An Experimental Study on Friction Stir Processing of AA-6061 Aluminum Alloy

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ABSTRACT

Friction stir processing (FSP) has promised for application of thermo mechanical processing techniques where aims to change the microstructural and mechanical properties of materials in order to obtain high performance and reducing the production time and cost.

In this study, friction stir processing on cold worked 6061 Aluminum alloy was employed. The ratio of rotational and translational speed (ω/f) was varied from 22 to 125 (rev/mm). The effect of the said parameter on the microstructure and mechanical properties was examined. The results show that FSP reduces the grain size in operational zone. Grain size decreases as ω/f increases. To a certain range of ω/f from 22 to 28 average hardness decrease and for range of ω/f from 22 to 25 tensile strength decreases which correspondingly causes increase in toughness and ductility of cold worked material. However, afterwards range of ω/f from 28 to 125 for average hardness and range of ω/f from 25 to 125, the trend becomes reverse. The effect of above parameter on surface quality was also observed visually. It has been found that within investigated range, the surface finish enhances with increasing ω/f. The result of microstructure shows that operation zones have small grain size with undefined directions. The effect of the multi passing (from 2 to 4) on grain size was also investigated. It was found that with increasing the number of passes, the size of grains decreases.

Keywords: Friction Stir Processing, Microstructure, Hardness, Tensile, Impact, Quality, AL6061.

ÖZ

Sürtünme hareketlenme işlemi (FSP) termo mekanik işleme tekniklerini kullanarak malzemelerin mikroyapı ve mekanik özelliklerini değiştiriyor. Bu teknik üretim masraflarını ve zamanı azaltıyor ve yüksek performans elde etmeye neden oluyor.

Bu çalışmada, sürtünme hareketlenme işlemi (FSP), soğuk işlenen 6061 Alüminyum alaşımı üzerinde kullanılmıştır. Dönme ve öteleme hızı oranı (ω/f), 22 ve 125 (devir/mm) arasında değişmiştir. Adı geçen parameterenin mikroyapı ve mekanik özellikler üzerindeki etkisi incelenmiştir. Elde edilen sonuçlarına göre, FSP operasyon alanındaki tanelerin boyunu azaltmıştır. Dönme ve öteleme hızı oranı (ω/f) arttığı zaman, tanelerin boyu kısalmıştır. Beli bir aralık için, 22 ile 28 (devir/mm) arasında ortalama sertlik azalmıştır ve 22 ile 25 (devir/mm) arasında gerilme mukavemeti azalmıştır. Bunlar soğuk işlenen malzemelerin darbe dayanımının ve yumuşaklığının artmasına neden oluyorlar. Halbuki, daha sonra ortalama sertliği 28 ve 125 (devir/mm) oranlar arasında ve gerilme mukavemeti 25 ve 125 (devir/mm) oranlar arasında ters oranla değişiyor. Incelenen parametrenin yüzey kalitesi üzerineki etkisi görsel olarak da gözlemlenmiştir. Elde edilen sonuçlara göre, yüzey kalitesi, ω/f oranının artmasıyla da artmaktadır. Mikro düzeyde edilen sonuçlara gore, operasyon alanında tanelerin boyu küçük ve yönleri belirsizdir. Aynı zamanda aynı malzeme üzerinde, operasyon sayısının (2`den 4`e kadar), tanelerin boylarındaki etkisi de araştırılmıştır. Sonuçlara göre bu sayı arttıkça, tane boyutu azalmaktadır.

Anahtar Kelimeler: Sürtünme hareketlenme işlemi,Mikroyapı, Sertlik, Çekme Darbe, Kalite, AL 6061.

To My Parents

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LIST OF SYMBOLS/ABBREVIATIONS

AA	Aluminum Alloy
FSP	Friction Stir Processing
TWI	Technique Welding Institute
ECAE	Equal Channel Angular Extrusion
TMAZ	Thermo Mechanical Affected Zone
HAZ	Heat Affected Zone
BM	Base Material
SEM	Scanning Electron Microscope
TEM	Transmission Electron Microscope
OIM	Orientation Imaging Microscope
LM	Light Metallography
ASEM	American Society for Engineering Management
CNC	Computer Numerical Control
RPM	Rapid Per Minute
HV	Vickers Hardness
HB	Bernie Hardness
VHN	Vickers Hardness
Ti	Titanium
AL	Aluminum
Zn	Zinc
Cu	Cupper
Cr	Chrome
Fe	Iron
MN	Manganese

Si	Silicon
Mg	Magnesium
ω	Rotational Speed
F	Traverse Speed
ω/f	Rotational Speed over Transvers Speed
No	Number
Mm/min	Millimeter over Minute
Rev/mm	Speed over Millimeter
P	Paper
Ml	Mill Liter
Mm	Millimeter
T	Thermal
Kg/m^3	Kilogram over Cubic Meter
GPA	Giga Pascal
MPA	Mega Pascal
H	Hardened
°C	Centigrade
μm	Micro Meter

Chapter 1

INTRODUCTION

1.1 Background

1.1.1 What is Heat Treating

Heat treating is a process of improving physical or/and chemical properties of materials, especially metals, through heating and cooling. In addition to metal industry, the process is widely used in glass industry as well. In fact, a correlation exists between microstructure and properties of material. By heating or cooling, the microstructure (or phase) of the material changes which in turn affect its mechanical properties. Thus a range of mechanical properties can be obtained by choosing different heating/cooling combinations [1].

1.1.2 Significance of Heat Treating

Heats treatment is often used for increasing the strength of the material. Moreover, it can be used to improve machinability and to enhance formability by restoring ductility after a cold working operation. Gaining the desired characteristics of materials by using a suitable heating treatment process has rendered it a promising material processing method of manufacturing engineering.

1.1.3 Heat Treating Techniques

1.1.3.1 Annealing

The process of heating a material to a specific temperature and then cooling it with specific rate is referred as annealing. This process will lead to producing a refined microstructure. The rate of cooling used in the annealing process is generally slow.

Annealing is used in various areas such as to soften a metal for cold working, to improve machinability or to enhance the properties like electrical conductivity [1].

1.1.3.2 Normalizing

To provide uniformity in the grain size and composition throughout alloy normalization process is employed. This is normally standing for ferrous alloys that have been austerities and then cooled in the open air [1]. This process will lead to producing Pearlite, Bainite and sometimes Martensite. However it results in stronger and harder steel, but it is also causing to have less ductility for same composition than full annealing.

1.1.3.3 Stress Relieving

The process of reducing the internal stress in a metal is referred to stress relieving. The internal stress in the metal may have various sources ranging from cold working to non-uniform cooling. The process of relieving the stress in metal is generally includes two steps which heats a metal below the lower critical temperature and then tries to cool it down uniformly [1].

1.1.3.4 Carburizing

Increasing the component's surface hardness using diffusion of carbon into the surface of a component is known as carburizing. This process is generally followed by quenching and tempering the materials [1].

1.1.3.5 Precipitation Hardening

This process is based on hardening metal through inducing second phase particles in the parent phase of material. Precipitation hardening is normally performed for non-ferrous and for some kinds of stainless steels [1]. After quenching in water, the metal is exposed to low temperature for extended time so as to induce second phase particles which provide strength to the metal.

