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

QASIM MHALHAL AZPEN

FK 2018 101
FRICITION-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
All material contained within the thesis, including without limitation text, logos, icons, photographs and all other artwork, is copyright material of Universiti Putra Malaysia unless otherwise stated. Use may be made of any material contained within the thesis for non-commercial purposes from the copyright holder. Commercial use of material may only be made with the express, prior, written permission of Universiti Putra Malaysia.

Copyright © Universiti Putra Malaysia
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 AA6060-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° and 48°; 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 keperluan 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° dan 48°; 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

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

Zulkifilie 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

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>i</td>
</tr>
<tr>
<td>ABSTRAK</td>
<td>iii</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td>v</td>
</tr>
<tr>
<td>APPROVAL</td>
<td>vi</td>
</tr>
<tr>
<td>DECLARATION</td>
<td>viii</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>xiii</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>xv</td>
</tr>
<tr>
<td>LIST OF SYMBOLS</td>
<td>xx</td>
</tr>
<tr>
<td>LIST OF ABBREVIATIONS</td>
<td>xxii</td>
</tr>
</tbody>
</table>

## CHAPTER

1 INTRODUCTION

1.1 Overview                                      1
1.2 Problem Statement                             4
1.3 Thesis Objectives:                            5
1.4 Significant of Study                         6
1.5 Scope and Limitations of the Study           7
    1.5.1 Scope                                     7
    1.5.2 Limitations                              7
1.6 Thesis outline                                7

2 LITERATURE REVIEW

2.1 Introduction                                   9
2.2 Single Point Incremental Forming              10
2.3 Theoretical background of SPIF Process.      11
    2.3.1 Forming limits                           11
    2.3.2 Deformation Mechanism                   15
    2.3.3 Forming Forces                           17
    2.3.4 Heat generation                          20
        2.3.4.1 Flash temperature estimation       22
2.4 Heat-assisted SPIF methods                    24
    2.4.1 Frictional Stir-Assisted SPIF           25
        2.4.1.1 Process Formability                26
        2.4.1.2 Forming Forces                     32
        2.4.1.3 Surface Roughness                  35
        2.4.1.4 Geometric Accuracy                 39
        2.4.1.5 Forming Time                       40
2.4.2 Heat Assisted-Electric SPIF
   2.4.2.1 Electric Hot Incremental Forming (EHIF)
   2.4.2.2 Electropulse-assisted incremental forming (EAIF)
   2.4.2.3 Induction Heating Assisted SPIF
2.4.3 Laser-Assisted SPIF

2.5 Summary

3 METHODOLOGY
   3.1 Introduction
   3.2 Materials Characterization
   3.3 Experimental Components and Setup of the Test Platform
      3.3.1 Forming Jig
      3.3.2 Forming Tools
      3.3.3 CNC Forming Machine
      3.3.4 Test Benchmark
      3.3.5 Tool Path Generation
      3.3.6 Sheet Specimens for SPIF Experiments
      3.3.7 Lubricant
   3.4 Design of Experiment
   3.5 Procedures and Equipment for Data Acquirement
      3.5.1 Calculating the Forming Wall Angle
      3.5.2 Measuring the Product Depth
      3.5.3 Measuring the Product Thickness
      3.5.4 Measuring the Forming Force
      3.5.5 Measuring the Surface Roughness
      3.5.6 Estimation of flash interface temperature
   3.6 Summary

4 RESULTS AND DISCUSSION
   4.1 Introduction
   4.2 Materials Characterization
   4.3 Experimental Results and Analysis
      4.3.1 Aluminum Alloy AA6061-T6
         4.3.1.1 Formability
         4.3.1.2 Forming Forces
         4.3.1.3 Surface Roughness
         4.3.1.4 Estimation of flash interface temperature
         4.3.1.5 Summary
      4.3.2 Composite Material AA6061/20%SiCp-T1
         4.3.2.1 Estimation of flash interface temperature
         4.3.2.2 Summary
4.4 Results Comparison for the Two Materials 101
   4.4.1 Formability 102
   4.4.2 Forming Forces 104
   4.4.3 Surface Roughness 106
4.5 Summary 107

5 CONCLUSION AND RECOMMENDATION FOR FUTURE RESEARCH 108
   5.1 Conclusions 108
   5.2 Research Contribution 109
   5.3 Future Work 110

