FRICTION STIR WELDING OF ALUMINIUM ALLOYS: MECHANICAL PROPERTIES AND METALLURGICAL OBSERVATIONS

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CERTIFICATE

I hereby certify that the work which is being presented in the thesis entitled **“Friction stir welding of Aluminium alloys: Mechanical properties and metallurgical observations”** in partial fulfilment of the requirement for the award of degree of **Master of Technology** and submitted in Department of Mechanical Engineering, Lovely Professional University, Punjab is an authentic record of my own work carried out during period of thesis under the supervision of **Mr. Prashant Kumar Pandey** (**Assistant Professor**) Department of Mechanical Engineering, Lovely Professional University, Punjab. I have not submitted the matter presented in this dissertation anywhere for the award of any other degree or to any other institute. .

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ABSTRACT

This review presents the detailed description about the Friction stir spot welding of aluminium alloys and their mechanical properties and metallurgical observations. Mechanical and metallurgical observation of friction stir welding is examined in this review. Experimental studies are discussed in terms of effect of some parameters such as tensile strength, shear strength, sheets thickness, temperature and temperature distribution in the welding. In this analysis of welding sheet thickness, material selection and methodology are discussed in detail. For the welding of two low cast iron metal sheets we chosen A6061.Sheets contains low carbon % and having high ductility and wieldable properties. The welding of workpiece is done upon the CNC machine and the temperature distribution phenomenon is measured with thermocouple. The resulting welded piece is consist two type of failure, weld nugget failure and shear strength failure. We consists three parameters, first we take round pin tool 2nd we take rectangular shape pin tool and 3rd we take triangular shape pin tool. With this result it creates different types of weld joint and their microstructure are also different and their strength also alters. In this we do no of experiments for calculating the different strength and their microstructure and try to improve their weldability in the different segment.

Key Words: Shear strength, research methodology, thermocouple, weld nugget failure, A6061

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DECLARATION

I, **ARUNABH MANI TRIPATHI,** student of **M.Tech** under Department of **Mechanical Engineering** of Lovely Professional University, Phagwara, Punjab, hereby declare that all the information furnished in this thesis report is my own intensive research and is genuine.

This thesis does not, to the best of my knowledge, contain part of any work, which had been submitted for the award of the degree either of this university or any other university, without proper citation.

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CHAPTER 1

INTRODUCTION

1.0 OVERVIEW

The primary purpose of this chapter is to build on understanding about present status of research in the field of Friction Stir Welding (FSW) process and Friction Stir spot Welding (FSSW) process of Aluminium and its alloys. The knowledge attained in the present chapter would be helpful in identifying research area for present work. This current chapter is divided into six sections. The first five sections discuss about history; applications; state of the art; comparison with conventional spot welding (resistance welding), research challenges in the field of FSW and FSSW. The sixth section describes motivation behind present work. Overview of the thesis is given in last section

1.1 INTRODUCTION

Friction Stir Welding (FSW) process and Friction Stir Spot Welding (FSSW) process are relatively new solid state joining processes. These techniques are environment friendly, energy efficient and versatile [Mishra & Ma, 2005] [1]. Mainly these processes can be used for joining of high strength aerospace components made up of Aluminium alloys and other metallic alloys that are very difficult to weld by conventional fusion welding. The FSW and FSSW processes are having wide application in the automobile industries. FSSW is considered the most important growth in metal joining in over a decade. FSSW is derived from the parent process i.e. Friction Stir Welding (FSW) which was invented at The Welding Institute (TWI) of UK in 1991 as a solid-state joining process [Thomas et. al, 1991: Dawes & Thomas, 1995] [2].

The complicatedness of making high-quality, exhaustion and break safe welds in aviation Aluminium amalgams has huge obstacles for wide utilization of welding procedures for the joining of aviation structures. These Aluminium compounds are for the most part delegated non-weld able in view of the poor hardening, flimsy grain size and porosity in the combination zone. Moreover, misfortune in mechanical properties when contrasted with base material is exceptionally critical. These elements make the joining of these combinations by traditional welding forms ugly. A portion of the Aluminium amalgams can be welded utilizing resistance welding, yet the surface planning is costly, with surface oxide arrangement being a noteworthy issue [Mishra & Ma. 2005] [1].

The working principle of FSSW is as shown below in **Fig. 1.1**. A non-consumable rotating tool with a specially designed pin and shoulder is inserted into the workpiece to be joined as lap joint. The tool serves following primary functions:

- **a.** Frictional heating between tool pin and workpiece material
- **b.** Frictional heating between tool shoulder and workpiece material
- **c.** Stirring of workpiece material with the help of tool pin
- **d.** Extrusion of workpiece material

The heating is accomplished by friction between tool pin and workpiece; and tool shoulder and workpiece which causes plastic deformation of the workpiece material. The localized heating softens the material around the tool pin and tool shoulder; and the tool rotation leads to mixing of the material in the vicinity of the tool pin.

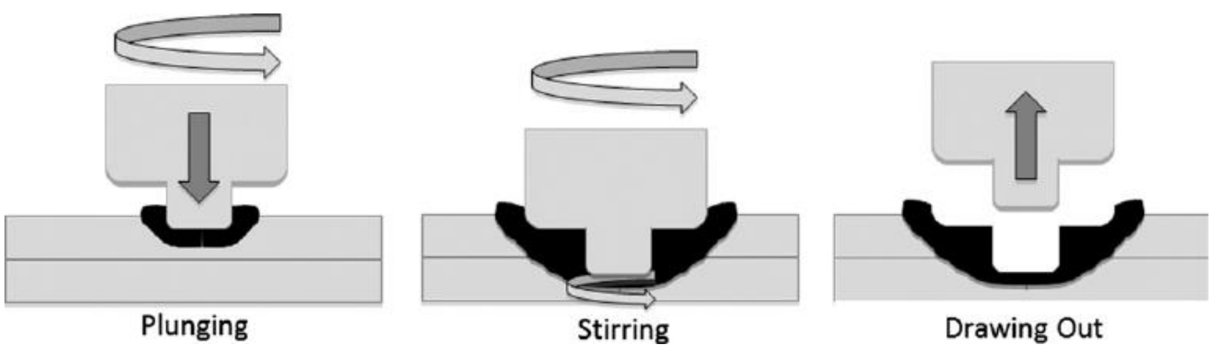


Fig. 1.1: A schematic illustration of FSSW process sequences. (a) Plunging, (b) stirring, and (c) drawing out [Shen et. al., 2013] [3]

As a result of this process the material flows from one position to another position where it is in re-crystallization temperature range and leads to formation of joint. The various geometrical features of the tool govern the material movement around the pin or pin profile [Mishra & Ma, 2005][1]. During FSW process, the material undergoes extreme plastic deformation at elevated temperature (0.6-0.8 times of melting temperature), resulting in formation of fine and equi-axed re-crystallized grains. The fine and equi-axed microstructure in friction stir welds delivers enhanced mechanical properties [Mishra & Ma, 2005] [1].

1.1.1 Advantages of FSW and FSSW

FSW and FSSW are considered to be the most significant development in metal joining in the past few years and are considered as a green technology due to its energy efficiency, environment friendliness, and versatility [Mishra & Ma, 2005] [1]. Both these joining processes consume considerably less energy as compared to the conventional welding methods. No cover gas or flux is used in these processes, thereby making the process environmentally friendly as well as hazard free for the user. In the contemporary industrial world, Environment, Health and Safety (EHS) have great significance. Both these joining processes comply with the EHS norms to a great extent. The joining in FSW and FSSW does not involve any use of filler metal. Therefore any Aluminium alloy can be joined without concern for the compatibility of composition, which is of great concern in fusion welding. Dissimilar metals, alloys and composites can be joined with equal ease as and when required [Murr et. al, 1998; Li et. al., 1999; Li et. al., 2000] [4]. The primary advantages of FSW and FSSW are listed below:

1. **Healthy environmental aspects of FSW and FSSW**

   Any new industrial process needs to be thoroughly assessed regarding its impact on the environment. Careful consideration of EHS (Environment, Health and Safety) issues at the workplace is of crucial importance to any company currently investing in new processes. It is additionally progressively regular for makers to screen an item's natural effect for the duration of its life cycle. FSW and FSSW offers various ecological favorable circumstances contrasted with other joining techniques. Moreover, "green considering" is bleeding edge in the modern division and of impressive showcasing esteem.

2. **Less weld seam preparation**

   Butt, blind and overlap welds are the chief weld applications for the FSW and FSSW process. For preparation of right bead configuration, workpieces having greater wall thicknesses frequently requires a special milling or cutting process.

3. **Fewer resources requirement**

The FSW and FSSW forms needs no protecting gas and in this manner no gas supply or plant venture, for example, weight tanks, pipe fittings and gas controllers, the length of it is connected to low dissolving temperature materials, for example, Aluminium. No requirement for consumables, disposing of the requirement for their capacity and transport inside the creation range, and maintaining a strategic distance from the requirement for their generation somewhere else. A FSW and generation zone and maintaining a strategic distance from FSSW unit implies less interest in the work environment. No compelling reason to ensure laborers/clients against UV or IR radiation. The FSSW procedure produces no smoke and, dissimilar to circular segment welding forms (particularly with Aluminium), a fumes framework is a bit much.

4. **Low noise emission**

Noise is a disparaged wellbeing danger, particularly in India. The commonest welding forms for Aluminium are the MIG-heartbeat or TIG square-wave systems. At the point when utilized for workpieces of medium thickness, both procedures require a great deal of vitality. Moreover, the beat or square-wave frequencies make commotion assurance for the laborer an absolute necessity, despite the fact that this is frequently disregarded. FSW and FSSW units transmit generally less clamor when contrasted with the previously mentioned welding procedures.

5. **Energy saving**

While considering vitality utilization, three variables must be evaluated: how much vitality is required to play out the weld, what is the aggregate vitality required working the hardware and subordinate gear, and how much vitality is required for post treatment (granulating and cleaning). For the most part, FSW and FSSW request less vitality contribution to the weld than MIG and TIG, however more than laser welding. Add up to vitality enter relies on upon the extent of the hardware being utilized and the thickness of the joint. FSW and FSSW offer the best vitality reserve funds at higher divider thicknesses.

6. Friction Stir Spot Welded components offer through-life environmental gains

Friction Stir and Friction Stir Spot Welded products are less heavy, compared to other joining methods. Especially with products such as cars, Lorries, trains and aircraft, that is constantly accelerating and decelerating, FSW and FSSW offers lower energy consumption, while reducing the requirement for powerful engines and brakes. Over a product's entire life cycle, this constitutes the greatest positive impact.

7. Excellent quality

This creative strong state welding strategy opens up a radical new scope of welding conceivable outcomes. The low liquefying purposes of delicate non-ferrous metals no longer represent an issue. Bowing and elastic tests have affirmed eminent unbending nature and superb weariness resistance. Post welding treatment is negligible and the completed joint includes unique material just, which implies no considerations or debasements. Weld quality is unrivaled. The total absence of voids and contaminations and the way that the material has been plasticized; and not dissolved, guarantees extraordinary weld quality. This makes the system particularly appropriate for the volume creation of level or bended boards, where wellbeing basic welds must be impeccable as in the transportation, seaward, rail and aviation businesses.