1.1.4 Limitations of Heat Treatment

Though heat treatment processes are useful, they are suffered from several drawbacks as well, which includes cracking, variation in mechanical properties, heavy surface oxidation and surface decarburization. Moreover, component distortion occurs which needs to be compensated by giving warp age allowance. This allowance latter is machined to obtain accurate product size, which consequences in increased product cost. Besides these issues, the heat treatment processes are expensive due to large consumption of energy and include long lead times because they require to expose metal to heating over extended times.

1.1.5 What is FSP

FSP has its roots in friction stir welding (FSW) which was developed by The Welding Institute (TWI) of the United Kingdom in 1991[2]. FSP is a relatively new thermo mechanical processing technique. The main goal behind FSP is to change the microstructural and mechanical properties in a single pass to gain maximum performance in particular reference to mechanical properties, cost and lead time. It is deemed to reduce, as compared to heat treatment, overall production time and product cost [18][19].

1.1.6 Advantages of FSP

One of the vital steps in many industrial applications is selecting the materials with the appropriate properties. Choosing alloys with specific properties such as high strength with homogenous grain structure is very decisive, especially in the aircraft and automotive industries.

Producing a material with small grain size with acceptable strength and ductility properties as well as production time and cost improvements is the main aim behind developing new materials processing techniques. Various processing methods are developed for this purpose. Recently introduced models such as Friction Stir Processing (FSP), Equal Channel Angular Extrusion (ECAE) pursued aforementioned goals. Furthermore, they attempted to bring improvements to the conventional processing techniques like the Rockwell process and powder metallurgy technique [47].

The FSP has a comprehensive function for the fabrication, processing, and synthesis of materials which makes it as a versatile technique. The superiority of FSP compared to other metalworking technique can be cited as follows [16][17]:

1. Micro structural refinement, densification and homogeneity can be achieved in a single step [22].

2. The FSP parameters and active cooling/heating can accurately control the microstructure and mechanical properties of the processed zone.

3. The processed zone depth can be adjusted easily by controlling the length of the tool pin. This advantage makes FSP flexible to optimize the depth with various depth ranges between several hundred micrometers and tens of millimeters.

4. Since it is employing friction and plastic deformation for producing heat input, it is green and energy-efficient. Also during its process it does not produce extra injurious gas, harmful radiation and noise.

5. The size and shape of components stays intact by using FSP method.

6. It is the affordable method because it does not need specialized tooling and equipment: available machines can be used such as conventional milling.

1.1.6 Principle of FSP

Since the materials being processed by FSP is in the solid state, the FSP is known as a solid-state process. FSP includes a rotating tool which comprises of a pin and shoulder with a dimension proportional to the sheet thickness. The pin in the rotating tool is designed in a way such that it is plunged into sheet material, and it can traverse in a desired direction. The heat generated by the contact of rotating tool and the sheet, is used to soften the material. Furthermore, the material within the processed zone undergoes intense plastic deformation yielding a dynamically-recrystallized fine grain microstructure.

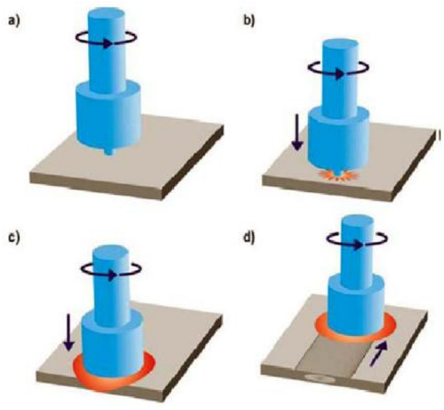


Figure 1.1: Friction Stir Processing: (a) Rotational Tool (b) Inserting Tool into Surface (c) Pushing to Desired Depth (d) Traverse of Tool

1.2 Motivations

In view of above stated advantages, FSP is a very cost effective and flexible process to replace the conventional property modification techniques. However, being new it has yet not been deployed widely. To use it effectively on commercial scale, knowledge on process needs to be enhanced. For an example, the method needs to be optimized for commercial usage. To obtain the desired grain size, process parameters such as rotational speed, translation speed and tool geometry should be controlled and defined precisely. Further, the optimal values of these parameters could vary from material to material.

In this study AL alloy 6061 has been chosen as an experimental material. Its advantages such as good strength, easy to machine and good resistance to corrosion has made it a useful aerospace and automobile material. Moreover, low price as compared to other alloys makes it a promising candidate for various engineering applications.

1.3 Objective of Thesis

The objectives of the current study are as below:

1. The capability of FSP to process 6061 aluminum alloy will be investigated.

2. The effect of variation in rotational speed and feed rate will be examined on microstructure of the above material.

3. The mechanical behavior of material (hardness, tensile strength and toughness) under varied conditions (i.e., speed and feed) will be tested.

4. The microstructure and mechanical properties of unprocessed material will be compared with processed material.

5. The effect of change in aforesaid parameters on surface quality will be studied.

1.4 Thesis Organization

The remaining of this thesis is organized as follows: In Chapter 2 general overview of friction stir processing, application and a detailed literature review are presented. Experimental investigations are explained in Chapter 3, the experimental setup and the methodologies used to conduct the experiments are explained, and microstructural investigation are presented and discussed in this chapter. Chapter 4 presents experimental results and also provides comparisons between base material and operated material in this study. Chapter 5 provides the conclusion drawn and information about future studies on this topic.

Chapter 2

LITERATURE REVIEW

2.1 Overview of FSP

A special non consumable cylindrical tool is used in FSP. The structure of this tool consists of a pin and a concentric large diameter shoulder which is shown in Figure 2.1 while the tool is rotating in the desired direction the pin is plunged into the sheet and shoulder comes in contact with the surface of the sheet. The attrition between the tool and the sheet causes to generate heat. This heat leads to softening the material but it is considered such that the material does not reach to the melting degree. Since the material is not melted in this process it is known as a solid state process. Moreover, since the rotation of the pin is not stirring action, the melted material does not undergo intense plastic deformation. This advantage causes to a have a dynamically recrystallized fine, equiaxed and defect free grain structure.

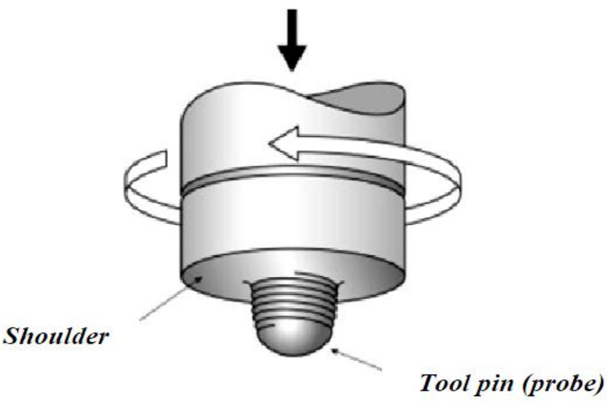


Figure 2.1: Schematic of FSP Tool

Since a large amount of deformation is imparted to the work piece through the rotating pin and the shoulder, FSP can be considered as a hot-working process. These deformations increase a weld nugget (whose extent is comparable to the diameter of the pin), a thermo-mechanically-affected region (TMAZ) and a heat-affected zone (HAZ).

