Manufacturing of Square Bar from Aluminium Scraps through Friction Stir-Back Extrusion Process

A thesis submitted by

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CANDIDATE DECLARATIONS

I hereby declare that the work which is being presented in this thesis entitled "**Manufacturing of Square Bar from Aluminium Scraps through Friction Stir-Back Extrusion Process**" in partial fulfilment of the requirements for the award of the degree of masters of science in Manufacturing Engineering is an authentic record of my own work carried out from **January to September 2017** under the supervision of **Dr. Perumalla Janaki Ramulu**, Program of Mechanical Design and Manufacturing Engineering, Adama Science and Technology University, Ethiopia.

The matter embodied in this thesis has not been submitted to any institute for the award of any other degree or diploma. All relevant resources of information used in this thesis have been duly acknowledged.

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Candidate	Signature	Date

This is to certify that the above declaration made by the candidate is correct to the best of our knowledge and belief. This thesis has been submitted for examination with our approval.

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ABSTRACT

Friction extrusion process was invented by The Welding Institute (Cambridge, UK) in the early 1990's. This process relies on the relative motion between plunger and rotary sample charged chamber to produce frictional heating to plasticize and extrude the aluminium scraps directly into useable product in one step. The aim of this thesis is to manufacture aluminium square bar on conventional lathe machine from aluminium wire scraps through the novelty of friction-stir back extrusion (FSBE) process and study the viability of the process to produce the square bar. The important tasks involved in this work are as follows: the components (chamber and plunger) used for experimental work was designed and manufactured, the thermo-mechanical progression of FSBE process was experimentally studied on adapted conventional lathe machine found in ASTU machine shop. The relation between controlled parameter (like rotational speed and consolidation time) and response parameter (like extrusion time, extrusion rate, grain structure and hardness) were analysed. Preliminary results show that, increasing or decreasing rotational speeds results in defects. Cold crack and twisting defect were shown on square bar fabricated using low rotational speed and hot crack defects were observed on surface of the bars produced by higher rotational speed. The manufactured square bars were tested using optical microscope and Vickers hardness tester. Microstructural studies reveal that initial grains of aluminium wire undergo significant refinement and results in equiaxed as well as recrystallized grains in the square bar fabricated through FSBE method. The hardness tests show almost even distribution of hardness in the specimen; but hardness was lower than parent aluminium; in comparison, uneven distribution of hardness was seen in parent aluminium. In addition to experimental investigation, finite element analysis of temperature distribution and extrusion force was discussed with respect to experimental result using DEFORM-3D software.

Keywords: *Aluminium Wire Scraps, Friction Stir Back Extrusion, Micro structure, Mechanical properties, recycle*

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ACRONYMS

AA - Aluminium Alloy

AISI - American iron and steel institute

Al - Aluminium

AR- As Resived

ASTU - Adama Science and Technology University

DXZ- Dynamic Recrystallization Zone

EDM - Electron Discharge Machining

FE – Finite Element

FSBE - Friction Stir Back Extrusion

FSP - Friction Stir Processing

FSW - Friction Stir Welding

H13 - High speed tool steel

MIdI-Metal Industry Development Institute

ml - millilitre

mm - millimetre

OM – Optical Microscope

RPM - Rotation per minute

SFTC – Scientific Forming Technology corporation

SiC – Silicon Carbide

SPD - Severe plastic deformation

ST- Short Transvers

CDRX- Continuous Dynamic Recrystallization

CHAPTER ONE: INTRODUCTION

1.1 Introduction

Aluminium is the most abundant metal in the Earth's crust and most widely used material after steel. Aluminium and its alloys have received much consideration as important materials in aerospace, automobile, construction and building wire etc. They are preferable due to their excellent high strength-to-weight ratio, physical properties such as high specific strength and stiffness, low density, high thermal conductivity, and good manufacturability for machining, forming and casting. Manufacturing operations, especially traditional machining, usually produce considerable amounts of aluminium waste. The amount of metal wastes left during manufacturing processes, such as machining chips, swarf, scraps, and small blocks, has substantially huge. As is known that, in the manufacturing industry, people have never stopped exploring new manufacturing techniques to recycle metal wastes and produce high performance products with lower costs at the same time (Matjaz Torkar, (2010) and M. Samuel, (2003)).

There are basically two primary methods of recycling Aluminium and its alloy to produce a useful product: the so-called 'conventional' method and the direct conversion method (Tekkaya *et al*. (2009), Tang and Reynolds, (2010)). Recycling of aluminium alloys scraps by conventional method requires several operations to achieve good ingot quality standards: scraps conditioning (cleaning, drying and compaction), melting, molten metal treatment (degassing, grain refinement and microstructure modification) and ingot production. The other method; direct recycling of aluminium chips via hot extrusion was first proposed and patented by (Stern ((1945)). Gronostajski and Matuszak (1999)) comminuted and compacted aluminium scraps followed by conventional hot extrusion. In comparison, direct recycling method does not have several steps to recover metal scraps. This solid-state process avoids formation of thick oxide skin; so the scraps can be converted to a finished product in single step without further processing. Compared with conventional recycling, the direct conversion of aluminium scrap into compact metal may result in '40% material, 26–31% energy and 16–60% labour cost savings' (Gronostajski *et al.* (2000)).

One recent development which categorized under the direct recycling method is friction stir extrusion, patented by the welding institute (Thomas *et al.* (1993)). Friction Extrusion is a novel energy-efficient solid-state material synthesis and recycling technology. The novelty of FSE is that it utilizes the frictional heating and extensive plastic deformation. It inherent to the process to stir, consolidate, mechanically alloy, and convert the powders, chips, and other recyclable feedstock materials directly into useable product forms in a single step as shown in figure 1.1. Basically, FSE shares the same deformation and metallurgical bonding principles as in the innovative friction stir welding (FSW) and friction stir processing (FSP) (Thomas *et al.* (1991)). Being a solid-state process, FSE eliminates the energy intensive melting and solidification steps, which are necessary in the conventional metal recycling processes.

The novelty of friction extrusion can be analogous to conventional extrusion of forward extrusion and backward extrusion types, either by contrasting or making similar direction of extrusion force and extruded product. Based on this, friction stir back extrusion is coming to picture which is a nominally solid-state process well suited for creating tubular material from particulate materials such as metal scraps or machining chips.

1.2 Basic Principles of the Friction Stir Back Extrusion Process

Friction stir Back extrusion (FSBE) is a solid-state joining and extrusion technique in which coalescence occurs owing to thermo-mechanical deformation of aluminium scraps and other recyclable feedstock metals as the resulting temperature exceeds the solidus temperature of workpieces. The FSBE process has been shown in figure 1.1. First, aluminium scraps are placed within the cavity of the chamber. Then, a non-consumable central hollow plunger is forced to the specimen placed in the rotating chamber. Meanwhile, the plunger has no axial motion and the friction between it and specimen generates heat to preheat the sample. After preheating of the specimen, the plunger is forced into the plasticized specimen. In this stage, severe plastic deformation occurs due to the combination of chamber rotational and stationary of plunger. Softened materials sticks and rotate relative to plunger Trapped heat also causes softening as well as joining and extruding of material upward in case of milling machine utilization and side in case of lathe machine utilization through the movement of the tool. The tool movement can be continued as long as the amount of aluminium scraps inside the chamber is sufficient to reach desirable depth.

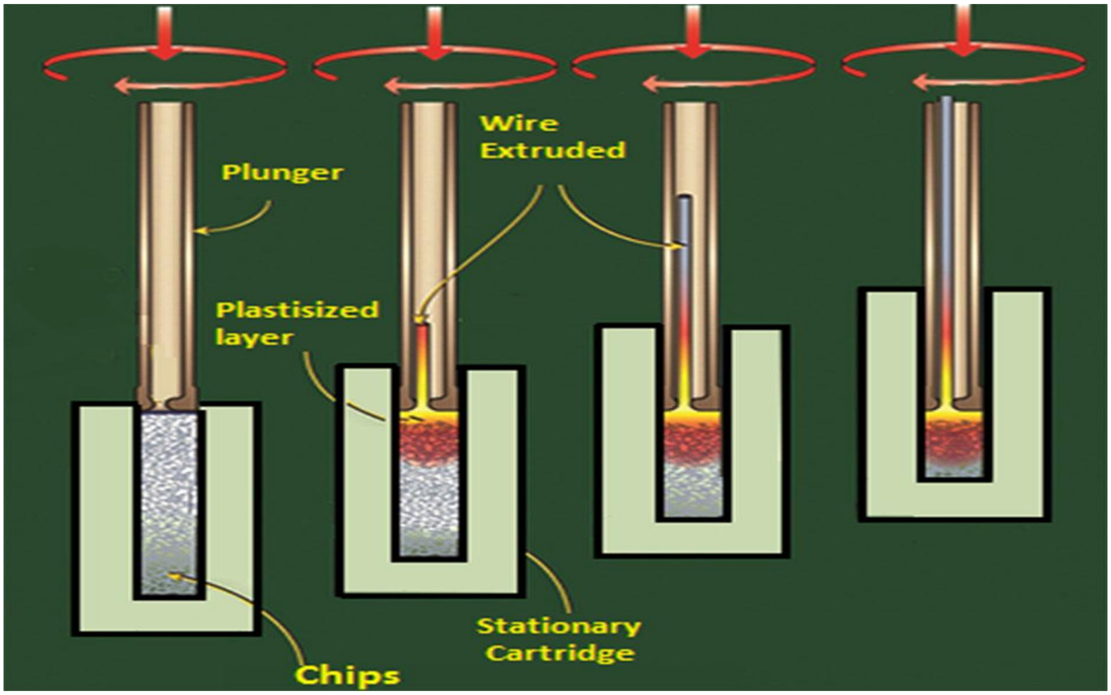


Figure 1.1 FSBE process (Behnagh *et al.* (2014))

In this thesis, FSBE is proposed as a convenient manufacturing process of square bar from aluminium wire scraps with one step process which has relative simpler equipment requirements compared to conventional recycle process. The physical properties is studied and illustrated, features of products are presented, the influence of process parameters on product were analysed and viability of being used for producing square profile has proven.

1.3 Statement of the Problem

Aluminium is everywhere, particularly in the packaging, soft drink cans, food plates, foil, siding, gutters, automotive part, as a form of wire or rod and more. Due to the production cycle and deterioration, the product of aluminium is rejected as a form of scraps. The most expertise advice is that, aluminium scraps is practically the perfect recyclable material. As a result, there are basically two recycling method: conventional recycling and direct recycling. Conventional recycling involves several operations and further processing to recycle aluminium scraps which consume a large amount of energy and it is not economically approved. Comparing to conventional recycling, the direct recycling of aluminium scraps into bulk materials does not request large amount of energy and cost. In addition, direct recycling uses mechanical action of spinning tool to consolidate and plasticized the sample material which is commonly called as frictions-stir back extrusion (FSBE). The FSBE process falls into the category of direct recycling methods and it has all the advantages. The friction-stir back extrusion process also represents a step forward in energy-efficient to recycle aluminium and deteriorated scraps in that it removes the melting step in conventional metal recycling and processing. So in this thesis, an effort is given to manufacture square bar from aluminium wire scraps through friction-stir back extrusion method and simultaneously showing the viability of the FSBE processes to produce square bar.

1.4 Thesis Objectives

1.4.1 General Objective

The main objective of this work is to manufacture square bars from aluminium wire scraps by friction-stir back extrusion process setup on conventional lathe machine and study the feasibility of FSBE to square bar.

1.4.2 Specific Objectives

- ✓ To design and manufacture of tools and fixtures for conventional lathe machine to perform extrusion process.
- ✓ To experimentally execute the manufacturing process of square bar on adapted lathe machine using FSBE method.
- ✓ To investigate physical, mechanical and microstructure behaviour of friction stir back extruded bar.
- ✓ To predict temperature distribution and extrusion force using finite element simulation and discuss with the experimental progresses.

1.5 Significant of the Study

Friction extrusion does not require melting material for consolidation. With the current situation of high energy costs and the desire to conserve material, the potential of this green and economical process has become increasing. The significance of this thesis is as follows:

- ✓ To extending the concept of FSE techniques to produce other shapes.
- ✓ Potential for metal recycling with much less energy compared to conventional process.

- ✓ Saving of material and labour when recycling metal scraps to produce useful products
- ✓ No melting and solidification (high energy efficient) material in recycling process
- ✓ Near zero emission of CO_2, metal oxide particulate and elimination of greenhouse gas (GHG) emissions

1.6 Scope of the Study

This study is focused in the areas related to Friction-stir back extrusion: (1) production of square bar, which has an approximate cross section of 5.6 x 5.6 mm from clean and dry aluminium wire (AA1050) scraps which is cleaned by using sand paper of different grade, (2) study the mechanical performance and microstructural evaluation of FSBE extruded square bar. In this work, aluminium wire scraps (AA1050) recycling is chosen as a showcase material for producing square bar, based on a few considerations. First, aluminium wire scraps are easy to work with; second the relatively low process temperature (300 to 450°C) and low process load do not pose major problems to tool materials and machine design for the FSBE process. Third, aluminium wire scraps are highly recyclable and representing the feasibility of FSBE process to recycle other scraps of aluminium alloys.

1.7 Limitation of this Thesis

The thesis on the manufacturing of square bar from aluminium scraps is limited due to different challenging problem. The machine utilized for this experimental work was conventional lathe machine which contained two most important process parameter for producing square bar through FSBE process. These process parameters were rotational speed from spindle speed and transvers rate from carriage through lead screw and feed rod. Obtaining and varying rotational speed was possible to know its influence on the produced square bare. In contrast, keeping transvers rate constant or varying it was impossible due to the damage of driving component inside carriage. Consequently, the plunging rate was provided by using man power via tailstock quill using hand wheel. As a result, discontinuous flow of plasticized material had been happened several times and made the research more difficult. In addition, due to the lack of pervious experiences in sample preparations for microstructural and difficulty of aluminium polishing and etching; results of microstructure and grain boundary were little blurred and it makes difficulty to calculate grain size.

The other important instrument expected to use was Infrared thermometer, which used to measure temperature history inside dies and this instrument was not used during the manufacturing process. Due to this, the experimental investigation was performed through trial and error. The other main problem encountered during manufacturing of square bar on lathe machine was power interruption during manufacturing of square bare. Even if, unlisted and discouragement of bureaucratic problems were existed; feasibility of producing square bar on conventional lath machine was successfully proved.

1.8 Thesis Layout

The thesis consists of six chapters.

Chapter one presents a brief introduction to the novelty of friction-stir back extrusion method and its feasibility to recycle aluminium scraps. The statement of problem, significant, scope, objectives, and limitation of this thesis are also elucidated.

Chapter two describes the general backgrounds about friction extrusion process, the idea and the principle of friction stir processing and a detailed literature review are presented. Related conventional extrusion process is also compared with friction extrusion.

Chapter three describes the general research design, material, tool design and manufacturing and experimental condition. In addition, the experimental setup and procedures as well as testing procedures are also explained in this chapter.

Chapter four explains results and discussion obtained from experimental observations. Characteristics of extruded square bar, macro and microscopically investigations, as well as mechanical properties of friction stir extruded square bar extensively discussed.

Chapter five describes finite element simulation and study the temperature and extrusion force during friction stir extrusion process. And finally, summary of the thesis outcome is stipulated in chapter six with the concluding remarks and provision of future works for further research directions.

CHAPTER TWO: LITERATURE REVIEW

2.1 General Background

Friction extrusion is a novel process which was invented by the welding institute of Cambridge, UK by Tomas *et al.* (1993). The novelty of FSE is that it utilizes the intrinsic frictional heating and extensive plastic deformation inherent in the process to stir, mechanically alloy, and consolidate aluminium scraps and other recyclable feedstock metals in to usable product. This chapter provides efforts of different researchers on the basic of friction stir process as well as previously reported studies of FSE in aluminium and its alloys will then be presented. The chapter closes with an extensive review of material flow and heat transfer, microstructure and mechanical properties, and process parameters in friction stir extrusion.

2.3 Comprehensive Review on Feasibility of Friction Extrusion

In present day scenario, the application of high strength, low weight metal alloys are increasing very rapidly in the aerospace, automobile and ship production arena, to produce next generation highly functional structural components for delivering infrastructure and expand to other markets and applications. According to available literatures, FSE technique can join by thermo-mechanical friction technique and extruding softened metal scraps including aluminium, magnesium, and their alloys. It is obvious, that most of the research work is concentrated on aluminium owing to its industrial applications and it eliminates the energy intensive melting and casting steps in current metal material synthesis process, thereby significantly reducing energy consumption.

South wire Company, (2011) investigated on the feasibility and potential viability of a highly energy efficient solid-state metal scraps recycling and synthesizing process using FSE process. Their project was determined the process and materials parameters for producing extruded product forms by direct conversion of recyclable materials. The materials can be chips or other recyclable feedstock through mechanical alloying and thermo mechanical processing in a single step using frictional heat. Process parameters were further optimized for die design, plunge forces, and rotational speed. Deferent aluminium alloys including 6082, 5052, and 1350 were successfully extruded. Both slugs and metal chips were used as feed stock material. A comparative analysis of the wires produced through regular melting, casting and drawing vs. friction stir extrusion revealed that the mechanical/electrical properties of the extruded products were comparable. From microstructural point of view, the samples contained both fine and coarse grains; leading to the decision that further optimization of the process is necessary to get a homogeneous structure. They determined that, the potential feasibility of friction stir processing to produce new alloys by coextruding different alloys, like aluminium alloys, 6201 and 1350 with nano-Al2O3 (alumina) particles, 5052/1350 and 6061/1350 were successfully coextruded.

Fadi Abu *et al.* (2012) studied experimentally the viability of producing fine-grained tubes from AA6063-T52 aluminium round bar via the novel concept of friction stir back extrusion (FSBE). Results showed that the process has capability to produce structurally-sound, void-free tube and there was a grain refinement in microstructure of starting material. Dinaharan *et al.* (2014) proved FSBE can produce sound copper tube and with the help of optical microscope the microstructure were studied and found homogenous microstructure were obtained along tube wall.