8. Rewarding economics

FSSW process is quite economic as compared to the conventional welding techniques. Following points illustrate this fact:

• Easy pre weld work-plate degreasing the only requirement

• No consumables for welding or shielding gas required

• No worker protection required from fumes because there is no generation of fumes

• Low energy consumption

• No post machining required

FSW and FSSW are emerging as a very effective solid-state joining/processing technique. Numerous successful applications of FSW and FSSW have been demonstrated in a relatively short duration after its invention [Mishra, 2005] [1]. The key benefits of FSW and FSSW are summarized in **Table 1.1.**

Table 1.1: Benefits of FSW and FSSW

Metallurgical benefits	**Environmental benefits**	**Energy benefits**
• This is an Solid state process • Very less distortion of work piece • Very good repeatability and dimensional stability • No alloying elements loss • Excellent metallurgical properties • Absence of cracking • Fine microstructure • Replace multiple parts joined by fasteners	• No requirement of any kind of shielding gas • No surface cleaning requirement • Eliminate grinding wastes • Eliminate solvents required for degreasing • Saving of Consumable materials like rugs, wire or gas	• Improved materials use (e.g., joining different thickness allows reduction in weight) • Only 2.5% of the energy needed for a laser weld • Decreased fuel consumption in light weight aircraft, automotive and ship applications

1.1.2 Disadvantages of FSW and FSSW

There are also some disadvantages that come along with FSW and FSSW processes. Indeed, some of the advantages listed above can be viewed in a less positive light in certain circumstances. The disadvantages associated with FSW and FSSW are listed below:

a. Disadvantages of fully mechanized nature of the process
b. Rigid and harry duty fixture required
c. Key hole left behind after welding

d. Power consumption depends on workpiece material and thickness

1.2 APPLICTIONS OF FSW AND FSSW

1.2.1 Aerospace

- Space Industry
- Civil aviation
- Aerospace R&D

1.2.2 Ship Building

- Application advances
- Parts and components

1.2.3 Automotive Industry

1.2.4 Automotive applications

1.3 PRESENT STATE OF RESEARCH IN SOLID STATE WELDING

Solid state welding is a type of welding process which produces temperatures essentially below the melting point of the base materials being joined, without the addition of brazing filler metal. Pressure may or may not be used. This group of welding processes includes cold welding, diffusion welding, explosion welding, forge welding, friction welding, friction stir welding, friction stir spot welding, hot pressure welding, roll welding, ultrasonic welding and resistance welding. In all of these processes time, temperature, and pressure individually or in combination produce coalescence of the base metal without significant melting of the base metals.

Solid state welding includes some of the very oldest of the welding processes and some of the very newest. Some of the processes offer certain advantages since the base metal does not melt and form a nugget. The metals being joined retain their original properties without the heat affected zone problems involved where there is base metal melting. When dissimilar metals are joined their thermal expansion and conductivity is of much less importance with solid state welding than with the arc welding processes.

Time, temperature and pressure are involved. However, in some processes the time element is extremely short, in the microsecond range or up to a few seconds. In other cases, the time is extended to several hours. As temperature increases time is usually reduced.

The state of research in the solid state welding can be classified in nine categories as follows:

- **Cold welding**
- **Diffusion welding**
- **Explosion welding**
- **Forge welding**
- **Hot pressure welding**
- **Roll welding**
- **Ultrasonic welding**
- **Friction Welding**
- **Friction Stir Welding (FSW) and Friction Stir Spot Welding (FSSW)**

1.4 FSSW versus Resistance Spot Welding (RSW)

Table 1.2: Comparison between FSSW and Resistance Spot Welding

FSSW	RSW
Workpiece need not be an electrical conductor	Workpiece should be essentially a good conductor of electricity
No elaborate surface preparation is required prior to welding	Surface preparation required is comparatively more as compared to FSSW
Poor aesthetics because of the hole left after the welding	Good aesthetic appeal as no surface feature is created after welding
Post welding treatment may be required	No post welding treatment required
Power consumption is less as compared to RSW	Power consumption is more as compared to FSSW
Good tensile and fatigue strength as	Lower tensile and fatigue strength

compared to RSW	
The mounting requires dedicated jig and fixture to hold the workpiece	Need someone to hold workpiece. Much risk of fracturing hands
Stable work bed to place the workpiece	Unstable pressurizing system

1.5 FSSW RESEARCH CHALLENGES

The major research challenge orbs field of FSSW is the lack of dedicated state of the art FSSW machinery. The present research work is carried out on vertical milling machines or heavy duty drilling machines. These machines are not dedicatedly designed for FSSW process. These machines require a lot of modifications to deliver quality performance for the process of FSSW.

Heavy duty machines are the pre-requisite for the process of FSSW If this is not met, there is a possibility of machine breakdown (burnt relays). In present study at low R.P.M., the machine spindle got stuck when the tool pin was inserted inside the workpiece. This clearly shows that a heavy duty machine is required for FSSW.

The factors that affect the weldability of materials using FSSW are work material, tool material, tool geometry and welding parameters like thrust force, feed rate, tool rotation speed, dwell time etc. These parameters also affect the welding process output quality characteristics like weld strength, flash formation, weld finish, gap between the overlapping plates etc. Conventional spot welding processes (resistance spot welding) and other solid stab welding processes have been employed in the recent years for welding of contemporary materials. Surface aesthetics achieved by these methods is much better than achieved by FSSW.

When welding hard materials, excessive tool wear and poor surface finish are the major problems. This affects the repeatability of the tool. Harder tools results in improved surface finish and reduced tool wear due to their better mechanical properties. But these tools are costlier and more prone to breakage, even if there is a little vibration in the machine. Therefore there is an imminent need to study the tool pin breakage in FSSW.

1.6 MOTIVATION

The discussion in the earlier sections of this chapter clearly demonstrates that Aluminium and its alloys are the back bone of the aerospace, automobile and shipbuilding industry. With a constant advancement in these materials, a parallel advancement in their processing techniques is of utmost importance. The advancement in the processing techniques for these materials is the present challenge. FSW and FSSW is a promising research area and still require efforts at extended length. These two facts have been the prime motivators behind the current research endeavor. The industrial applicability of the process can be further enhanced if the end user is delivered with certain relationships between the welding parameters and the output i.e. the weld quality. In this regard, it is a descent proposal to study holistically, the process of FSSW.

The use of FSW and FSSW to join materials un-wieldable by any other conventional welding techniques made this topic more interesting as well as challenging for investigation. FSW and FSSW are being successfully applied to join Aluminium magnesium alloys, steels, polyethylene sheets, titanium and copper alloys. FSW and FSSW are also used to weld dissimilar materials. Hence, a researcher is available with a wide variety of materials to work on. This prompted to work in the field of welding of Aluminium 6061 using friction stir spot welding.

FSW and FSSW are complex welding processes. The output is measured to terms of weld quality, which reflected through the tensile strength of the weld. This output is governed by numerous factors and their interactions. The literature reveals that researchers are constantly working on the parameters like tool design, tool rotational speed, dwell time; tool feed rate and the axial load/pressure which affects the weld quality in some way or the other. This motivated me to work on any of these or all of these parameters.

The tool geometry can be extremely complex in the process of FSW and FSSW. One can study the effect of change in tool pin profile, tool pin diameter, tool pin length, tool pin feature (threads, grooves) etc. The tool pin profile can be cylindrical, rectangular, triangular and of any other geometrical shape. One can also investigate the tool shoulder in detail by varying the tool shoulder diameter and by varying its surface profile. Tool shoulder can be flat, concave or convex. It can be with feature (grooved, threaded) or featureless.

FSW and FSSW can be carried out on heavy duty CNC vertical milling machine or a drilling machine. All the above mentioned reasons finally culminated and motivated me to work and investigate the welding of Aluminium 6061 using Friction Stir Spot Welding (FSSW).

1.7 OVERVIEW OF THESIS

The present thesis is divided into ten chapters.

CHAPTER I: INTRODUCTION

This chapter discusses history and evolution of the process of FSW and FSSW along with present state of research in these fields. It discusses about the advantages, disadvantages, applications and motivation behind present research work. In addition this chapter also gives an overview of the thesis.

CHAPTER 2: TERMINOLOGIES

This chapter consists of the basic term which is used in FSW and FSSW processes. The main objective is to clarify all the terminologies which are works on the solid state joining process and their significance in the welding phenomenon.

CHAPTER 3: REVIEW OF LITERATURE

This chapter critically reviews previous investigations pertaining to present work and identifies potential areas of research in the process of FSSW. Based on gaps and opportunities established during the review, formulation of problem has been obtained. The objectives, scope and methodology associated with the work have been high lightened.

CHAPTER 4: RATIONALE AND SCOPE OF STUDY

This chapter aims to study the problem related with current research. The chapter is divided into two major sections. The first section discusses in detail about the various process parameters involved in the FSW and FSSW processes. This section contains the material selections, tool selections and the parameters. Second section explore about the gaps between the previous works which can be done by different researchers and scholars. The opportunity find out in between the research work can be explored in our study.

CHAPTER 5: OBJECTIVE OF STUDY

This chapter aims to study about the objective of our research work which can be done furtherly .This chapter contains only one section which tells about the work can be done in the thesis work by significant manner.

CHAPTER 6: EQUIPMENT AND MATERIALS

A systematic method to plan the experiments is requirement for efficient conduct of experiments. The planning of experiments is carried out by statistical design of experiments; subsequently factual statistics will be collected and investigated by statistical procedures resulting in effective and objective oriented inferences. Physical experimentation involves experimental errors and the statistical method is the only objectives approach to analysis these experimental results including errors. Therefore there are two phases of an experimental problem: experimental design and statistical analysis. These two facts are meticulously associated since the technique of analysis directly depends on the experimental design employed.

CHAPTER 7: RESEARCH METHODOLOGY

This chapter is describes the whole research work in brief.

CHAPTER 8: EXPERIMENTAL WORK

This chapter is intended to discuss procedure followed during experimentation phase. This chapter enlightens about friction stir spot welding process parameters in detail and how they work in separate conditions like different speed ,feed and dwell time , also the tool geometry was altered.

CHAPTER 9: RESULT AND DISCUSSIONS

This chapter is concluded all the results of mechanical and metallurgical properties of AL6061 alloys. This chapter elaborates different results obtained from tensile shear fracture load testing, micro-hardness analysis and macrographs of FSSW specimens. The effect of investigated process parameters on tensile shear fracture load has been discussed in detail. The observations from micro hardness analysis, visual inspection of fractured wels and macro graphs has been presented and discussed in detail.

CHAPTER 10: CONCLUSION AND FUTURE SCOPE

In present chapter the results are thoroughly analyzed and optimal process parameters for FSSW of Aluminium 6061 alloy are selected. The chapter is divided into four main parts. The first contains discussion on the tensile behavior of FSSW joint. The second part discusses about the micro hardness of FSSW joints respectively. The third part contains the conclusions. Scope for future work is detailed in the last part.

CHAPTER 2

TERMINOLOGY

2.0 OVERVIEW

This chapter aims to study the terminology which related with current research. The chapter is tells about different sections of FSSW. The all terms discusses in detail about the various process parameters involved in the FSW and FSSW processes. The prospective study area has been identified from among these parameters. All the terms explores about the operations and performance cycle of FSW and FSSW. The following terminologies are discussed in details.

- **Probe**
- **Shoulder**
- **Clamps**
- **Plunge depth**
- **Tool traverse speed**
- **Tool rotation speed**
- **Dwell time**
- **Downward forces**
- **Friction force**
- **Pin profile**
- **Nugget Zone**
- **Heat affected zone**
- **Thermo-mechanically affected Zone**

- **Probe:** The probe or pin is the end part of the FSW /FSSW tool, which penetrates into the workpiece. The probe is in direct contact with the workpiece.
- **Shoulder:** The shoulder also penetrates the workpiece up to a little depth and avoids the spatter of material in plastic state.
- **Clamps:** The equipment to properly hold the job in its place.

