgrebe, D. (2016). Hot single-point incremental forming assisted by induction heating. *The International Journal of Advanced Manufacturing Technology, 82* (5-8), 1163-1171.

Al-Obaidi, A., Kräusel, V., and Landgrebe, D. (2017). *Implementing Thermomechanical Properties of 22MnB5 Steel during Hot Single-Point Incremental Forming.* Paper presented at the Materials Science Forum.

Allwood, J. M., Braun, D., and Music, O. (2010). The effect of partially cut-out blanks on geometric accuracy in incremental sheet forming. *Journal of Materials Processing Technology, 210* (11), 1501-1510.

Ambrogio, G., Bruschi, S., Ghiotti, A., and Filice, L. (2009). Formability of AZ31 magnesium alloy in warm incremental forming process. *International Journal of Material Forming, 2*, 5-8.

Ambrogio, G., Costantino, I., De Napoli, L., Filice, L., Fratini, L., and Muzzupappa, M. (2004). Influence of some relevant process parameters on the dimensional accuracy in incremental forming: a numerical and experimental investigation. *Journal of Materials Processing Technology, 153*, 501-507.

Ambrogio, G., De Napoli, L., Filice, L., Gagliardi, F., and Muzzupappa, M. (2005). Application of Incremental Forming process for high customised medical product manufacturing. *Journal of Materials Processing Technology, 162-163*, 156-162.

Ambrogio, G., Duflou, J., Filice, L., Aerens, R., Cueto, E., and Chinesta, F. (2007). *Some considerations on force trends in Incremental Forming of different materials.* Paper presented at the AIP Conference Proceedings.

Ambrogio, G., Filice, L., and Gagliardi, F. (2012a). Formability of lightweight alloys by hot incremental sheet forming. *Materials & Design, 34*, 501-508.

Ambrogio, G., Filice, L., and Gagliardi, F. (2012b). Improving industrial suitability of incremental sheet forming process. *The International Journal of Advanced Manufacturing Technology, 58* (9), 941-947.

Ambrogio, G., Filice, L., Gaudioso, M., and Manco, G. (2010). Optimised tool-path design to reduce thinning in ISF process. *International Journal of Material Forming, 3*, 959-962.

Ambrogio, G., Filice, L., Guerriero, F., Guido, R., and Umbrello, D. (2011). Prediction of incremental sheet forming process performance by using a neural network approach. *The International Journal of Advanced Manufacturing Technology, 54* (9), 921-930.

Ambrogio, G., Filice, L., and Manco, G. (2008). Warm incremental forming of magnesium alloy AZ31. *CIRP Annals-Manufacturing Technology, 57* (1), 257-260.

Ambrogio, G., Filice, L., and Micari, F. (2006). A force measuring based strategy for failure prevention in incremental forming. *Journal of materials processing technology, 177* (1), 413-416.

Ambrogio, G., and Gagliardi, F. (2015). Temperature variation during high speed incremental forming on different lightweight alloys. *The International Journal of Advanced Manufacturing Technology, 76* (9-12), 1819-1825.

Ambrogio, G., Gagliardi, F., Bruschi, S., and Filice, L. (2013a). On the high-speed Single Point Incremental Forming of titanium alloys. *CIRP Annals-Manufacturing Technology, 62* (1), 243-246.

Ambrogio, G., Gagliardi, F., and Filice, L. (2013b). Robust design of incremental sheet forming by taguchi's method. *Procedia CIRP, 12*, 270-275.

Ambrogio, G., Ingarao, G., Gagliardia, F., and Di Lorenzo, R. (2014). Analysis of energy efficiency of different setups able to perform single point incremental forming (SPIF) processes. *Procedia CIRP, 15*, 111-116.

Amino, H., Lu, Y., Ozawa, S., Fukuda, K., and Maki, T. (2002). *Dieless NC forming of automotive service panels*. Paper presented at the Proceedings of the conference on Advanced Techniques of Plasticity.

Anandakrishnan, V., and Mahamani, A. (2011). Investigations of flank wear, cutting force, and surface roughness in the machining of Al-6061–TiB 2 in situ metal matrix composites produced by flux-assisted synthesis. *The International Journal of Advanced Manufacturing Technology, 55* (1), 65-73.

Asghar, J., and Reddy, N. (2013). *Importance of tool configuration in incremental sheet metal forming of difficult to form materials using electro-plasticity.* Paper presented at the Proc. of the World Congress on Engineering.

Azevedo, N. G., Farias, J. S., Bastos, R. P., Teixeira, P., Davim, J. P., and de Sousa, R. J. A. (2015). Lubrication aspects during single point incremental forming for steel and aluminum materials. *International Journal of Precision Engineering and Manufacturing, 16* (3), 589-595.

Bagudanch, I., Centeno, G., Vallellano, C., and Garcia-Romeu, M. (2013). Forming force in Single Point Incremental Forming under different bending conditions. *Procedia Engineering, 63*, 354-360.

Bagudanch, I., Garcia-Romeu, M., Centeno, G., Elías-Zúñiga, A., and Ciurana, J. (2015a). Forming force and temperature effects on single point incremental forming of polyvinylchloride. *Journal of materials processing technology, 219*, 221-229.