2.3.1 Thermo-Mechanical Dynamics of Friction Stir Extrusion

To understand the working principle of friction stir extrusion, it is necessary to explore the physics related to heat generation. Mechanical friction work is initiated when rotating sample material surfaces are in contact with the immediate stationary surface of central hollow plunger under a normal load. Friction work is assumed based on Coulomb’s dry friction model between solid bodies. In details, the mechanical work and heat generation relationship in the presence of sliding friction is explained by contact conditions between hard and soft metallic material interaction. It involves very small scale asperities at the contact surfaces of hard and soft material. As normal force is acting on the rotating sample material, it is being distributed onto smaller area asperities at the contact surfaces which resulted in a very high pressure per unit force. Due to relative velocity difference, the normal force causes ploughing of the soft material by the hard materials’ asperities. The soft material gets agitated, deformed and finally broken, releasing the stored energy in the form of heat. The heat generation mechanisms occur continuously throughout the extrusion process. Through friction heat mechanism, rotating work material temperature under the stationary plunger is increased to a degree where work material layer at plunger tip interface started to lose it strength, yielded, stick, metallurgical bonded and finally extruded through hole (Sherwood *et al.* (1984)).

2.3.2 Heat Transfer and Material Flow

Material flow in friction stir extrusion are studded by different literatures using the material flow principle of friction stir welding as initial for modelling. Fonda *et al.* (2013) explained multi-layer material flow and onion ring structure in friction stir welding but none of them are complete. Seidel and Reynolds (2001) applied a marker insert technique to illustrate the material flow in the friction stir welding process. It was noting that in FSW heat generation comes from both plastic deformation and the friction between the tool and work- piece. It was reported that more than 80% of heat generation originates from the friction between the tool shoulder and work- piece. In case of FSE, heating from friction and stirring of material created in the friction extrusion process makes friction extrusion different from traditional extrusion (which involves melting of materials). The plastic deformation associated with the friction extrusion process should provide a strong homogenizing effect to the initial extrusion charge (Li *et al*. ((2015)). Due to this homogenizing effect, wire with customized chemical composition can be made by extrusion.

Recently heat transfer phenomenon and the temperature field in the friction extrusion process of aluminium alloy 6061 were experimentally investigated by Zang *et al.* (2015). The mechanical power input during the experiment was recorded and the temperature variations with time at several key points surrounding the process chamber were measured using inserted thermal couples. A numerical thermal model for the experimental system was developed. The model included a rotating extrusion die, a material being processed inside an extrusion chamber, a chamber wall, and a back plate at the bottom of the chamber wall. The experimentally measured mechanical power was used as input to the model to predict the temperature field in the experiment.

Li *et al.* (2013*)* performed experiments and investigated material flow patterns in friction extrusion using a marker material. Zhang *et al.* (2014) studied numerically material flow fields in friction extrusion using a fluid dynamics model. Process studied analytically, numerically, and experimentally. CFD simulation predictions had verified analytically and validated experimentally. To understand how a material particle moves during the friction stir process, path line of the particle was used. Figure 2.2 shows the path lines of four particles; as the particles move upwards, the path lines (except of the one that started at r=0) begin to become spirals, suggesting that the material has reached a region where material deformation becomes severe. The radii of the spirals decrease gradually as the path lines enter the extrusion hole.

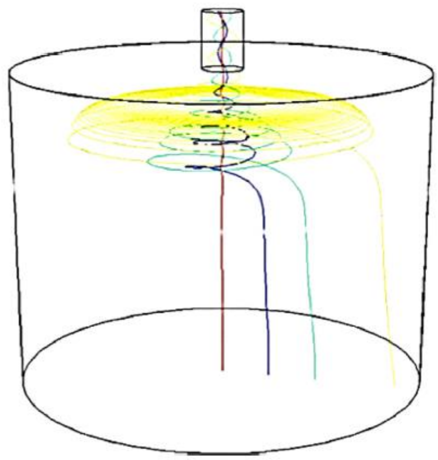


Figure 2. 1 Path lines of particles inside Chamber (Zhang *et al.* (2014))

The other researches, Gianluca Buffa *et al.* (2015) experimentally studied AZ31 magnesium alloy and 3D helical material flow was highlighted through metallurgical observation of the specimens as shown in Fig 2.3. Tang and Reynolds, (2013) conducted the experimental investigation on AA6061 wire with AA2195 and reported differences in material flow with changes in die geometry, rotation rate and extrusion force and location of marker insert were presented and discussed with reference to metallographic cross-sections of resulting wire and remaining billet. According to their study, shape of the marker material in the wire and material flow consolidation during extrusion was highly dependent on die rotation rate and extrusion force. Grain size and crystallographic texture development and their variation during wire extrusion of AA6061 and AA2195 also explained.

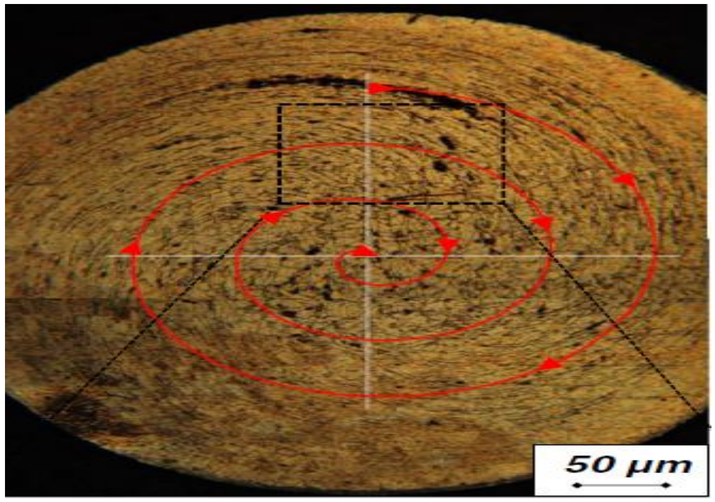
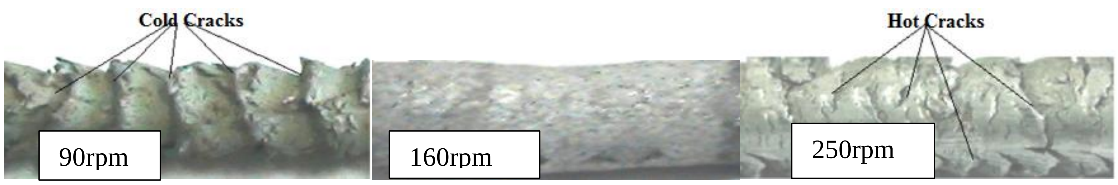


Figure 2.2 Helical material flow (Gianluca Buffa *et al.* (2015))

To explore the material deformation behaviour during FSE process, flow visualization experiments were conducted by X. Li *et al*, (2015) using AA6061 billets with AA2195 as a marker insert. Marker shape was used to make an approximation of imposed strain during the extrusion as a function of relative extrusion temperature. These wires were cut into several segments and the distribution of AA2195 marker in the AA6061 wire cross-sections was determined by optical microscopy and used to qualitatively visualize material deformation and to semi-quantitatively determine the strain at various stages of the extrusion. At all cross sections, the AA2195 marker forms spiral patterns on the wire cross section. However, there were differences in the distribution of marker material and the grain size as functions of extruded length. The number of revolutions of marker material spirals on a cross section decreases from the beginning to the end of the wire. A reasonable interpretation of the marker observations was that as the length of wire increases, the extrusion process was approximating a "conventional" extrusion: that is, die rotation was producing less deformation per rotation as the process proceeds or, alternatively, the extruded length per rotation was increasing.

2.3.3 Microstructure and Mechanical properties

The properties of extruded product by friction extrusion are extensively studded through experimental testing both as-extruded and post-extruded form. Tang and Reynolds, (2010) investigated the production of fully consolidated wires from aluminium alloy AA2050 and aluminium alloy AA2195 machining chips via the friction extrusion process. In this work, the extrusion rate was proportionally related to the power input/die rotational speed. Also, they determined that the FSE process was limited by extrusion temperature which, if too low and high, resulted in cold crack (Fig. 2.4 A) and hot crack (Fig. 2.4 B). From Fig. 2.4 B, it observed that the wire surface was structurally sound at the rotation speed of 160 rpm. Furthermore, the possibility of the FSE process on AA7277 aluminium alloy chips was investigated by Raza Abdi *et al.* (2014). They indicated that there were various zones in the cross-section of recycled wires. In this study, the wires' microstructure was observed to be equiaxed and recrystallized grains in the centre by optical microscopy. The microstructure of the sample shown in figure2.5; in which A-the representative of fine, equiaxed and uniform structure at the centre of wire and B-corresponds to the area near the outer surface. This area was surrounded by a region with a significantly different microstructure (D). The grain growth was obvious in this region. Far enough away from the centre is a rather uniform region (E), beyond which the structure contains the combination of fine and coarse grains.



A) B) C)

Figure 2. 3 Extruded wires with different rotational speeds

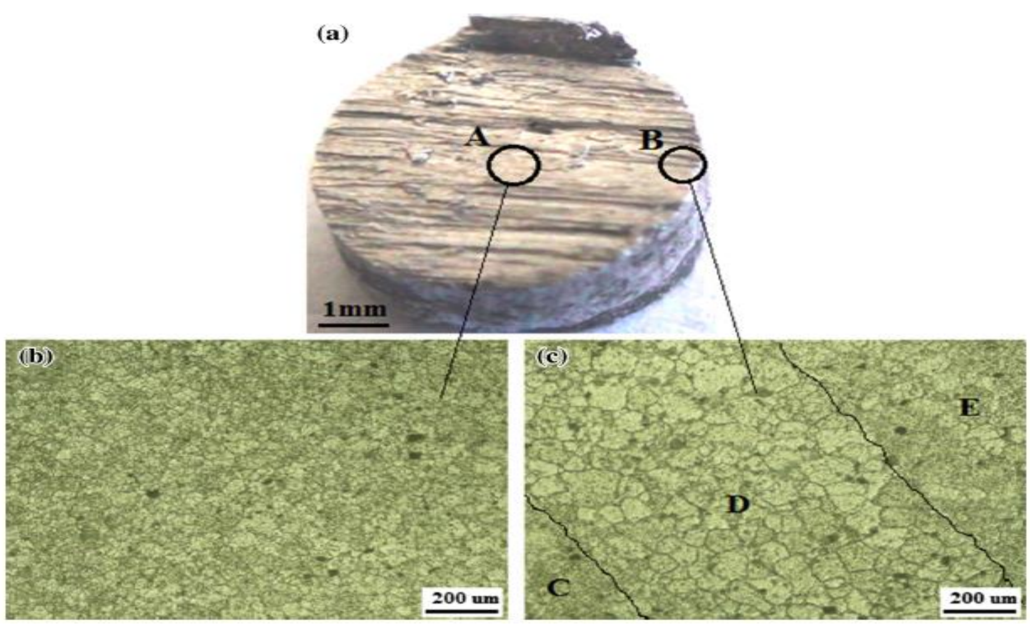


Figure 2. 4 (a) Macroscopic appearance of cross-section of extruded wire with 160 rpm rotational speed. (b) Micrograph showing centre of the sample. (c) micrograph showing various zones formed in the wire cross-section (Raza Abdi *et al.* (2014))

Furthermore, *Gianluca Buffa et al.* (2015) investigated experimentally on AZ31 magnesium alloy through FSE by considering variable tool rotation and extrusion ratio. Accordingly, appearance of defects and fractures were related to either too high or too low power input. The extruded rods were studied both metallurgical and mechanical resistance of about 80 % of the base material was observed for the best combination of process. Recently M. Ahmadkhanbeigi *et al.* (2016) investigated the feasibility, mechanical properties and microstructural evaluation of the processed aluminium tube through FSBE and reported the reduction in grain size and grain refinement occurs across the inner wall of the formed tube as well as strain gradient along the tube wall. They conduct tensile and hardness tests and found the ultimate strength and elongation at failure increases from the initial value of 183–225 MPa and 19–22 %, respectively. As well as micro-hardness assessments represent an increase in initial value from 74 to 86 Hv.

The feasibility to recycle pure magnesium scraps via solid-state recycling technique of FSE was investigated experimentally by Reza Abdi *et al.* (2016). Due to a refined grain microstructure, good mechanical properties in strength and elongation were obtained for samples produced by the rotational speed of 250 rpm and plunge rate of 14 mm/min. On their study, they included metallo-thermo-mechanical coupled analysis were further conducted to understand the effects of process parameters and the analysis were carried out with a multistep two dimensional (2D) coupled Eulerian–Lagrangian finite-element (FE) method using ABAQUS.

2.3.4 Process Parameters

Throughout the literature many authors studied the effects of FSE parameters on different mechanical properties by altering either one or two parameters at one or two levels. The most common parameters to vary in the process were that of traverse speed rate and rotational speed rate as they were the easiest to control. This section will attempt to compile the previous work that was done on process parameter effect on the FSE extruded product.

The process parameters for friction extrusion can broadly classified into three groups: (a) tooling related parameters: linear velocity; (b) machine related parameters: plunge force or depth, spindle speed, axial force rate, extrusion speed etc. and (c) other related parameters: die material, texture of die and tool, size of the die etc. The FSE influencing process parameters in the view of literatures are summarized and illustrated using a root cause-effect diagram in figure 2.6.

The effects of process parameters such as traverse speed rate and die rotational speed on physical and micro structural properties were experimentally investigated by A.Hosseini *et al.* (2012). The aluminium chips used as extruded material was AA2025-T8 aluminium and the production of wire was carryout on conventional lathe machine in which the stationary chamber was fixed on the tailstock quill and the rotating plunger was mounted to the spindle speed. The process parameters considered in this study were traverse speed rate and die rotation speed and the study were carried out by altering process parameter. There are three common imperfection encountered during their experiment: twist, tear (or cold crack) where low rotational speed (200 rpm) used and hot cracks in which high rotational speed (600 rpm) is utilized. Those imperfections are eliminated with increasing rotational speed from 200 to 400 rpm, and the optimum traverse speed for stationary chamber is 10 mm/min or lower.

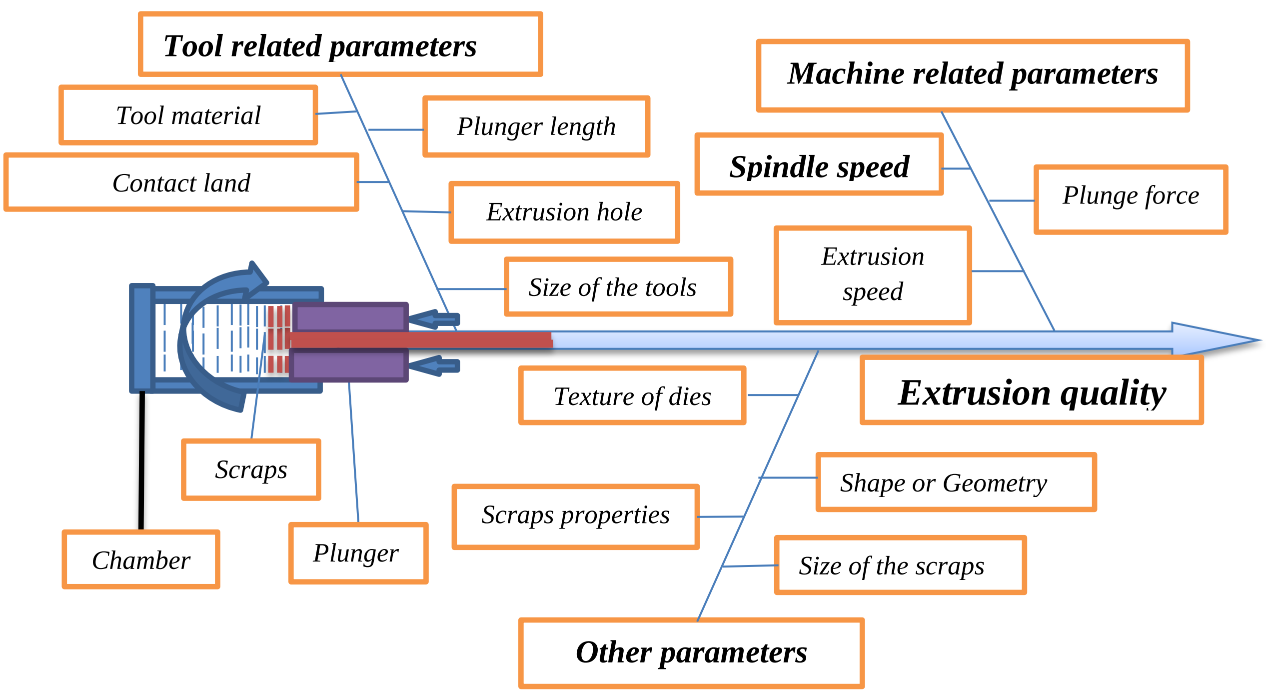


Figure 2. 5 Process parameters of FSE

The process parameters optimization, including rotational speed (RS), plunge rate (PR) and hole size (HS) as a tool geometry parameter were studied by Mohammad Ali Ansari *et al.* (2015). The material used for their study was clean and dry Mg chips which were produced from Mg ingot through planning machine without cutting fluid. The rotating plunger had scrolled face pattern to facilitate the stirring action and the inner hole of the plunger have a contact land (extrusion channel) of 4 or 5 mm in diameter which determine the size of the extruded wire and 2 mm in length. The Taguchi method was used to optimize the extrusion parameters by selecting L8 orthogonal array with seven DOF to evaluate the effects of the extrusion parameters on the average grain size. The data analysis was carried out by using signal to-noise (S/N) ratios. Among the performance characteristics of S/N (i.e. smaller- the-better, larger-the-better, and nominal-the-best); smaller-the-better was selected to determine the minimum grain size (GS). Finally, analysis of variance (ANOVA) was implemented to discuss the statistically significant process parameters on the average GS of the fabricated wires. The results of ANOVA indicate that the considered process parameters are highly significant factors affecting the GS of FSE specimens in the contribution order of RS (71.6%), PR (24.5%) and extrusion HS (3.8%).

2.2 Friction Stir Processing

Friction extrusion has many commonalities with friction stir processing (FSP) and friction stir welding (FSW) in many aspects, like use of mechanical action in heat generation, metallurgical bonding and plastic deformation, experimental devices, and applicable material and microstructural behaviours. Consequently, it is very important to overview friction stir processing and friction stir welding as headstream of friction extrusion. R.S. Mishra *et al.* (1999) firstly proposed friction stir processing (FSP). This processing techniques was believed to have a greatly enhance super-plasticity of many aluminium alloys as comprehensively studied by R. Mishra et *al.* (2005) and Ma *et al.* (2004). The most commonly well-known and used of friction stir processing was friction stir welding (FSW), which was patented by the welding institute in 1991 (Thomas *et al.* (1991)). Both rely on plastic dissipation for heat generation and may be considered severe plastic deformation processes (SPD). In FSP and FSW a specially designed rotating cylindrical tool that comprises of a pin and shoulder that have dimensions proportional to the sheet thickness. The pin of the rotating tool is plunged into the sheet material and the shoulder contact with the surface of the sheet, and then traverses in the desired direction as shown in figure 2.1. The contact between the rotating tool and the material generate heat which softens the material below the melting point of the sheet and with the mechanical stirring caused by the pin, the material within the processed zone undergoes intense plastic deformation yielding a dynamically-recrystallized fine grain microstructure.