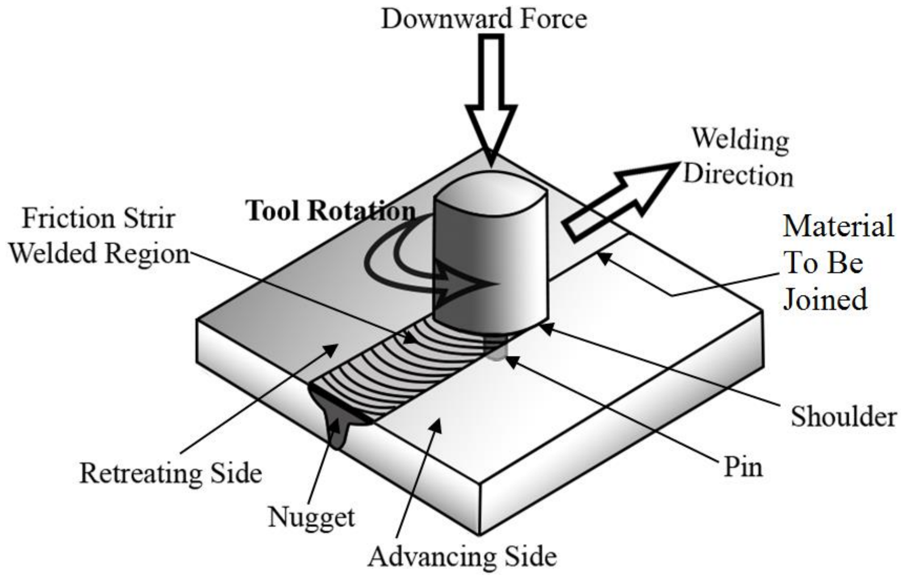


Fig. 2.1: Schematic diagram of FSW, tool with featured tool pin and shoulder

- **Plunge depth:** The distance up to which the shoulder plunges into the workpiece.
- **Tool traverse speed:** The speed with which the tool moves forward during FSW.
- **Tool rotation speed:** The speed of tool in RPM in clockwise or anticlockwise direction.
- **Dwell time:** The time till which the tool remains at a fixed position while rotating at a constant speed.
- **Downward force:** The force that the tool head applies in the downward direction on to the workpiece.
- **Friction force:** The force resisting the relative motion of solid surface fluid layers and material elements sliding against each other.
- **Pin profile:** the shape and design of tool probe.
- **Nugget zone:** The weld zone which is directly affected by the profile of the tool.
- **Heat affected zone:** The zone at which the maximum heat is generated during welding.
- **Thermo-mechanically affected zone:** The partial recrystallization of the material occurs in TMAZ

CHAPTER 3

REVIEW OF LITERATURE

3.0 OVERVIEW

This chapter aims to study the literature related with current research. The chapter is divided into six sections. The first section discusses in detail about the various process parameters involved in the FSW and FSSW processes. The prospective study area has been identified from among these parameters. Second and third section explores previous investigations concerning FSSW of contemporary materials, particularly Aluminium. On the basis of outcomes from literature various gaps and opportunities have been discussed in the fourth section. In the fifth section problem formulation and research scope for the current work has been presented which covers problem definition, objectives and scope of investigation. The last section summarizes the literature review and problem formulation.

3.1 DISCUSSION ON VARIOUS PROCESS PARAMETERS OF FSSW

Friction Stir Spot Welding (FSSW) works under multivariable process parameters. These parameters include geometry of welding tool, tool material, workpiece material and controlled machine tool parameters. The machine tool parameters include welding tool rotational speed, feed rate, dwell time etc. Thus the performance of the FSSW joint has been governed by the different input process parameters. Therefore it become imperative to optimize these input process parameters to get the optimal weld performance in term of tensile strength, fatigue strength, cross tension strength and the tool reusability.

3.1.1 Tool Rotational Speed

FSSW involves severe plastic deformation along with complex material movement. Tool rotational speed effects significantly the material flow pattern and temperature distribution in the vicinity of the weld zone, thereby influencing the micro structure of the material [Mishra & Ma 2005] [1].

Different researchers have different opinion over the effect of tool rotational speed parameter on the weld strength. Few of the researchers reported that higher strength can be obtained by lowering rotational speed [Shen et al. 2013] [3]. Sakano et al. (2001) [5], Arul et al. (2008) [6] and Lathabai et al. (2006) observed that the lap shear load primarily increased and then decreased as the tool rotation speed increased. Tozaki et al (2007) [7], Freeney et al. (2006) [8] and Merzoug et al. (2010) [9] found that tensile and shear strength decreased with increasing tool rotational speed [Zhang et. al. 201 I]. Freeney et al. (2006) and Tozaki et al. (2007) reported that higher weld strength can be attributed to a larger stir zone size attained by lowering tool rotation speed However. Hunt et al. (2006)[10] pointed out that increasing the tool rotational speed increased the joint strength at the range of lower rotational speed, but had no effect at the range of higher rotational speed. Hence, the effect of tool rotational speed on the mechanical properties is not well established and required more extensive investigation to explore behaviour of tool rotational speed on mechanical properties of weld. Freeney et al. (2006) [8] shown that nugget size of AA5052 FSSW joints decreased with increasing tool rotational speed. As a result, the decreasing nugget size may be one of the reasons which can be used to explain the decreasing tensile/shear strength at the higher rotational speed.

On the other hand it is also believed that higher strength can be attributed to a larger stir zone size in case of higher tool rotational speed. The increasing effective weld width may be responsible for superior mechanical properties. The presence of larger effective weld width results in stronger weld. It can be concluded that the effective weld width offers resistance against external loading and plays a dominant role in determining the strength of the spot weld [Shen et al. 2013] [3].

3.1.2 Tool Pin Profile

Tool profile is the significant feature of FSSW process. The tool profile plays a important role in material mixing. The uniformity of microstructure, properties of weld, forces induced in during welding etc. are governed by the tool design. From the heating aspect, the relative size of pin and shoulder is important, as compared to other design features of the welding tool. In the initial phase of tool plunge, the heating results principally from the friction between pin and workpiece. Additional heating is produced because of deformation of material. The tool plunged into the overlapping plates till the shoulder touches the workpiece. Additional heating is produced because of deformation of material. The tool is plunged into the overlapping plates till the shoulder touches the workpiece.

Researchers have investigated the effect of various types of tool pin profiles on the process of FSSW. Most investigated pin profile shapes are the conventional cylindrical pin and triangular pin. The partial metallurgical bond (hook) formed in the weld region between the overlapped metal sheets is significantly affected by the tool pin geometry [Badarinarayan et al. 2009] [11]. Few tool pin features are shown in **Fig. 3.1**.

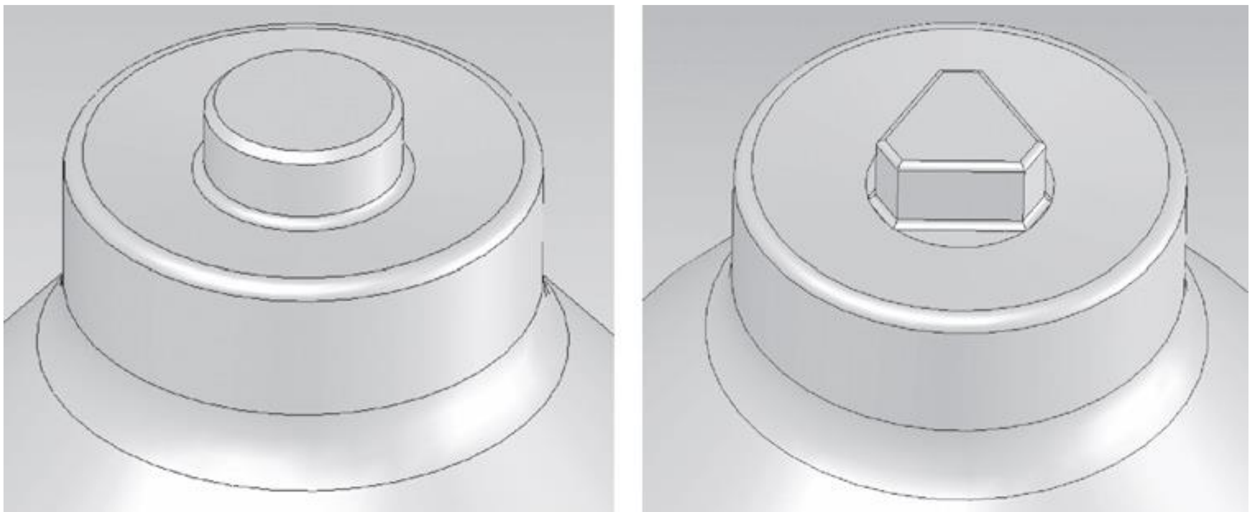


Fig. 3.1: Schematic diagram of FSSW tool with featured tool pin and shoulder (Badarinarayan et al. 2009) [11].

3.1.3 Dwell Time

Literature reveals that dwell time effects the final tensile strength achieved in FSSW. It is a dominant factor along with tool rotational speed which imparts necessary heat for the process. Most of the researchers believe that increasing the dwell time or the tool holding period increases the tensile strength of the weld. Tozaki et al. (2007) [7] pointed out that tensile shear strength increased with the corresponding increase in the dwell time.

A few researchers have opinion that increase in dwell time is beneficial up to some extent. After that with further increase in dwell time, the problem of shoulder penetration into the surface of the upper sheet becomes predominant. This leads to poor tensile strength because the hook formed has increased angle of curvature [Yin et al. 2010] [12]. It also leads to the decrease in the effective top sheet thickness, which later on enables the crack to propagate easily resulting in premature failure.

3.2 FSSW LITERATURE REVIEW

The welding process in Friction Stir Spot Welding (FSSW) is extremely complex phenomenon encompassing several governing factors. A lot of research work is happening in the field of FSW and FSSW, as both these welding energy efficient and environment friendly; hence making them a much sought after research field in the manufacturing industry. A lot of research has been already accomplished in these fields with particular emphasis on mechanisms responsible for the formation of welds and microstructural refinement. Researchers are analyzing the effects of FSSW parameters on resultant microstructure and final mechanical properties. The different parameters influencing the performance of FSSW are tool profile, pin design, shoulder design, tool feed rate, tool rotational speed, tool material, work piece material and dwell time. While the bulk of the information is related to Aluminium alloys, important results are now available for other metals and alloys as well. Hereunder is presented the literature review for the process of FSSW. The principal aim of this literature review is to results deliver groundwork from the literature unfolding the research in the expansion stage of FSSW. Major percentage of this literature is associated with the FSSW of Aluminium alloys. In addition, within the literature is added the study on FSSW of steels, magnesium alloys, dissimilar materials and polyethylene sheets.

D.A Wang, S.C. Lee [2007] [13] find out the microstructure and the failure properties of the FSSW for the A6061 materials. They used lap joint method of observations. Mechanical properties and microstructure was also checked in this research work. The sample strength checked after the shear failure observation and microstructure also altered.

Yasunari Tozaki et al. [2007] [7] generates the different tool for the welding of samples of A6061 alloys. They also used different parameters and the different feed and speed for the welding of samples. The method used in this welding phenomenon is FSSW. The tool was rotating with different speed and feed

Y. Hovanski et al. [2007][14] studied about the two different types of materials first one is Boron steel and second one is alternative and the tool used in this section was made of polymer of boron nitride. They also capture some microstructures and the hardness of the grains in between.

They also compare the results with the original boron particle and their mechanical strength was also checked in this work.