Bagudanch, I., Lozano-Sánchez, L. M., Puigpinós, L., Sabater, M., Elizalde, L. E., Elías-Zúñiga, A., and Garcia-Romeu, M. L. (2015b). Manufacturing of polymeric biocompatible cranial geometry by single point incremental forming. *Procedia Engineering, 132*, 267-273.

Bahloul, R., Arfa, H., and BelHadjSalah, H. (2014). A study on optimal design of process parameters in single point incremental forming of sheet metal by combining Box–Behnken design of experiments, response surface methods and genetic algorithms. *The International Journal of Advanced Manufacturing Technology, 74* (1-4), 163-185.

Bahloul, R., Arfa, H., and Salah, H. B. (2013). *Application of response surface analysis and genetic algorithm for the optimization of single point incremental forming process.* Paper presented at the Key Engineering Materials.

Bambach, M., Araghi, B. T., and Hirt, G. (2009). Strategies to improve the geometric accuracy in asymmetric single point incremental forming. *Production Engineering, 3* (2), 145-156.

Bambach, M., Todorova, M., and Hirt, G. (2007). *Experimental and numerical analysis of forming limits in CNC incremental sheet forming.* Paper presented at the Key Engineering Materials.

Bao, W., Chu, X., Lin, S., and Gao, J. (2015). Experimental investigation on formability and microstructure of AZ31B alloy in electropulse-assisted incremental forming. *Materials & Design, 87*, 632-639.

Bhattacharya, A., Maneesh, K., Reddy, N. V., and Cao, J. (2011). Formability and surface finish studies in single point incremental forming. *Journal of manufacturing science and engineering, 133* (6), 061020.

Bhushan, B. (2000). Frictional heating and contact temperatures *Modern Tribology Handbook, Two Volume Set* (pp. 257-294): CRC Press.

Bouffioux, C., Lequesne, C., Vanhove, H., Duflou, J., Pouteau, P., Duchêne, L., and Habraken, A. (2011). Experimental and numerical study of an AlMgSc sheet formed by an incremental process. *Journal of Materials Processing Technology, 211* (11), 1684-1693.

Breyfogle III, F. W. (2003). *Implementing six sigma: smarter solutions using statistical methods*: John Wiley & Sons.

Buffa, G., Campanella, D., and Fratini, L. (2013a). On the improvement of material formability in SPIF operation through tool stirring action. *The International Journal of Advanced Manufacturing Technology, 66* (9-12), 1343-1351.

Buffa, G., Campanella, D., and Fratini, L. (2013b). On the improvement of material formability in SPIF operation through tool stirring action. *The International Journal of Advanced Manufacturing Technology*, 1-9.

Campbell, F. C. (2012). *Lightweight Materials: Understanding the Basics*: ASM International.

Cao, J., Xia, Z., Gutowski, T., and Roth, J. (2012). A hybrid forming system: electrical-assisted double side incremental forming (EADSIF) process for enhanced formability and geometrical flexibility. *Northwestern University, Document ID: DE-EE0003460*

Cao, T., Lu, B., Xu, D., Zhang, H., Chen, J., Long, H., and Cao, J. (2015). An efficient method for thickness prediction in multi-pass incremental sheet forming. *The International Journal of Advanced Manufacturing Technology, 77* (1-4), 469-483.

Centeno, G., Bagudanch, I., Martínez-Donaire, A., Garcia-Romeu, M. L., and Vallellano, C. (2014). Critical analysis of necking and fracture limit strains and forming forces in single-point incremental forming. *Materials & Design, 63*, 20-29.

Christy, T., Murugan, N., and Kumar, S. (2010). A comparative study on the microstructures and mechanical properties of Al 6061 alloy and the MMC Al 6061/TiB2/12p. *Journal of Minerals and Materials Characterization and Engineering, 9* (01), 57.

Davarpanah, M. A., Mirkouei, A., Yu, X., Malhotra, R., and Pilla, S. (2015). Effects of incremental depth and tool rotation on failure modes and microstructural properties in Single Point Incremental Forming of polymers. *Journal of materials processing technology, 222*, 287-300.

Duflou, J., Callebaut, B., Verbert, J., and De Baerdemaeker, H. (2007a). Laser assisted incremental forming: formability and accuracy improvement. *CIRP Annals-Manufacturing Technology, 56* (1), 273-276.

Duflou, J., Callebaut, B., Verbert, J., and De Baerdemaeker, H. (2008). Improved SPIF performance through dynamic local heating. *International Journal of Machine Tools and Manufacture, 48* (5), 543-549.

Duflou, J., Tunckol, Y., Szekeres, A., and Vanherck, P. (2007b). Experimental study on force measurements for single point incremental forming. *Journal of Materials Processing Technology, 189* (1), 65-72.

Duflou, J. R., Szekeres, A., and Vanherck, P. (2005). *Force measurements for single point incremental forming: an experimental study*. Paper presented at the Advanced Materials Research.

Durante, M., Formisano, A., and Langella, A. (2011). Observations on the influence of tool-sheet contact conditions on an incremental forming process. *Journal of materials engineering and performance, 20* (6), 941-946.