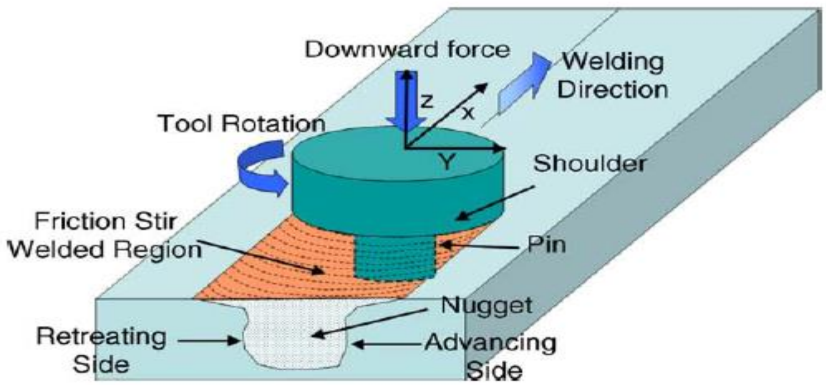


Figure 2. 6 Friction stir welding process (R. Mishra *et al.* (2005))

The advantages of FSP and FSW can be also the advantages of friction extrusion. More specifically the main benefits of friction extrusion techniques are listed as follows:

Table 2.1 Key benefits of Friction Stir Extrusion

Metallurgical benefits	**Energy Benefits**	**Environmental Benefits**
✓ Solid phase processing ✓ Fine and equiaxed microstructure ✓ No loss of alloying elements ✓ Improve yields (90% FSE vs 75% conventional) ✓ Reduction of cracking ✓ Mechanical alloying Synthesize of advanced material ✓ Good dimensional stability and repeatability	✓ 90% more energy efficient by eliminating melting ✓ Improved materials use (i.e. 100% scrap metals as input charges) ✓ FSE save energy (less than 15% of conventional) ✓ Considerable labour savings (16-60%) ✓ Lower operational cost and equipment cost. ✓ Equipment needed is not complicated	✓ CO_2, SO_2 emission free ✓ No emission of metal oxide, no fumes, no particulate and no molten metal oxidation ✓ 3Rs: Recycle, reuse, re-cover ✓ Green technology and eco-friendly ✓ Reduce fund for ✓ environmental protection

In friction stir based processing, tool material is the first thing to be determined. Tool material plays critical role in heat generation, material flow pattern, metallurgical bonding plastic deformation and quality of the processed sample. For material as aluminium or its alloys, tool steel like AISI H13 chromium molybdenum hot-worked air-hardened steel is most commonly used due to its good elevated-temperature strength and wear resistant (Rai, *et al.* (2011)).

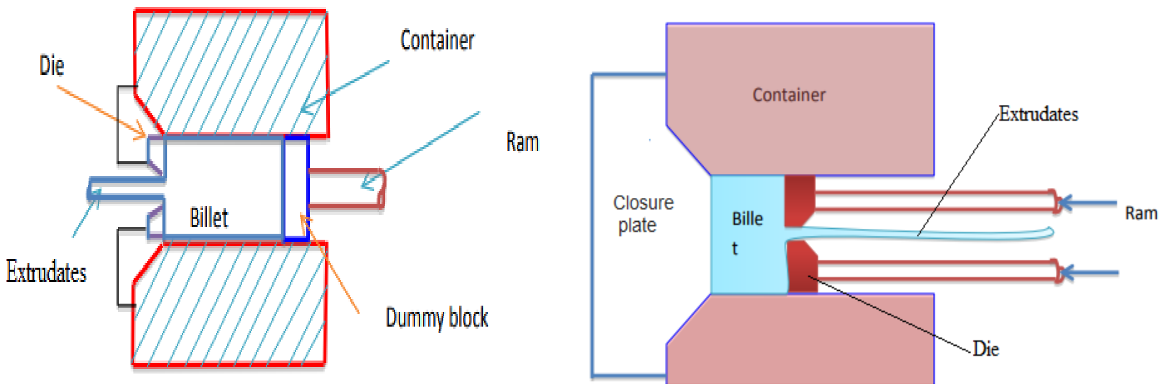
During friction stir welding and friction extrusion, the portion where the actual stirring takes place which leads to micro structural changes and experienced the high strain is usually referred as dynamically recrystallized zone, so the severe plastic deformation in friction stirred zone brings about fine and equiaxed grain structure to material. The high temperature and severe plastic deformation during welding in the stirred zone results in a new equiaxed fine grain structure as studded by R. Mishra and Mahoney, (2001). Therefore, the studies of microstructure evolution in friction stir welding were instructive in the analysis of friction extrusion process.

2.4 Conventional Extrusion Process

Extrusion is a compressive deformation process in which a block of metal is squeezed through an orifice or die opening to obtain a reduction in diameter and increase in length of the metal block. The resultant product will have the desired cross-section. Extrusion involves forming of axisymmetric parts. Dies of circular on non-circular cross-section are used for extrusion. Generally, extrusion involves greater forming forces.

The two main advantages of extrusion process over other manufacturing processes are its ability to create very complex cross-sections, and to work materials that are brittle, because the material only encounters compressive and shear stresses(Commonly extruded materials include metals, polymers, ceramics, concrete, modelling clay, and foodstuffs. The products of extrusion are generally called "extrudates".

Extrusion is classified in general into four types. They are: Direct extrusion, indirect extrusion, impact extrusion and hydrostatic extrusion. Among those, direct and indirect extrusion is illustrated in figure 2.7 a and b).



a) b)

Figure 2. 7 Conventional direct and indirect extrusion types

Friction extrusion differs from conventional extrusion in that the charge (billet or other precursor) rotates relative to the extrusion dies. An extrusion force is applied to push the charge against the die. In case of friction extrusion method either the die or the charge may rotate or they may be counter-rotating. The relative rotary motion between the charge and the die has several significant effects on the process. Except this, there are many concepts and definition can be used in both processes. Therefore, it is significant to review them and specify the commonalities and differences.

2.5 Extrusion Parameters

a) Extrusion ratio (R): It is the ratio of area of cross-section of the billet to the area of cross-section of the extrudate.

$$R = \frac{Ao}{Af} \qquad \text{Eq (2.1)}$$

Where Ao is the cross-sectional area of initial billet and Af is the cross-sectional area of the final product. Based on the equation 2.1, the extrusion ratio used in this thesis was 8:1

b) Shape factor: Ratio of perimeter to the cross-section of the part.

c) True strain: based on extrusion ratio the true strain can be written as;

$$\epsilon = \ln\left(\frac{Ao}{Af}\right) = la(R) \qquad \text{Eq (2.2)}$$

d) The ideal extrusion force: without considering friction force for perfectly plastic material the extrusion force is;

$F = AoY \ln (\frac{Ao}{Af)})$ Eq (2.3)

Where Y is yield stress

2.6 Extrusion Defect

Defects in extruded products occur predominantly due to friction and non-homogeneous material flow. Further, temperature variations across the billet during hot extrusion can also lead to inhomogeneous deformation. Three types of defects are prominent in extrusion. They are: extrusion defect, surface cracks and internal cracks.

A. Extrusion defect

This is basically due to inhomogeneous deformation; in which the material at the centre of the billet comes across least resistance compared to the material near the die wall. As a result, rapid flow happens at center. After one third of the billet is extruded, the material from periphery gets entrained towards the center and flows rapidly. This defect is known as pipe or tail pipe or extrusion defect. By reducing the friction and temperature variation between centre and periphery, this defect can be reduced. Using a dummy block smaller in diameter than the billet may form a thin film of metal and protect the billet against oxidation.

B. Surface cracks

Too high extrusion speed, too large a friction too high a temperature may result in formation of surface cracks. Fir-tree cracks are transverse cracks which often occur in aluminium or magnesium due to hot shortness. Longitudinal tensile stresses may be induced on the outer layer, causing the cracks. At lower temperatures, stick-slip phenomenon may cause cracks especially in hydrostatic extrusion where pressures are very high. Sticking may happen due to thick viscous oil film.

C. Internal cracks

Secondary tensile stress at the centre can cause centre cracks called chevron crack or centre burst. Such defects are known to occur under low friction conditions and low extrusion ratio. Additionally, die angle and contact length play major role in centre burst. Larger the die angle, more the inhomogeneous deformation, thereby causes chevron cracks. Large h/L values cause secondary tensile stress at centre, because the material at centre has not reached plastic stage – due to non-homogeneous deformation.

D. Defect in Friction Extrusion

The material in the chamber is in solid state and gets plasticized close to plunger tip. So there is a negligible time in contact to chamber wall, as a result the defect caused due to internal defect is totally avoided. The variation of temperature across plasticized material in extrusion channel is insignificant and the extrusion pressure is uniformly distributed to the extrudate consequently, the formation of piping is eliminated. On the other hand hot and cold crack can be occurred on the surface of product due to either too high or too low die rotational speed.

CHAPTER THREE: METHODOLOGY

3.1 Introduction

The detailed methodology used for experimental study of friction stir back extrusion is provided in this chapter. To recycle, fabricate and study the behaviour of square bar from aluminium wire scraps via FSBE, tools were manufactured at Metal Industry Development Institute (MIDI) and the manufacturing process of square bar was carried out at ASTU machine shop using conventional lathe machine. In addition to experimental investigations, finite element analysis (FEA) was carried out in order to visualize the processes of FSBE and predict extrusion temperature as well as extrusion force required for the process. Accordingly, to achieve the general objective of the research; the general research design was described in figure 3.1

The experimental setup for the FSE process consists of two major systems: (a) tool and work piece holding system (b) motion supply machine frame. The issues that was considered during experimental works includes the process parameter based factors, method of specimen preparing and collecting, temperature, heat and force applied, is the critical aspects to be take care. As for the geometry-based parameter, the die design determines the level of strain, metallurgical structure, material flow and pressure imposed to promote the inter-chip welding and extrusion quality during the process. The following section will introduce the FSBE tool designing and manufacturing, material, instrumentation, and machine modifications used in this work.

3.2 Tool Designing and Manufacturing

For this experiment, the tool called plunger was made from D2 tool steel heat treated to Rockwell hardness C of 55 (see appendix D for composition). The plunger has round head with diameter of 40 mm and 50 mm in length at one end and tapered tail which used for rigidly mount into the tailstock quill. The plunger has an external diameter of 40 mm and central through extrusion channel of 6 mm in diameter and 1 mm of height before square side of 5.6 x 5.6 mm which defines the resulting shape. The height of square side channel is 2.5 mm and after this the hole is widening to 8 mm in diameter; to avoid unnecessary friction force imposed to extrude product. The plunger tip pattern was a scrolled surface. The scroll plunger is rotated in a clockwise direction (when die tip faced downward as in experiment setup), so that the scroll pattern can gather plastic-state material toward the centre.

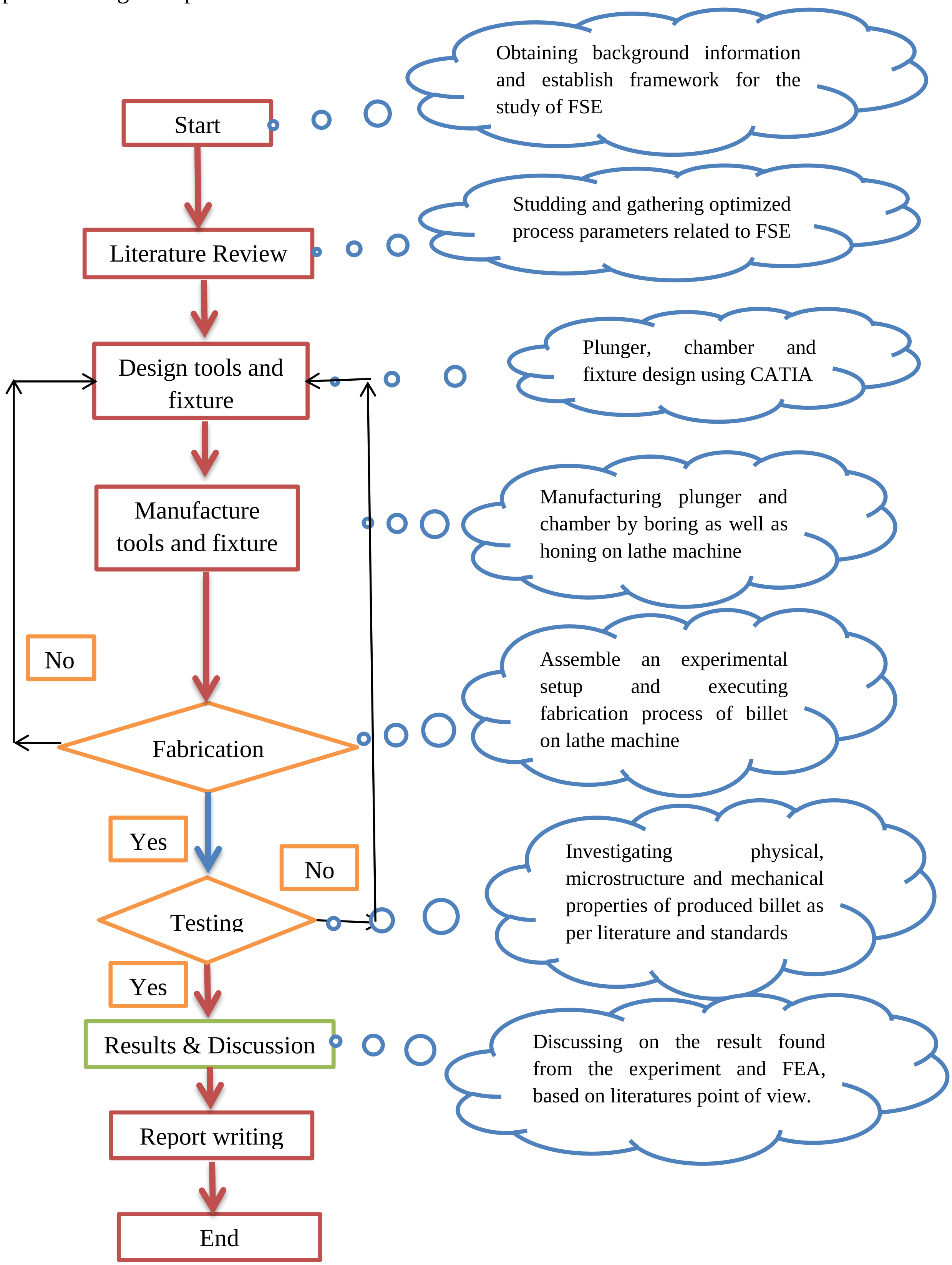


Figure 3.1 Research design flow chart

The scroll pattern was manufactured on CNC milling machine at MIDI and the G-code used for generating scroll pattern is presented in appendix B. The detailed design and manufactured of the plunger was represented in the figure 3.2.

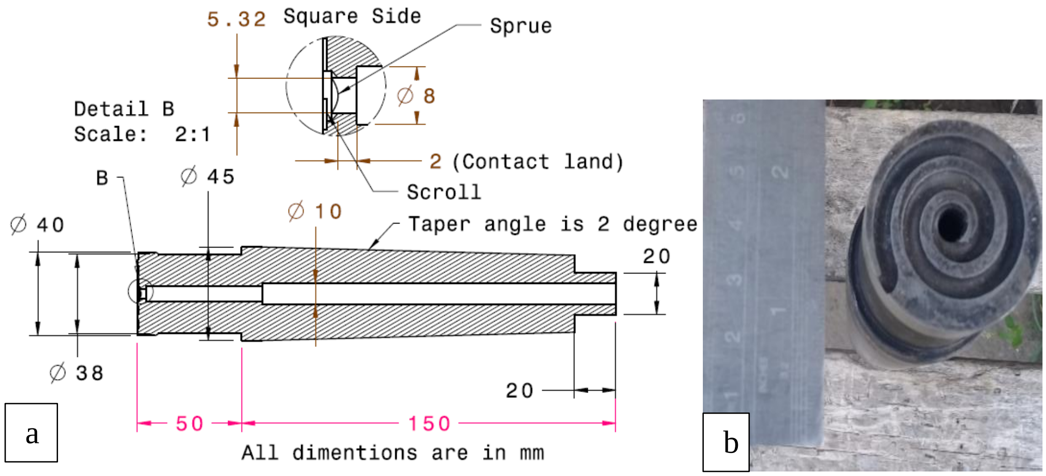


Figure 3.2 a): Detailed schematic of the Plunger, b): Manufactured Plunger

The other key component of the friction stir extrusion device is rotating chamber or container. This component was made of quenched and tempered D2 tool steel. The inner and outer diameters of the rotary chamber (shown in figure 3.3) were 40.2 mm and 65 mm, respectively, and the depth of the chamber is 60 mm. This component has parts in both ends: at one end a dedicated fixture was designed in order to mount the chamber rigidly to the spindle speed of the machine and on the other end it designed to fill and accommodate aluminium scraps.

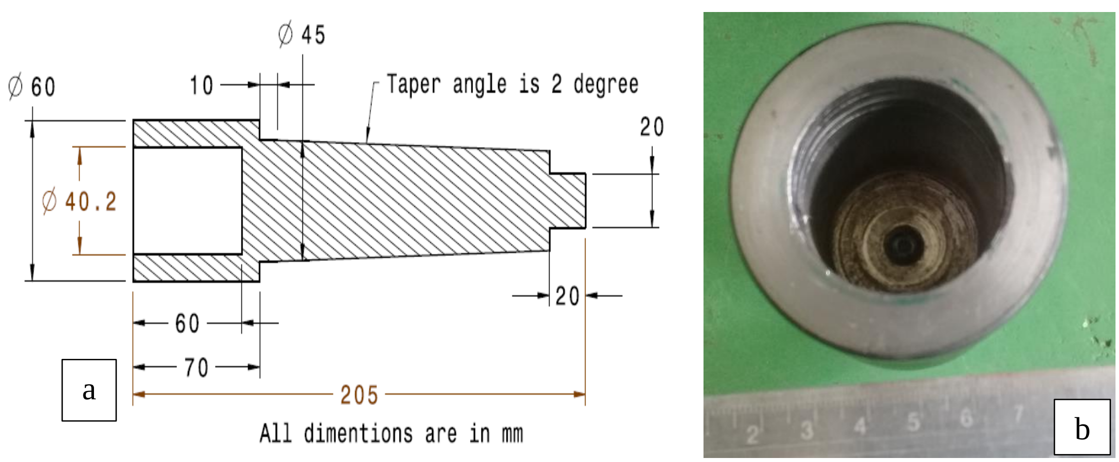


Figure 3.3 a) Detailed schematic of the chamber, b) The manufactured Chamber

The manufacturing process of plunger and chamber was performed on NC lathe machine at the metal industry development institute (MIDI). Harrison M 460 lathe (as shown in figure 3.4) was used to manually create the geometry from the round stocks. It has an accuracy of 0.001 mm.