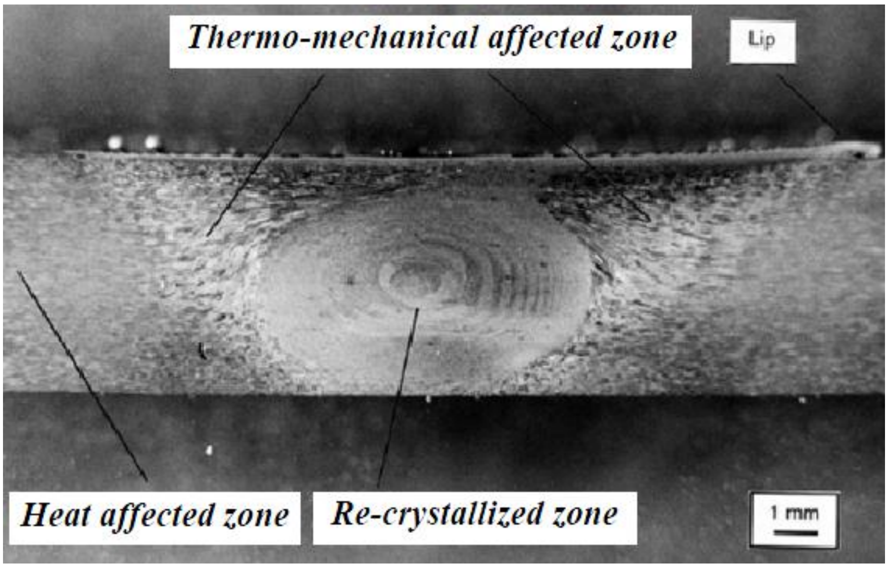


Figure 2.2: Cross-Section of Welding Zones

2.2 Applications of FSP

Application of FSP includes aerospace, shipping, aircraft and automotive industries. In aerospace it includes rivet replacement, repair of aging aircraft, fabricated structures [21][20].

Also the application of FSP is very successful in industrial automotive and shipping industry for joining aluminum alloy sheets in order to obtain low weight and high fuel economy and improving the speed of process [18][19].

2.3 Previous Works

There are lots of studies focused on the microstructure of friction stir welded aluminum alloys. The main focus of these studies is on the grain size obtained in the weld zone. Also there are studies on the temperature distribution effect over the entire weld zone and its effects on the microstructure. On the other hand, some studies focused on the precipitation phenomenon the types of precipitants thus obtained in the weld region._Furthermore, hardness profiles for different weld regions, effects of rotational speed on microstructure, mechanical properties such as tensile strength of a friction stir welded joint and also tool wear and different optimum tool designing methods are studied and are used to design various experiments so far.

2.4 Related Previous Works in FSP

Most of previous works in this area are focused on investigating the effect of process parameters on microstructure and mechanical properties of the materials. Also they covered microstructural investigations using different techniques such as optical microscopy, Transmission Electron Microscopy (TEM), Scanning Electron Microscopy (SEM), and Orientation Imaging microscopy (OIM). Furthermore, in some studies they focused on applying several mechanical testing; such as tensile test, hardness test, micro hardness test and etc.

Studying the resulting microstructure of friction stir processed commercial 7075 Al alloy can be found in Su et al [3]. Also the grain structure of the FS processed area was examined by TEM. Su et al. As they reported, the microstructure of FS processed area did not have a uniform grain size distribution. Also they reported that the average grain size decreases from top to bottom. Furthermore, they observed diffraction rings which confirm the existence of large disorientations between the individual rings. Non-uniform plastic deformation was introduced in the recrystallized grains during FSP. This can be because of the dislocation density which is not uniform within the stir zone even with similar grain size. Any desired sheet size can be processed to an ultrafine grained microstructure by running multiple overlapping passes. The studies and experiment shows the fabrication of large bulk ultrafine grain material with relatively uniform microstructure, can be gained effectively by using the multiple overlapping passes indicated.

The microstructures of Al 2024 friction stir welds investigated in Bensavides et al study [4]. They also compared the grain sizes of friction stir welding for different temperature at 30°C and -30°C. The observations show that the increase in the weld zone equiaxed grains size from the bottom to the top at room temperature. On the other side, for the low temperature the difference from bottom to top is smaller. Moreover, in the low temperature weld the grain size is considerably smaller. These observations show that there is a direct relation between temperature and grain growth. The average sizes of the grain are between 3 and 0.65 μm.

The hardness and tensile strength of the friction stir-processed 1050 aluminum alloy was investigated in a Kwon et al study [5]. They observed that the hardness and tensile strength has an indirect relation to tool rotation speed. The results show that at 560 RPM, the hardness tensile strength increases as a result of grain refinement by up to 37% and 46% respectively compared to the as-received material. The hardness was higher on the advancing side than that of the retreating side. The result of this study reveals that friction stir processing technique is extremely beneficial for creating improved mechanical properties resulting from grain refinement.

Itharaju et al. [6] tried to relate the study the relation of grain sizes to the generated forces in friction stir processed 5052 aluminum sheets. They employed the different combinations of rotational and translational speeds. The observation of this study reveals that the resulting average grain size of the FS processed AA5052 sheet is between 1.5 and 3.5 μm depending on the process parameters, compared to 37.5 μm for the unprocessed sheet. This observation is an evidence of great refinement. They also concluded that the plunging force has direct relation with rotational speed. Increasing the rotational speed causes to increase the plunge force which is independent of translational speed.

To maintain superplastic behavior in the weld region, Salem et al. [7] employed the ability of fiction stir welded 2095 sheet. For example a welding rate of 2.1 mm/s at 1000RPM casus sub-grain coarsening which appears as reduced superplastic capability. Furthermore, developments of microstructures consisting of tangled dislocation structures and sub-grains with small disorientations and increasing in the density of dislocations are the results of high welding rate. Sheets welded at 3.2 and 4.2 mm/s displayed uniform superplastic deformation up to strains of ≈1.3.

The effects of overlapping passes of friction stir processing on super plasticity in Aluminum alloys is presented in the Mishra et al [8] study. In this study, they used 7075 Aluminum sheet were friction stir processed by nine overlapped passes. To investigate the effect of strain rate on forming they conducted a constant velocity punch forming test. Furthermore, tensile test were applied for several samples taken from various area of the FSP sheet. The results of the microstructure investigations reveal that the grains become finer and equiaxed after FSP.

In the study of Liu et al. [9], to characterize the microstructure in FS weld zone they used light metallography (LM) and transmission electron microscopy (TEM). Also they used these materials to compare them with the original 6061-T6 Al. they reported the extension of micro hardness profiles from work piece and through the weld zone. This study shows the variation of residual hardness from 55 and 65 VHN in weld zone. Also the variation changes from 85 and 100VHN in the work piece near top and bottom. Furthermore, the weld zone grain size is considered as 10μm as compared to 100μm in the work piece.

2.5 Limitation of FSP

There are some significant problems of FSP process. Generally they are some limitations that include rigid clamping of the work pieces, backing plate requirement, existing the keyhole at the end of each pass, being less flexible in compared with manual and arc processes, difficulties with thickness variations and non-linear, having slower traverse rate than some fusion welding techniques and lack of predictive models for the resulting microstructure.

In this study to deal with these limitations, we have proposed our solution by controlling each part of work regarding its own difficulties. For instance, for solving the rigid clamping problem, all samples regarding their shape have been established rigid using the clamping tools. Moreover, a steel plate was used to deal with the problem of backing plate. For removing the effect of the keyhole on the samples, before starting the processes, we have extended the length of samples so that at the end of the work the extended parts have been eliminated by cutting the samples. The tool moving has been considered linearly to solve the problem of flexibility. Based on the achievements of recently researches related in this topic, we have tuned the parameters such as rotational speed and feed rate to overcome the lack of simulation software to estimate the microstructure behavior of materials.