Durante, M., Formisano, A., Langella, A., and Minutolo, F. M. C. (2009). The influence of tool rotation on an incremental forming process. *Journal of Materials Processing Technology, 209* (9), 4621-4626.

Emmens, W., Boogaard, A., and Weijde, D. (2009). The FLC, enhanced fromavbility, and incremental sheet forming.

Emmens, W., and Van den Boogaard, A. (2009). An overview of stabilizing deformation mechanisms in incremental sheet forming. *Journal of Materials Processing Technology, 209* (8), 3688-3695.

Essa, K., and Hartley, P. (2011). An assessment of various process strategies for improving precision in single point incremental forming. *International journal of material forming, 4* (4), 401-412.

Fan, G., and Gao, L. (2014a). Mechanical property of Ti-6Al-4V sheet in one-sided electric hot incremental forming. *The International Journal of Advanced Manufacturing Technology, 72* (5-8), 989-994.

Fan, G., and Gao, L. (2014b). Numerical simulation and experimental investigation to improve the dimensional accuracy in electric hot incremental forming of Ti–6Al–4V titanium sheet. *The International Journal of Advanced Manufacturing Technology, 72* (5-8), 1133-1141.

Fan, G., Gao, L., Hussain, G., and Wu, Z. (2008). Electric hot incremental forming: a novel technique. *International Journal of Machine Tools and Manufacture, 48* (15), 1688-1692.

Fan, G., Sun, F., Meng, X., Gao, L., and Tong, G. (2010). Electric hot incremental forming of Ti-6Al-4V titanium sheet. *The International Journal of Advanced Manufacturing Technology, 49* (9), 941-947.

Fang, Y., Lu, B., Chen, J., Xu, D., and Ou, H. (2014). Analytical and experimental investigations on deformation mechanism and fracture behavior in single point incremental forming. *Journal of Materials Processing Technology, 214* (8), 1503-1515.

Figueiredo, L., Ramalho, A., Oliveira, M., and Menezes, L. (2011). Experimental study of friction in sheet metal forming. *Wear, 271* (9), 1651-1657.

Filice, L., Ambrogio, G., and Gaudioso, M. (2013). Optimised tool-path design to reduce thinning in incremental sheet forming process. *International journal of material forming*, 1-6.

Filice, L., Ambrogio, G., and Micari, F. (2006). On-line control of single point incremental forming operations through punch force monitoring. *CIRP Annals-Manufacturing Technology, 55* (1), 245-248.

Filice, L., Fratini, L., and Micari, F. (2002). Analysis of material formability in incremental forming. *CIRP annals-Manufacturing technology, 51* (1), 199-202.

Fratini, L., Ambrogio, G., Di Lorenzo, R., Filice, L., and Micari, F. (2004). Influence of mechanical properties of the sheet material on formability in single point incremental forming. *CIRP Annals-Manufacturing Technology, 53* (1), 207-210.

Frolova, A., and Stolyarov, V. (2013). Effect of pulse current on deformability, structure, and properties of NbTi alloy superconductor. *Journal of Machinery Manufacture and Reliability, 42* (4), 325-330.

Gaitonde, V., Karnik, S., Achyutha, B., Siddeswarappa, B., and Davim, J. P. (2009). Predicting burr size in drilling of AISI 316L stainless steel using response surface analysis. *International Journal of Materials and Product Technology, 35* (1-2), 228-245.

Galdos, L., Sáenz de Argandoña, E., Ulacia, I., and Arruebarrena, G. (2012). *Warm incremental forming of magnesium alloys using hot fluid as heating media.* Paper presented at the Key Engineering Materials.

Gatea, S., Ou, H., and McCartney, G. (2016). Review on the influence of process parameters in incremental sheet forming. *International Journal of Advanced Manufacturing Technology, 87* (1), 479-499.

Giuseppina, A., Claudio, C., Luigino, F., and Francesco, G. (2016). Theoretical model for temperature prediction in Incremental Sheet Forming–Experimental validation. *International Journal of Mechanical Sciences, 108*, 39-48.

Gologlu, C., and Sakarya, N. (2008). The effects of cutter path strategies on surface roughness of pocket milling of 1.2738 steel based on Taguchi method. *Journal of materials processing technology, 206* (1), 7-15.

Göttmann, A., Bailly, D., Bergweiler, G., Bambach, M., Stollenwerk, J., Hirt, G., and Loosen, P. (2013). A novel approach for temperature control in ISF supported by laser and resistance heating. *The International Journal of Advanced Manufacturing Technology, 67* (9-12), 2195-2205.

Göttmann, A., Diettrich, J., Bergweiler, G., Bambach, M., Hirt, G., Loosen, P., and Poprawe, R. (2011). Laser-assisted asymmetric incremental sheet forming of titanium sheet metal parts. *Production Engineering, 5* (3), 263-271.

Hagan, E., and Jeswiet, J. (2003). A review of conventional and modern single-point sheet metal forming methods. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 217* (2), 213-225.

Hagan, E., and Jeswiet, J. (2004). Analysis of surface roughness for parts formed by computer numerical controlled incremental forming. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 218* (10), 1307-1312.