Figure 3.4 Harrison M 460 lath machine

Heat treatment was carried out to the tools to achieve high hardness and better wear resistance. According to the guideline provided by the supplier of the tool steel, the tool underwent hardening, quenching, and tempering procedure to achieve hardness of HRC 55 as referred in table 3-1.

Table 3.1 Guide line for heat treating D2 tool steel

Hardening austenitizing temperature	Soaking time	Quenching media	Tempering	Rockwell hardness
1020^{o}C	Soaked at temperature 20 minute plus 2 for each mm thickness and quenched in air.	Oil	300^{o}C	55HRC

3.3 Lathe Machine Modifications

Extrusion of square bar was carried out on a conventional lathe machine fit with an attachment modified to accommodate required experiments. The lathe machine spindle was used to rotate the scraps charged chamber (spinning tool). The plunger was mounted on the tailstock quill which was manually driven longitudinally into the spindle speed as shown in figure 3.5. The lathe machine tailstock quill was assembled with a central square hollow plunger enabling the extrusion of square bar through it.

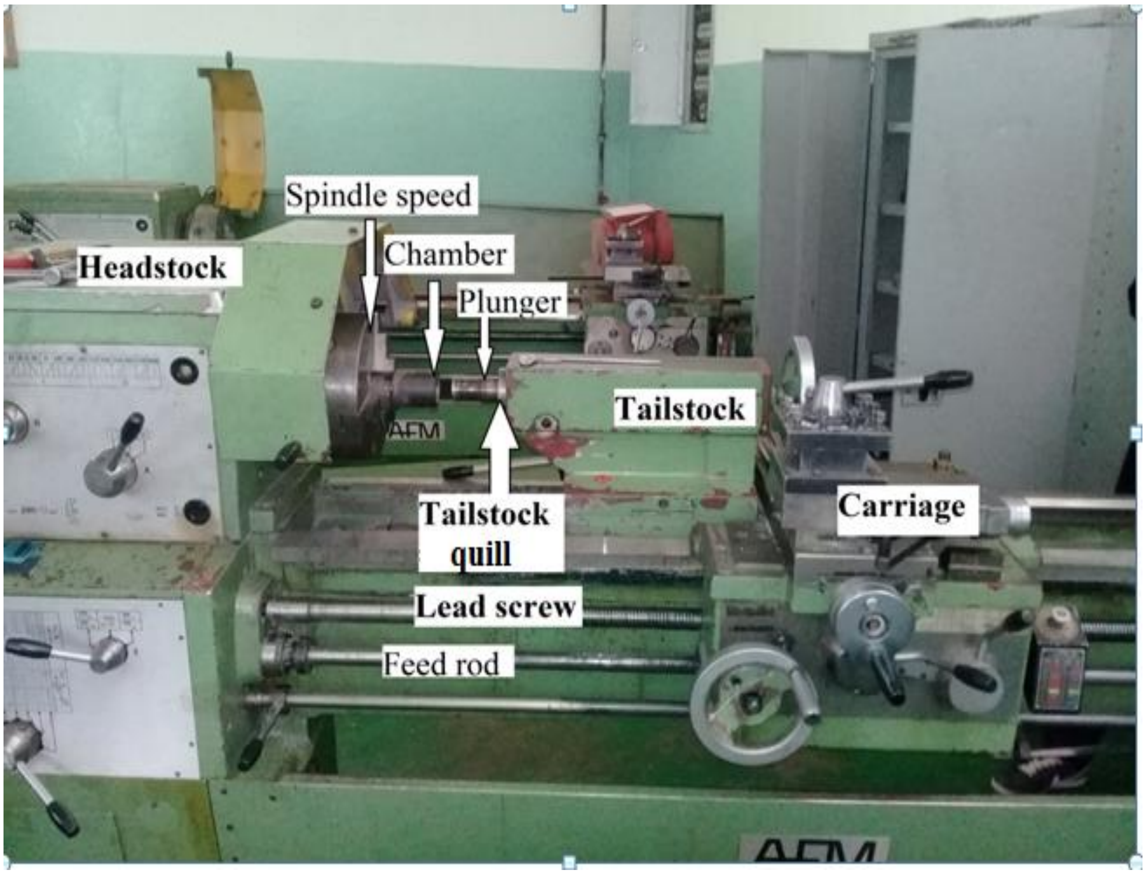


Figure 3. 5 Lathe machine configuration

3.4 Experimental Procedures

3.4.1 Material and Composition

The material was used for experimental work was AA1050 aluminium alloy wire scraps. The raw material was received in wire form and chopped on shearing machine of the length of 60 mm. The chopped wire scraps was cleaned macroscopically with the use of sand paper as shown in figure 3.6. The nominal composition of the aluminium wire scrap shown in table 4-1.

Figure 3. 6 Aluminium wire scraps used for the experiments

Table 3. 2 Nominal compositions of Aluminium Alloy 1050

Element	Al	Si	Fe	Cu	Mn	Mg	Ti
Wt%	99.22%	0.24%	0.4%	0.02%	0.03%	0.05%	0.04%

3.4.2 Friction-stir Back Extrusion

The extrusion process was carried out as follows. First the counter clockwise rotating chamber which contained aluminium wire scraps sample was mounted and actuated by the spindle speed of the lathe machine. Then the stationary plunger which mounted into tailstock quill was moved longitudinally until its tip was in contact with the sample. Once plunger tip is contact with the sample; the chamber begun rotation at desired rate and maintained for specified time. The plunger was kept constant until the sample materials were heated by friction between plunger tip and surface of sample. Schematic illustration of designed setup for experimental study can be seen in figure 3.7 and furthermore, the experimental set up of FSBE as shown in the figure 3.8.

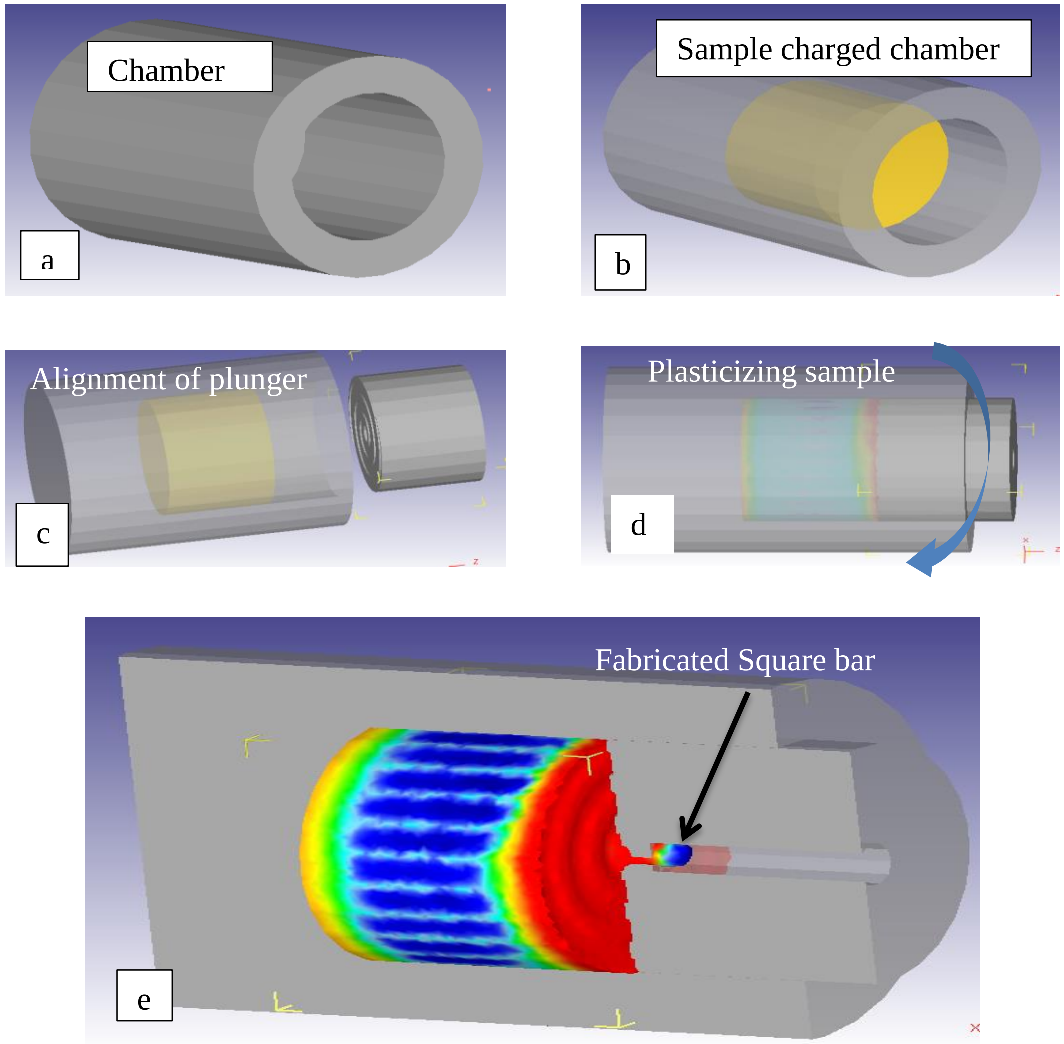


Figure 3. 7 Schematic representation of FSBE process

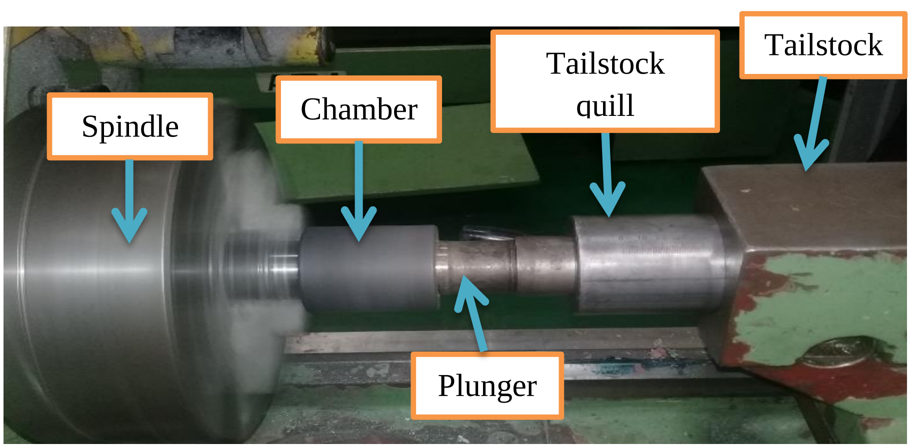


Figure 3. 8 Experimental setup of friction stir back extrusion process

3.5.3 Experimental condition

The parameter chosen to investigate for this study was rotational speed. It contributed about 71.6 % to the overall extrusion parameters (Ansari *et al.* (2015)). Die rotational speed is related with temperature, extrusion rate, surface finish and material flow. This parameter was chosen in order to understand its influence on the resulting physical and mechanical properties of the extruded product. The selected rotational speeds through trials to perform experimental work were 280 rpm, 400 rpm, 560 rpm and 800 rpm.

The Z-axis of the lathe machine was coincident with the extrusion axis, so that the Z-force was the extrusion force. In the experimental work, it was difficult to know extrusion force which exerted to extrude the square bar; because the extrusion pressure was applied manually via the use of tailstock wheel. On the other hand, it was possible to calculate average extrusion rate by assuming the volume of die advanced equals the volume of extruded bar and finding the corresponding time of plunge distance as indicated in equation 3.2. In the current die design, due to the length of die and hence of the extrusion hole, when the extruded material filled the entire hole and reached the confined shaft, the friction extrusion process ended and an aluminium square bar of about 290 mm in length was produced. Hence, controlling transvers rate of plunger and knowing its influence is difficult in the current manufacturing of square bar on the conventional lathe machine, as a result approximate processing time was captured to calculate average extrusion rate for each product at specified rotational speed. Once extrusion time and length of product known, one can calculate average extrusion rate for each extruded product.

Assume that internal chamber area times plunge distance is equal to cross-section area of square bare times square bare length.

$$(h_1 - h_0) \times \pi r_c^2 = s^2 L \qquad \text{Eq (3.1).}$$

Where, r_c is the radius of the chamber, ‘s’ is the cross-sectional height of square bar, L is the length of extruded square bar, h_1 and h_0 are the final and initial Z position of the plunger, respectively. h_0 can be determined as the lowest position of the die. So h_1 can be calculated by Eq (3.1). Find the corresponding time of h_1 and h_0, extrusion time is t derived. Let L divided by t.

$$\text{Average extrusion rate} = \frac{L}{t} \qquad \text{Eq (3.2)}$$

The helix angle can be found by separating the helix from the square bar, representing the section as a right angle triangle, and calculating the angle (α) that is formed as shown in figure 3.9.

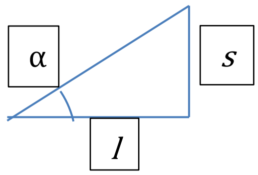


Figure 3. 9 Right angle triangles for helix angle calculation

$$\alpha = \arc\tan\left(\frac{s}{l}\right) \qquad \text{Eq (3.3)}$$

Where, '*s* ' is the cross-sectional height of square bar and '*l* ' is lead length of the square bar.

3.5 Extruded Sample Testing Procedure

3.5.1 Sample preparation for Microstructure and hardness

An extruded sample was selected and sectioned using an Abcut-M abrasive cutter machine along transvers direction. For the optical microscopy (OM) and micro-hardness test, the samples were prepared to the dimensions of 5.6×5.6×12 mm and sectioned in the short transverse (ST) directions. After the sample was cut, it must be prepared for the examination of microstructure and hardness as per the standard procedure. This usually involves two stages: mounting and polishing. The mounting operation is used to facilitate the handling of samples that would be difficult to handle during the grinding and polishing operation.

The two most common mounting techniques are cold mount and hot mount. Cold mount are simply putting the sample in the acrylic hardener and acrylic powder solution that hold the specimen during polishing as shown in figure 3.10 a. When hot mounting was employed, the specimen was embedded in the thermosetting plastic as shown in figure 3.10 b.

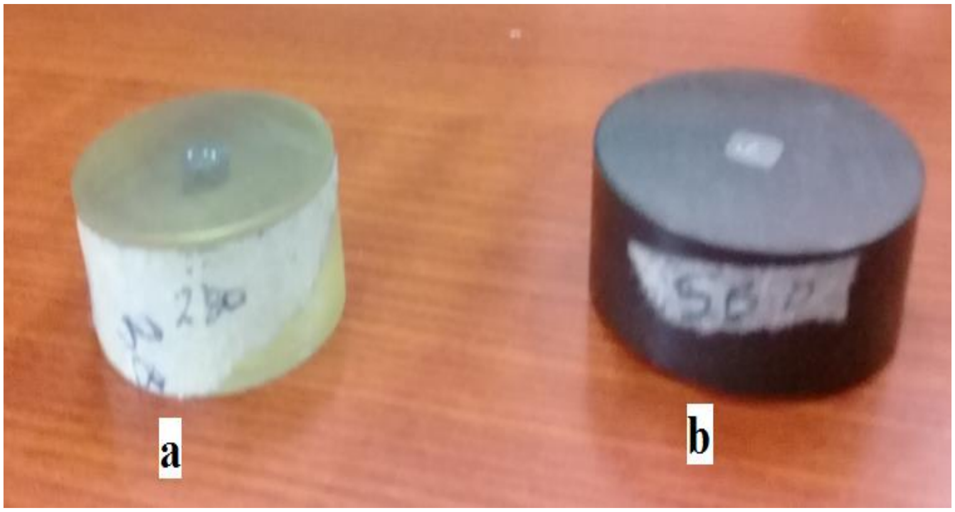


Figure 3. 10 Samples mounting: a) Cold mount, b) Hot mount

After the specimen was mounted through either means it was polished. Polishing takes place over a series of hand grinders using sand papers and polishing wheels. The sanding treatment gets progressively smaller at each stage and the specimen must be washed after each sanding to ensure than none of the particles from the last stage remain. The purpose of polishing the specimen is to achieve a scratch-free surface to be viewed under the metallographic microscope. Any scratches present will cause a distortion in the reflected light and the microscopic features will not be visible. Polishing of As Received (AR) FSBE processed square bar samples was completed following the schedule outlined in table 3.3 using Mtpol-II polishing wheels. This initial examination involves the as-polished specimen.

Table 3.3 Polishing procedure for microscopy

Step	Abrasive	Time	RPM
1	220 Grit SiC Paper	1min	-
2	800 Grit SiC Paper	1min	-
3	1200 Grit SiC Paper	1min	-
4	2000 Grit SiC Paper	1min	-
5	3μm Metadi Diamond Suspension	2min	200
6	1μm Metadi Diamond Suspension	2min	350
7	0.05 μm Colloidal Silica	2min	500

After the samples were polished and get free from scratches it must be etched in order to see the grain structure and grain boundaries. Etching is the process of immersing a specimen in a chemical etchant. Etchants are unique to the metal under examination. The proper etchant for pure aluminium is methanol solution which has a composition of listed in table 3.4. A chemical etchant attacks the boundaries between metal grains. This gives the boundaries a rougher appearance than the as-polished boundaries. This causes the boundaries to appear darker under the microscope.

Table 3.4 Etchant used for microstructure observation

<table>
<tr><th>Etchant</th><th>Composition</th><th>condition</th></tr>
<tr><td rowspan="4">Methanol</td><td>Methanol 25ml</td><td rowspan="4">10-60 seconds</td></tr>
<tr><td>Hydrochloric acid 25ml</td></tr>
<tr><td>Nitric acid 25ml</td></tr>
<tr><td>Hydrofluoric acid one drop</td></tr>
</table>

3.5.2 Etching and Examination

The specimen was placed on the optical microscope for examination. The specimen was examined at 50x magnification in order to observe major features of the structure. The magnification was then increased to 100x in order to observe the finer details of the structure. Photomicrographs were taken at each magnification as documentation of the features observed at both stages.