Chapter 3

METHODOLOGY

3.1 Material and Properties

Because of its extensive applications in aerospace, automobile and chemical industries, the 6061 AL alloy was used as the experimental material. Its detailed composition has been shown in Table 3.1. As can be seen, the alloy is mainly composed of Mg and Si. An 8mm thick plate was purchased and was cut into 200*75mm blanks as schematized in Figure 3.1.

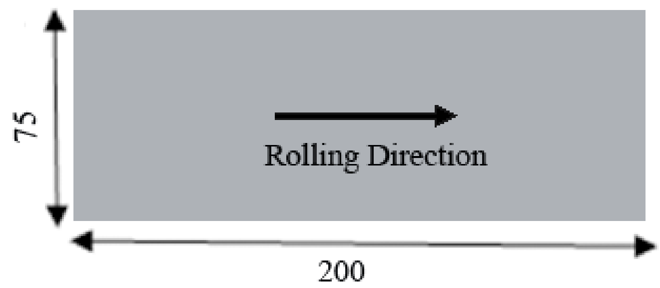


Figure 3.1: Sample Dimensions

Table 3.1: Compositions of Aluminum Alloy 6061

AL	Ti	Zn	Cu	Cr	Fe	Mn	Si	Mg
97.49	0.05	0.08	0.22	0.14	0.7	0.12	0.4	0.8

3.1.1 Material Properties and Applications

Table 3.2 shows the mechanical properties of AL 6061. These were determined by conducting tensile test, the details of which have been presented in a forthcoming section. The properties listed in Table 3.2 renders AL6061 as a material having good formability, weld ability, corrosion resistance, strength in the T-tempers and good general-purpose alloy made it suitable to be used in various areas [46]. The Material is pre-strained (cold worked) before FSP operation.

Table 3.2: Mechanical Properties of Material

Properties	Value
Density (1000 kg/m^3)	2.7
Poisson s Ratio	0.33
Elastic Modulus (Gpa)	70-80
Tensile Strength (Mpa)	115
Yield Strength (Mpa)	48
Elongation (%)	25
Hardness (HB500)	30
Shear Strength (Mpa)	83
Fatigue Strength (Mpa)	62

3.2 Experimental Setup

Utilization of readily available machine such as a milling machine is one of the most important features of the FSP. Moreover, FSP results in using inexpensive and simple tools which simplify the conduct process. In the rest of this section, the basic equipment and experimental setup which are required to control FSP process are discussed.

3.2.1 FSP Tool

Designing an appropriate and precise tool plays a crucial role in friction stir technology [23][24][25]. Since it is an important process, in this study we used a tool made of H13 steel to improve the strength and wear resistance through the thermal process. After the process, the characteristics of tool are changed. These changes are as follows, the hardness of tool reached from 58 to 61 Rockwell C. During the experiment the pin diameter was 5mm, length was 3.5mm and the shoulder diameter was equal to 16mm. Figure 3.2 shows an overall shape of the tool.

Figure 3.2: FSP Tool

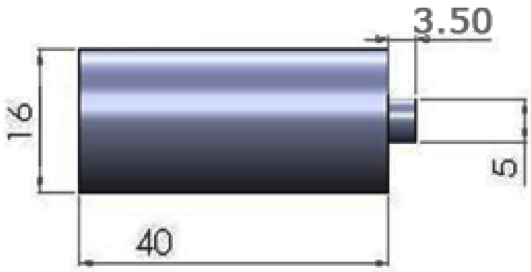


Figure 3.3: Dimensions of Tool

3.2.2 Machines Used

One of the FSP advantages is using a readily available machine in the conduct process. In this study we also used vertical milling machine (WERNIER 06340) which is shown in Figure 3.4.

Figure 3.4: Vertical Milling Machine (WERNIER 0640)

The sample which is chosen for the friction stir process should be firmly clamped to a work table using clamps and backing plate. This will keep working pieces fixed during applying the processes.

Figure 3.5: Samples Clamping During the FSP Operation

3.3 Experimental Plan

Different combinations of rotation (ω) and translation (f) speed were employed in the thesis. These combinations applied on several samples. The dimensions of samples used in this thesis are: 200 *75*8 mm.

Table 3.3: Diffrent Parameters for Each Sample

Samples No	Rotational Speed (RPM)	Feed Rate (mm/min)	ω/f (rev/mm)
1	710	25	28.4
2	1000	40	25
3	1400	63	22.22
4	2000	16	125

3.4 Experimental Procedure

3.4.1 Hardness

The Vickers hardness tester is employed in this study. The test load used is 60 kg f. And also the dwell time is considered as 3 seconds. The test is applied on various samples using different rotational speed and feed rate. Also for precise test different zones are used during the test process.

As a first step, the operated area has been divided into 7 different zones which are schematized in Figure 3.6. The center of the sample is selected as zone A. The respective coordinate of the considered center is (100*37.5). In the second step, the remained zones are distributed in the right side and left side of zone A in the longitudinal axis in alphabetically order. The distance between the preceding zones and the following zone is considered 20 mm.

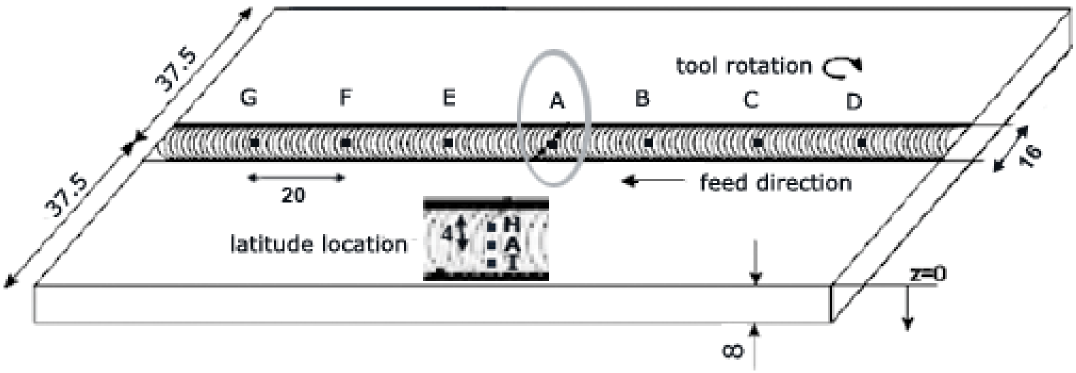


Figure 3.6: Different Distances of Hardness Zones

Regarding Figure 3.6 for examination hardness along latitudinal axis, operational zone is divided in three zones. Zone A which is drawn at the center of operational zone .The other two zones are named as zone H and zone I. Zone H is 4 mm above the center and Zone I is 4 mm below the center. The interval between these zones is considered equal to 4mm. Figure 3.7 shows the hardness tester machine.

Figure 3.7: Hardness Tester Machine

The hardness of each zone is measured using below formulas:

$$HV = \frac{1.854\ F}{d^2} \qquad Eq. 3.1$$

$$\text{Average } d = \frac{d_1 + d_2}{2} \qquad Eq. 3.2$$

3.4.2 Tensile Test

The tensile samples were designed by using ASEME9 standard where the sample thickness is regarded. Figure 3.8 shows size of sample for tensile test. In the next step, the specimens were cut in both basic and operation sections using CNC vertical milling machine (model DUGARD EAGLE 760) which is shown in Figure 3.9. The surface of the sample was polished using sand paper (P1000). Figure 3.10 shows the shape of samples after cutting for tensile test. These steps aim to insure the surface quality and prevent stress concentration. Figure 3.11 shows the Tensile Tester Machine.