REFERENCES 111
APPENDICES 129
BIODATA OF STUDENT 138
PUBLICATIONS 139
## LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Advantages and disadvantages of sheet metal forming processes</td>
</tr>
<tr>
<td>2.2</td>
<td>Stresses and strains states via SPIF and conventional stamping processes</td>
</tr>
<tr>
<td>3.1</td>
<td>Process parameters and their levels</td>
</tr>
<tr>
<td>3.2</td>
<td>Orthogonal array L8 (4^1.2^3) of the experimental runs</td>
</tr>
<tr>
<td>4.1</td>
<td>Thermal and physical properties of the materials</td>
</tr>
<tr>
<td>4.2</td>
<td>Chemical composition (%) of the two materials</td>
</tr>
<tr>
<td>4.3</td>
<td>Orthogonal array L8 (4^1.2^3) and the formability results</td>
</tr>
<tr>
<td>4.4</td>
<td>Analysis of variance for the wall angle</td>
</tr>
<tr>
<td>4.5</td>
<td>Analysis of variance for the height</td>
</tr>
<tr>
<td>4.6</td>
<td>Analysis of variance for the thinning effect</td>
</tr>
<tr>
<td>4.7</td>
<td>Statistical results of the developed regression models of the formability indicators</td>
</tr>
<tr>
<td>4.8</td>
<td>Estimation of the coefficient for the wall angle regression</td>
</tr>
<tr>
<td>4.9</td>
<td>Estimation of the coefficient for the height regression</td>
</tr>
<tr>
<td>4.10</td>
<td>Estimation of the coefficient for the thinning effect</td>
</tr>
<tr>
<td>4.11</td>
<td>The DoE matrix, maximum forming forces and resultant forces in the three directions at the peak point</td>
</tr>
<tr>
<td>4.12</td>
<td>Analysis of variance for the Fz_p</td>
</tr>
<tr>
<td>4.13</td>
<td>The DoE matrix and the results for surface roughness and S/N ratios</td>
</tr>
<tr>
<td>4.14</td>
<td>Analysis of variance for the surface roughness</td>
</tr>
<tr>
<td>4.15</td>
<td>Statistical results of the developed regression equation of the surfaces roughness</td>
</tr>
<tr>
<td>4.16</td>
<td>Maximum temperature at the tool- AA6061-T6 sheet interface</td>
</tr>
</tbody>
</table>
4.17 The three formability indicators of the composite material 98
4.18 The maximum axial and resultant forces of the composite material 99
4.19 The experimental results of the surface roughness 99
4.20 Maximum temperature at the tool- AA6061-T6 sheet interface 100
LIST OF FIGURES