Ham, M., and Jeswiet, J. (2006). Single point incremental forming and the forming criteria for AA3003. *CIRP Annals-Manufacturing Technology, 55* (1), 241-244.

Ham, M., and Jeswiet, J. (2007). Forming limit curves in single point incremental forming. *CIRP Annals-Manufacturing Technology, 56* (1), 277-280.

Ham, M., and Jeswiet, J. (2008a). Dimensional accuracy of single point incremental forming. *International journal of material forming, 1*, 1171-1174.

Ham, M., and Jeswiet, J. (2008b). Single point incremental forming. *International Journal of Materials and Product Technology, 32* (4), 374-387.

Hamilton, K., and Jeswiet, J. (2010). Single point incremental forming at high feed rates and rotational speeds: Surface and structural consequences. *CIRP Annals-Manufacturing Technology, 59* (1), 311-314.

Henrard, C., Bouffioux, C., Eyckens, P., Sol, H., Duflou, J., Van Houtte, P., Van Bael, A., Duchene, L., and Habraken, A. (2011). Forming forces in single point incremental forming: prediction by finite element simulations, validation and sensitivity. *Computational mechanics, 47* (5), 573-590.

Hino, R., Kawabata, K., and Yoshida, F. (2014). Incremental forming with local heating by laser irradiation for magnesium alloy sheet. *Procedia Engineering, 81*, 2330-2335.

Hölscher, H., Schirmeisen, A., and Schwarz, U. D. (2008). Principles of atomic friction: from sticking atoms to superlubric sliding. *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences, 366* (1869), 1383-1404.

Honarpisheh, M., Abdolhoseini, M., and Amini, S. (2016). Experimental and numerical investigation of the hot incremental forming of Ti-6Al-4V sheet using electrical current. *The International Journal of Advanced Manufacturing Technology, 83* (9-12), 2027-2037.

Hussain, G., Dar, N., Gao, L., and Chen, M. (2007a). A comparative study on the forming limits of an aluminum sheet-metal in negative incremental forming. *Journal of Materials Processing Technology, 187*, 94-98.

Hussain, G., and Gao, L. (2007). A novel method to test the thinning limits of sheet metals in negative incremental forming. *International Journal of Machine Tools and Manufacture, 47* (3), 419-435.

Hussain, G., Gao, L., and Dar, N. (2007b). An experimental study on some formability evaluation methods in negative incremental forming. *Journal of Materials Processing Technology, 186* (1), 45-53.

Hussain, G., Gao, L., and Hayat, N. (2011). Forming parameters and forming defects in incremental forming of an aluminum sheet: correlation, empirical modeling, and optimization: part A. *Materials and Manufacturing Processes, 26* (12), 1546-1553.

Hussain, G., Gao, L., Hayat, N., Cui, Z., Pang, Y., and Dar, N. (2008a). Tool and lubrication for negative incremental forming of a commercially pure titanium sheet. *Journal of Materials Processing Technology, 203* (1), 193-201.

Hussain, G., Gao, L., Hayat, N., and Dar, N. (2010). The formability of annealed and pre-aged AA-2024 sheets in single-point incremental forming. *The International Journal of Advanced Manufacturing Technology, 46* (5), 543-549.

Hussain, G., Gao, L., and Zhang, Z. (2008b). Formability evaluation of a pure titanium sheet in the cold incremental forming process. *The International Journal of Advanced Manufacturing Technology, 37* (9), 920-926.

Hussain, G., Hayat, N., and Gao, L. (2008c). An experimental study on the effect of thinning band on the sheet formability in negative incremental forming. *International Journal of Machine Tools and Manufacture, 48* (10), 1170-1178.

Hussain, G., Hayat, N., and Lin, G. (2012). Pyramid as test geometry to evaluate formability in incremental forming: Recent results. *Journal of mechanical science and technology, 26* (8), 2337-2345.

Hussain, G., Khan, H., Gao, L., and Hayat, N. (2013). Guidelines for tool-size selection for single-point incremental forming of an aerospace alloy. *Materials and Manufacturing Processes, 28* (3), 324-329.

Ingarao, G., Di Lorenzo, R., and Micari, F. (2011). Sustainability issues in sheet metal forming processes: an overview. *Journal of Cleaner Production, 19* (4), 337-347.

Ingarao, G., Vanhove, H., Kellens, K., and Duflou, J. R. (2014). A comprehensive analysis of electric energy consumption of single point incremental forming processes. *Journal of Cleaner Production, 67*, 173-186.

Isidore, B. L., Hussain, G., Shamchi, S. P., and Khan, W. A. (2016). Prediction and control of pillow defect in single point incremental forming using numerical simulations. *Journal of Mechanical Science and Technology, 30* (5), 2151-2161.

Jeswiet, J., Adams, D., Doolan, M., McAnulty, T., and Gupta, P. (2015). Single point and asymmetric incremental forming. *Advances in Manufacturing, 3* (4), 253-262.

Jeswiet, J., Duflou, J. R., and Szekeres, A. (2005a). *Forces in single point and two point incremental forming.* Paper presented at the Advanced Materials Research.