The specimen was then taken to the fume hood for etching. The specimen was immersed in a methanol etchant for 30 seconds and then removed from the etchant and immediately rinsed with water and alcohol. After the alcohol rinse the specimen was dried with the air compressor. The etched sample was returned to the metallurgical microscope for further examination.

The specimen was examined first at the 50x magnification setting to observe the larger features of the structure. The magnification was again increased to 100x to observe the finer features. Photomicrographs were again taken at both stages as a record of the observations. Once the photomicrographs were taken, the microstructure of the square bar was determined.

3.5.3 Hardness testing

Vickers Hardness of friction stir back extruded 1050 square bars was measured using Vickers hardness tester. The test load applied was 1kg and the dwell time was 10 seconds. Various samples of FSBE processed at different rotational speed were tested. The averages of five values of hardness within each tested area were considered. All samples were taken from the transverse section of the processed square bar.

CHAPTER FOUR: RESULTS AND DISCUSSION

4.1 Square Bar Product and Process Progress Analysis

The manufacturing of square bar through FSBE process was successfully performed on conventional lathe machine. The square bars from aluminium wire scraps made by FSBE process on conventional lathe machine is about 190mm to 290mm long as shown in figure 4.1. The length of bars is only limited due to the space inside tailstock quill. The surface of the square bars is clean and smooth except at start and ending. No obvious surface defect was observed. But due to the rotating feature of FSBE process, the square bar was twisted.

Figure 4.1 Manufactured square bars

The processes of manufacturing square bars via FSBE can be divided in to two regimes; the first one is consolidation regime which occurred inside chamber and the other one is extrusion regime which created inside plunger. For the first time, wire scraps was largely compressed using ordinary hammer in to the chamber as shown in figure 4.2 a. Then sample charged chamber rotation speed is fixed to 280 RPM and plunger was pushed longitudinally until the tip is contacted with the sample. Then, the friction between rotating aluminium scraps and plunger generated local plastic deformation and consequential heat and start to consolidate. Along with increased temperature and severe plastic deformation, wire scraps were kind of “welded” together and thus, consolidation happened.

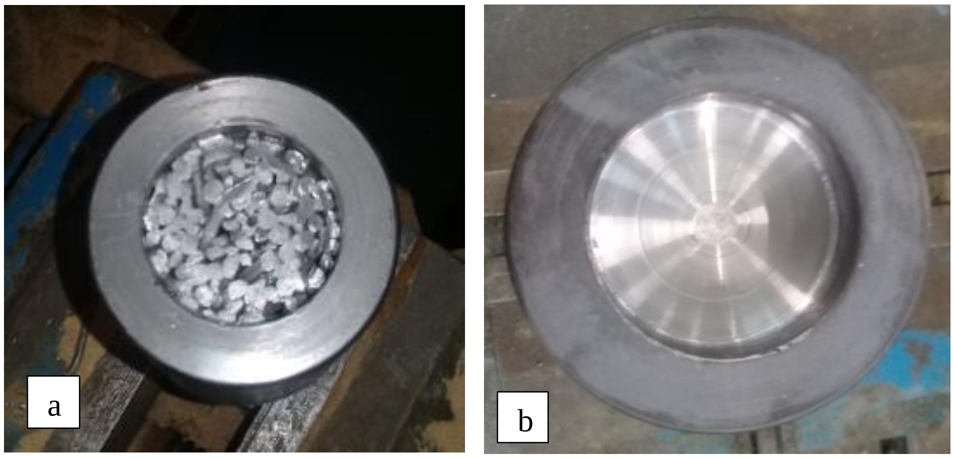


Figure 4. 2 Compression (a) and Consolidation process (b)

Under steady high compressive force and torque, more material involved and generated more plastic deformation further and produced a great amount of heat. The flow stress of aluminium alloy decreased to a low value as a result of elevated temperature. The upper wire scraps which was near die tip turned into highly mobile plastic state quickly. The portion located close to extrusion hole exited first. The extruded material left the heat source before melting and cooled quickly. It was confined by die hole and consolidated to form a square bar. Thereupon, die gradually moved longitudinally and adjacent material replenished, deformed, got heated up and softened, finally extruded out as well. Such balance continued and square bar product was produced.

Prior to extrusion of square bar, partially consolidated of disc is formed inside chamber due to the heat generated by the friction between the plunger tip and sample. As a result, the sample material close to the die tip became softened partially and form disc as shown in Figure 4.3. From Figure 4.3 one can also understand the similarity between friction stir welding and friction stir extrusion. The consolidated disc by FSBE technique has three zones; which is consistent with the zones of friction stir welding. The three zones observed in FSBE processes are:

plasticized zone, thermo-mechanical affected zone and heat affected zone; and each zones are described below;

4.1.1 Plasticized zone

The portion where the actual stirring takes place which leads to micro structural changes and experienced the high strain is usually referred as Dynamically Recrystallized Zone (DXZ) or nugget zone in case of FSW. The high temperature and severe plastic deformation (SPD) during welding in the stirred zone results in a new equiaxed fine grain structure. When it comes to FSBE, the substantial level of plastic deformation in this region of relative rotary motion can promote solid state welding of few layers near plunger tip which is effectively consolidate prior to extrusion. Through frictional heating; the softened sample material flowed into the scroll, gets homogenized and finally extruded. In this region, the material has been plastically deformed by the friction stir extrusion tool, and the heat from the process will also have exerted some influence on the material. In the case of aluminium, it is possible to get significant plastic strain without recrystallization in this region, and there is generally a distinct boundary between the recrystallized zone and the deformed zones of the TMAZ. The comparison of experimentally found and finite element simulated disc is represented in appendix E.

4.1.2 Thermo-mechanical affected zone

Thermo-mechanical affected zone (TMAZ) is a transition zone which is unique in FSW. During welding, this region experiences both temperature and deformation, which are not sufficient to induce the recrystallization in the material. TMAZ is located between the upper plasticized zone and lower heat affected zone. In this region, which clearly lies closer to the plasticized centre, the material has experienced a thermal cycle which has modified the microstructure and/or the mechanical properties. However, there is no plastic deformation occurring in this area.

4.1.3 Heat affected zone

The heat affected zone is the part of consolidated disc and located at the lower area of the disc. In heat affected zone, material is influenced by heat (thermal cycle). Heat in this zone does not induce any plastic deformation and which although it may have experienced a thermal cycle from the transition zone.

Figure 4. 3 Friction consolidated wire disc with three different zones

4.2 Effects of Rotational Speed and Related Parameter Characterization

The three replicate of the experiment was considered during experimental condition for each rotational speed. The trials with selected rotational speed and resulting square bar length as well as related parameters of extruded products are illustrated in table 4.1.

Table 4.1 Trials with varying rotational speed for 1050 aluminium wire scraps and results

Sample name & extrusion run #	RPM	Extrusion time (s)	L (mm)	Extrusion rate (mm/s)	Consolidation time (s)	Helix angle (degree)
1050-01	280	300	190	0.63	350	1.7
1050-02	400	210	210	1	230	1.5
1050-03	560	150	265	1.8	120	1.2
1050-04	800	90	290	3.2	80	1.1

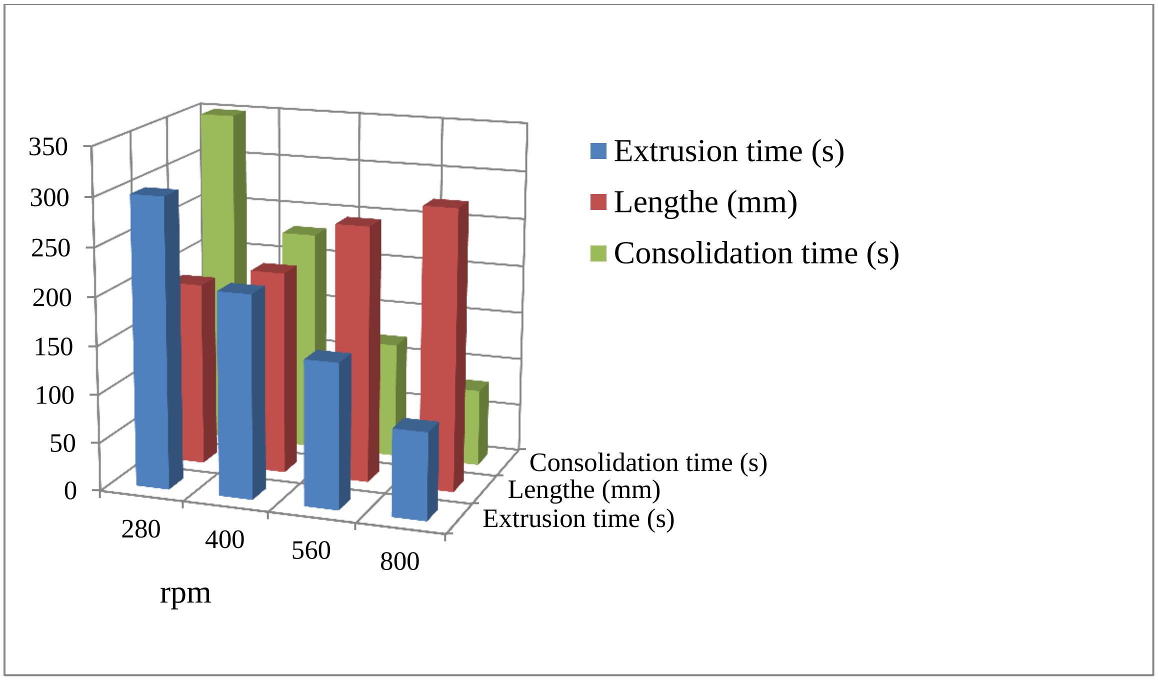


Figure 4. 4 Graphical representation of process parameters

Several continuous lengths of 1050 aluminium square bar are successfully extruded with length range up to 290 mm in a single run with the parameters in run 1050-04 (table 4.1). Figure 4.4 clearly represent the influence of rotational speed on the extrusion time and consolidation time of friction stir back extruded bar. As it is seen in figure 4.4 with increasing rotational speed from 280 to 800 rpm, the extrusion time required to produce a bar is decreasing and the same trends was observed for consolidations time. It means that in high rotational speed high heat is imposed to the surface of the sample by mechanical action; as a result enough heat generated and conducted to reach the scraps to softening temperature. In addition, in high rotational speeds, a high shear strain rate is developed at the boundary between the scrolled plunger and the extruded material (aluminium wire scraps), and within the plastic zones of the extruded material. The ensuing temperature rise can lead to deformation at localized regions in short time.

Higher rotational speed, which corresponds to higher power input, accelerates the evolution of the process toward "conventional" extrusion. This phenomenon can be explained by the following assumption: more power input will increase processing temperature, so the material's flow stress is lower and mobility is better. In other words, the extrusion rate is higher (Li *et al.* (2015)).

4.3 Macrostructure and Rotational Speed

The surface appearances of the square bar produced by the FSBE process are shown in figure 4.5. Good and poor surface quality of bar is observed. The photographic view of produced square bars using deferent rotational speed from (280-800 rpm) is presented in figure 4.5. The photographic view (figure 4.5 A) shows that the product produced using 800 rpm and the surface of the square bare is formed completely. The surface is smooth and there are a few discontinuities observed on the surface of the bar. The discontinuity observed on the surface of square bar was occurred due to non-constant traverse speed of tailstock quill which was driven manually. Surface appearance suggests that the temperature involved during FSBE due the friction is sufficient for smooth follow of plasticized aluminium. There was no sticking of plasticized aluminium to the wall of the die. The formation of the cold crack can be attributed to the initial stages of the square bar forming process which is insignificant. This cold crack defect is happened in all extruded square bar tip and has an average length of 12mm. The reasons are; the area at the center of the sample is not stirred simultaneously with the periphery of the sample; as a result insufficient temperature distribution to the spacemen surface is not equal at the beginning of the process. However, the defect is gradually decreases as we go down from the tip of the bar. Cold portion can be trimmed easily as scrap form from the square bare during production. On the other hand, an excessively high rotational speed of the sample charged chamber would result in excess heat input during the extrusion procedure (figure 4.5 (C)). At higher rotation speeds, a higher shear strain rate is developed at the boundary between the plunger tip and the sample material surface, as well as within the plastic zones of the extruded material. The consequent temperature rise can lead to deformation at localized areas presented in figure 4.5, (C) in which a localized deformation occurred on the surface of bar which is commonly called as hot crack. In comparison, at lower rotational speed (280 rpm) hot crack was not occurred on square bars (figure 4.5 B).

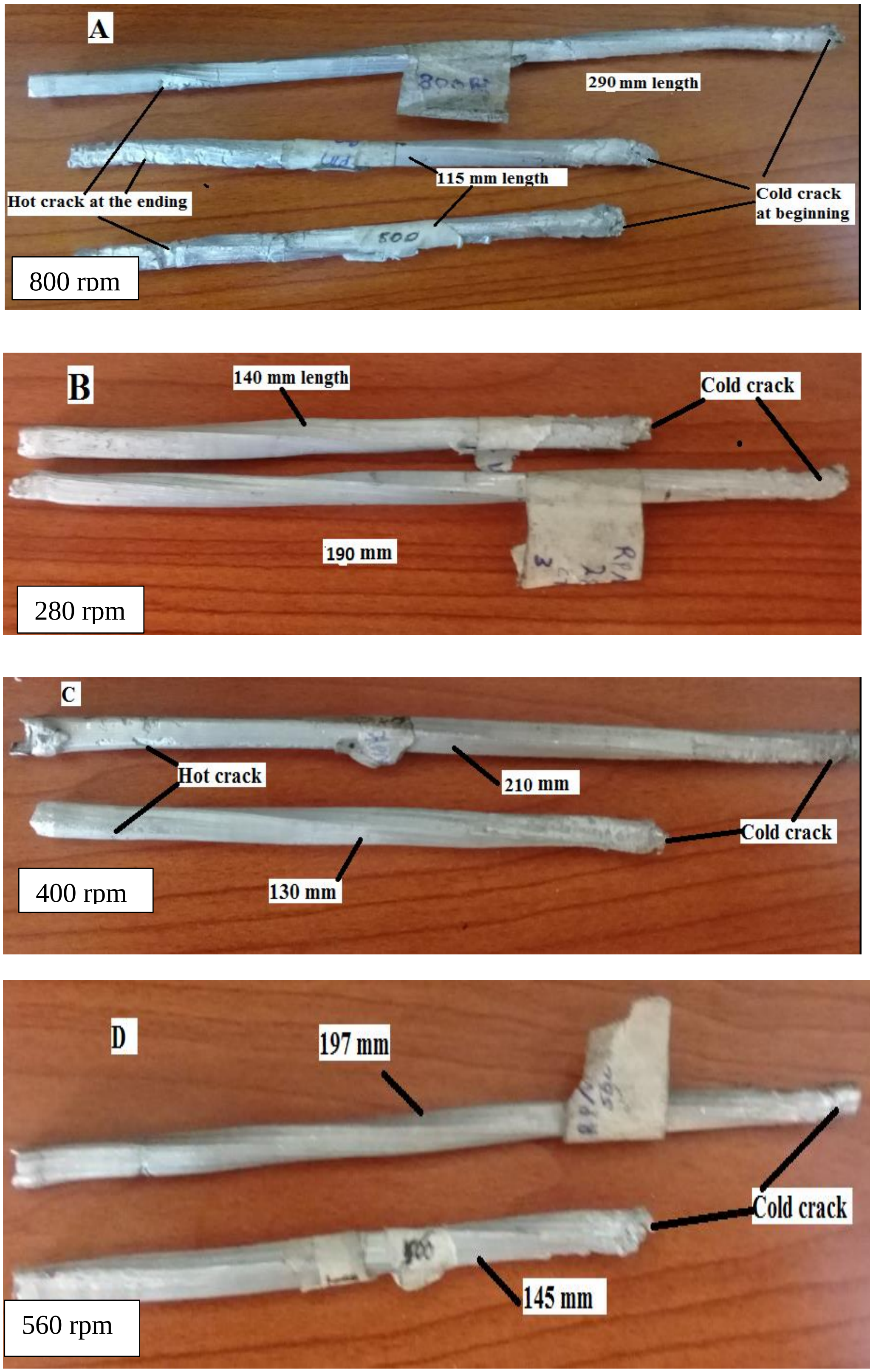


Figure 4. 5 Macro-views of various 1050 aluminium square bar produced by concept of FSBE

The most defects observed on the surface of all square bar is twisting due to the rotating nature of FSBE process. As it is clearly plotted on figure 4.6 rotational speed and helix angle has invers proportionality. The rotational speed has influence on the formation of twist as it is highlighted by literatures (Abdi *et al*. (2014)) and (Tang and Reyonlds, (2010)). According to their study, as rotational speed increases; more power input created and the process looks likely 'conventional' extrusion process and rotation of plasticized material could be reduced; so inertia created due to rotation of softened material would-be reduced.