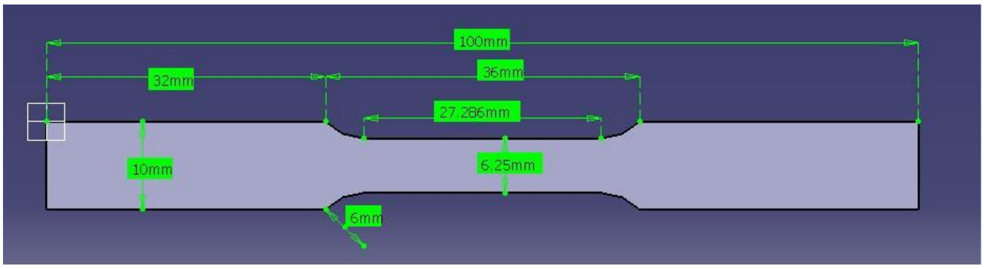


Figure 3.8: Sizes of Sample for Tensile Test

Figure 3.9: Vertical CNC Machine (EAGLE 760)

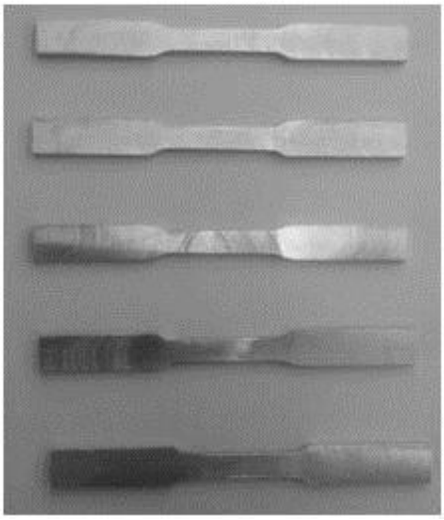


Figure 3.10: Shape of Samples After Cutting For Tensile Test

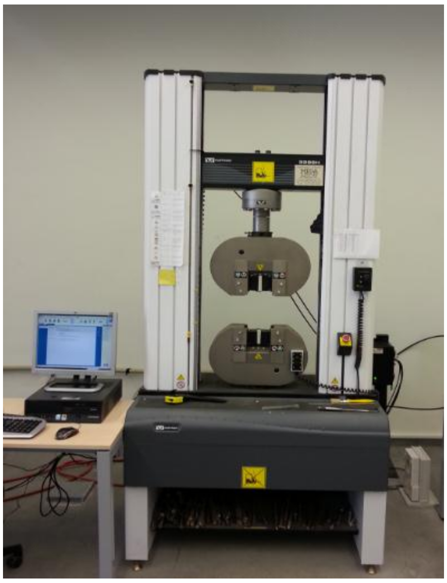


Figure 3.11: Tensile Tester Machine

3.4.3 Impact Test

Each FSP sample was cut in latitudinal axis to have samples with appropriate shape and size which is shown in Figure 3.12. Then samples were converted to the pins with a diameter of 8 mm and length of 45mm (Figure 3.13). For this purpose the lathe machine (Harrison M300) was employed (Figure 3.14).

Furthermore, notching machine was used to establish a groove on the pins (Figure 3.15). The grove was located on the area of a pin which is used for no extra operation. Finally, the impact machine is used to measure the required energy to fail each specimen (Figure 3.16 and Figure 3.17).

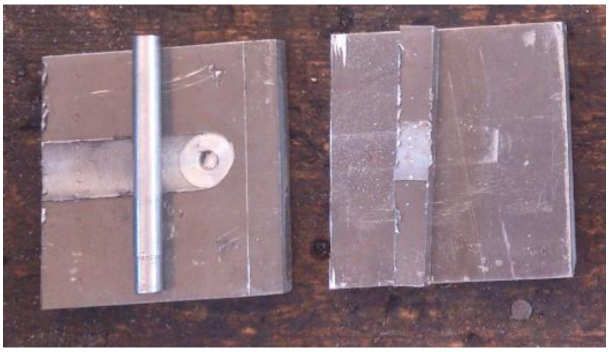


Figure 3.12: Impact Test Sample Before and After Cutting

Figure 3.13: Grooved Pin

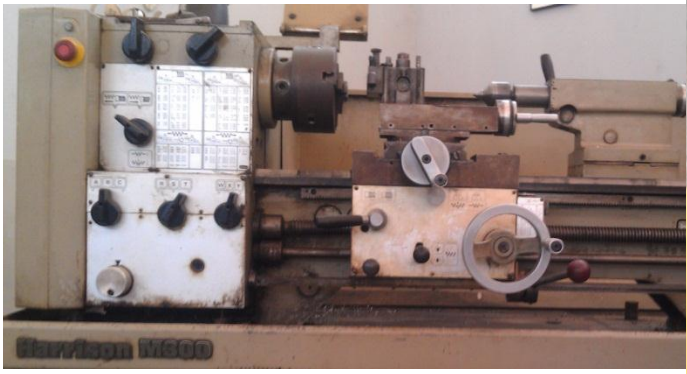


Figure 3.14: Lathe Machine (Harrison M300)

Figure 3.15: Notching Machine

Figure 3.16: Impact Tester Machine

Figure 3.17: Impact Sample Inside the Impact Tester Machine

3.5 Microstructure Investigation

The microstructural investigation was done with the collaboration of Sahand University of Technology of Tabriz-Iran, department of material science Engineering. Various microscopy techniques were employed to investigate the microstructure of material. The main techniques used for this purpose are: Optical microscopy and Orientation Imaging Microscopy (OIM) which was used to give more quantitative information. The sample is prepared for the microscopic investigation using grinding and sand paper polishing. The sand paper models P800, P1000, P2000, P3000 and P5000 are used in polishing process.

All microstructural samples are taken from the transverse section of the processed area at the middle of the sheet thickness as shown in Figure 3.18. Also several samples with different combinations of rotational and translational speeds are investigated microscopically.

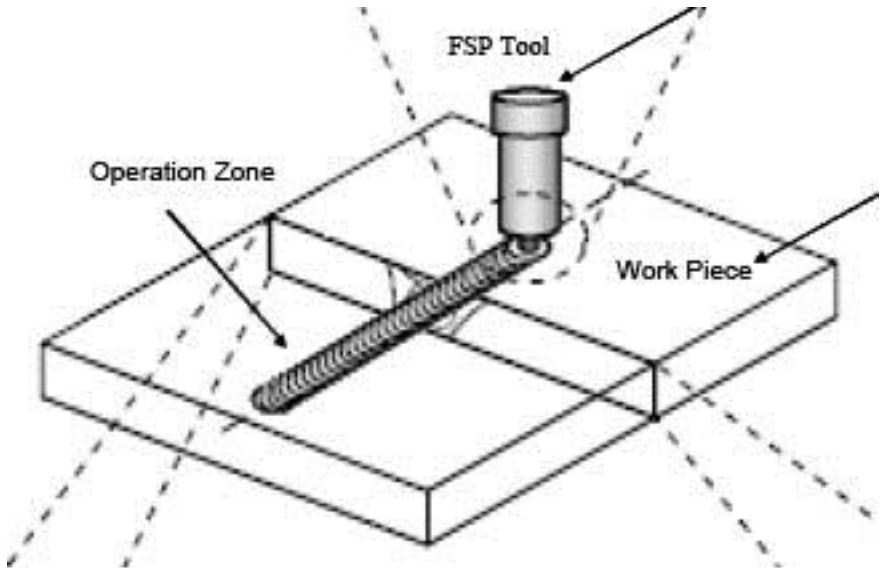


Figure 3.18: Preparing Samples for Microstructure Test

After polishing process, the samples were etched to highlight the large amounts of energy stored along the grain boundaries. Figure 3.19 shows the heat affected zone (HAZ) after performing etching process. The etching solution is made of Poll ton which is comprised of 30ml HCI,40ml HNO3,2.5ml HF,12gr Cro3 and 42.5ml H2O.