Jeswiet, J., Geiger, M., Engel, U., Kleiner, M., Schikorra, M., Duflou, J., Neugebauer, R., Bariani, P., and Bruschi, S. (2008). Metal forming progress since 2000. *CIRP Journal of Manufacturing Science and Technology, 1* (1), 2-17.

Jeswiet, J., and Hagan, E. (2004). Analysis of surface roughness for parts formed by computer numerical controlled incremental forming. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 218* (10), 1307-1312.

Jeswiet, J., Micari, F., Hirt, G., Bramley, A., Duflou, J., and Allwood, J. (2005b). Asymmetric Single Point Incremental Forming of Sheet Metal. *CIRP Annals - Manufacturing Technology, 54* (2), 88-114.

Jeswiet, J., Micari, F., Hirt, G., Bramley, A., Duflou, J., and Allwood, J. (2005c). Asymmetric single point incremental forming of sheet metal. *CIRP Annals-Manufacturing Technology, 54* (2), 88-114.

Ji, Y., and Park, J. (2008). Formability of magnesium AZ31 sheet in the incremental forming at warm temperature. *Journal of materials processing technology, 201* (1), 354-358.

Jones, J. J., and Mears, L. (2013). Thermal response modeling of sheet metals in uniaxial tension during electrically-assisted forming. *Journal of Manufacturing Science and Engineering, 135* (2), 021011.

Kalpakjian, S., and Schmid, S. (2008). Manufacture Processes for Engineering Materials. *Chapter, 2*, 52-53.

Keeler, S. P., and Backofen, W. A. (1963). Plastic instability and fracture in sheets stretched over rigid punches. *Asm Trans Q, 56* (1), 25-48.

Kegg, R. L. (1961). A new test method for determination of spinnability of metals. *Transactions of the ASME, Journal of Engineering for Industry, 83*, 119-124.

Khazaali, H. (2014). Determining frustum depth of 304 stainless steel plates with various diameters and thicknesses by incremental forming. *Journal of Mechanical Science and Technology, 28* (8), 3273-3278.

Kleiner, M., Geiger, M., and Klaus, A. (2003). Manufacturing of lightweight components by metal forming. *CIRP Annals-Manufacturing Technology, 52* (2), 521-542.

Krajnik, P., Kopac, J., and Sluga, A. (2005). Design of grinding factors based on response surface methodology. *Journal of Materials Processing Technology, 162*, 629-636.

Lasunon, O. U. (2013). *Surface roughness in incremental sheet metal forming of AA5052*. Paper presented at the Advanced Materials Research.

Le, V., Ghiotti, A., and Lucchetta, G. (2008). Preliminary studies on single point incremental forming for thermoplastic materials. *International Journal of Material Forming, 1*, 1179-1182.

Le, V. S. (2009). MODELING OF SINGLE POINT INCREMENTAL FORMING PROCESS FOR METAL AND POLYMERIC SHEET.

León, J., Salcedo, D., Ciáurriz, C., Luis, C., Fuertes, J., Puertas, I., and Luri, R. (2013). Analysis of the influence of geometrical parameters on the mechanical properties of incremental sheet forming parts. *Procedia Engineering, 63*, 445-453.

Leszak, E. (1967). Apparatus and process for incremental dieless forming: Google Patents.

Li, C., Jiang, S., and Zhang, K. (2012a). Pulse current-assisted hot-forming of light metal alloy. *The International Journal of Advanced Manufacturing Technology, 63* (9), 931-938.

Li, C., Zhang, K., Jiang, S., and Zhao, Z. (2012b). Pulse current auxiliary bulging and deformation mechanism of AZ31 magnesium alloy. *Materials & Design, 34*, 170-178.

Li, M., Feng, C., Zhang, Z., Liu, X., Ma, W., Xue, Q., and Sugiura, N. (2011). Optimization of electrochemical ammonia removal using Box–Behnken design. *Journal of electroanalytical chemistry, 657* (1), 66-73.

Li, X., Zhou, Q., Zhao, S., and Chen, J. (2014a). Effect of pulse current on bending behavior of Ti6Al4V alloy. *Procedia Engineering, 81*, 1799-1804.

Li, Y., Daniel, W. J., Liu, Z., Lu, H., and Meehan, P. A. (2015). Deformation mechanics and efficient force prediction in single point incremental forming. *Journal of Materials Processing Technology, 221*, 100-111.

Li, Y., Liu, Z., Daniel, W., and Meehan, P. (2014b). Simulation and experimental observations of effect of different contact interfaces on the incremental sheet forming process. *Materials and Manufacturing Processes, 29* (2), 121-128.

Li, Y., Liu, Z., Lu, H., Daniel, W. B., Liu, S., and Meehan, P. A. (2014c). Efficient force prediction for incremental sheet forming and experimental validation. *The International Journal of Advanced Manufacturing Technology, 73* (1-4), 571-587.

Li, Y. L., Liu, Z. B., Lu, H. B., Daniel, W., and Meehan, P. A. (2014d). *Experimental study and efficient prediction on forming forces in incremental sheet forming*. Paper presented at the Advanced Materials Research.

