UNIVERSITI PUTRA MALAYSIA

DIE SYSTEM DESIGN WITH FINITE ELEMENT FOR IMPROVING MECHANICAL PERFORMANCE OF EXTRUDED ALUMINUM ALLOYS AND COMPOSITES

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By

HANI MIZHIR MAGID AL-JARYAWY

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

November 2015

DEDICATED TO

My Father

My mother

My wife

My children

My brothers and sisters

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

DIE SYSTEM DESIGN WITH FINITE ELEMENT FOR IMPROVING MECHANICAL PERFORMANCE OF EXTRUDED ALUMINUM ALLOYS AND COMPOSITES

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November 2015

Chairman : Prof. Shamsuddin Sulaiman, PhD

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Aluminum extrusion is a forming process to produce a large variety of products with different and complex cross-sections. Understanding of the mechanics of aluminum extrusion process is still limited. It is necessary to improve the tools geometry in such a way that the extruded aluminum profile complies with high customer demands regarding to surface quality and dimensional accuracy. The extrudability of some aluminum alloys, specially the aluminum metal matrix composites (AMMCs) and their behavior and properties after extrusion process need to be improved. The objectives of this work are to improve the mechanical properties, accuracy and surface quality of aluminum extruded parts and composite extruded parts based on the selected parameter settings. Improvement was accomplished theoretically and experimentally through a completed series of steps, starting with designing all the required tools including group of die inserts with different geometries and extrusion rates, followed by fabrication of all these inserts with a completed tool sets for experimental purposes. Finite element analysis and simulation method was utilized in this research to determine the optimum values of parameters before carrying out the experimental test. This ensures reducing the time for the trial and error, and gives more insight in the extrusion process and enhances the consistency of the results. The empirical part of this research includes a series of experimental tests for three types of alloys; aluminum alloy LM6, composite aluminum LM6/TiC, and aluminum alloy L168 as a hard alloy for comparison purpose. The aim is to assess the extrudability of composite alloy and their mechanical properties for each material after the process, and to identify the parameters that have a significant effect on mechanical properties. Experimental results show that, the product quality is dependent on the extrusion angle, die hardness, extrusion speed, temperature difference between tools and the billet, extrusion force and billet container length. The laboratory tests followed the experiments, like tensile and hardness tests, which gave indication of significant improvement of the mechanical properties after extrusion. Microstructure test, by Scanning Electron Microscope (SEM) and Energy Dispersive X- Ray Spectrometer (EDS) show a good improvement in parts micro-structures and grain size boundary layers after extrusion process. Both experimental and analytical results show a good indication of the possibility of extrusion of these alloys at different rates with good mechanical properties in both cold and hot extrusions. Moreover, one of the important contributions of this research is solving the sticking problem between the product with the die and container after extrusion, which leads to a high deformation during the product removal. This problem was studied and solved by design system which takes all these factors and variables into consideration.

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

SISTEM REKA BENTUK ACUAN DENGAN UNSUR TERHINGGA UNTUK MENINGKATKAN PRESTASI MEKANIKAL ALOI ALUMINIUM TERSEMPERIT DAN KOMPOSITNYA