Figure 3.19: Heat Affected Zone (HAZ) After Etching Process

Chapter 4

RESULTS and DISCUSSION

In previous studies ω and f have been investigated separately [5][6][7]. Since the variation of both ω and f leads in changing temperature of operation and cooling rate which affects in mechanical properties of material and microstructure. We have investigated the ω relative to f (ω/f) which is more meaningful. We have examined the effect of this parameter on various mechanical properties and the microstructure of AA6061 aluminum alloy.

4.1 Effect of Variation in ω/f on Microstructure

Figure 4.1 shows the effect of w/f on grain size. As can be seen, the grain size of the cold worked AA6061 aluminum decreases with increase in ω/f. This most probably occurs due to localized heating, above recrystallization temperature, caused by FSP tool [35][36][40].

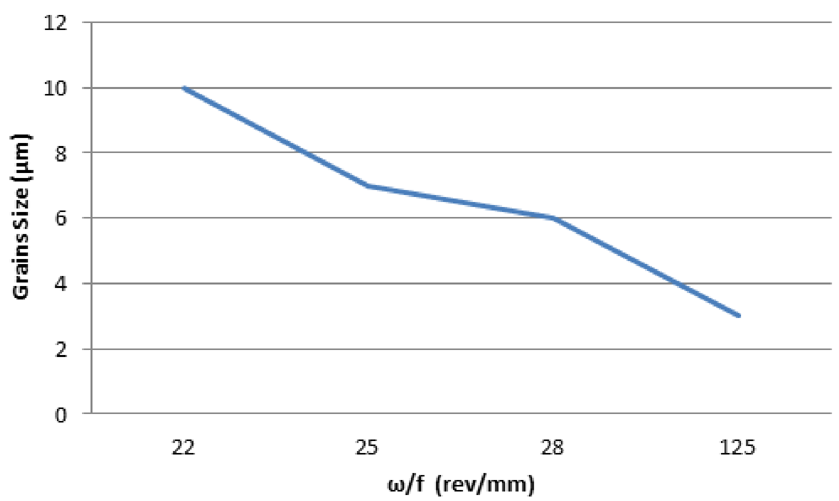


Figure 4.1: The Effect of ω/f on the Size of Grains

Figure 4.2 shows that the deformation zone is divided into three zones: the welding zone (Nugget), the thermo mechanical affected zone (TMAZ) and heat affected zone (HAZ) [34][37][43]. Figure 4.3 shows base material and rolling direction.

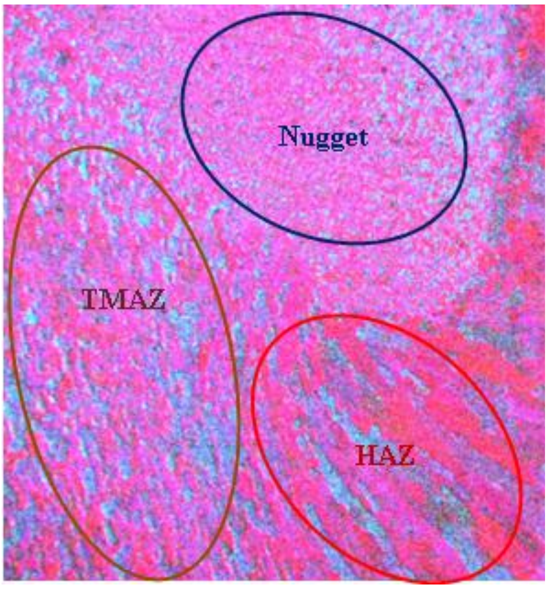


Figure 4.2: The Nugget, TMAZ and HAZ Zones

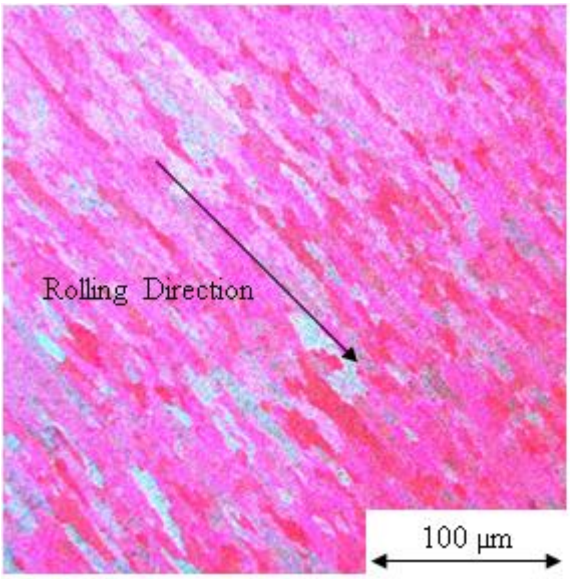
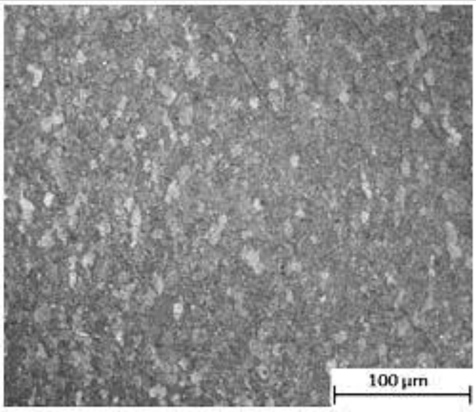
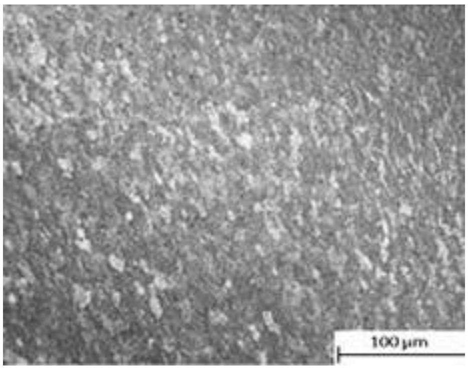
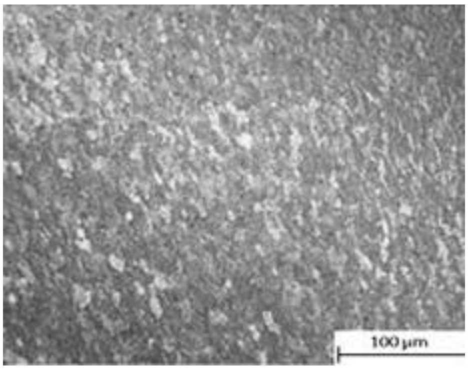
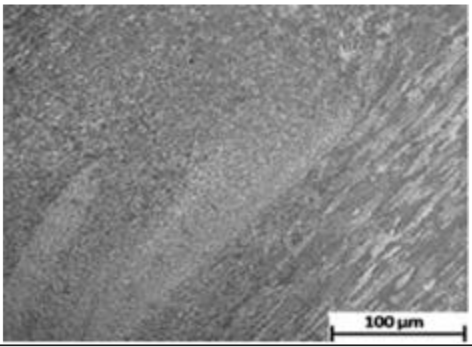


Figure 4.3: Base Material Grains Direction and Size (70 μm)

Table 4.1 shows the grain size and shape in nugget zone for each ω/f value. The size of grains located in nugget zone is smaller than other zones. Moreover, the grain size in TMAZ is smaller than that in HAZ. These findings are consistent with [38][42][45][48].