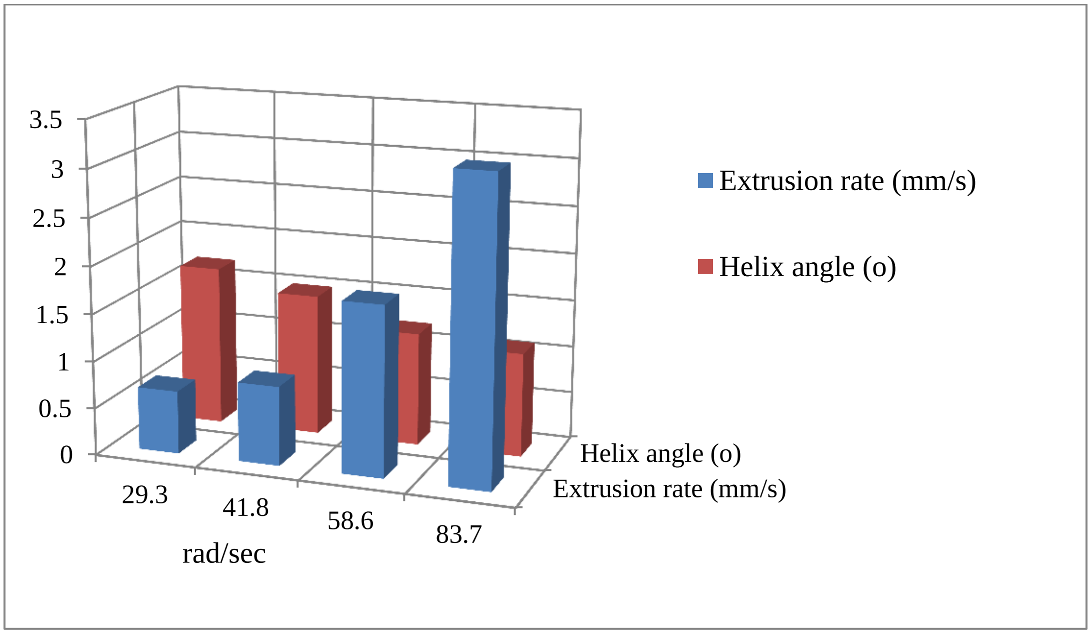


Figure 4. 6 Effect of rotational speed on helix angle

For more clarification of twisting created on the surface of the square bar; one can see the particle path line created (Section 2.3.2 and see figure 2.2) during friction stir extrusion which was studded by Zhang *et al.* (2014). The approximated twist angle observed on square bare was less than 2 degree. Even if rotational speed is increased twisting defect were not removed from the square bar. This implies that there could be other influencing parameter and might be resulted from plunge design and it could be contact land or extrusion channel height; *which will be investigated in the future work.*

These preliminary results were the first validation of the proposed friction-stir back extrusion technique to produce square bar. The friction-stir back extrusion is found to be capable of recycling waste aluminium wire and converting them back into usable product.

4.4 Microstructural Analysis of Square Bar

4.4.1 Grinding and Polishing

From the polishing it was determined that extreme care should be taken at every phase of the polishing operation. It would be possible to improve the end results of the polishing operation if the sample would visually checked for the absence of scratches at every step. Thorough washing was absolutely necessary between each step also. Another way to improve the final results of polishing would be to incorporate the metallographic microscope at various stages throughout the polishing operation. This would ensure that the major scratches from prior stages have been removed. Over all it is determined that proper polishing technique requires patience and practice. The progress of grinding and polishing of the samples made by different rotational speeds are represented in figure 4.7.

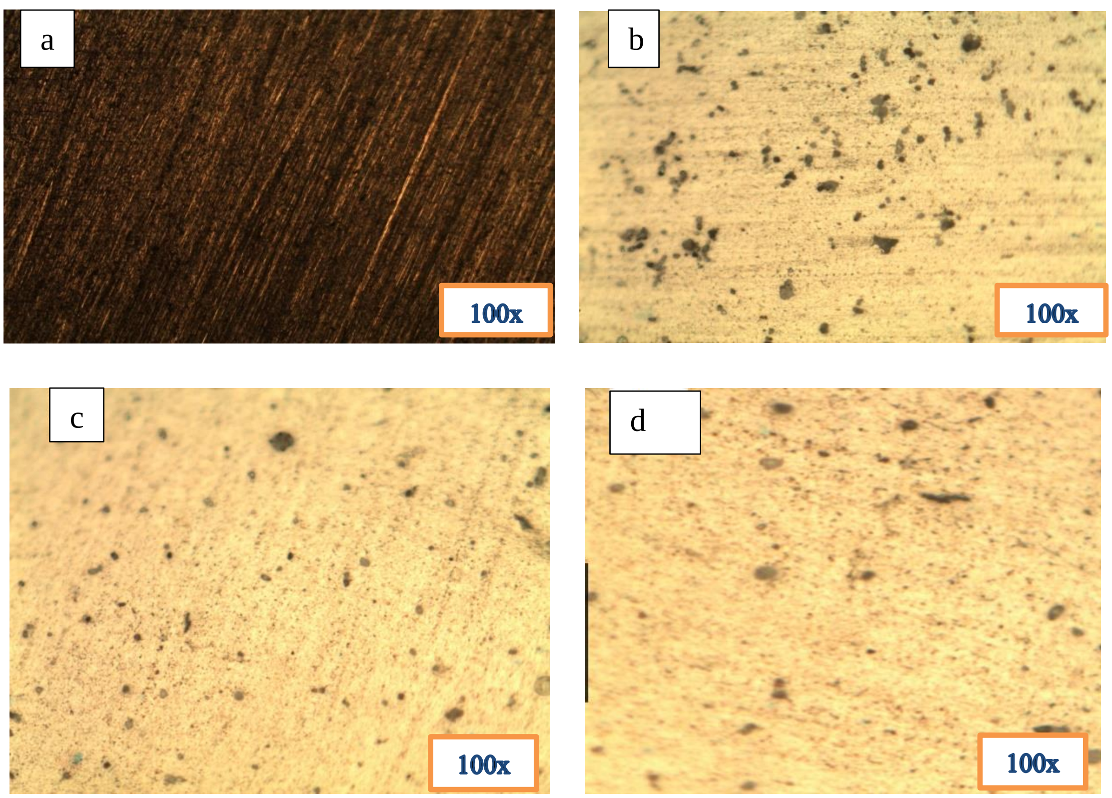
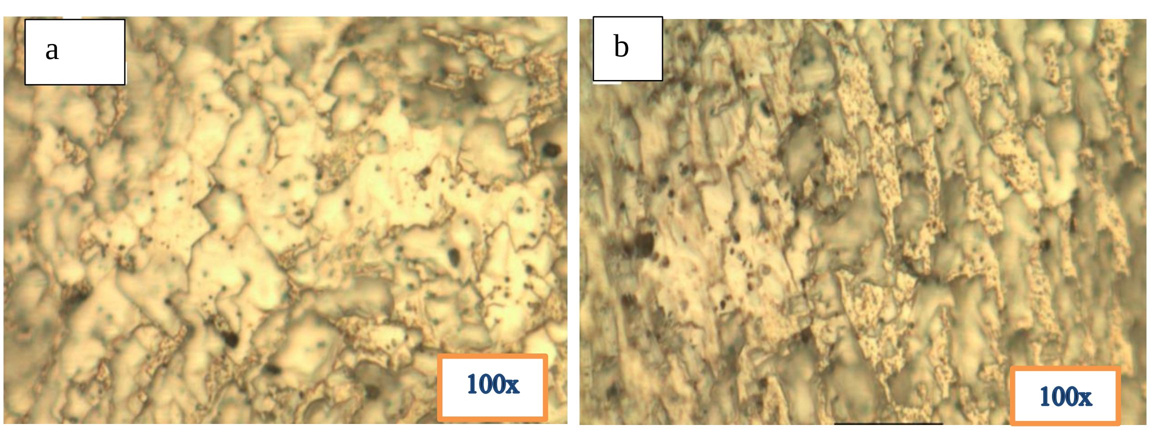


Figure 4. 7 Micrographs showing grinding and as-polished of samples, a) grinded; b) polished at 280 rpm; c) polished at 400 rpm; d) polished at 560

Figure 4.7 a) describes micrographs of grinded samples with sand papers. It is observed that, the samples had too many scratches to make any accurate observations. As a result, the specimen was polished at the 1μm polishing wheel for ten minutes in an attempt to remove the scratches. After the samples were polished, the surface specimens were free from scratches under 100x magnification as shown in figure 4.7 (b-d). The photomicrograph did reveal that the aluminium specimen was porous; with the samples produced at 280 rpm as shown in figure 4.7 b). At a low rotational speed, the heat input during the process was insufficient. Hence the material couldn't get fully homogenous. With increasing rotational speed of die to 400 and 560 rpm, these voids are reduced (see Fig 4.7 c and d). But the rest of the material processed under higher rotational speed has good micrograph appearances.

4.4.2 Etching and Examination of Microstructure

The appearance of slightly blurred grain structures suggests that the etchant had been stained during etching process. However, the etching process appeared to have been carried out correctly as the boundaries became slightly blurred when removed from the etchant. The examination showed several key features of the aluminium specimen. Figure 4.8 compares grain structure and grain boundaries taken by optical microscopic. As it can be seen the optical image of the parent aluminium is shown in figure 4.8 a). From figure 4.8 (a) it can be understood that large grains are distributed in the parent material. As it can be seen in figure 4.8 b), in samples produced with rotational speed of 280 rpm, there was a voids and refinement of grains compared to parent aluminium. The relatively fine structure of the aluminium suggests a recrystallization of grain was carried out during FSBE process as shown in figure 4.7 c and d. In this case the plasticized aluminium would not have had time to form larger grains.



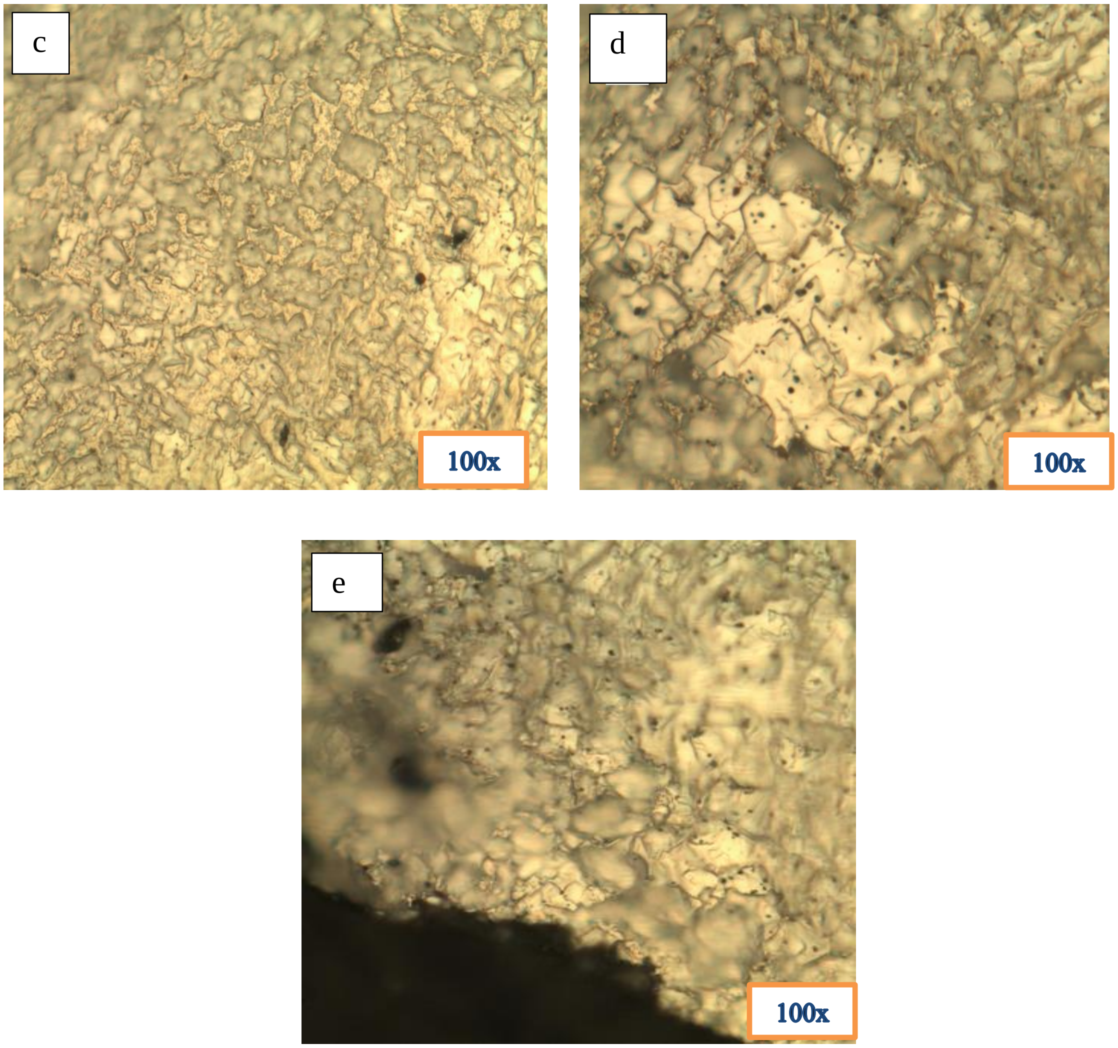


Figure 4. 8 Optical micrographs of wires produced at different rotational speeds: a) base aluminium; b) 280 rpm; c) 400 rpm; d) 560 rpm

Analysing the cross section of the extrudates, almost uniform and fine equiaxed microstructure (see Figure 4.8 c) can be observed in all the “sound” case studies (i.e. the ones not presenting hot and cold cracks on the external surface). Figure 4.8 c) clearly shows a significant amount of grain refinement in the microstructure of the material. It shows how the grain structure becomes finer and equiaxed in friction stir back extrusion compared to base material at rotational speed of 400 rpm. Because of different amounts of frictional heat and deformation rate, the averaged grains are varies from one specimen to another for different process conditions (i.e. rotational speed). This is consistent with the previous results (Tang and Reyonlds, (2010) on the friction stir extrusion of wire. The equiaxed grain directly implies that recrystallization of grains were takes places during the plasticization of aluminium wires via FSBE processes. From figure 4.8 (d) it can be seen that, the grain became enlarged which were processed using 560 rpm. Figure 4.8 (e) shows grain structure at the periphery of processed sample and it revealed that, there was a grain refinement and even distribution throughout the sample. More photographic view of microstructure of square bare produced FSBE presented on appendix F.

These results of optical microscope provide additional validation of the proposed friction stir back extrusion technique, as it is shown to refine and homogenize the microstructure of the as-received aluminium wire scraps while turning it into a square bar.

4.5 Mechanical Properties of Extruded Square Bar

4.5.1 Vickers hardness test

Hardness testing provides useful information, which can be correlated to tensile strength, wear resistance, ductility, and other physical characteristics. Hardness testing is therefore useful for monitoring quality control and for the materials selection process.

Once the samples were fine polished, it was subsequently tested for hardness across the extruded section using the Vickers hardness tester as shown in figure 4.9 (a). An indentation left in FSBE processed aluminium bar after a Vickers hardness test were used for obtaining diagonals length as shown in figure 4.9 (b). A total of 5 hardness tests were performed across the base aluminium and for each extruded bar cross-sections. Hardness profiles taken from the cross section of the square bar after friction-stir back extrusion are presented and plotted in figure 4.10.

For the rotational speed of 280 rpm, due to the voids (see fig.4.7 (b)) that occurred in the bar, the hardness results were slightly lower than others. As seen in figure 4.10, the hardness presented for base aluminium wire was an uneven distribution. However, even distribution of hardness was observed in friction-stir back extruded bar. The maximum value of hardness (3.56 HV) was found in the 400 rpm processed square bar, which has relatively fine grains (see figure 4.8 c) compared to the samples processed by higher rotational speed. And it was shown that as the rotational speed increases the hardness decreases and this agrees with the results reported by Sato *et al.* (2003). According to the Hall-Petch relationship the hardness increases as the grain size decreases, the hardness results supported the conclusion that more grain refinement is obtained at lower rotational speed that is what really happened at 400rpm.

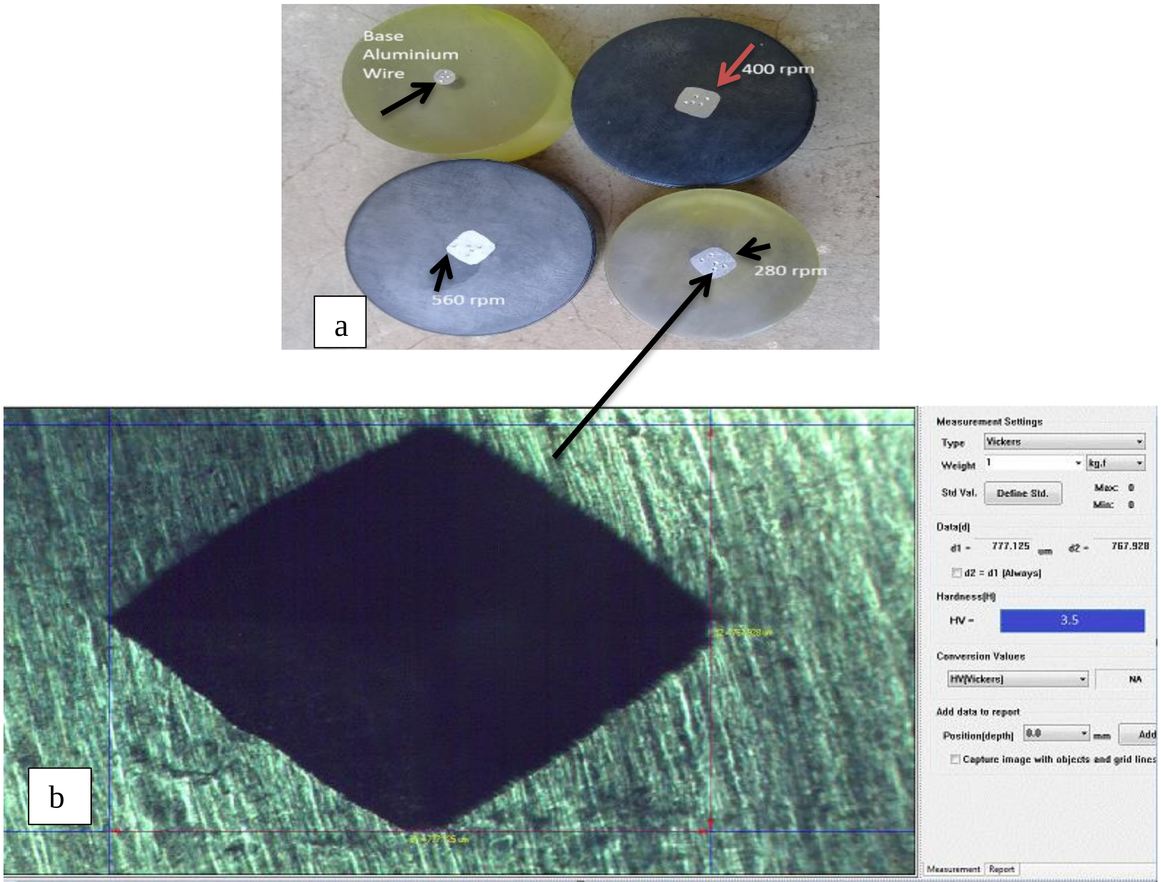


Figure 4. 9 (a) Testing positions of Vickers hardness for base material and processed bars (b) Indentation left

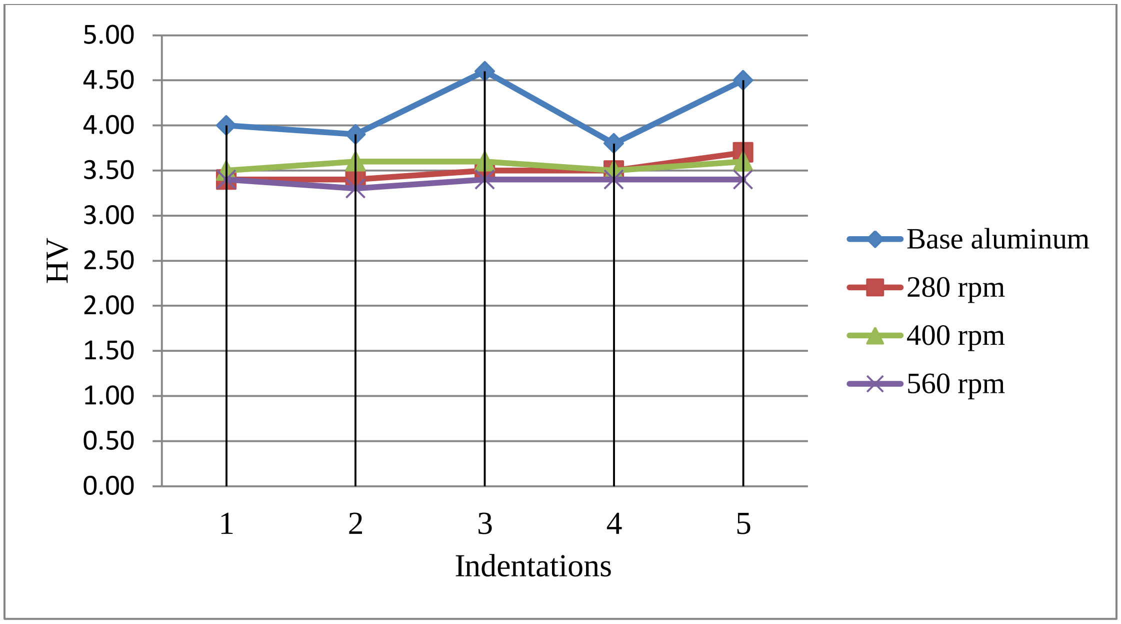


Figure 4. 10 Hardness profiles

The results show that the friction stir back extruded bar has a lower Vickers hardness value (i.e. nearly 15%) less than the original aluminium wire. The average Vickers hardness obtained after the sample test were 4.16HV for base aluminium wire, 3.5HV at 280rpm, 3.56HV at 400rpm and 3.38HV at 560rpm FSEB processed square bar. The other important things that can be clearly observed from figure 4.10 were hardness differences in base aluminium wire and FSBEed sample. This difference of hardness created due to strain hardening mechanism of AA1050 wire during conventional manufacturing process. On the other hand, friction-stir back extruded bar were tested as-extruded form or without strain hardening.