A.P. Gerlicha and T. Shibayanagi [2009] [15] finding out the properties of aluminium, copper and magnesium alloy material. They used the FSSW process for the same. The dislocations and the microstructures of the grain boundaries were also are captured in this work of research. They use different rpm like 750 to 1400 rpm for making different samples. Also be carried out the conclusions of welding process parameters along with.

Y. Uematsu et al. [2009] [16] investigated about the mechanical and tensile behavior of the aluminium alloys. The phenomenon used in this process is FSSW. The fatigue behavior was also being considered in this paper. They used a special tool which have a flat shoulder and pin. This can refill the probe hole after joint.

H. Badarinarayan et al. [2009] [17] investigated the effect of tool geometry (shoulder and pin geometry) on the hook formation and material flow y of friction stir spot welded 5754-O Aluminium alloy.

Choi et al. (2009) [18] tells about the FSSW tool wear problems .in this study they using WC-CO alloy tool and after that analysis about the welding phenomenon and their characteristics and their joint strength.in this study the steel plates welded by the FSSW process .all the characteristics and phenomenon are analyzed and measure on the different measurement system like 3D measuring system, SEM, XRD. It produces that the tool will getting shear failure and the shape of welded area will getting damaged a bit.

Mohamed Merzoug et al. [2009] [9] was studied about the parameters which was taken in the welding of A6060 alloys .they determined about the weld joint property. The property was changing after the welding.

G. Buffa et al. [2009] [19] considered the four different type of tools for the welding of workpiece. They investigated about the tunneling of the weld pool area and try to improve the weld quality, material weldability with FSSW process.

Kim.Dongun et al. [2009] [20] was investigated about their thermal properties with the FVM method of simulation. They also used aluminium alloys of lower higher grade and the method used is butt welding techniques in FSSW.

V. Tozaki et al. [2010] [21] developed a new type of tool which consists of only shoulder. By this type of tool they make a weld on 6061 alloys and clarify their wieldable properties and the tool efficiency.

Dung An Wang et al. [2010] [22] investigated the mechanical and metallurgical properties of the lower grade of the aluminium alloys they investigated about the joining of the sheets with FSSW method and compare with the conventional process of welding.

Q. Yang et al. [2010] [23] investigated about the flow of material technique. In this paper they justified the behavior of the tool and technic of the welding of grooves. They used to weld firstly bottom sheet of material after that the upper sheet so they used a pin and shoulder type of tool for making firstly grooves and then welding.

Y.H. Yin et al. [2010] [12] investigated the micro-structural features and properties of two different type of material. They also use different type of tool material for the welding purpose. They used pin and pin less tool for welding .the phenomenon will followed is FSSW.

W.Yuan et al. [2010] [24] evaluated FSSW process for aluminium alloys. They also used different parameters for the welding purpose and the phenomenon used in this welding is that is pin less tool with different dwell time and rotational speed.

Hvung-Seop Shin, Yoon-Choi Jung [2010] [25] investigated the welding quality of FSSW method. In this paper they use aluminium alloys and BMG material for the welding purpose. They use different parameters with the vertical load variation of Al and Mg properties in different workpieces.

Don-Hyun Choi et al. [2010] [26] produced the joint with help of FSSW process. They also used the Al and Mg alloys for the sample. And calculate the material properties and the mechanical strength of the weld joints. They also calculate the effect of the process parameter of the weld bead.

P.H.F. Oliveira et al. [2010] [27] in their work investigated the joining of two polymers with the FSSW process. In this section they analyzed the mechanical properties and their strength of the weld joints .they used a polymer tool for joining the workpieces which was already made up of polymer of lower grade.

Bozzi et al. [2010] [28] was investigated about the shear failure load with the increasing of thickness of the intermetallic compound of weld bead. They also used 6061 alloys for making the setup of welding.

J. Jeon et al. (2011) [29] was studied about the crystal structure of the welded work piece of Aluminium sheets alloys, and also studied about the shear deformation regarding this. In this study the microstructure shown that the single crystal structure was breaks into simple grain polycrystalline aggregate.

Pierluigj Fanelli et al. [2011] [30] performed the polymer behaviour of a welded joint with the FSSW process. They found the properties of weld and their strength with the help of simulation software.

Mustafa Kemal Bilici [2011] [31] in their study presented the use of Taguchi and further applying the ANOVA table method for calculating the strength of the welded material shear strength .They also used an orthogonal arrays for the same. The FSSW technique is very much popular at that time of investigation so they also measure their micro hardness and their mechanical properties like S/N ration.

U.F.H. Suhuddin et al. [2012] [32] measured the thermal properties with the joining of different type of alloys in FSSW method. The alloys of Al and Mg were summaries into well-mannered and they weld .during the welding they inserted a thermocouple for the measuring of thermal properties with it. They also calculate the mechanical and optical properties also.

Chi-Sung JEON et al. [2012][33] investigated the two different aluminium alloys for joining by FSSW process and further calculate their strength and the mechanical properties as well as micro hardness of the compositions. In this study they used A6061 and A 5052 alloys for the joining purpose.

H.M. Rao et al. [2012] [34] investigated the fatigue behaviour of the FSSW process under the alloys of magnesium. They manufactured the two different types of weld joints for the calculation of the weld bead. They also used the different parameters for the same.

Zhikang Shen et al. [2013] [35] in their paper investigated the effect of different parameter like tool speed, dwell time and tool profile for the sampling the material. They also used the A6061 alloys for the making the weld sample for the same.

Soran Hassanifard et al. [2013] [36] introduced the new technique for joining the two sheets. Which was increases the weld properties and the strength of the workpiece. A7075 alloys were used for the same for investigation in FSSW method. The main purpose is to weld the sample is to reduce the cracks and cold working phenomenon.

Y.F. Sun et al. [2013] [37] applied FSSW method on the low carbon steel for making the weld. They also use different parameters like dwell time, rpm and the tool profile. They also used load for repressing the material because they uses very thin plates for the welding of material.

K.W. Zeng et al. [2013] [38] developed the removal procedure for the FSSW method. They also used the aluminium alloys like 6061 sheets for joining. They applied some parameters like dwell time, feed rate and the tool parameter. The micro-hardness was also justified in this process.

B.T. Gibson et al. [2013] [39] in their article provided the different type of parameters in the FSW method of welding. They also compares the properties and the application of the weld material. They also measure the weld quality, shear failure phenomenon, micro hardness and the tool design parameters.

H.M. Rao et al. (2014) [40] studied about material contains the rare earth containing ZEK100 magnesium alloy sheets which are joined with FSSW process. In this study we create under some condition like shear lap strength and various tool geometry tool rotation and shoulder plunge depth etc. the result of this study was also differ because variation take place. If the rpm increases from 1500 rpm to 2000 rpm it will show the failure but if the thickness will increases the failure will decreases.

D'Urso (2015) [41] was studied about that how temperature distribution affects the welding parameters in FSSW process. In this study they select the AA6060-T6 Aluminium alloys plate which was weld about lap formation. There was 5 thermocouple inserted in the sample after joining process. A number of set of experiments were carried out in this process with different parameters. After that they simulate it on ANSYS and give the result about the temperature variation. After that they just check their shear properties of the welded material. Whit the help of FEM simulation was finally the result were validated.

E. Fereiduni et al. (2015)[42] was investigated about the effect of rotation speed dwell time and microstructure and tensile strength of FSSW process upon the AL-5083 Aluminium alloy steel plates. The rotational speed not more than 900 and 1100 rpm were applied. And the dwell time not more than 5s to 15 s. the temperature distribution were also recorded with the thermocouple during the joining process. The EDS were also used for the optical measurement and reading. Sometimes SEM also used. The layer thickness of sheets should not more the 2 mm in this case.

Hsieh et al. (2015) [43] was tells about the FSSW process on the low carbon steel SS400 plate with separate thickness. And tool using in this FSSW process was assembly-embedded rod (AER) and force applied on 8 KN, and rpm using 1200 and the dwell time is 100 s. when they using the thickness of plate less than 3 mm then it will causing failure but the load also matters in this.

Mubiayi and Akinlabi (2016) [44] investigated the weld which was generated by different rotation speed. The tool geometry plunger and shoulder pin also varying in this section. With the presence of CU in this process it gives more strength to the weld joints because the CU moves up on the surface of Aluminium plate and joints become much stronger. The microstructure will also show that the intermetallic properties of the Aluminium to CU. the tensile strength also varies with the variation of shoulder pin length and shoulder plunge depth. In this process failure occurs. A nugget pull-out failure also occurs in FSSW process and shear failure also arriving in this type of techniques.

Hangai et al. (2017) [45] was investigated about the al foam in between the two alloys .This paper investigated about the foaming behavior and the foam generation and their fabrication were studied. The two Cu plates were placed and the tool and plate friction state generates the foam. After that they investigated about their mechanical and metallurgical properties.

3.3 PREVIOUS INVESTIGATION ON FSSW

Table 3.1: Previous investigations on FSSW

Author(s)	Material	Findings	Inferences
Mohamed Merzoug et al. (2009)	Al 6060-T5 alloy	• The tensile strength of the welded sample decreases as the tool rotational speed increases • The dwell time first strengthens the weld up to certain value and later on weakens the weld	• Higher tool rotational speeds should be avoided • Optimum dwell time should be selected for FSSW • Tool parameters also causes the failure properties of friction stir spot welds • Tool dwell time is insignificant as compared to other FSSW parameters welds. • Coarser grain size at elevated tool rotational speeds results in poor joint strength • Different Al alloys behaves differently
Y.H. Yin et al. (2010)	AM60, AZ31 alloys	• The welding getting failure by weld nugget • This distance varies with variation in tool geometry	
Zhaohua Zhang et al. (2011)	Al 5052 alloy	• The microstructure grows coarser with increasing tool rotational speed • Hardness distribution exhibits a W-shaped appearance across the weld. • The joint strength decreases with increasing tool rotational speed while it is almost independent of the tool dwell times	
Chi Sung Jeon et al. (2012)	Al 5052-H32, Al 6061-T6	• The thrust force as a function of tool displacement vary significantly during FSSW • FSSW of two dissimilar combinations has quite different material mixing in the stir zone • The failure mechanism of all the FSSW joints is strongly affected by the typical stress concentration	

<table>
<tr><td></td><td></td><td>induced by the hook near the stir zone</td><td rowspan="5">at elevated temperatures

• The different mixing behaviour of dissimilar alloys is due to different viscosity at different temperatures

• Failure of lap FSSW joints is initiated at the hook

• Most coarse grains are in the HAZ hook

• The softening of the material in SZ is by a significant reduction of dislocation density and precipitate distributions

• Dwell time increases the bonded width and</td></tr>
<tr><td>W. Yuan et al. (2010)</td><td>Al 6061-T4 alloy</td><td>• Tool rotation speed and plunge depth profoundly influenced lap shear separation loads
• Three different separation modes were observed; interfacial separation, nugget fracture separation and upper sheet fracture separation
• There is no direct relationship between micro-hardness and separation modes
• HAZ is the softest region</td></tr>
<tr><td>D.A. Wang, S.C. Lee (2006)</td><td>Al 6061-T6 alloy</td><td>• Circumferential failure mode or the nugget pull-out failure mode was observed
• The micro-hardness distribution shows a W-shaped profile
• Failure is initiated near the SZ in the middle part of the nugget</td></tr>
<tr><td>Y. H. Yin et al. (2010)</td><td>AZ31 alloy</td><td>• Hook region is formed at the outermost boundary of lower sheet material displaced upwards demarcates the boundary between the TMAZ and HAZ regions
• Weld made without the application of dwell period are poor</td></tr>
<tr><td>H. Badarinarayan et al. (2009)</td><td>Al 5754-O alloy</td><td>• Welds made with tools having concave shoulder yielded higher static strength than with tools having</td></tr>
</table>