Liu, Z. (2017). Friction stir incremental forming of AA7075-O sheets: investigation on process feasibility. *Procedia Engineering, 207*, 783-788.

Liu, Z., Li, Y., and Meehan, P. A. (2013). Experimental investigation of mechanical properties, formability and force measurement for AA7075-O aluminum alloy sheets formed by incremental forming. *International Journal of Precision Engineering and Manufacturing, 14* (11), 1891-1899.

Liu, Z., Liu, S., Li, Y., and Meehan, P. A. (2014a). Modeling and optimization of surface roughness in incremental sheet forming using a multi-objective function. *Materials and Manufacturing Processes, 29* (7), 808-818.

Liu, Z. B., Li, Y. L., Daniel, W., and Meehan, P. (2014b). *Taguchi optimization of process parameters for forming time in incremental sheet forming process.* Paper presented at the Mater. Sci. Forum.

Lu, B., Chen, J., Ou, H., and Cao, J. (2013). Feature-based tool path generation approach for incremental sheet forming process. *Journal of Materials Processing Technology, 213* (7), 1221-1233.

Lu, B., Fang, Y., Xu, D., Chen, J., Ou, H., Moser, N., and Cao, J. (2014). Mechanism investigation of friction-related effects in single point incremental forming using a developed oblique roller-ball tool. *International Journal of Machine Tools and Manufacture, 85*, 14-29.

Manco, G., and Ambrogio, G. (2010). Influence of thickness on formability in 6082-T6. *International Journal of Material Forming, 3*, 983-986.

Marques, T. A., Silva, M. B., and Martins, P. (2012). On the potential of single point incremental forming of sheet polymer parts. *The International Journal of Advanced Manufacturing Technology, 60* (1-4), 75-86.

Martínez-Romero, O., García-Romeu, M. L., Olvera-Trejo, D., Bagudanch, I., and Elías-Zúñiga, A. (2014). Tool Dynamics During Single Point Incremental Forming Process. *Procedia Engineering, 81*, 2286-2291.

McAnulty, T., Jeswiet, J., and Doolan, M. (2017). Formability in single point incremental forming: A comparative analysis of the state of the art. *CIRP Journal of Manufacturing Science and Technology, 16*, 43-54.

Meier, H., Zhu, J., Buff, B., and Laurischkat, R. (2012). CAx process chain for two robots based incremental sheet metal forming. *Procedia CIRP, 3*, 37-42.

Micari, F. (2004). *Single point incremental forming: recent results.* Paper presented at the Seminar on Incremental forming.

Micari, F., Ambrogio, G., and Filice, L. (2007). Shape and dimensional accuracy in single point incremental forming: state of the art and future trends. *Journal of Materials Processing Technology, 191* (1), 390-395.

Milutinovića, M., Potranb, R. L. M., Vilotića, D., Skakuna, P., and Plančaka, M. (2014). Application of single point incremental forming for manufacturing of denture base. *Journal for Technology of Plasticity, 39* (2)

Mishra, R. S., De, P. S., and Kumar, N. (2014). *Friction stir welding and processing: science and engineering*: Springer.

Mugendiran, V., Gnanavelbabu, A., and Ramadoss, R. (2014). Parameter optimization for surface roughness and wall thickness on AA5052 Aluminium alloy by incremental forming using response surface methodology. *Procedia Engineering, 97*, 1991-2000.

Myers, R. H., Montgomery, D. C., and Anderson-Cook, C. M. (2016). *Response Surface Methodology: Process and Product Optimization Using Designed Experiments*: Wiley.

Najafabady, S. A., and Ghaei, A. (2016). An experimental study on dimensional accuracy, surface quality, and hardness of Ti-6Al-4 V titanium alloy sheet in hot incremental forming. *The International Journal of Advanced Manufacturing Technology, 87* (9-12), 3579-3588.

Nee, A. Y. (2015). *Handbook of manufacturing engineering and technology*: Springer London: Imprint: Springer.

Neugebauer, R., Altan, T., Geiger, M., Kleiner, M., and Sterzing, A. (2006). Sheet metal forming at elevated temperatures. *CIRP Annals-Manufacturing Technology, 55* (2), 793-816.

Neugebauer, R., Bouzakis, K.-D., Denkena, B., Klocke, F., Sterzing, A., Tekkaya, A., and Wertheim, R. (2011). Velocity effects in metal forming and machining processes. *CIRP Annals-Manufacturing Technology, 60* (2), 627-650.

Obikawa, T., Satou, S., and Hakutani, T. (2009). Dieless incremental micro-forming of miniature shell objects of aluminum foils. *International Journal of Machine Tools and Manufacture, 49* (12), 906-915.

Oleksik, V., Pascu, A., Deac, C., Fleacă, R., Bologa, O., and Racz, G. (2010). Experimental study on the surface quality of the medical implants obtained by single point incremental forming. *International Journal of Material Forming, 3*, 935-938.

Otsu, M., Ichikawa, T., Matsuda, M., and Takashima, K. (2011). Formabilities of AZ 31, AZ 61 and AZ 80 Magnesium Alloy Sheets and Mechanical Properties of Formed Parts by Friction Stir Incremental Forming-Development of Friction Stir Incremental Forming 2 nd Report. *Journal of the Japan Society for Technology of Plasticity, 52* (605), 705-709.