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Aluminum penyemperitan adalah satu proses yang membentuk untuk menghasilkan pelbagai jenis produk dengan keratan rentas yang berbeza dan kompleks. Memahami mekanik proses penyemperitan aluminum masih terhad. Ia adalah perlu untuk memperbaiki alat geometri dalam apa-apa cara bahawa profil aluminum tersemperit itu mematuhi permintaan pelanggan yang tinggi mengenai permukaan kualiti dan ketepatan dimensi. Juga keboleh semperitan sesetengah aloi aluminum, khas yang aluminuim komposit matriks logam (AMMCs) dan tingkah laku dan sifat mereka selepas proses penyemperitan perlu diperbaiki. Tujuan kajian ini adalah untuk meningkatkan sifat-sifat mekanikal, ketepatan dan kualiti permukaan mekanikal bahagian aluminum tersemperit berdasarkan tetapan parameter dipilih. Penambahbaikan telah dicapai secara teori dan uji kaji melalui siri lengkap langkah, bermula dengan mereka bentuk semua alat yang diperlukan termasuk sekumpulan acuan dengan geometri yang berbeza dan kadar penyemperitan, diikuti oleh pembuatan semua sisipan ini dengan lengkap set alat untuk tujuan eksperimen. Analisis unsur terhingga dan proses simulasi adalah langkah seterusnya untuk menentukan parameter optima sebelum ujian eksperimen dijalankan. Ini akan membantu untuk mengurangkan masa percubaan dan kesilapan, dan memberikan gambaran yang lebih dalam proses penyemperitan serta meningkatkan konsistensi keputusan. Bahagian empirikal kajian ini termasuk satu siri ujian percubaan tiga jenis aloi; aluminum aloi LM6, aluminum komposit TiC dan aloi aluminum L168 sebagai aloi keras untuk tujuan perbandingan. Tujuannya adalah untuk menilai keboleh semperitan aloi komposit dan sifat mekanikal bagi setiap bahan selepas proses tersebut, dan untuk mengenal pasti parameter yang mempunyai kesan yang besar ke atas sifat-sifat mekanikal. Keputusan eksperimen menunjukkan bahawa, kualiti produk adalah bergantung kepada sudut penyemperitan, kekerasan acuan, kelajuan penyemperitan, perbezaan suhu antara alat dan bilet, daya penyemperitan dan panjang bekas bilet. Ujian makmal mengikuti eksperimen, seperti ujian tegangan, ujian kekerasan, yang memberikan petunjuk peningkatan yang ketara daripada sifat-sifat mekanikal selepas penyemperitan. Ujian mikrostruktur, dengan Mikroskop Imbasan Elektron (SEM) dan Tenaga serakan X-Ray Spektrometer (EDS) menunjukkan peningkatan yang baik di bahagian-bahagian mikro-struktur dan saiz butiran lapisan sempadan selepas proses penyemperitan. Kedua-dua keputusan eksperimen dan analisis menunjukkan petunjuk yang baik tentang kemungkinan penyemperitan aloi ini pada kadar yang berbeza dengan sifat-sifat mekanikal yang baik dalam kedua-dua penyemperitan sejuk dan panas. Selain itu, salah satu daripada sumbangan utama kajian ini adalah penyelesaian masalah yang melekat di antara produk dengan acuan dan bekas selepas penyemperitan, membawa kepada perubahan bentuk yang tinggi semasa produk dikeluarkan. Masalah ini telah dikaji dan diselesaikan dengan sistem reka bentuk yang mengambil kira semua faktor-faktor dan pembolehubah.

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I Certify that a Thesis Examination Committee has met on 27 November 2015 to conduct the final examination of Hani Mizhir Magid Al-Jaryawy on his thesis entitled “Die System Design with Finite Element for Improving Mechanical Performance of Extruded Aluminum Alloys and Composites” 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 recommended that the student be awarded the Doctor of Philosophy.

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LIST OF SYMBOLS AND ABBREVIATIONS

3D	3 Dimensional
A_o	Cross-sectional area of billet
A_1	Cross-sectional area of extrudate profile
AISI	American Society of Mechanical Engineering
Al	Aluminum
ALE	Arbitrary Lagrangian Eulerian
ASTM	American Society of Testing and Materials design
BS	British Standard
CAD	Computer aided design
CATIA	Computer Aided 3-Dimensional Interactive Application
EBSD	Electron Backscatter Diffraction
F	Force
FE	Finite Element
FEM	Finite Element Method
HB	Hard Brinell
HRC	Hard Rockwell C
JIS	Japanese International Standard
k	Thermal conductivity
LM6	Type of aluminum alloy
MMCs	Metal Matrix Composites
P	Extrusion pressure
SEM	Scanning Electron Microscopy
Si	Silicon
SiC	Silicon Carbide
SLF	Slip line field
T	Temperature
TEM	Transmission Electron Microscopy
Ti	Titanium
Ti C	Titanium Carbide
UPM	Universiti Putra Malaysia
UTS	Ultimate tensile strength
YS	Yield strength
ε	Strain
$\acute{\varepsilon}$	Strain Rate
ρ	Density
σ	True Stress

CHAPTER 1

INTRODUCTION

1.1 Background of Extrusion

Extrusion is a plastic deformation process in which a block of metal (billet) is forced to flow by compression through the die opening of a smaller cross-sectional area than that of the original billet (Koopman, 2009). High value indirect-compressive forces are developed by the reaction of the work piece (billet) with the container and die. The reaction of the billet with the container and die results in high compressive stresses that are effective in reducing the cracking of the billet material during primary stages. Extrusion is the best method for refining the cast structure of the billet, because the billet is subjected to compressive forces only. Extrusion can be cold or hot, depending on the alloy and the method used. In hot extrusion, the billet is preheated to facilitate lower force plastic deformation. Below are the descriptions of the extrusion:

A- Cold extrusion is the process done at room temperature or slightly elevated temperatures. This process can be used for most materials subject to designing robust enough tooling that can withstand the stresses created by extrusion. There are many materials which can be extruded in this method like lead, tin, aluminum alloys, copper, titanium, molybdenum, vanadium, steel. Examples of cold extruded parts are collapsible tubes, aluminum cans, cylinders, gear blanks and others. There are many advantages of cold extrusion:

1- Good surface finish with the use of proper lubricants.
2- No oxidation.
3- Good mechanical properties due to severe cold working as long as the temperatures created are below the re-crystallization temperature.