The hardness profile and grain size measurements indicate a high level of homogeneity across the square bar cross-section. It can be observed that the hardness profile is roughly uniform. The slight difference between hardness values along the cross-section can be attributed to the different amount of plastic deformation or maybe existence of impurities.

CHAPTER FIVE: FINITE ELEMENT SIMULATION OF TEMPERATURE AND EXTRUSION FORCE IN FSBE 1050 ALUMINIUM ALLOYS

5.1 Introduction

A similar material process to the friction-stir back extrusion process has been studied widely and applied to industries for years which is the friction stir welding process, also a friction based process. In friction stir welding, a rotating tool is used to generate frictional heat in the workpieces and to create material flow and mixing in the workpieces, leading to the formation of a solid-state weld joint. A key similarity of friction extrusion and friction stir welding is that the heat source comes from severe plastic deformation in the metal and from the friction between the tool and metal (Tomas *et al.* (1993).). Due to the similarities between FSBE and FSW and the lack of numerical studies of the FSBE process in the literature, it is also useful to consider the approaches applied to the friction stir welding which can be also applicable for friction-stir back extrusion process. One of the important aspects that have been studied numerically well in the FSW is the heat transfer phenomenon. In addition to heat generation, force and strain imposed due to rotating tool was also investigated by many researchers. Many thermal models have been developed to approximate the heat generation and as well force prediction during the friction stir welding.

Khandkar *et al.* (2003) proposed a pure thermal model, in which the moving heat source is correlated with the actual machine power input on the interfaces between the tools and workpiece, to predict the temperature distribution and a good agreement between predictions and experimental measurements was obtained. Buffa *et al.* (2006) have done a three dimensional analysis of FSW in DEFROM-3D to predict temperature history, strain profile and axial force during FSW process. They have used flow stress as function of temperature, strain and strain rate. Regression analysis is used to calculate material constants. Zhang and Zhang (2007) have developed a fully coupled three dimensional analysis to estimate temperature and stress-strain profiles. Material flow is also simulated for different time intervals of the simulation. They have used arbitrary lagrangian and eulerian analyses to simulate FSW in ABAQUS/Explicit. Simple coulomb law of friction is considered for the analysis. Therefore, using the concept of friction stir welding process, finite element simulation of temperature distribution and force prediction for square bar production during FSBE process is presented in this chapter.

The Finite element simulation for friction stir back extrusion process of aluminium scraps was carried out by using a software package DEFORM-3D, using a Lagrangian implicit code designed for simulating metal forming processes. In order to elaborate the simulation model of the extrusion process on DEFORM software; the following aspects have been taken into account. Establishing a set of parameters which have a significant influence on the extrusion process: dimensional parameters of the raw part (billet): thickness, length, diameter; geometry of the tools, elastic-plastic behaviour of the material properties. For the prediction of temperature and force during FSEB process, 400 rpm was used because better macro and microstructural results was obtained during experimental work compared to other rotational speed.

5.2 Description of the Model

5.2.1Geometric model

A three dimensional simulation of FSBE is performed in DEFORM-3D. Lagrangian implicit code. AA1050 aluminium alloy is taken as work piece material and is modelled as plastic material. Dimension of work piece is 40 mm diameter and 30 mm height. Work piece is meshed with 20249 nodes which forms 99998 tetrahedral elements. Tool steel D3 is used as the tool material from tool library of DEFORM which is modelled as a rigid body i.e. temperature, stress and strain are not calculated for the tools. Since, yield stress of tool steel is much higher than aluminium alloy considering rigid tool is a valid assumption. Tools and workpiece were designed on CATIA V5 modelling software. The finite element package DEFORM-3D was used for the pre-processing, solving and post-processing of the data.

Boundary conditions assigned to FSBE model were: bottom surface and the periphery of work piece were assigned to be contact with the rotating chamber so that it can rotate relative to plunger. Longitudinal transvers velocity was assigned to the plunger. The workpiece, representing the aluminium wire scraps was modelled as a unique cylinder. The extrusion chamber was fixed in space and allowed to counter rotate, while the punch moves longitudinal toward chamber along its longitudinal axis and was plunged into the extrusion chamber. Figure 5.1 shows prepared billet and tetrahedral mashed single-billet.

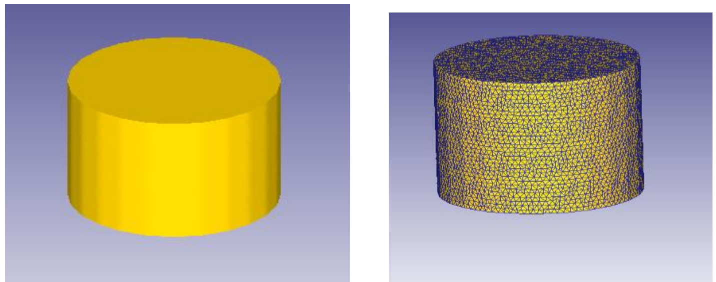


Figure 5. 1 Isometric view and meshed billet

The plunger has scrolled pattern at the tip. The scroll was rotated in a clockwise direction (when die tip faced downward as in experiment setup) so that the scroll pattern can gather plastic-state material toward the centre. Figure 5.2 shows billet charged chamber and plunger; as well as positions of friction-stir back extrusion process.

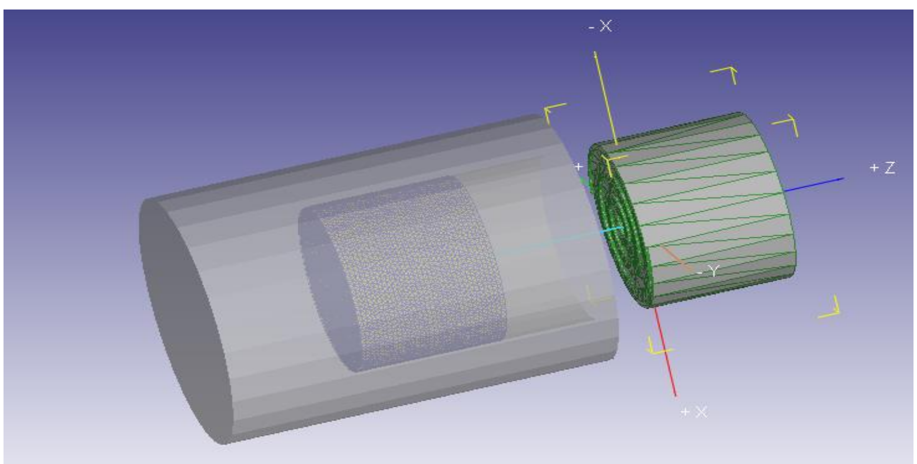


Figure 5. 2 Schematic position representation of FSBE process

5.2.2 Material model

Flow stress is a function of strain, strain rate, temperature as given in equation 5.1. Therefore to define flow stress, stress-strain behaviour, at different strain rates, temperature from DEFORM material library and isotropic hardening rule are considered.

$$\sigma = \sigma(\varepsilon, \dot{\varepsilon}, T) \qquad \text{Eq. (5.1)}$$

Where, σ is flow stress, ε is strain, $\dot{\varepsilon}$ is strain rate, T is temperature.

5.2.3 Thermal and frictional model

Temperature generated during FSW is the range from 0.3-0.8T_m (where, T_m is the melting point in degree centigrade scale); it also changes the mechanical response of the material (South wire Company, (2011)). Fourier law of heat conduction is used to calculate temperature distribution.

$$k\nabla 2T + q\cdot = \rho cp\frac{\partial T}{\partial t} \quad \text{Eq (5.2)}$$

Where, k is thermal conductivity of material, T is temperature, $q\cdot$ is heat generation, ρ is material density and cp is specific heat capacity. Thermal properties of material are independent of temperature to avoid non-linearity in thermal calculation. Contact interaction between tool and work piece is very critical and to simulate this, sticking condition (shear stress at the interaction remains constant) is considered.

$$\tau^\circ = m\tau_{max} \quad \text{Eq (5.3)}$$

Where, τ° is frictional shear stress at the interface, m is shear friction factor and its value is 1, τ max is equivalent shear stress of material which is 0.577 times of the yield stress of material. The physical properties of 1050 aluminium alloy are presented in table 5.1.

Table 5.1 Physical properties of 1050 aluminium alloy

Properties	Values
Density	2.71kg/m^3
Thermal conductivity	222 W/m.K
Thermal expansion	24x 10^{-6} /K
Poisson’s ratio	0.3

5.3 Simulation Result

5.3.1 Temperature profile

In FSBE certain amount of heat is required to plasticise the material, which allows stirring of material to achieve a good metallurgical bond and plastic deformation. Heat is generated in FSBE due to plastic deformation of material and frictional heat generated between plunger and work piece. The latter depends on shear friction factor and contact area. Figure 5.3 shows the simulated temperature distribution in workpiece and extruded bar. The rotation of plasticized aluminium billet relative to plunger produce high heat; and scroll contributes agitation to soften sample and forces toward the center. As a result maximum temperature is obtained at the contact land where the actual shape of square bar is created.

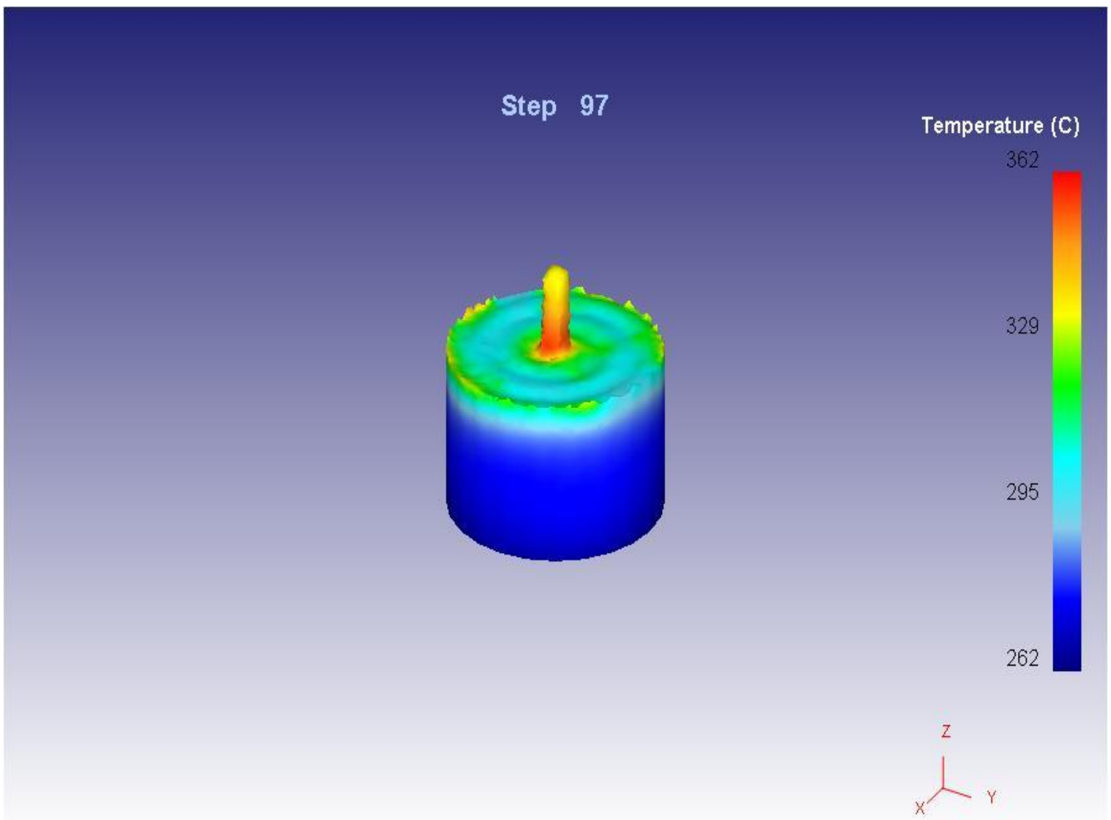


Figure 5. 3 Temperature distribution

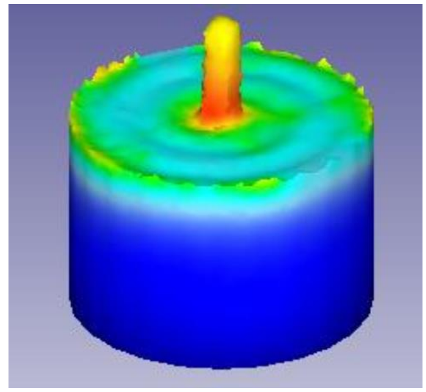


Figure 5.4 Experimental and simulated disc

As it can be seen in the figure 5.4 the temperature distribution throughout the simulated billet and wire disc obtained from experimental work looks the same. Therefore, the preliminary results of simulation show the conformity to experimental investigation. From experimental observation the contact area between plunger and material to be processed is constituted by a plasticized layer in which solid bonding has already occurred and three distinct zones are clearly seen (see section 4.1.1 of this thesis). Therefore the predicted temperature that can plasticize and extrude 1050 aluminium alloy through FSBE could be 362^{o} c.

5.3.2 Strain profile

Plastic deformation of material plays a vital role in material movement and hence in formation of good extrusion. It also affects the microstructure of the extruded product along with thermal history. Therefore it is important to study the strain distribution to understand the deformation of material. Figure 5.5 shows the effective strain distribution in longitudinal direction of the billet and extruded bar for 400 rpm and 0.2 mm/s traverse speed. Figure 5.5 clearly depicts that strain is higher on the top surface of the billet.

It is known that during solid bonding dominated phenomena the processed material undergoes high levels of strain rate and temperature which enables microstructural modifications as Continuous Dynamic Recrystallization (CDRX) (Buffa *et al.* 2014a). As it is clearly showed in the figure 5.5, three different zones are found in the simulated billet. First, close to the external surface of the billet. It should be observed that this area, labelled as "I" in figure 5.5, can be characterised as highest values of strain and strain rate. Moving toward the billet center (zone

“II”), a transition area is found, characterized by less strain and strain rate. However, the stirring action due to the material flow still results in significant deformation. Finally, in the center (zone “III”), where maximum strain and strain rate is found due to temperature rise. Therefore, it can be inferred that, this zone is the responsible for the formation of fine morphology and equaxied grain through the extrusion channel.

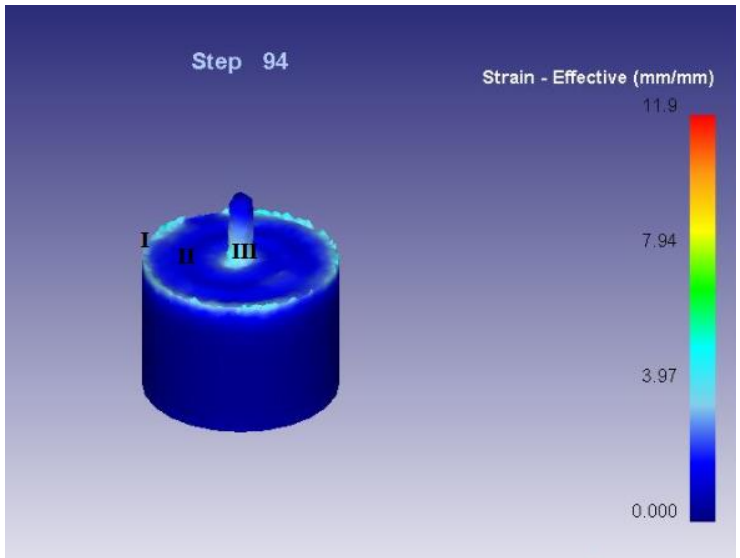


Figure 5.5 Strain distribution

5.3.3 Extrusion force profile

The model was capable of predicting extrusion forces history required to generate extruding square bare. Figure 5.6 shows the FEM predicted forces for 400 rpm rotational speeds. As it can be shown in figure 5.6 there are three different zones with distinct characteristics; for the first few seconds, the plunger moves toward the billet which is represented in zone 1. After the plunger get contacted with billet surface, the plasticization and softening of the material started for approximately for 15 seconds (see zone 2) and then after the material is fully homogenised extrusion process is immediately started as it is represented in zone 3. Based on figure 5.6 extrusion force used to extrude square bar from AA1050 via FSBE process might be from 14kN to 15.5kN.