Table 4.1: Grains Shape and Direction in Nugget Zone for Each Value of ω/f

ω/f (rev/mm)	Grains Size in Nugget Zone	Grains Shape and Direction in Nugget Zone
22.22	10 µm	
25	7.7 µm	
28.4	6.25 µm	
125	Not Defined	

In conclusion, with increasing the value of ω/f, the temperature of operation will be increased and cooling rate will be decreased [39][44]. It causes to decrease the size of grains.

4.2 Effect of ω/f on Hardness

As shown in Figure 4.4 with increasing the value of ω/f, the average hardness of zone A decreased, consistent with [26][27].

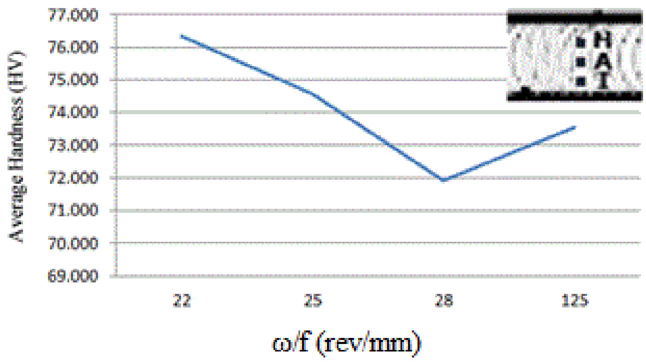


Figure 4.4: Effect of ω/f on the Average Hardness in Zone A

Figure 4.5 shows the curve variations of hardness for a sample with ω/f=28.4 in all three zones A, H and I [28][29][30].

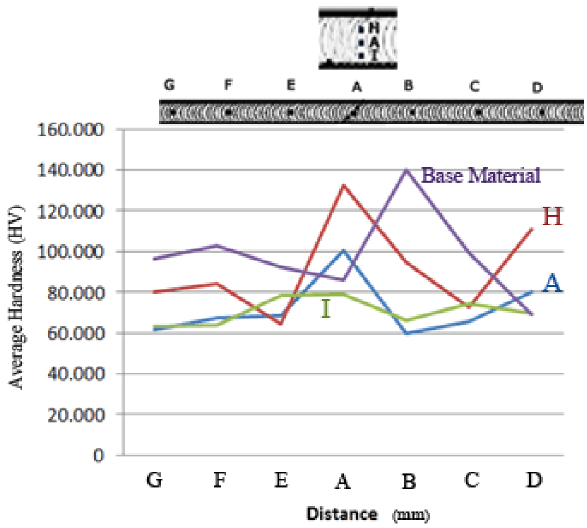


Figure 4.5: The Variation of Hardness in a sample process with w/f=28.4

With increasing the ω/f the size of grains will be decreased which was shown in Figure 4.1. Therefore, FSP on cold worked material performs like annealing and leads to decrease the hardness which is consistent with [39][44].

4.3 Effect of ω/f on Tensile Strength

Regarding Figure 4.6 with increasing the ω/f the value of yield strength and ultimate strength will be decreased [31][32][33].

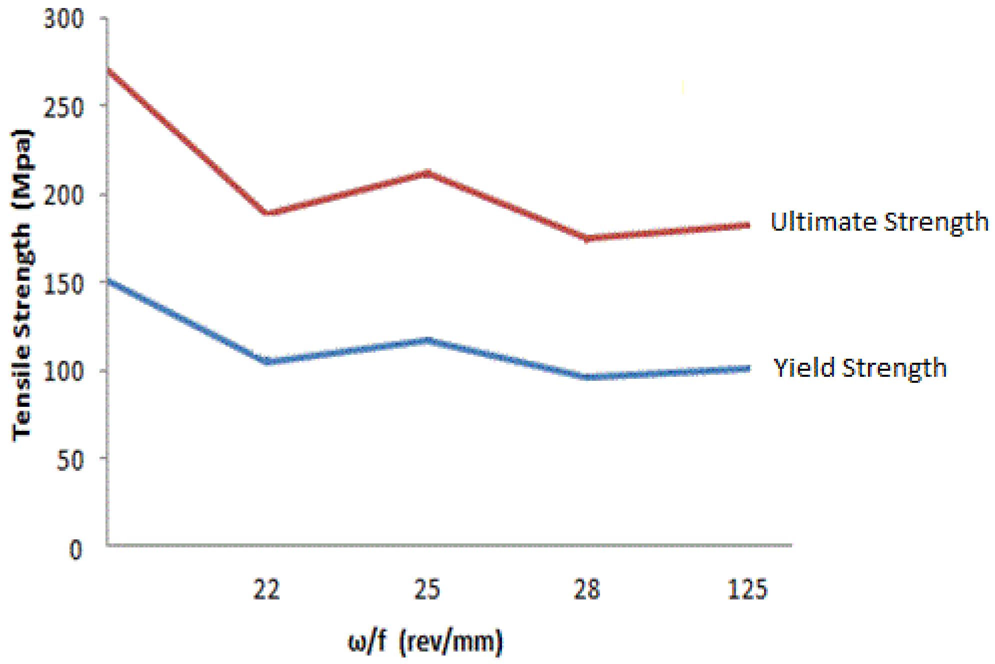


Figure 4.6: The Effect of ω/f on Yield Strength and Ultimate Strength

Figure 4.7 shows with increasing ω/f the value of strain will be increased as well [15].