B- Hot extrusion is done at high temperatures, approximately (50 - 75%) of the melting point of the metal. The range of the pressures can be normally from (35-700 N mm^{-2}). Good lubrication is required due to the high temperatures and pressures and its Detrimental effect on the die life as well as other components. Glass powder is used at higher temperatures, whereas oil and graphite work at lower temperatures (Davis, 1999). Good mechanical properties are imparted to the work piece due to the severe cold working. Also good surface finish with the use of proper lubricants and no oxidation of the work piece, are the main advantages of cold extrusion as opposed to hot extrusion. Extrusion produces shear and compressive forces in the stock. No tensile force is produced, which makes high deformation possible without tearing the metal. Figure 1.1 illustrates the main parts in extrusion process (Altan and Gegel, 1983).

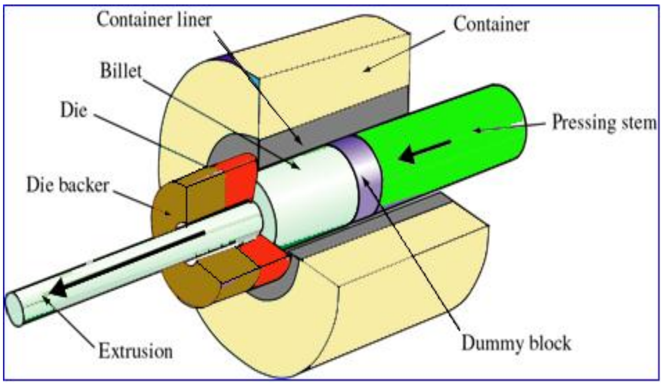

Figure 1.1: The main parts of extrusion process (Altan and Gegel, 1983).

Typical parts produced by extrusions are trim parts used in automotive and construction applications, window frame parts, railings, aircraft structural parts and other parts.

The importance of aluminum as a metal is complemented by the versatility of extrusion process. Flexibility of aluminum to be extruded into many shapes, high strength-to-weight ratio, with tight tolerances, makes it an ideal material for design applications which require maximum versatility from a cross-sectional area. The high cost effectiveness of aluminum extrusions is due to the fact that it requires virtually no machining or maintenance **(**Chen, 2008).

1.2 Importance of the Study

The most important aspects of any product are the mechanical and electrical properties. Improvement process normally depends on multiple factors and parameters. The product may also be needed for many mechanical, chemical, electrical processes and multiple steps are needed to get this improvement. Quality of the parts which are produced by the extrusion process are affected by many variables, such as material composition, heat treatment, and the condition of the manufacturing equipment i.e. the press tools and molds. Adjusting and controlling these parameters, starting from the mold design and tool fabrication will help the manufacturer to acquire the most suitable properties.

Experimental and numerical methods are employed in analysis of aluminum extrusion in order to attain the best performance in terms of process parameters like external die geometry, friction conditions, back pressure application, material properties, microstructure and textural evolution during the process. The main purpose of all these processes is to enhance the mechanical properties of the products. Analytical method cannot cover and explain all the effecting parameters but, finite element method (FEM) is a most effective tool to consider these effects to yield better simulation results. The combination of experimental results, literature reviews, with the finding of analysis and simulation from finite element method (FEM) can improve process and material performance for a wide range of metals and alloys **(**Valiev and. Langdon, 2006)**.**

The mechanical properties are highly dependent on the microstructure of the material, which has direct influences on these properties. That means any thermo mechanical process is possible to change the material's mechanical properties **(**Askeland and Donald, 1994)**.** Based on the above mentioned properties, it can be concluded that, aluminum is suited to be used as a matrix metal. Aluminum can accommodate a variety of reinforcing agents, including continuous boron, Al_2O_3, SiC, TiC, graphite fibers, and various particles, short fibers, and whiskers. Many application requirements can be satisfied due the high melting point of aluminum **(**Davis, 1999).