<table>
<tr><td></td><td></td><td>convex and flat shoulder
• The thrust force is lowest for the concave shoulder tool
• Tool with triangular pin yields higher static strength than the tool with circular pin</td><td rowspan="4">hence the joint strength

• Concave shoulder tool generates a higher effective top sheet thickness

• The tool with circular pin generates a large stir zone in the weld region

• The tool with triangular pin generates a narrow stir zone in the weld region

• A finer grain structure is formed in the vicinity of the weld keyhole with triangular pin due to asymmetric rotation
• The presence of large effective weld width results in stronger weld</td></tr>
<tr><td>H. Badarinarayan et al. (2008)</td><td>Al 5083 alloy</td><td>• The cross tension strength of the weld made with the triangular pin twice that of weld made with the cylindrical pin
• The hook points downward to the weld bottom in case of circular pin
• The hook points upward to the stir zone in case of triangular pin</td></tr>
<tr><td>Yasunari Tozaki et al. (2007)</td><td>Al 6061 alloy</td><td>• The tensile shear strength increased with increasing probe length
• Cross tension strength was not affected by the probe length
• Tensile shear strength increased with increasing tool rotational speed and tool holding time, while the cross tension strength decreased</td></tr>
<tr><td>Zhikang Shen et al. (2013)</td><td>Al 6061-T4 alloy</td><td>• A preferable appearance of the joint can be obtained at higher rotational speed and longer duration time
• The Vickers hardness profile of the welded sheets showed a W-shaped
• The tensile strength increases with the increasing rotational speed at a given duration time</td></tr>
</table>

CHAPTER 4

RATIONALE AND SCOPE OF STUDY

4.0 OVERVIEW

This chapter aims to study the problem related with current research. The chapter is divided into two major sections. The first section discusses in detail about the various process parameters involved in the FSW and FSSW processes. This section contains the material selections, tool selections and the parameters. Second section explore about the gaps between the previous works which can be done by different researchers and scholars. The opportunity find out in between the research work can be explored in our study.

4.1 PROBLEM FORMULATION AND SCOPE OF STUDY

Based on the literature review and related gaps and opportunities observed, experimental investigation in Friction Stir Spot Welding of Aluminium 6061 alloy is proposed and a research problem is formulated. The problem undertaken is discussed in the following sections with its definition, objectives, scope of proposed investigation and methodology.

4.1.1 Problem Definition

Some investigation of FSSW of Aluminium 6061 alloy, through experimentation and subsequent analysis (Taguchi), in order to develop understanding of the process and to obtain optimal values of Process parameters.

4.1.2 Scope of investigation

The scope of present investigation in terms of material, response characteristics and process parameters is presented below:

4.1.3 Materials: The investigation is planned to study **Aluminium 6061 alloy**, which finds wide application in the automobile industry because of its good mechanical properties and light weight.

4.1.4 Process parameters: Following five process parameters planned (at three levels) are to be studied:

1. Tool pin profile (circular, square, triangular)
2. Tool rotational speed (RPM)
3. Dwell time (sec)

4.1.5 Response characteristics: Following three response characteristics are decided to be studied:

1. Lap shear tensile load (N)
2. Micro hardness (HV)
3. Microstructure

4.2 GAPS AND OPPORTUNITIES

The literature review in the previous section reveals the following gaps for research in the area of consideration:

- The effect of tool rotational speed on weld quality characteristics (QCs) is not well known. Researchers have different opinion on the effect of tool rotational speed on the mechanical properties of the FSSW weld. Hence, extensive investigation is required to study the effect of tool rotational speed on FSSW QCs.
- Literature reveals that pin profile is the most influencing process parameter in FSSW. Researchers have worked on different pin profiles but still further study on effect of pin profile on FSSW weld quality is required. Most of the previous investigation work is concentrated on cylindrical and triangular pin. More tool pin profiles need to be studied, which may lead to better output performance parameters.
- Dwell time is least studied parameter in the literature. Nevertheless, it is contributing in heat generation which ultimately decides the quality of FSSW weld. Therefore dwell time should be further investigated to establish its effect on FSSW process.
- Application of FSSW is mostly concentrated on Aluminium and its alloys. FSSW finds very little application when it comes to other competitive materials.
- The effect of tool material is hardly mentioned in the literature.

- Various researchers have supported the practical and cost effective friction stir spot welding process for the welding of Aluminium alloys. Yet, the manufacturing and technical problems related with FSSW results defects.
- Post weld machining is least investigated by the researchers. The aesthetics of the weld are not at all discussed. However, it might raise the overall cost and complexity of the process.
- The performance of the friction stir spot weld at elevated as well as cryogenic temperatures has not been reported in the literature.
- The use and effect of coolant in the process of FSSW has not been investigated.

1)-The above stated gaps generate opportunities to carry out research in the development of FSSW Process:

2)-The design and development of techniques for the implementation of FSSW is an area wide open to be explored.

3)-The joining of Aluminium alloys by FSSW established its superiority in terms of simple and cost effective method. Therefore, FSSW can be prospective area for joining of Aluminium alloys.

4)-The application of FSSW as a joining process should defend the economics and its practicality. Therefore, development of FSSW process is another area of interest for researchers while maintaining its simplicity and cost effectiveness to produce sound welds.

5)-Study of the effect of process parameters for the joining of materials by FSSW can be investigated.

6)-The effect of tool material on the process of FSSW can be investigated. The tools can be heat treated and used for FSSW.

7)-State of the art FSSW machinery could be developed at low costs.

8)-Post weld machining to cover up the hole can be investigated and developed.

9)-The performance of FSS welded materials at elevated as well as cryogenic temperatures can be studied. This will give find applications in power plant boilers, engines, space shuttles, high altitude appliances etc.

10)-The effect of coolant on the weld performance can be studied.

CHAPTER 5

OBJECTIVE OF STUDY

5.0 OVERVIEW

This chapter aims to study about the objective of our research work which can be done furtherly .This chapter contains only one section which tells about the work can be done in the thesis work by significant manner.

5.1 OBJECTIVES

- To develop an arrangement for the defect free welding of Aluminium 6061 alloy plates by FSSW incorporating different process parameters.
- To observe and characterize the developed weld by stereo microscope.
- To conduct the mechanical strength tests on the welded plates to ascertain the benefits (if any) of FSSW process as compared to other conventional spot welding processes.
- To study the effect of heat in different heat affected zones by studying micro hardness profile of weld section.
- Experimental investigation using design of experiments for understanding weld strength behaviour of the welded Aluminium 6061 alloy to determine the tensile strength. These results can be used to establish the weld characteristics of the joined Aluminium plates.
- Optimization of FSSW process parameters for welding of Aluminium 6061 plates.

CHAPTER 6

EQUIPMENT AND MATERIALS

6.0 OVERVIEW

A systematic method to plan the experiments is requirement for efficient conduct of experiments. The planning of experiments is carried out by statistical design of experiments; subsequently factual statistics will be collected and investigated by statistical procedures resulting in effective and objective oriented inferences. Physical experimentation involves experimental errors and the statistical method is the only objectives approach to analysis these experimental results including errors. Therefore there are two phases of an experimental problem: experimental design and statistical analysis. These two facts are meticulously associated since the technique of analysis directly depends on the experimental design employed. The benefits of experimental design are as follows:

- Significant reduction in the number of trials
- Identification of process parameters that control and improve the performance of the product or process
- Optimum setting of the parameters can be found out
- Qualitative approximation of parameters can be made
- Experimental error can be projected

In current experimental investigation, the Taguchi's method has been used to conduct the experiments and consequently analysis of the collected data.

6.1 TAGUCHI EXPERIMENTAL DESIGN AND ANALYSIS

The Taguchi methodology for performing experimentation and its analysis is used in this research. Following steps are used for the experimental design and analysis:

6.1.1Selection of orthogonal array (OA)

The following information is required for the appropriate selection of OA:

- Selection of process parameters and/or interactions to be evaluated

- Selection of number of levels for the selected parameters

The determination of parameters to be investigated hinges upon the product or process performance characteristics or response of interest (Ross, 1988). The brainstorming, flow charting, cause-effect diagram are some methods suggested by Taguchi for determining the parameters to be included in the experiment. Three parameters and their three levels are used here for the experimental design. The parameters used are Tool rotational speed, Tool geometry and Dwell time. Taguchi method based design of experiment**,** L_9 (3^3) orthogonal array was used for experimental investigation. The total degree of freedom of an experiment is a direct function of total number of trials. If the number of levels of a parameter increases, the DOF of the parameters are also increases because the DOF of a parameter is the number of levels minus one. **Table 6.1** represents L_9 (3^3) orthogonal array was considered for experimentation.

Table 6.1: L_9 (3^3) orthogonal array

Expt. No	**Column**		
	1	2	3
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

6.1.2 Experimentation and Data Collection

The experiment is performed against each of the trial conditions of the inner array as shown in **Table 6.1**. Each experiment at a trial condition is repeated simply (if outer array is not used) or according to the outer array (if used). Randomization should be carried to reduce bias in the experiment.

6.1.3Methodology used for Parametric Optimizations

Taguchi's widespread classification of quality engineering is one of the premier engineering accomplishments of the 20th century. Taguchi's approach emphasis on the effective application of engineering tactics instead of advanced statistical methods. It contains both upstream and shop floor engineering. Upstream methods proficiently use small scale trials to decrease inconsistency and remain economical, and robust designs for large scale production and market place. Shop floor methods offer cost based, real time approaches for observing and conserving quality in manufacturing. The farther upstream a quality method is applied, the greater influences it creates on the enhancement, and the more it decreases the price and time. Taguchi's viewpoint is originated on the subsequent three very simple and important ideas [Ross, 1988; Roy, 1990]:

- Quality should be designed into the product and not inspected into it.
- Quality is best achieved by minimizing the deviations from the target. The product or process should be so designed that it is immune to uncontrollable environmental variables.
- The cost of quality should be measured as a function of deviation from the standard and the losses should be measured system wide.

Dr. Taguchi has combined two components such as desirable and undesirable into one performance measure called as Signal to Noise (S/N) ratio. There are three categories of quality characteristic such as Smaller-the better, Normal-the best and Larger-the better.

The S/N ratio is used to measure the quality characteristics and it is also used to measure the significant machining parameters through Analysis of Variance (ANOVA) and "F" test value.

6.1.4 Larger-the-better principle

In micro cutting, material removal is considered as the quality characteristics based on the summary statistics of the lager-the better principle. The summary statistic, η (dB) of the lager-the better performance characteristic is expressed as follows:

$$\eta = -10.\log_e\left[\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right] \quad I = 1, 2, \ldots\ldots\ldots n; \qquad \textbf{(6.1)}$$

Where, η is the S/N ratio in dB,

n is the number of replication of i^{th} experiments,

y_i is the response value or quality characteristics at i^{th} experiments.

The Lap Shear Strength is calculated utilizing the above mathematical relation **Eq. 6.1.**

6.1.5 Smaller-the better principle

In micro cutting, spark gap width is considered as the quality characteristics based on the summary statistics of the smaller-the better principle. The summary statistic, η (dB) of the smaller-the better performance characteristic is expressed as follows:

$$\eta = -10.\log_e\left[\frac{1}{n}\sum_{i=1}^{n}y_i^2\right] \quad I = 1, 2, \ldots\ldots\ldots n; \qquad \textbf{(6.2)}$$

Where, η is the S/N ratio in dB,

n is the number of replication of i^{th} experiments,

y_i is the response value or quality characteristics at i^{th} experiments.