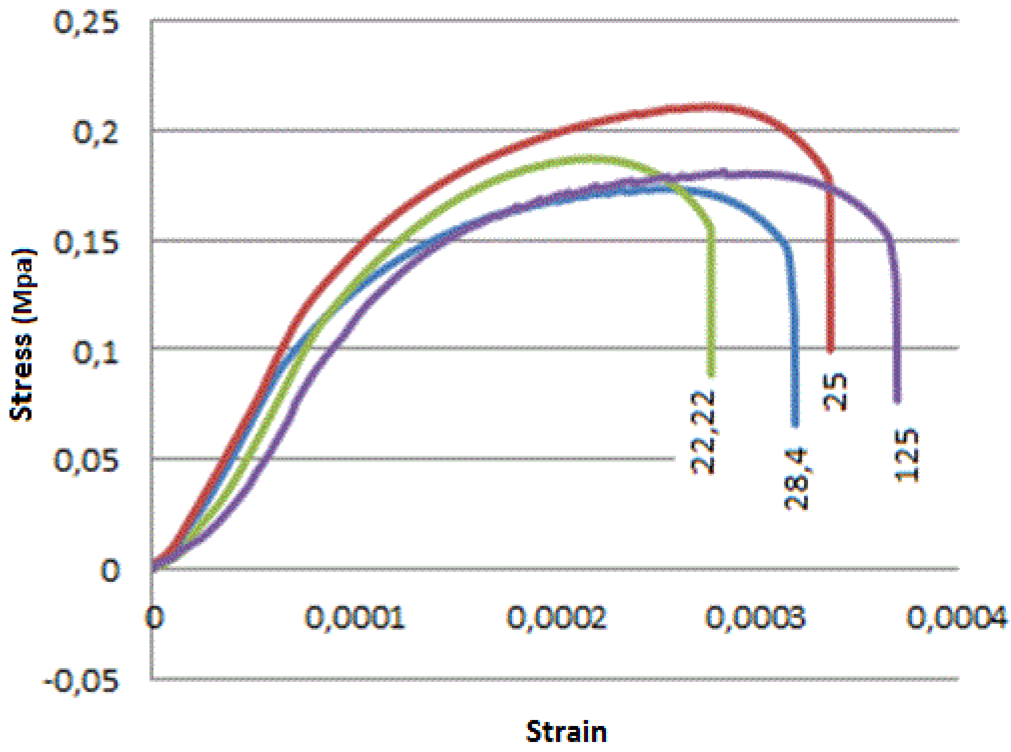


Figure 4.7: The Stress-Strain Curves for Each ω/f Rate

4.4 Effect of ω/f on Impact Strength

Regarding Figure 4.8 with increasing ω/f the impact strength of sample will be increased [28]. The impact resistance of base material is 10.8.

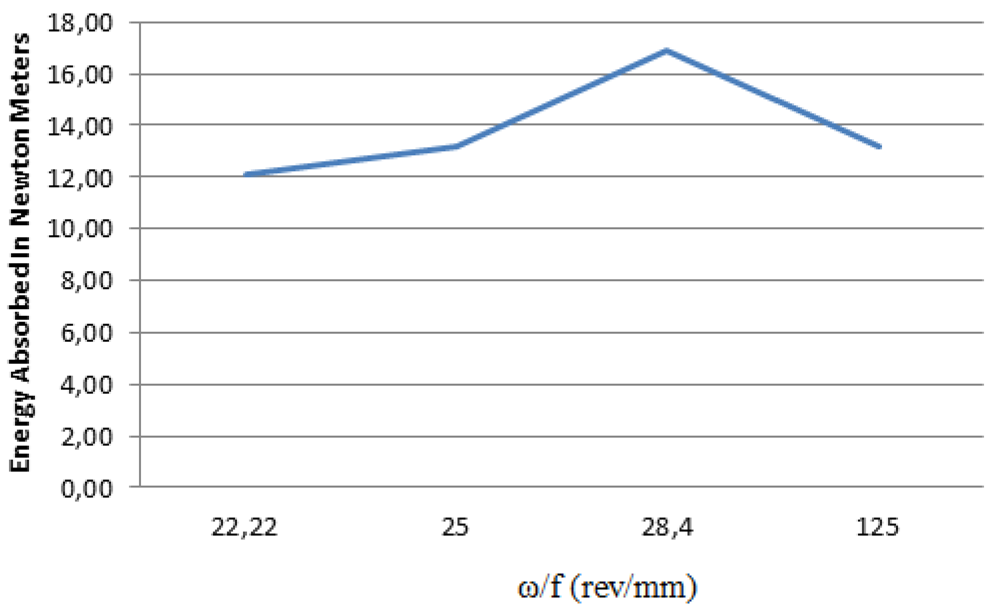


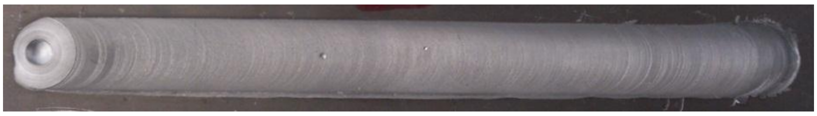
Figure 4.8: The Effect of ω/f on the Impact Resistance

With increasing the impact strength the ductility of material will be increased.

4.5 Effect of ω/f on Surface Quality

Regarding Table 4.2 with increasing ω/f leads to improve the surface quality. Moreover, increasing the number of passes leads to decreasing the surface quality.

Table 4.2: The Effect of ω/f on Surface Quality

Value of ω/f (rev/mm)	Surface Quality (From infront)
28.4	
25	
22.22	
125	
125	

4.6 Effect of Number of Passes on Mechanical Properties

Regarding Table 4.3 with increasing the number of passes the value of average hardness will be increased [7]. Also the impact resistance of samples increases.

Table 4.3: The Effect of Number of Passes on Mechanical Properties

Samples No	ω/f (rev/mm)	Energy Absorbed In Newton Meters	Average Hardness (HV)
2 passes	125	16	57
3 passes	125	16.3	63
4 passes	125	17.5	67

Chapter 5

CONCLUSIONS

In this study, the effect of variation of ω/f on cold worked AA6061 aluminum was investigated. The important conclusions of the study are as below:

1. An increase in ω/f leads to decrease in grain size, especially in operational zone.
2. For ω/f ranging from 22 to 28, the average hardness decreases from 76 to 71 HV. Afterwards for ω/f ranging from 28 to 125, the average hardness increases from 71 to 73 HV.
3. For ω/f ranging from 0 to 22, the yield tensile strength decrease from 150 to 103 Mpa. Afterwards for ω/f ranging from 22 to 25, the yield strength increases from 103 to 116 Mpa. After that, for ω/f ranging from 25 to 28, the yield strength decreases from 116 to 95 Mpa. Finally, for ω/f ranging from 28 to 125, the yield strength increases from 95 to 100 Mpa.
4. For ω/f ranging from 0 to 22, the ultimate strength decrease from 270 to 187 Mpa. Afterwards for ω/f ranging from 22 to 25, the ultimate strength increases from 187 to 210 Mpa. After that, for ω/f ranging from 25 to 28, the ultimate strength decreases from 210 to 173 Mpa. Finally, for ω/f ranging from 28 to 125, the ultimate strength increases from 173 to 181 Mpa.
5. For ω/f ranging from 0 to 28, the impact strength increases from 10.8 to 16.9. Afterwards for ω/f ranging from 28 to 125, the impact resistance decreases from 16.9 to 13.2.
6. An increase in ω/f results in improved surface quality.

7. For ω/f =125 with increasing the number of passes, the impact resistance increases from 13.2 to 17.5.Moreever, for ω/f =125 with increasing the number of passes, the average hardness decreases from 98 to 57 HV. Afterwards the average hardness increases from 57 up to 67 HV.

8. The results presented here will act as guidelines to the FSP users in order to modify the properties of cold worked metals.

In summary for the usefulness of this study in industry it is to be noted that FSP has significant usage in automobile, aircraft and shipping industry; sometimes it is needed to have low hardness and strength but high impact resistance in some sections of parts. The above discussed results show that the FSP can be successfully employed for such applications.

FUTURE WORKS

Future works may include the following:

- Investigating the effect of using several tools with different designs on the microstructure results
- Investigating the effect of operation temperature on results with using thermocouples and infrared technology
- Employing cooling rate in different situations in order to discover its effect on the process and the results of microstructure
- Changing the value of rotational and traverse speeds of tool to achieve the optimal result
- Measuring, controlling and analyzing the force on the sample during process
- Employing pre-heating method on the samples before doing the operation
- Using other series of aluminum alloy and comparing the results with current study

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