The main benefit of making composites and the major principle which applies to all types of properties – mechanical, chemical, physical is to improve the density and perhaps the cost. There are many examples of composites which include concrete reinforced with steel, carbon black in rubber, epoxy reinforced with glass/graphite fibers and others (Gijs, 2009).

The purpose of composite materials is to enhance material properties by the process of combination. In engineering practice, to make best use of the favorable properties of the components while simultaneously mitigating the effects of some of their less desirable characteristics; it is common principle that two or more components may be combined to form a composite material.

Aluminum possesses a good corrosion resistance, high thermal conductivity, low density and medium strength, and these properties make the aluminum alloys very suitable as the matrix material. The reinforcements are normally fibers or ceramic powders which possess high Young's modulus but are quite brittle with high yield strength. TiC, SiC and Al_2O_3 are commonly used as reinforcement material for the aluminum matrix since they possess the necessary properties and are compatible with the matrix.

To overcome the limitations of conventional aluminum alloys, they are re-engineered by using aluminum alloys reinforced with particles of TiC, Al_2O_3 or SiC. Improvement of strength and stiffness as well as greater wear resistance and improved high temperature properties is the main advantages of composites **(**Sakaris, 1994)**.**

1.3 Problem Statements

Most aluminum extruded parts are unique due to constant cross-sectional geometries along the lengths. To maintain the product quality, it is important to control on temperature, length and diameter of billet before extrusion, also controlling the temperature and speed of the extruded part after the process.

Nowadays, mechanical properties are the crucial factors for competition in the market. It is possible to enhance these properties by many different ways. One of the most important methods is through using the composite materials. It is the reinforcement elements, which include the natural chemicals (oxides, carbides, nitrides) and different forms (continuous fibers, short fibers, whiskers, particulates). The important things in this process, is the selection of the types and the volume fraction of this composite.

Design of the extrusion tools (die geometry, billet container, other tools) is the starting point and will affect the subsequence process. Therefore it is necessary to enhance the design process using the simulation software. Nowadays, understanding of the mechanics of the aluminum extrusion process is still limited. The flow of aluminum within the die is governed by tribo- mechanical and temperature-dependent effects that have not yet been fully mathematically modeled. As a result, it is difficult to design the die geometry in such a way that the aluminum profile complies with high customer demands regarding dimensional accuracy and surface quality. If the die design do not supported with a large extent and high level of automation equipment, it may causes a large variation in the performance of dies (Gijs, 2009).

Fabrication of tools is time consuming and money. Finite element method approach makes it possible to investigate the condition inside the tool cavity, where the tool cavity is divided into small elements, and the results from the analysis will show the most critical areas in the tool cavity (Chen 2009; Ouwerkerk 2002).

The effects of tool geometry, alloying elements and their chemical compositions on mechanical properties need more understanding. In this work, several variables (extrusion ratio, billet container diameter, billet diameter) are available for testing purposes. Although the physics of the extrusion process is well known, the main challenge for the optimization of the product properties by using many models of the process that are suited for this purposes are placed in achieving reasonable computation for all variables which are used to facilitate the design and implementation. Based on the findings of many researchers in this field (Sayuti and Suraya, 2011), the following issues need to be given a high consideration in this research in order to improve the mechanical properties and determine the optimum parameters:

1- High compression force that are used during extrusion of composite alloys may cause fracture and deformation in the material, which may lead to pulling of the reinforcement elements out of the aluminum matrix and cause deterioration of, or defects in the surface of product (Karl Ulrich, 2013). It would be desirable to establish improved design geometry for the tools, and select suitable extrusion parameters which will help to solve this problem and improve the mechanical properties of the extruded product.

2- Extrudability of hard aluminum alloys, like aluminum casting alloy (LM6) and aluminum composite material (LM6/TiC) MMCs is still challenging to manufacturers. It is important to solve these problems by increasing the understanding and enhancing the data base experimentally and theoretically.

3- Fabrication of tools and dies are costly, and time consuming. It is important to find a suitable solution to minimize this cost and time.

1.4 Research Objectives

The objectives of this research are:

1- To simulate the aluminum extrusion process and build knowledge of how a FE model is created and propose various strategies to improve the tool design and improve the product quality in the currently used aluminum extrusion process.

2- To determine the extrudability of hard aluminum alloys; L168, LM6, and composite LM6 reinforced with 2 wt. % TiC particles.

3- To establish die design system for the cylindrical and symmetrical polygon parts, in which one can solve the sticking problems between the tools and billet and overcome or reduce the force required to remove the product from the die at the end of the process without any deformation.