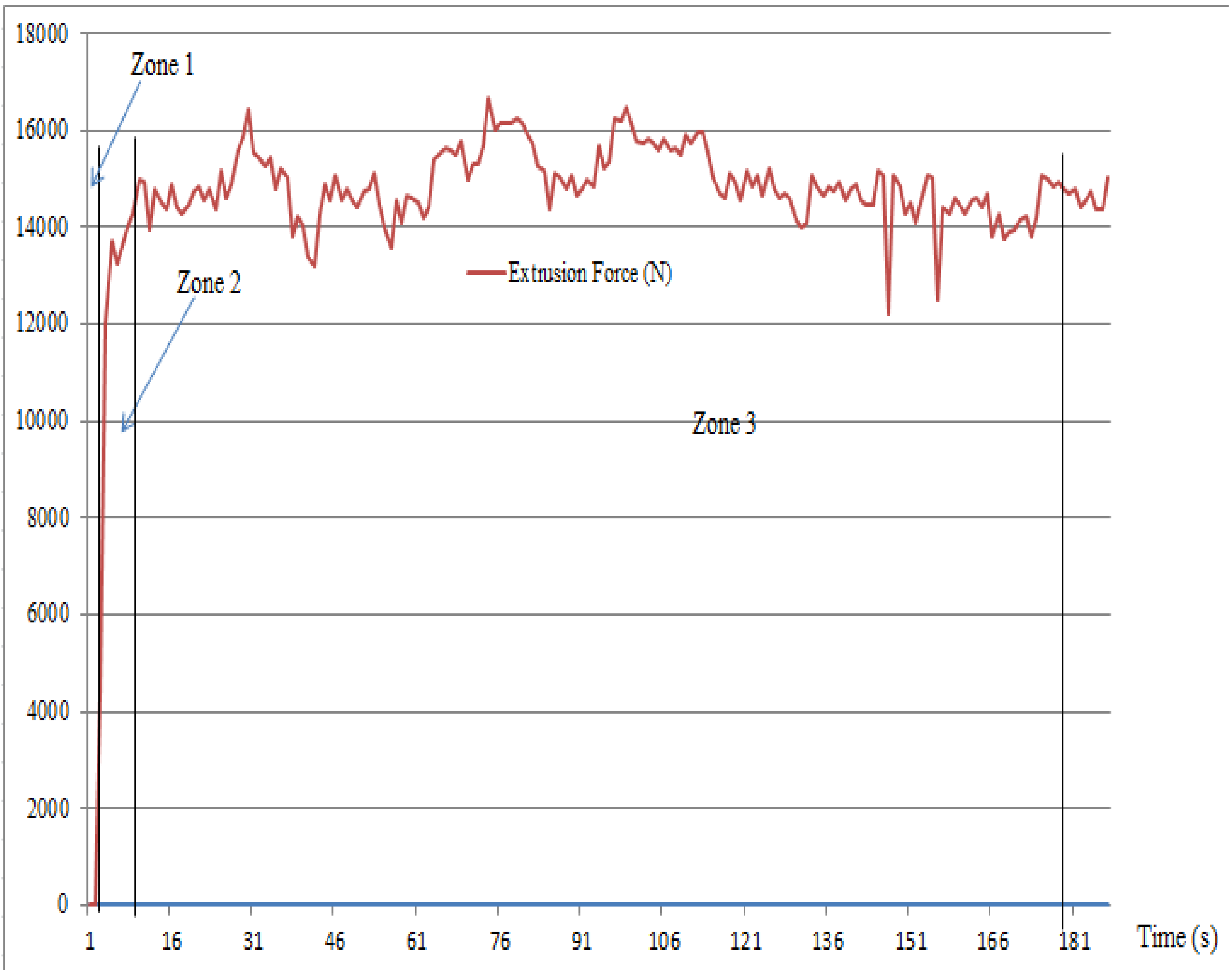


Figure 5. 6 Extrusion Force profile

CHAPTER SIX: CONCLUSIONS AND FUTURE WORK

6.1 Conclusions

Friction-stir back extrusion is a unique metal processing technology because it bypasses the melting step and does not use the conventional solidification mechanisms. The FSBE is a single step process to convert scraps and unusable material to usable products of excellent properties. Therefore, this process is reducing the energy consumption of re-melting.

In thesis, the manufacturing of square bars from aluminium wire scraps have been studied successfully through experimental investigation using the novelty of FSBE process. In this work, friction-stir back extrusion process has clearly showed the capability of solid-state process for recycling of aluminium wire scraps with excellent properties without considerable defects.

The major works performed in this thesis were a design and manufacturing of tools for FSBE process, material selection and preparation (AA1050), assembling of component in conventional lathe machine and executing the manufacturing process using selected process parameter (rotational speed). Finally, temperature distribution in billet and extrusion force for friction-stir back extruded square bar of 1050 aluminium wire scraps was simulated and predicted on DEFORM-3D.

To understand the mechanism of friction-stir back extrusion, experiments were performed with different die rotational speeds. Square bars produced under different rotational speed were sectioned; then metallurgically examined to reveal microstructure using optical microscope. The mechanical properties were studied using Vickers hardness tester. Surface quality was sufficient and no disturbances at the surface were visible due to the bonding of the individual wire scraps by mechanical action of spinning tool. Based on the experimental investigation, macro and microstructural analysis and numerical discussion, the following conclusions could be drawn:

1. By friction stir back extrusion processing method, defect free square bar from aluminium wire scraps can be fabricated that had been produced through other manufacturing processes.

2. During the manufacturing of square bar, a partial consolidated disc was observed which was consistent with simulated billet with three distinct zones; plasticized, thermo-mechanical affected and heat affected zone which were analogous to FSW.
3. From finite element simulated billet, the temperature used to extrude 1050 aluminium alloy via FSBE process might be 362^{o} C and predicted force were 14kN to15.5kN.
4. The lengths of fabricated square bars are about 150-290mm which is only limited by the space found in the tailstock quill.
5. From macro and microscopic evaluations, it can be concluded that the optimum condition for processing AA1050 square bar was 400 rpm.
6. Defect free 1050 aluminium square bar can be directly produced from aluminium wire scraps via the friction-stir back extrusion process. The variation of rotation speed leads to the change in extrusion temperature that, if too high, results in what seems to be a form of hot cracking, and if too low, results in cold tearing as well as twisting.
7. The extruded square bare experienced a small range of twist angle during friction-stir back extrusion that varied in a small range somewhat below 2 degree.
8. Mechanical hardness tests showed almost 15% of hardness (without strain hardening) variation existed in all recycled AA1050 bars when compared to parent 1050 aluminium wire at room temperature. In addition even distribution of hardness was observed in recycled square bare compared to parent aluminium wire.
9. Fine, equiaxed and dynamic recrystallization microstructures are observed in fabricated square bars at 400rpm.

6.2 Future Work

Based on the above investigations, results, conclusions and current understanding of friction-stir back extrusion; future work or interested body might be work on the following proposed area:

(1) Optimization of process parameters (rotational speed, transvers rate, extrusion ratio diameter and contact land, etc…) and studding of the influence of each on the extruded product.
(2) Establish more precise theoretical, and simulation model to better describe heat generation, predict heat transfer.

(3) A specialized machine with horizontal extrusion direction and longer chamber can help to produce friction-stir back extruded products with longer length and stable mechanical quality. Consequently, either this machine must be designed and built or a little modification must be done for conventional turning machine to execute friction extrusion technique.

(4) Apply an effective thermal management system on friction extrusion process with capabilities like pre-heat chamber and die, fast heat extraction, etc. Therefore, better control on temperature, extrusion rate and even microstructure and texture of square can be realized.

(5) The discontinuous nature of the batch mode friction-stir back extrusion process needs further research and making the process continuous thought innovative process concepts will be one of the primary objectives of future work.

(6) Friction-stir back is not limited to aluminium and its alloys but feasibly of the method need to be studded to the other material too.

(7) Other shapes can also be able to be produced via the concept of FSBE with proper design of the die and related process conditions.

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Appendix A

Relation of Rotational Speed with Extrusion rate and Helix angle

Rad/sec	Extrusion rate (mm/s)	Helix angle (degree)
29.3	0.67	1.7
41.8	0.84	1.5
58.6	1.8	1.2
83.7	3.2	1.1

Appendix B

CNC G-code for Manufacturing Scroll pattern on Plunger tip

```
%
O0001
N100 G21
N102 G0 G17 G40 G49
G80 G90
N106 G0 G90 G54 X-
1.526 Y-.522  S600 M3
N108 G43 H1 Z25.
N110 Z10.
N112 G1 Z-.5 F50.
N114 X-1.583 Y-.787 F50.
N116 X-1.6 Y-1.008
N118 X-1.587 Y-1.218
N120 X-1.512 Y-1.556
N122 X-1.38 Y-1.875
N124 X-1.187 Y-2.181
N126 X-.925 Y-2.475
N128 X-.607 Y-2.732
N130 X-.225 Y-2.949
N132 X.071 Y-3.067
N134 X.382 Y-3.152
N136 X.864 Y-3.215
N138 X1.347 Y-3.206
N140 X1.832 Y-3.125
N142 X2.325 Y-2.966
N144 X2.799 Y-2.734
N146 X3.254 Y-2.424
N148 X3.557 Y-2.158
N150 X3.843 Y-1.85
N152 X4.101 Y-1.507
N154 X4.315 Y-1.153
N156 X4.595 Y-.52
N158 X4.775 Y.137
N160 X4.857 Y.823
N162 X4.84 Y1.52
N164 X4.717 Y2.239
N166 X4.491 Y2.941
N168 X4.165 Y3.611
N170 X3.736 Y4.25
N172 X3.413 Y4.629
N174 X3.055 Y4.978
N176 X2.413 Y5.476
N178 X1.72 Y5.877
N180 X.975 Y6.184
N182 X.192 Y6.392
N184 X-.642 Y6.501
N186 X-1.488 Y6.499
N188 X-2.333 Y6.388
N190 X-3.161 Y6.17
N192 X-3.978 Y5.839
N194 X-4.751 Y5.406
N196 X-5.468 Y4.876
N198 X-6.129 Y4.249
N200 X-6.515 Y3.798
N202 X-6.864 Y3.317
N204 X-7.339 Y2.497
N206 X-7.707 Y1.637
N208 X-7.97 Y.737
N210 X-8.124 Y-.192
N212 X-8.17 Y-1.159
N214 X-8.1 Y-2.127
N216 X-7.917 Y-3.084
N218 X-7.624 Y-4.017
N220 X-7.216 Y-4.931
N222 X-6.703 Y-5.794
N224 X-6.093 Y-6.596
N226 X-5.384 Y-7.337
N228 X-4.877 Y-7.775
N230 X-4.327 Y-8.183
N232 X-3.743 Y-8.552
N234 X-3.146 Y-8.87
N236 X-2.162 Y-9.281
N238 X-1.15 Y-9.577
N240 X-.11 Y-9.76
N242 X.946 Y-9.829
N244 X2.026 Y-9.782
N246 X3.096 Y-9.618
N248 X4.146 Y-9.338
N250 X5.161 Y-8.947
N252 X6.148 Y-8.44
N254 X7.077 Y-7.829
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N256 X7.938 Y-7.122
N258 X8.725 Y-6.324
N260 X9.355 Y-5.544
N262 X9.913 Y-4.703
N264 X10.395 Y-3.806
N266 X10.699 Y-3.114
N268 X10.951 Y-2.408
N270 X11.267 Y-1.191
N272 X11.446 Y.039
N274 X11.489 Y1.283
N276 X11.397 Y2.526
N278 X11.173 Y3.754
N280 X10.81 Y4.977
N282 X10.316 Y6.155
N284 X9.699 Y7.277
N286 X8.965 Y8.329
N288 X8.123 Y9.299
N290 X7.166 Y10.192
N292 X6.119 Y10.98
N294 X4.993 Y11.656
N296 X3.801 Y12.212
N298 X2.55 Y12.645
N300 X1.475 Y12.906
N302 X.374 Y13.075
N304 X-.73 Y13.15
N306 X-2.092 Y13.113
N308 X-3.438 Y12.937
N310 X-4.761 Y12.626
N312 X-6.046 Y12.182
N314 X-7.282 Y11.61
N316 X-8.475 Y10.906
N318 X-9.593 Y10.084
N320 X-10.624 Y9.153
N322 X-11.559 Y8.123
N324 X-12.391 Y7.002
N326 X-13.073 Y5.87
N328 X-13.649 Y4.677
N330 X-14.113 Y3.434
N332 X-14.463 Y2.15
N334 X-14.675 Y.981
N336 X-14.792 Y-.206
N338 X-14.813 Y-1.393
N340 X-14.709 Y-2.844
N342 X-14.466 Y-4.273
N344 X-14.086 Y-5.673
N346 X-13.573 Y-7.032
N348 X-12.932 Y-8.336
N350 X-12.159 Y-9.593
N352 X-11.269 Y-10.771
N354 X-10.269 Y-11.86
N356 X-9.171 Y-12.852
N358 X-7.981 Y-13.738
N360 X-6.784 Y-14.47
N362 X-5.524 Y-15.095
N364 X-4.213 Y-15.608
N366 X-2.858 Y-16.006
N368 X-1.625 Y-16.26
N370 X-.372 Y-16.418
N372 X.884 Y-16.48
N374 X2.421 Y-16.424
N376 X3.941 Y-16.227
N378 X5.438 Y-15.892
N380 X6.898 Y-15.42
N382 X8.31 Y-14.818
N384 X9.68 Y-14.079
N386 X10.977 Y-13.218
N388 X12.192 Y-12.242
N390 X13.315 Y-11.159
N392 X14.337 Y-9.979
N394 X15.259 Y-8.697
N396 X16.062 Y-7.337
N398 X16.742 Y-5.908
N400 X17.291 Y-4.423
N402 X17.71 Y-2.881
N404 X17.901 Y-1.913
N406 G2 X19.372 Y-.704
I1.471 J-.29
N408 G1 X19.427 Y-.705
N410 X19.93 Y-.722
N412 G0 Z100.
M05
M30
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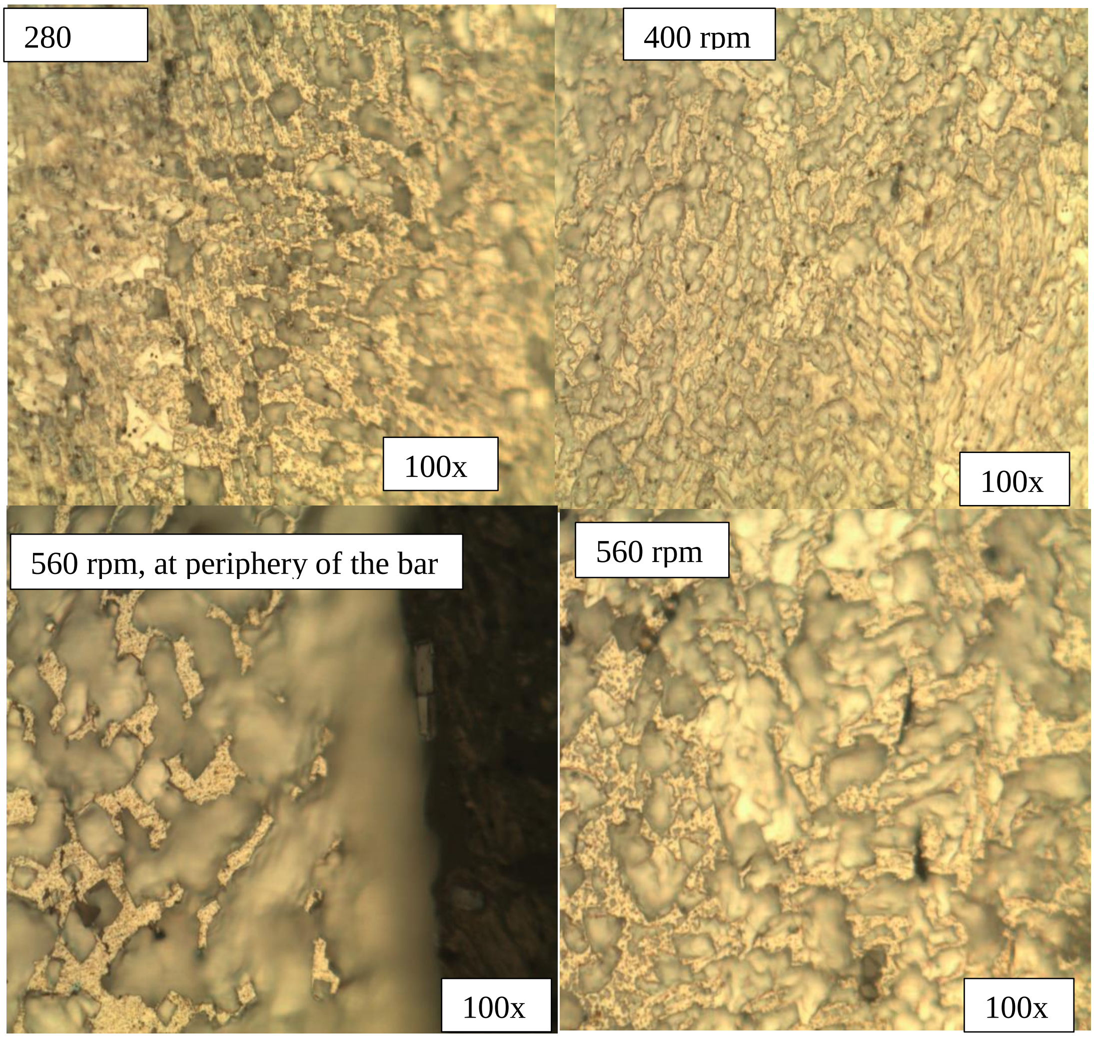
Appendix C

Microstructure of square bare processed by different rotational speed



Appendix D

Compositions of D2 tool Steel

D2 tool steel	Carbon, C	Silicon, Si	Manganese, MN	Chromium, Cr	Molybdenum, MO	Vanadium, V
%	1.5	0.3	0.4	11.3	0.8	0.8