6.2 TOOL MATERIAL AND DESIGN

In this thesis, different tool designs have been used for the welding of Aluminium 6061 alloy. Three high carbon high chromium (HCHCr) steel tools having hardness of 270 HV were manufactured based on the Taguchi's experimental design. The tools were fabricated on a heavy duty lathe machine using carbides inserts. The tool material selection was based on the literature review. The salient features of HCHCr steel tool are that it is very easy to machine into the desired geometry using solid carbide tools and its hardness is almost four times of the Al alloy plates to be welded. The parameters that were considered for tool design are tool shoulder diameter, tool pin diameter and tool pin profile. The tool shoulder diameter was taken as 12 mm, tool pin diameter 6 mm and profiles are circular, triangular and square.

The chemical composition, mechanical and thermal properties of HCHCr steel are presented in the **Table 6.2** and **Table 6.3** respectively.

Table 6.2: Chemical composition of HCHCr steel

Component		**C**	**Si**	**Mn**	**P**	**S**	**Cr**	**W**	**V**	**Ni**	**Cu**	**Fe**
Wt. %	**Max.**	2.18	0.60	0.60	0.03	0.03	12.25	1.00	1.00	0.30	0.25	Bal

Table 6.3: Mechanical and thermal properties of HCHCr steel

Density (g/cm^3)	**Poisson's Ratio**	**Modulus of Elasticity (GPa)**	**Thermal Expansion (10^{-6}/ ^{0}C)**
7.7	0.27-0.30	190-210	12

Schematic diagrams of tools used in the experiment are shown in following figures

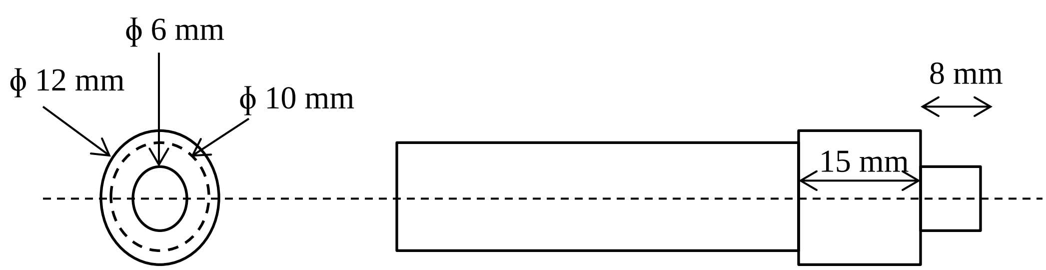


Fig. 6.1: Schematic diagram of tool with circular pin of 8 mm diameter and a shoulder diameter of 12 mm

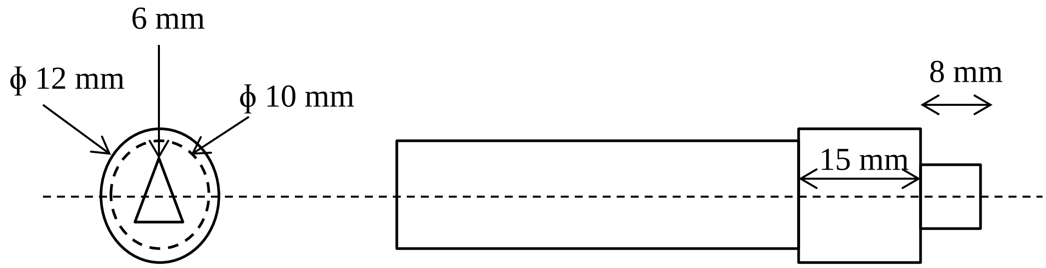


Fig.6.2: Schematic diagram of tool with triangular pin of 8 mm diameter and a shoulder diameter of 12 mm

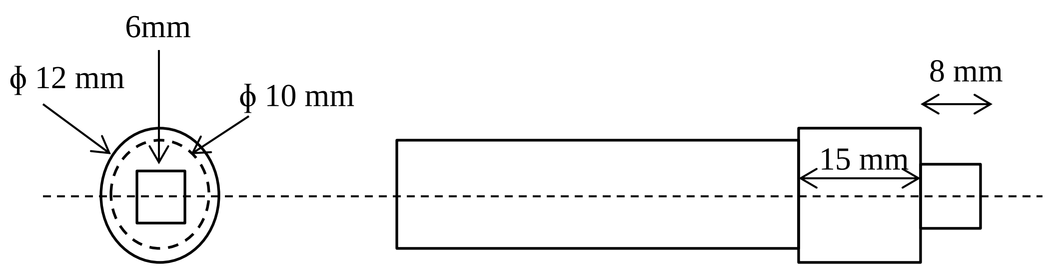


Fig. 6.3: Schematic diagram of tool with square pin of 8 mm diameter and a shoulder diameter of 12 mm

Fig. 6.4: Actual image of tool with triangular, square & circular pin of 8 mm diameter and a shoulder diameter of 12 mm

The hardness of the tool material was examined on Vickers micro-hardness tester: HV-1000B; as shown in figure 6.5. The tool material hardness value is 270 HV. This value is calculated by taking the average of three values. The hardness values were examined at 1000gf load and a dwell time of 10 seconds.

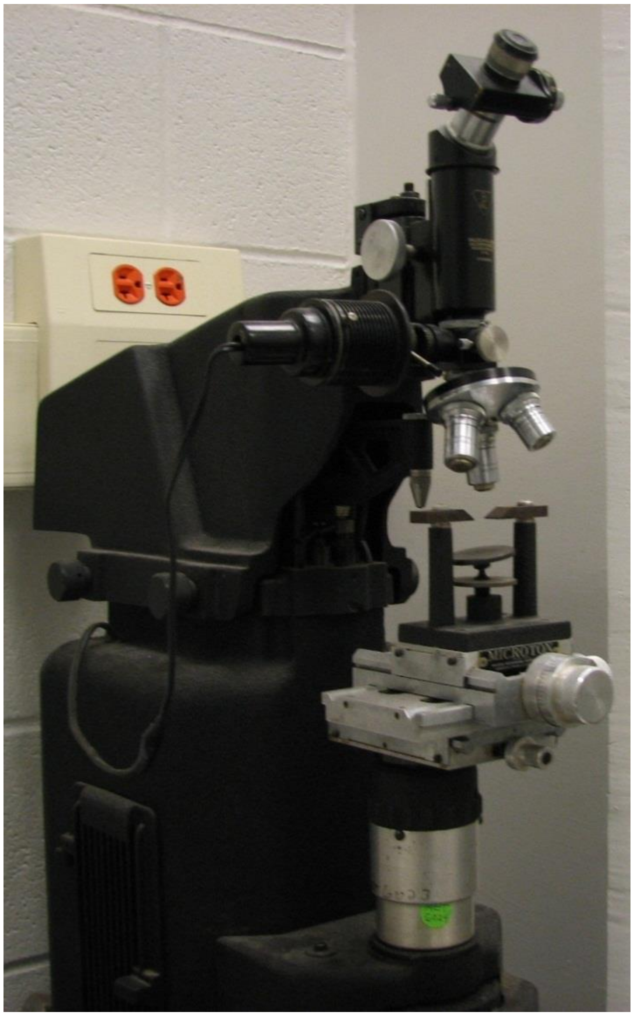


Fig. 6.5: Micro hardness tester HV-1000B

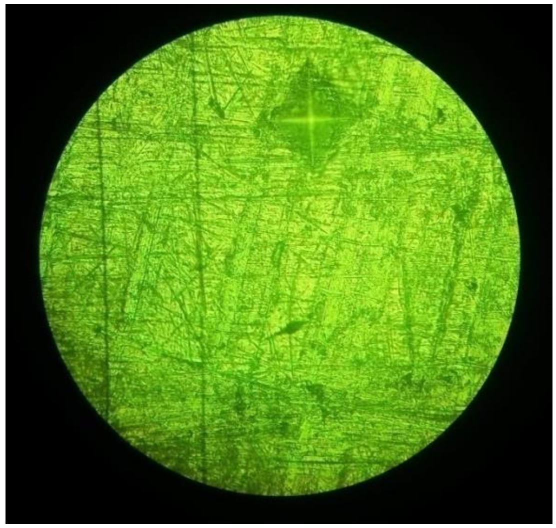


Fig. 6.6: Micro hardness spot of the tool material

6.3 WORKPIECE MATERIAL AND DESIGN

Aluminium 6061 plates of 6 mm thickness are used in the study for joining of similar materials. Aluminium is selected for study because of its wide application almost everywhere. Some of the many uses for Aluminium metal are in:

- Transportation
- Packaging
- Construction
- Electrical transmission lines for power distribution
- Street lighting poles
- Sailing ship masts
- Heat sinks for electronic appliances such as transistors and CPU's

The surface hardness of Al 6061 plates was examined on Vickers Micro hardness tester HV-1000B. The hardness value on the surface is 50.7 HV. This value was arrived at by averaging three values taken at different point on the plate surface. The chemical composition, mechanical and thermal properties of Aluminium 6061 are presented in the **Table 6.4 and Table 6.5** respectively.

Table 6.4: Chemical composition of Aluminium 6061 alloy

Component		Al	Cr	Cu	Fe	Mg	Mn	Si	Ti	Zn	Other	Other Total
Wt. %	Min.	95.8	0.04	0.15		0.8		0.4				
	Max.	98.6	0.35	0.4	0.7	1.2	0.15	0.8	0.15	0.25	0.05	0.15

Table 6.5: Mechanical and Physical properties of Aluminium 6061 alloy

Modulus of Elasticity (GPa)	68.9
Tensile yield strength (MPa)	276
Ultimate tensile strength (MPa)	310
Elongation (%)	12
Poisson's Ratio	0.33
Fatigue strength (MPa)	96.5
Density (g/cm^3)	2.7
Electrical resistivity (ohm-cm)	3.99e-006
Thermal conductivity (W/m-k)	167
Melting range (^{0}C)	582-652
Specific heat capacity (J/g-^{0}C)	0.896
Hardness (HRB)	60

For the tensile test the plates with following dimensions were prepared: 100mm * 15mm with a 40mm * 15 mm overlap area. The plates were cut off from a big rectangular rod of 6mm thickness. **Figure 6.7** shows the schematic view of Al 6061 plated and **Figure. 6.8** shows schematic diagram of lap joint configuration of Al plates.

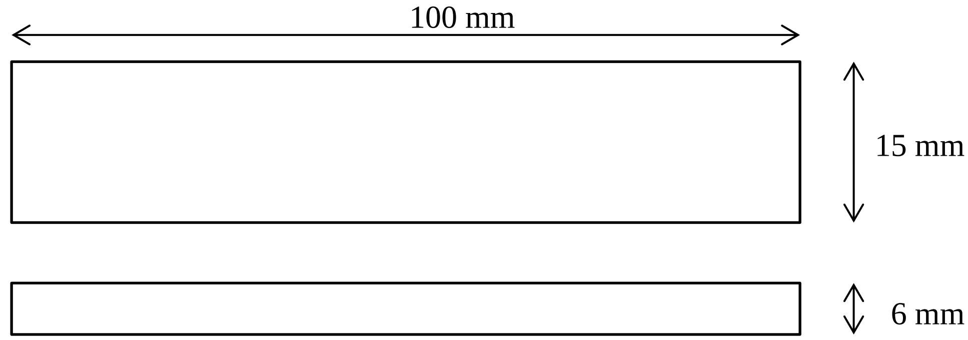


Fig. 6.7: Schematic diagram of Aluminium 6061 plates

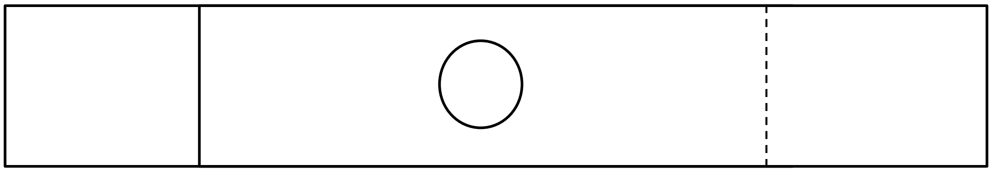


Fig. 6.8: Configuration of a lap shear test specimen

6.4 CNC VERTICAL MILLING MACHINE

A heavy duty HAAS CNC vertical milling machine is used to for joining of Al 6061 plates in the lap configuration using the friction stir spot welding process. This Vertical Machining Center has an dimension of 762 x 406 x 508 mm, 22.4 kW vector drive, 400-8100 rpm, inline direct-drive, 20-station carousel tool changer, 25.4 m/min rapid travel, power-failure detection module, USB port, 1 GB program memory, 15" color LCD monitor, memory lock key switch, rigid tapping and 208 liter flood coolant system. The machine is shown in the **fig.6.9.**

Fig. 6.9: CNC vertical milling machine

6.5 TESTING MACHINES

The welded samples were tested for lap shear tensile strength, micro-hardness and macrostructure.