Figure | Description | Page
---|---|---
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] | 2
1.2 | Some of the medical parts manufactured by ISF: a) (Bagudanch et al., 2015b), b) (Ambrogio et al., 2005) and c) | 2
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) | 2
1.4 | Some of the intricate parts produced by ISF | 3
2.1 | Single point incremental point | 10
2.2 | Two point incremental forming: a) with partial die and b) with full die | 10
2.3 | Forming limit curves of the various loading patterns (modified from) | 12
2.4 | Geometries of the ISF experimental test for: a) cone frustum and b) pyramid frustum | 13
2.5 | Terminology of the CAD model of the conical frustum part | 14
2.6 | Schematic representation of the Cosine’s law in shear-deformed part | 14
2.7 | Schematic representation of stresses: a) (modified from Bhattacharya et al., 2011) and b) instantaneous deformation zones (modified from Silva et al., 2009b) via SPIF | 16
2.8 | Graphical presentation of the forming forces in SPIF | 18
2.9 | Graphical presentation of the axial, tangential, and radial forces versus the generatrix line of the formed cone made from DCO1 material | 19
2.10 | The schematic presentation of the forming tool paths with the concept of the climb and conventional forming | 22
2.11 | Three steps of two contact asperities | 23
2.12 | The nature of heat generation and utilization in ISF | 24
<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.13</td>
<td>The relationship between maximum forming angle and tool radius-sheet thickness ratio</td>
</tr>
<tr>
<td>2.14</td>
<td>The variation of axial force with: a) tool diameter, b) wall angle, c) incremental depth, and d) sheet thickness</td>
</tr>
<tr>
<td>2.15</td>
<td>Forming forces ($F_z$ and $F_x$) at various tool rotation speeds</td>
</tr>
<tr>
<td>2.16</td>
<td>The relationship between surface roughness and the forming tool diameter at different step sizes and wall angle of 20°</td>
</tr>
<tr>
<td>2.17</td>
<td>The relationship between surface roughness and the forming tool diameter at different step sizes and wall angle of 60°</td>
</tr>
<tr>
<td>2.18</td>
<td>Geometrical errors via the SPIF process</td>
</tr>
<tr>
<td>2.19</td>
<td>EHIF introduced by (Fan et al., 2008)</td>
</tr>
<tr>
<td>2.20</td>
<td>Stress-strain curve of Ti6Al4V titanium alloy with and without electroplastic (EP) effect</td>
</tr>
<tr>
<td>2.21</td>
<td>Schematic presentation of (EAIF)</td>
</tr>
<tr>
<td>2.22</td>
<td>Induction heating assisted SPIF</td>
</tr>
<tr>
<td>2.23</td>
<td>Warm incremental forming by heater band</td>
</tr>
<tr>
<td>2.24</td>
<td>Experimental setup for the laser assisted SPIF</td>
</tr>
<tr>
<td>3.1</td>
<td>The flowchart of the study methodology</td>
</tr>
<tr>
<td>3.2</td>
<td>Laser cutting machine</td>
</tr>
<tr>
<td>3.3</td>
<td>Tensile test specimen dimensions (in mm), in CATIA</td>
</tr>
<tr>
<td>3.4</td>
<td>INSTRON universal testing machine</td>
</tr>
<tr>
<td>3.5</td>
<td>Forming jig</td>
</tr>
<tr>
<td>3.6</td>
<td>The hemispherical-end forming tools</td>
</tr>
<tr>
<td>3.7</td>
<td>OKUMA MX-45VA vertical milling machine</td>
</tr>
<tr>
<td>3.8</td>
<td>SPINNER VC450 vertical milling machine</td>
</tr>
<tr>
<td>3.9</td>
<td>Geometric illustration of the truncated cone profile</td>
</tr>
<tr>
<td>3.10</td>
<td>Setting the tool trajectory parameters using CITIA software</td>
</tr>
<tr>
<td>3.11</td>
<td>SPIF specimen dimensions (in mm)</td>
</tr>
<tr>
<td>Section</td>
<td>Description</td>
</tr>
<tr>
<td>---------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>3.12</td>
<td>Samples failed due to use high levels of rotation speeds and feed rates</td>
</tr>
<tr>
<td>3.13</td>
<td>Samples failed due to use a small tool size.</td>
</tr>
<tr>
<td>3.14</td>
<td>Terminology and illustration of the CAD model of the designed part</td>
</tr>
<tr>
<td>3.15</td>
<td>Digital high gauge</td>
</tr>
<tr>
<td>3.16</td>
<td>The cutting of the produced parts into quarter portions: a) top view and b) front view</td>
</tr>
<tr>
<td>3.17</td>
<td>Sawing machine</td>
</tr>
<tr>
<td>3.18</td>
<td>The forces measuring system</td>
</tr>
<tr>
<td>3.19</td>
<td>The surface roughness apparatus</td>
</tr>
<tr>
<td>4.1</td>
<td>The flowchart to navigate the chapter headlines</td>
</tr>
<tr>
<td>4.2</td>
<td>True stress-strain curve of the two material</td>
</tr>
<tr>
<td>4.3</td>
<td>The main effects of $\omega$, $f$, $z$ and $D$ on: a) wall angle, b) height and c) thinning</td>
</tr>
<tr>
<td>4.4</td>
<td>Interaction plots for: a) wall angle, b) height and c) thinning</td>
</tr>
<tr>
<td>4.5</td>
<td>The relationship between: a) wall angle, b) height, and c) thinning and the four parameters</td>
</tr>
<tr>
<td>4.6</td>
<td>Normal probability plot for: a) wall angle, b) height and c) thinning</td>
</tr>
<tr>
<td>4.7</td>
<td>The sample fractured after forming by SPIF: a) outside view and b) inside view</td>
</tr>
<tr>
<td>4.8</td>
<td>The forming forces in the three directions for the cone produced with the run 1</td>
</tr>
<tr>
<td>4.9</td>
<td>The forming forces in the three directions for the cone produced with the run 2 (Fz_p max. (3.81836 KN))</td>
</tr>
<tr>
<td>4.10</td>
<td>The forming forces in the three directions for the cone produced with the run 3</td>
</tr>
<tr>
<td>4.11</td>
<td>The forming forces in the three directions for the cone produced with the run 4</td>
</tr>
</tbody>
</table>
4.12 The forming forces in the three directions $X$, $Y$, and $Z$ for the cone produced with the run 5

4.13 The forming forces in the three directions $X$, $Y$, and $Z$, for the cone produced with the run 6 ($F_{z_p}$ min. (2.44781 KN))