Otsu, M., Katayama, Y., and Muranaka, T. (2014). *Effect of Difference of tool rotation direction on forming limit in friction stir incremental forming.* Paper presented at the Key Engineering Materials.

Otsu, M., Matsuo, H., Matsuda, M., and Takashima, K. (2010). Friction stir incremental forming of aluminum alloy sheets. *Steel Research International, 81* (9), 942-945.

Ozturk, F., Ece, R. E., Polat, N., Koksal, A., Evis, Z., and Polat, A. (2013). Mechanical and microstructural evaluations of hot formed titanium sheets by electrical resistance heating process. *Materials Science and Engineering: A, 578*, 207-214.

Palumbo, G., and Brandizzi, M. (2012). Experimental investigations on the single point incremental forming of a titanium alloy component combining static heating with high tool rotation speed. *Materials & Design, 40*, 43-51.

Park, J.-J., and Kim, Y.-H. (2003). Fundamental studies on the incremental sheet metal forming technique. *Journal of Materials Processing Technology, 140* (1), 447-453.

Park, J., Kim, J., Park, N., and Kim, Y. (2009). Study of Forming Limit for Rotational Incremental Sheet Forming of Magnesium Alloy Sheet. *Metallurgical and Materials Transactions A, 41* (1), 97-105.

Penalva Oscoz, M., Zettler, J., and Papadopoulos, M. P. (2011). Innovative manufacturing of complex Ti sheet components (INMA). *International Journal of Structural Integrity, 2* (4)

Petek, A., Kuzman, K., and Kopac, J. (2009). Deformations and forces analysis of single point incremental sheet metal forming. *Archives of Materials science and Engineering, 35* (2), 35-42.

Rauch, M., Hascoet, J.-Y., Hamann, J.-C., and Plenel, Y. (2009). Tool path programming optimization for incremental sheet forming applications. *Computer-Aided Design, 41* (12), 877-885.

Reddy, N. V., and Cao, J. (2009). Incremental sheet metal forming: A review. *Department of Mechanical Engineering, Indian Institute of Technology Kanpur, Kanpur, India. nvr@ iitk. ac. in*

Ren, H., Moser, N., Zhang, Z., Ndip-Agbor, E., Smith, J., Ehmann, K. F., and Cao, J. (2015). Effects of Tool Positions in Accumulated Double-Sided Incremental Forming on Part Geometry. *Journal of Manufacturing Science and Engineering, 137* (5), 051008.

Salandro, W. A., Bunget, C. J., and Mears, L. (2011). Several factors affecting the electroplastic effect during an electrically-assisted forming process. *Journal of Manufacturing Science and Engineering, 133* (6), 064503.

Sarraji, W. K., Hussain, J., and Ren, W.-X. (2012). Experimental investigations on forming time in negative incremental sheet metal forming process. *Materials and Manufacturing Processes, 27* (5), 499-506.

Schaeffer, L., Castelan, J., Gruber, V., Daleffe, A., and Marcelino, R. (2009). *Development of customized products through the use of incremental sheet forming for medical orthopaedic applications.* Paper presented at the 3rd International Conference on Integrity, Reliability and Failure, Porto/Portugal.

Shanmuganatan, S., and Kumar, V. S. (2013). Metallurgical analysis and finite element modelling for thinning characteristics of profile forming on circular cup. *Materials & Design, 44*, 208-215.

Silva, M., Alves, L., and Martins, P. (2010). Single point incremental forming of PVC: Experimental findings and theoretical interpretation. *European journal of mechanics-A/Solids, 29* (4), 557-566.

Silva, M., Skjødt, M., Atkins, A., Bay, N., and Martins, P. (2008). Single- point incremental forming and formability—failure diagrams. *The journal of strain analysis for engineering design, 43* (1), 15-35.

Silva, M., Skjødt, M., Bay, N., and Martins, P. (2009a). Revisiting single-point incremental forming and formability/failure diagrams by means of finite elements and experimentation. *The Journal of Strain Analysis for Engineering Design, 44* (4), 221-234.

Silva, M., Skjødt, M., Martins, P. A., and Bay, N. (2009b). *Single point incremental forming of metal sheets.* Paper presented at the Annual Winter Meeting of Danish Society for Metallurgy, Jutland, Denmark.

Silva, M. B., Nielsen, P. S., Bay, N., and Martins, P. A. (2011). Failure mechanisms in single-point incremental forming of metals. *The International Journal of Advanced Manufacturing Technology, 56* (9-12), 893-903.

Silva, P. J., Leodido, L. M., and Silva, C. R. M. (2013). *Analysis of incremental sheet forming parameters and tools aimed at rapid prototyping.* Paper presented at the Key Engineering Materials.

Skjødt, M. (2008). *Rapid Prototyping by Single Point Incremental Forming of Sheet Metal*.

Skjødt, M., Hancock, M. H., and Bay, N. (2007). *Creating helical tool paths for single point incremental forming.* Paper presented at the Key Engineering Materials.