4- To find the relationship between the mechanical properties and microstructures of the aluminum LM6 alloy and the composite alloy LM6 reinforced with 2 wt. % TiC particles.

1.5 Scope and Limitations

The scope of this work is to clearly define the specific field of the research and ensure that the entire content of this thesis is confined to the scope. Achieving extrusion process for three types of alloys, and improving the mechanical properties through different methods were the main goals of the research. For this purpose, many geometrical parts were required in modeling and simulation process. Design and developing of such models of the extrusion process as well as the simulation process will be the optimal control strategies to achieve extrusion and get the finding for the whole models range. In finite element analyses the linear elastic material model will be used. The fundamental idea is that finite element analysis of the surface topography will provide better characterization of the surface than empirical techniques. This is especially true for aluminum alloys, which cannot readily be classified by tensile or ultimate strength.

In this study, the aim is to establish the main parameters which control the product quality; therefore study should be able to determine adequate values for the part's parameters that give a close approximation of the reality. A model is implemented for 2-D, axi-symmetric problems.

Making appropriate assumptions regarding to the material flow, velocities, pressure, and strain rate distributions are important in the modeling of this process. The stress - strain analysis will be evaluated experimentally and analytically. This analytical approach allows for a considerable reduction in computation times as compared to the usual FEM for the modeling of extrusion processes.

Highly accurate simulation of extrusion processes is a requirement to reduce the tool design costs, improve tool life and product quality, therefore, the realistic representation of the boundary conditions is a crucial issue in metal forming simulations.

The next step is to perform experimental studies on the extrusion of aluminum alloys to determine the significant parameters affecting the surface quality, dimensions accuracy and all mechanical properties. The knowledge of the initial mechanical and chemical properties of the billet prior to loading it into the container as well as impurities entering the system is very important. These properties include hardness, elongation, yield limit and chemical compositions. These results of the experiment are analyzed and compared with those obtained from simulations to get the best conclusion and recommendations.

Due to the large volume and surface area of the tools, only one half of the tool and the cavity have been modeled. The behaviors of the tools and the materials during the course of the extrusion simulation with ABAQUS are determined by means of an explicit FE method computation. The method being explicit causes a source of inaccuracy due to instabilities and retarded thermal response of the tools. The FEM requires generation of internal meshes for the intrinsically unavoidable computation of internal temperatures. Fortunately the internal values of the tool temperatures are not needed for the thermal boundary conditions. To investigate the feasibility of the F.E computation of work piece deformation with the boundary element computation of tool temperatures, the scope is limited for axisymmetric model.
There are some practical limitations during the experiments, because it is difficult find an extrusion machine for research purpose in all academic institutes. Also most industrial companies do not cooperate in these types of research which cause delay in their production plan and schedule. Here some assumptions in boundary conditions:

- Geometric difficulties, such as flow around sharp edges and within thin-walled sections.
- Some thermal boundary conditions may cause inaccurate or even incorrect results when they are not specified properly. Also heat convection from the tool cavity to the surroundings and radiation has been neglected.

1.6 Thesis Layout

The first chapter is an introduction to the work conducted within this study. It provides an idea to the reader about the work program covered and discussed in this thesis. This chapter also summarizes the state of the art on die design for extrusion, and their importance. It explains the main objectives and problem statement of this research.

Basic literature survey of related topics has been covered in Chapter 2. Advantages and disadvantages of the material, benefits of the use of these alloys, cost comparison with the aluminum alloys, and the wide range of applications are discussed in this chapter.

The mechanisms of how all the simulation and experiments were carried out to give better idea to the reader are discussed in Chapter 3. This chapter describes the application of FEM techniques in extruding many shapes, discusses and compare of simulation results with experimental results and then made a measurements during the extrusion trials. Also includes a description of the modeling geometry, analysis and simulation. Both (2D) and (3D) models are developed for more details. The simulations are repeated many times and tracking algorithm is implemented. The boundary conditions at the aluminum billet-tooling interface and the mesh generation was presented. There is full description in this chapter for improving the die design steps. Also the experimental works are explained in this chapter, which includes many tests for each type of extrusion.

Chapter 4 presents the simulation and experimental results and discussion. Simulation and experimental results are compared to assess the reliability of these results. This gives a good validity to the FE analysis results and verifies the assumptions made and proves the accuracy of the implemented material parameters. It also describes further development and implementation of the design system into software tools.

Chapter 5 provides conclusions and recommendations for further research.

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