6.5.1 Lap shear tensile load testing

Instron dual column floor model (5900 series) system for high capacity testing was used for the lap shear tensile load testing. The capacity of the machine used is up to 600 kN. It has robust, heavy-duty frames for the most demanding applications. It is commonly used for high-strength metals and alloys, advanced composites, aerospace and automotive structures, bolts, fasteners and plate steels. The 5900 series universal testing instruments offer exceptional performance and are designed with enhancements that deliver unparalleled accuracy and reliability, improved ergonomics and an enhanced overall experience for the operator.

The most common uses of these mechanical testing systems are for tensile, compression, bend, peel, shear, tear and cyclic tests. Configured systems are fully capable of meeting test requirements as per ASTM, ISO, DIN, TAPPI, GB, JIS, ANSI, NAS etc. **Fig. 6.10 and fig. 6.11** shows testing machine and specimen holding.

The control panel is an integral component of the testing system, decreasing set up time and increasing testing efficiency through the use of programmable live displays and soft keys. Tests can be set up and run directly from the control panel. Instron testing instruments are routinely found in applications and industries such as plastics, metals, composites, elastomers, components, textiles, aerospace, automotive and biomedical.

Fig. 6.10: Instron tensile load testing machine

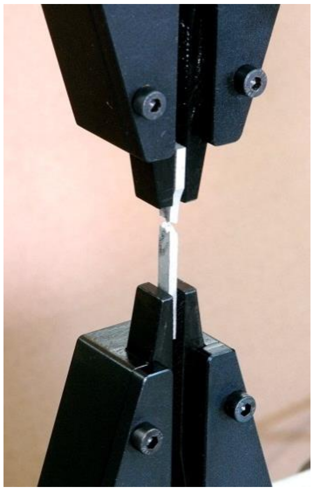


Fig. 6.11: Sample with machine clamps

6.5.2 Microhardness testing

The micro hardness testing of all the samples is done in order to examine the variation of hardness across the welded region.

Samples are prepared by using hand hacksaw in order to cut down the samples. After cutting down the samples, each sample is polished by using emery papers of different scales to remove the scaling and scratches. After removig all the scratches samples were then polished with the help of velvet cloth and brasso solution in order to produce mirror like finish. The readings are taken at a distance of 1 mm across the welded region.

HV-1000B micro hardness tester (as shown in fig. 6.5) was used for micro hardness testing of the welded samples. It is suitable for testing the Vickers or Knoop hardness of micro metal parts, thin plates, metallic foil as well as hardened layer. It can also be used for metallographic microscpoe to observe the organization and structure of material.

The diamond pyramid indenter is penetrated into the surface of the specimen tested under certain test forces which shall be removed after retaining for certain period of time. After measuring the length of the diagonal lines of the indentation the hardness value is calculated by the formula. The formula for calculation of hardness varies according to the shape of the indentor. Dwell time is taken as 12 seconds and the load applied is 300 gf. In case of micro-Vickers hardness tester the indenter should be rectangular pyramid whose two diagonal are 136^0 and the fromula is:

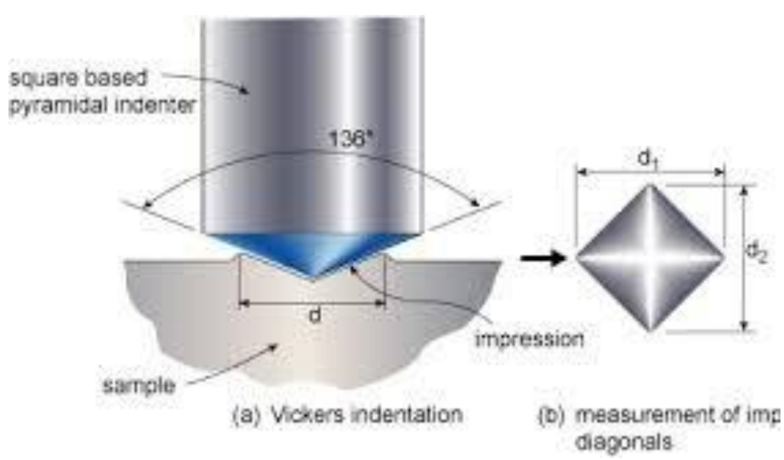


Fig. 6.12: Mark geometry for measurement of the hardness

$$HV = \frac{2\,F\,Sin\frac{136^0}{2}}{d^2}$$

$HV = 1.854\,\frac{F}{d^2}$ approxiametely

HV = symbol of mciro-Vicker hardness (Kgf/mm^2)

F = Test force applied on the specimen (Kgf)

D1 = Length of the diagonal line of indentation

D2 = Length of the diagonal line of indentation

6.5.3 Microstructure analysis

The microstructure of the welded specimen was observed using a Axio microscope. The model used in this study is ZESIS Axio Microscope **(Fig. 6.13).** Axio microscope is an optical tool differnet from other types in instrumentation and working principles. The regular device has one eyepiece and one objective lens. The objective of this lens configuration is to create a clearer three-dimensional image. A Axio is a binocular magnifying tool with different zoom capacity, used for viewing a three-dimensional (3D) image of the specimen. The samples broken after tensile test is checked by using this microscope.

Fig. 6.13: ZESIS Axio Microscope

CHAPTER 7

RESEARCH METHODOLOGY

7.0 OVERVIEW

This chapter we have describe the whole research work in brief manner as shown in figure.

Fig. 7.1: Research methodology

CHAPTER 8

EXPERIMENTAL WORK

8.0 OVERVIEW

This chapter is intended to discuss procedure followed during experimentation phase. This chapter enlightens about friction stir spot welding process parameters in detail and how they work in separate conditions like different speed ,feed and dwell time , also the tool geometry was altered.

8.1 INTRODUCTION

Welding is difficult and one of the costiliest processes in the fabrication of components from Aluminium and its alloys. It is because of the poor weldability of Aluminium and its alloys using conventioanl weldign processes. The surface penetration, oxide layer formation, thermal distortion, excessive heating of base material are some of the problems associated with welding of Aluminium and its alloys using traditional welding methods. FSSW is developing solid state welding process and is being progressively used to join Aluminium and its alloys. The output quality characteristics of FSS welds are governed by numerous input process parameters i.e. tool pin diameter, tool pin profile, tool shoulder diameter, tool shoulder features, tool rotational speed, dwell time and feed rate etc. the process parameters in FSSW can be broadly classified into wo categories: Machine parameters and Tool parameters.

8.1.1 Machine Parameters

The literature review reveals that the weld quality and strength substaintially depends on machine tool parameters such as tool rotational speed, feed rate etc. The machine used in present study is a heavy duty CNC vertical radial milling machine with RPM range of 400-8100, which can be varied between this range. The literature is ambiguoes on the effect of tool rotaional speed on FSSW output quality characteristics. Hence tool rotational speed was selected for the study to establish its effect on the FSSW performance in isolation as well as in interaction with other parameters. One-factor-at-time (OFAT) approach was used to select the working rage of tool rotational speed for present investigation. FSSW of Aluminium 6061 was attempted at different toll rotational sppeds, starting from 400 RPM. Output responses under consideration were gap between the plates, flash level and lap shear fracture load that the specimen can bear. Defects free welds were obtained at 900 RPM and hence it was selected as the lowest level for experimentation. Highest level of 2100 RPM was selected because beyond this value, problems of excessive vibration surfaced. Hence, 900 RPM, 1400 RPM and 2100 RPM were selected as three levels of the process parameters of toll rotational speed.

The literature review revels the effect of dwell time on weld strength obtained from FSSW. The dwell time was selected as a parameter because it is one of the major contributors of heat in FSSW and hecne requires extended research. OFAT approach was applied to select the levels of dwell time for expermentation. FSSW of Aluminium 6061 alloy was attempted using different dwell time starting from one second. It is basically depends upon the thickness of the plates to be weld. Good quality welds were obtained at a dwell time of 25 second. Hecne, three dwell times were taken for th investigations are 30, 45 and 60 second. The dwell times were noted normally using a stop watch.

8.1.2 Tool Parameters

In this research tool pin profile were studied in detail. Parameter is varied at three levels. so the tool pin profiles taken for this study are circular, square and triangular. As the literature suggests, tool geometry is the most important parameters for determining the FSSW performances. In most of the studies only the circular profile (with and without shoulder) has been used. In few studies triangular profiles were also used. The three controllable parameters and their chosen levels are given in **Table 8.1.**

Table 8.1: Process parameters and their levels

Sr. No.	Factors	Parameters Designation	Level 1	Level 2	Level 3
1.	Tool Profile	P	Circular	Square	Triangular
2.	Tool Rotational Speed	R	900 RPM	1400 RPM	2100 RPM
3.	Dwell Time	T	30 sec	45 sec	60 sec

8.2 FSSW EXPERIMENTATION

Experimentation begins with judicious selection of the Orthogonal Array (OA). Before selecting a particular OA for an experiment, information about the number of parameters (including interactions) and their number of levels is must. The OA selected must satisfy the following inequality:

Total DOF of the OA $\geq$ Total DOF required for the experiment

Since three parameters are selected for the study in which all the parameters are at three levels, the design becomes an equal level design. Drgree of freedom (DOF) corresponding to each parameter is 2. Hecne total DOF for all the three parameters taken together is 6. The selection of L_9 ($3^{3)}$ orthogonal array is 8. Assignment of factors has been done using the L_9 ($3^{3)}$ orthogonal array table as shown in **Table 8.2**. The final array with columns assigned is shown in **Table 8.3.**

Table 8.2: L_9 ($3^{3)}$ orthogonal array

Expt. No	Column		
	1	2	3
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

Table 8.3: L_9 ($3^{3)}$ orthogonal array used to adjust different parameters, their coded and actual values considered for experimentation

Expt. No	Parametric levels and their coded values			Parametric levels and their actual values		
	P	**R**	**T**	**P**	**R (RPM)**	**T (sec)**
1	1	1	1	**Square**	900	30
2	1	2	2	**Square**	1400	45
3	1	3	3	**Square**	2100	60
4	2	1	2	**Circular**	900	45
5	2	2	3	**Circular**	1400	60
6	2	3	1	**Circular**	2100	30
7	3	1	3	**Triangular**	900	60
8	3	2	1	**Triangular**	1400	30
9	3	3	2	**Triangular**	2100	45