Sortais, H. C., Kobayashi, S., and Thomsen, E. G. (1963). Mechanics of Conventional Spinning. *Journal of Engineering for Industry, 85* (4), 346-350.

Suresh, K., Khan, A., and Regalla, S. P. (2013). Tool path definition for numerical simulation of single point incremental forming. *Procedia Engineering, 64*, 536-545.

Suriyaprakan, P. (2014). Single point incremental forming and multi-stage incremental forming on aluminium alloy 1050.

Swamy, N. P., Ramesh, C., and Chandrashekar, T. (2010). Effect of heat treatment on strength and abrasive wear behaviour of Al6061-SiCp composites. *Bull. Mater. Sci, 33* (1), 49-54.

Tian, X., Kennedy, F., Deacutis, J., and Henning, A. (1992). The development and use of thin film thermocouples for contact temperature measurement. *Tribology Transactions, 35* (3), 491-499.

Tian, X., and Kennedy, F. E. (1994). Maximum and average flash temperatures in sliding contacts. *Journal of tribology, 116* (1), 167-174.

Tisza, M., Kovács, P. Z., and Lukács, Z. (2012). *Preliminary studies on the determination of FLD for single point incremental sheet metal forming.* Paper presented at the Key Engineering Materials.

Troitskii, O. (1978). *Electroplastic drawing of steel, copper and tungsten.* Paper presented at the Dokl. Akad. Nauk SSSR.

Troitskii, O., and Likhtman, V. (1963). *The Anisotropy of the Action of Electron and gamma Radiation on the Deformation of Zinc Single Crystals in the Brittle State.* Paper presented at the Soviet Physics Doklady.

Uheida, E. H. A. (2017). *Development and optimisation of incremental sheet forming of titanium grade 2: process mapping.* Stellenbosch: Stellenbosch University.

Uppaluri, R., Reddy, N. V., and Dixit, P. (2011). An analytical approach for the prediction of forming limit curves subjected to combined strain paths. *International Journal of Mechanical Sciences, 53* (5), 365-373.

Villeta, M., Rubio, E., De Pipaón, J. S., and Sebastián, M. (2011). Surface finish optimization of magnesium pieces obtained by dry turning based on Taguchi techniques and statistical tests. *Materials and Manufacturing Processes, 26* (12), 1503-1510.

Wang, J., Li, L., and Jiang, H. (2016a). Effects of forming parameters on temperature in frictional stir incremental sheet forming. *Journal of Mechanical Science and Technology, 30* (5), 2163-2169.

Wang, J., Nair, M., and Zhang, Y. (2016b). An efficient force prediction strategy for single point incremental sheet forming. *The International Journal of Advanced Manufacturing Technology*, 1-9.

Wang, J., Nair, M., and Zhang, Y. (2016c). An Efficient Force Prediction Strategy in Single Point Incremental Sheet Forming. *Procedia Manufacturing, 5*, 761-771.

Xu, D., Lu, B., Cao, T., Chen, J., Long, H., and Cao, J. (2014). A comparative study on process potentials for frictional stir-and electric hot-assisted incremental sheet forming. *Procedia Engineering, 81*, 2324-2329.

Xu, D., Wu, W., Malhotra, R., Chen, J., Lu, B., and Cao, J. (2013). Mechanism investigation for the influence of tool rotation and laser surface texturing (LST) on formability in single point incremental forming. *International Journal of Machine Tools and Manufacture, 73*, 37-46.

Yamashita, M., Gotoh, M., and Atsumi, S.-Y. (2008). Numerical simulation of incremental forming of sheet metal. *Journal of materials processing technology, 199* (1), 163-172.

Yanagimoto, J., Oyamada, K., and Nakagawa, T. (2005). Springback of high-strength steel after hot and warm sheet formings. *CIRP Annals-Manufacturing Technology, 54* (1), 213-216.

Yuan, M., Yang, Y., Li, C., Heng, P., and Li, L. (2012). Numerical analysis of the stress–strain distributions in the particle reinforced metal matrix composite SiC/6064Al. *Materials & Design, 38*, 1-6.

Zhang, Q., Guo, H., Xiao, F., Gao, L., Bondarev, A., and Han, W. (2009). Influence of anisotropy of the magnesium alloy AZ31 sheets on warm negative incremental forming. *Journal of Materials Processing Technology, 209* (15), 5514-5520.

Zhang, Q., Xiao, F., Guo, H., Li, C., Gao, L., Guo, X., Han, W., and Bondarev, A. (2010). Warm negative incremental forming of magnesium alloy AZ31 Sheet: New lubricating method. *Journal of Materials Processing Technology, 210* (2), 323-329.

Zhu, H., Liu, Z., and Fu, J. (2011). Spiral tool-path generation with constant scallop height for sheet metal CNC incremental forming. *The International Journal of Advanced Manufacturing Technology, 54* (9), 911-919.

Ziran, X., Gao, L., Hussain, G., and Cui, Z. (2010). The performance of flat end and hemispherical end tools in single-point incremental forming. *The International Journal of Advanced Manufacturing Technology, 46* (9), 1113-1118.