4.14 The forming forces in the three directions for the cone produced with the run 7

4.15 The forming forces in the three directions for the cone produced with the run 8

4.16 The main effects plot for the $F_{z_p}$

4.17 The interactions plot for the $F_{z_p}$

4.18 Graphical representation of the interaction effects on the $F_{z_p}$

4.19 Normal distribution of the $F_{z_p}$

4.20 The main effects graphs of the various factors for the surface roughness

4.21 Main effect plot for SN ratios for the surface roughness

4.22 Graphical representation of the interaction effects of the various factors on the surface roughness

4.23 Normal distribution of the surface roughness

4.24 The main effects graphs of the various factors on the maximum temperature

4.25 The forming forces in the three directions for the cone produced from the composite material according to run 5

4.26 The forming forces in the three directions for the cone produced from the composite material according to run 6

4.27 The forming forces in the three directions for the cone produced from the composite material according to run 7

4.28 The forming forces in the three directions for the cone produced from the composite material according to run 8

4.29 The composite sample fractured after forming by SPIF: a) outside view and b) inside view

4.30 The main effects graphs of the various factors on the maximum temperature
4.31 Comparison between the maximum forming angles obtained for both materials 102
4.32 Comparison between the maximum heights obtained for both materials in the experiments 103
4.33 Comparison between the thinning rates obtained in both materials 103
4.34 Thinning in the aluminum samples: a) cut formed cone and b) thinning section 104
4.35 Thinning in the composite samples: a) cut formed cone and b) thinning section 104
4.36 Comparison between Fz_p obtained for both materials 105
4.37 Comparison between Fxy obtained for both materials 105
4.38 Comparison between FR obtained for both materials 106
4.39 Comparison between the surface roughnesses obtained for both materials 107
**LIST OF SYMBOLS**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_0$</td>
<td>Initial sheet thickness</td>
</tr>
<tr>
<td>$t$</td>
<td>Instantaneous part wall thickness</td>
</tr>
<tr>
<td>$\theta$</td>
<td>Forming wall angle</td>
</tr>
<tr>
<td>$\delta$</td>
<td>Thinning limit</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Meridian stress</td>
</tr>
<tr>
<td>$\epsilon$</td>
<td>Circumferential stress</td>
</tr>
<tr>
<td>$\epsilon_t$</td>
<td>Thickness stress</td>
</tr>
<tr>
<td>$\epsilon_1$</td>
<td>Major strain</td>
</tr>
<tr>
<td>$\epsilon_2$</td>
<td>Minor strain</td>
</tr>
<tr>
<td>$F_x$</td>
<td>Forming force in X-direction</td>
</tr>
<tr>
<td>$F_y$</td>
<td>Forming force in y-direction</td>
</tr>
<tr>
<td>$F_z$</td>
<td>Forming force in z-direction</td>
</tr>
<tr>
<td>$F_{xy}$</td>
<td>The in-plane reaction force</td>
</tr>
<tr>
<td>$F_{z,p}$</td>
<td>Peak forming force in Z-direction</td>
</tr>
<tr>
<td>$F_{z,s}$</td>
<td>Steady state force in Z-direction</td>
</tr>
<tr>
<td>$F_r$</td>
<td>Radial force</td>
</tr>
<tr>
<td>$F_t$</td>
<td>Tangential force</td>
</tr>
<tr>
<td>$\omega$</td>
<td>Spindle speed</td>
</tr>
<tr>
<td>$f$</td>
<td>Feed rate</td>
</tr>
<tr>
<td>$z$</td>
<td>Step size</td>
</tr>
<tr>
<td>$D$</td>
<td>Tool diameter</td>
</tr>
<tr>
<td>$h$</td>
<td>Height of the sample</td>
</tr>
<tr>
<td>$F_{z,max}$</td>
<td>Maximum axil force</td>
</tr>
<tr>
<td>$Ra$</td>
<td>Surface roughness</td>
</tr>
<tr>
<td>$F$</td>
<td>Friction force</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
</tr>
<tr>
<td>( V_i )</td>
<td>Relative velocity between the forming tool and the sheet metal</td>
</tr>
<tr>
<td>( T_{\text{max}} )</td>
<td>Maximum tool-sheet interface temperature</td>
</tr>
<tr>
<td>( \mu )</td>
<td>Coefficient of friction</td>
</tr>
<tr>
<td>( P_0 )</td>
<td>Mean pressure</td>
</tr>
<tr>
<td>( H )</td>
<td>Hardness</td>
</tr>
<tr>
<td>( l )</td>
<td>Effective contact length of the tooltip with the sheet metal at instant forming angle</td>
</tr>
<tr>
<td>( U_1 )</td>
<td>Sliding velocity of the forming tool</td>
</tr>
<tr>
<td>( U_2 )</td>
<td>Sliding velocity of the sheet metal</td>
</tr>
<tr>
<td>( K_1 )</td>
<td>Thermal conductivity</td>
</tr>
<tr>
<td>( \rho_1 )</td>
<td>Density</td>
</tr>
<tr>
<td>( C_1 )</td>
<td>Specific heat</td>
</tr>
<tr>
<td>( R^2 )</td>
<td>Regression coefficient</td>
</tr>
<tr>
<td>Pred.( R^2 )</td>
<td>predicted ( R^2 )</td>
</tr>
<tr>
<td>Adj.( R^2 )</td>
<td>Adjusted ( R^2 )</td>
</tr>
</tbody>
</table>
# LIST OF ABBREVIATIONS

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

![Image of intricate parts produced by ISF](image)

**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%SiCp-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%SiCp 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 the 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).


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


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*