8.2.1 Observation from visual inspection of fractures specimens

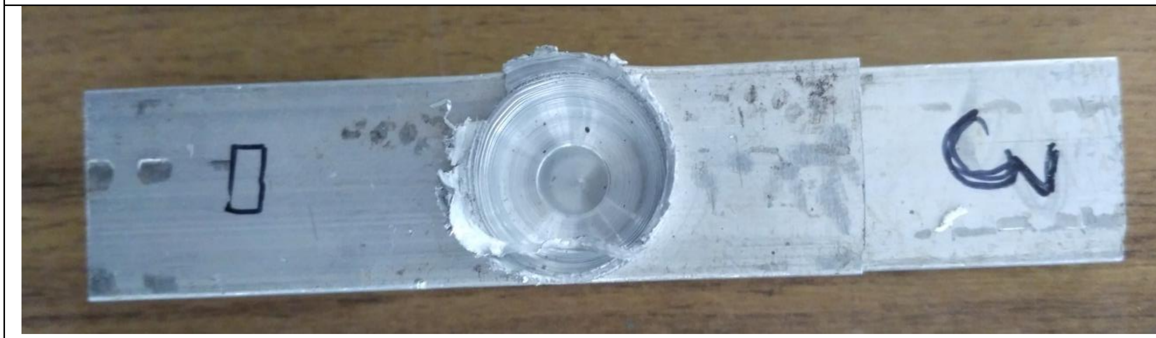
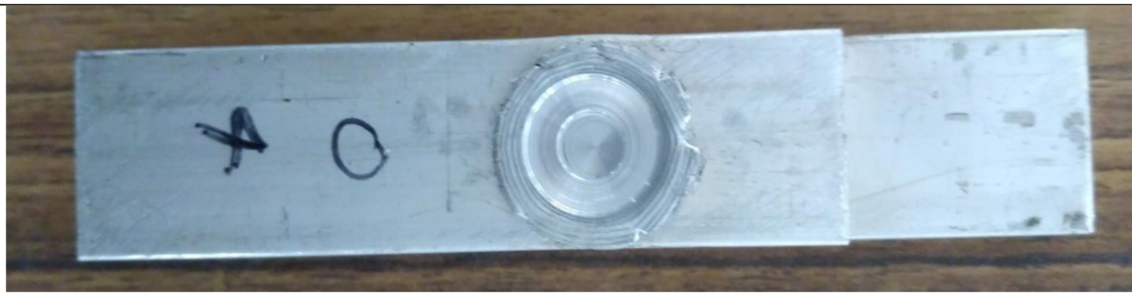
Visual inspection of fractured FSSW specimens (top and bottom views of upper sheet and top view of lower sheet) was carried out to check the level of flash generated. Flash is the volume of metal which is forced out of the working mass and gets accumulated around the weld. In FSSW, excessive flash is a problem because it invites costly post treatments. Observations from the visual inspection of fractured samples are shown in **Table 8.4.**

Table 8.4: Observations from fractured samples

Sr. No.	Parameters	Top view of top sheet	Top view of bottom sheet	Observations
1.	P= Square R= 900 RPM T= 30 sec			Flash level: Less
2.	P= Square R= 1400 RPM T= 45 sec			Flash level: Normal
3.	P= Square R= 2100 RPM T= 60 sec			Flash level: Excess
4.	P= Circular R= 900 RPM T= 45 sec			Flash level: Normal
5.	P= Circular R= 1400 RPM T= 30 sec			Flash level: Less
6.	P= Circular R= 2100 RPM T= 60 sec			Flash level: Excess
7.	P=			Flash level:

	Triangular R= 900 RPM T= 60 sec			Normal
8.	P= Triangular R= 1400 RPM T= 30 sec			Flash level: Normal
9.	P= Triangular R= 2100 RPM T= 45 sec			Flash level: Excess

Sr. No.	**FSSW Specimen**
1.	P= Square; R= 900 RPM; T= 30 sec 
2.	P= Square; R= 1400 RPM; T= 45 sec 

3.	P= Square; R= 2100 RPM; T= 60 sec 
4.	P= Circular; R= 900 RPM; T= 45 sec 
5.	P= Circular; R= 1400 RPM; T= 30 sec 
6.	P= Circular; R= 2100 RPM; T= 60 sec 
7.	P= Triangular; R= 900 RPM; T= 60 sec

	
8.	P= Triangular; R= 1400 RPM; T= 30 sec
	
9.	P= Triangular; R= 2100 RPM;T= 45 sec
	

The general observation from visual inspection of top view of top plate is that with higher tool rotational speed and greater dwell time and interaction between them generated excessive flash. This may be because of high heat input generated by high tool rotational speed and greater dwell time renders the workpiece material relatively softer. This leads to shoulder penetration into the upper plate of workpiece, which displaces material out of the weld in the form of flash. On the contrary, flash level is lesser at low rotational speed and smaller dwell time. Normal flash level was observed either at high tool rotational speed and less dwell time or vice versa.

CHAPTER 9

RESULTS AND DISCUSSIONS

9.0 OVERVIEW

This chapter is concluded all the results of mechanical and metallurgical properties of AL6061 alloys. This chapter elaborates different results obtained from tensile shear fracture load testing, micro-hardness analysis and macrographs of FSSW specimens. The effect of investigated process parameters on tensile shear fracture load has been discussed in detail. The observations from micro hardness analysis, visual inspection of fractured wels and macro graphs has been presented and discussed in detail.

9.1 FSSW RESULTS AND DISCUSSIONS

9.1.1 Results of Tensile shear fracture load

The tensile shear fracture load for the friction stir spot welded samples was measured on Universal (INSTRON) testing machine. The value of maximum tensile force applied on the sample before failure was recorded from the display of the machine and results are tabulated in **Table. 9.1.**

Table 9.1: Experimental results of tensile shear fracture load

Sr. No.	Parametric levels and their coded values			Specimen	Tensile Shear Fracture Load (kN)	S/N Ratio (dB)
1.	1	1	1	P= Square; R= 900 RPM; T= 30 sec	1812	65.1632
2.	1	1	1	P= Square; R= 1400 RPM; T= 45 sec	1645	64.3233
3.	1	1	1	P= Square; R= 2100 RPM; T= 60 sec	1523	63.6540
4.	2	2	2	P= Circular; R= 900 RPM; T= 45 sec	1932	65.7201

5.	2	2	2	P= Circular; R= 1400 RPM; T= 30 sec	1756	64.8905
6.	2	2	2	P= Circular; R= 2100 RPM; T= 60 sec	1658	64.3917
7.	3	3	3	P= Triangular; R= 900 RPM; T= 60 sec	2446	67.7691
8.	3	3	3	P= Triangular; R= 1400 RPM; T= 30 sec	2215	66.9075
9.	3	3	3	P= Triangular; R= 2100 RPM; T= 45 sec	2019	66.1027

Maximum tensile shear fracture load of 2446 kN was achieved for specimen of having friction stir spot welding at triangular tool profile, 900 RPM tool rotational speed and dwell time of 60 sec, whereas minimum tensile shear fracture load of 1523 kN was achieved for specimen of having friction stir spot welding at square tool profile, 2100 RPM tool rotational speed and dwell time of 60 sec. ANOVA was performed on raw data and results were obtained as shown in **Table 9.1 and Fig. 9.1** shows the effect of Process parameters on S/N ration and tensile shear fracture load **Fig. 9.2** shows the four in one graphs for the tensile shear fracture load data as shown in **Table 9.2.**

Table 9.2: ANOVA results for Tensile Shear fracture load

Sr. No.	**Parameters**	**DOF**	**SS**	**V**	**F-value**	**P-value**	**% Contribution**
1.	Tool Profile (X_1)	2	533724	266862	122.00	0.008	75.62
2.	Tool Rotational Speed (X_2)	2	164737	82368	37.66	0.026	23.34
3.	Dwell Time (X_3)	2	2907	1453	0.66	0.601	0.41
4.	Error	2	4375	2187			0.61
5.	Total	8	705742				
R^2 (Model) = 99.38 %							

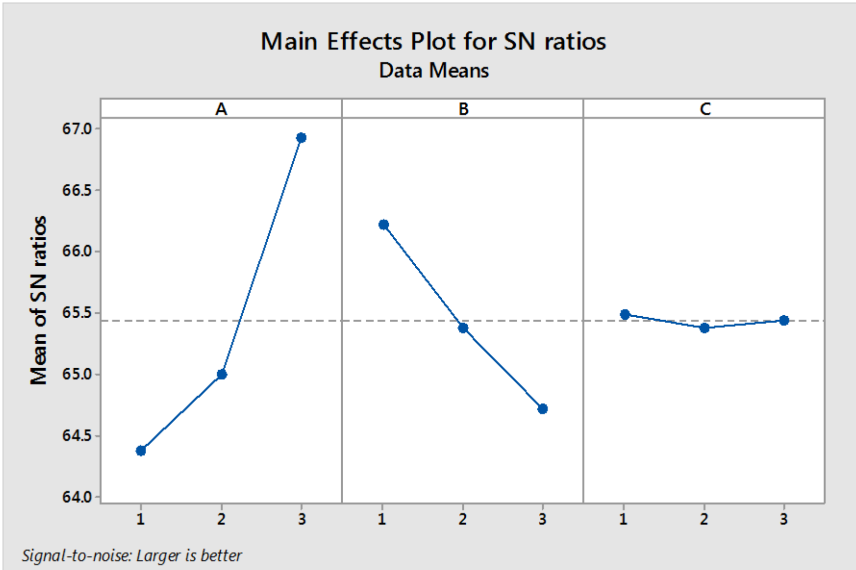


Fig. 9.1: Effect of Process parameters on S/N ration and tensile shear fracture load

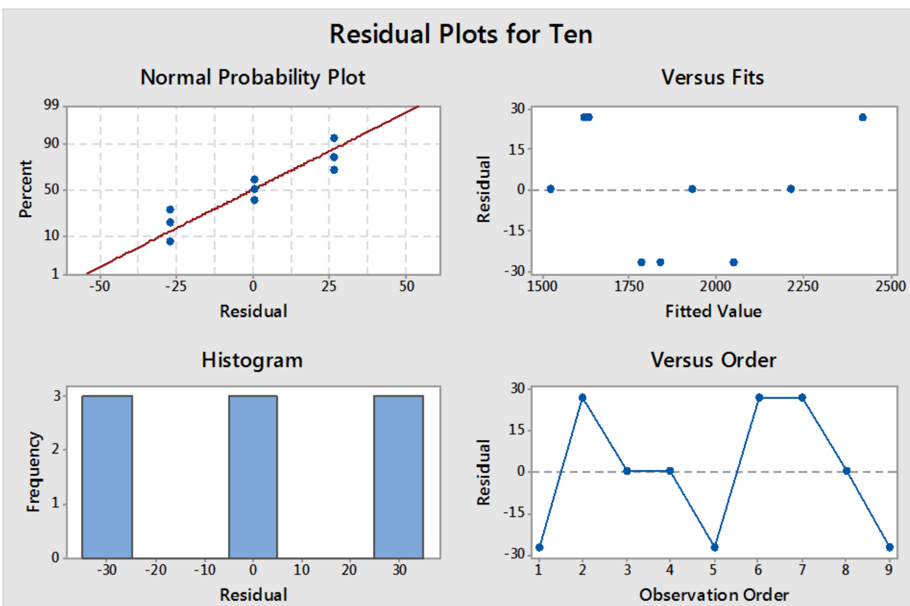


Fig. 9.2: Four in one graph for tensile shear fracture load

9.1.2 Effect of Tool Pin Profile on Tensile Strength

Three tool pin profiles were investigated in present study. The profiles chosen for experimentation were square, circular and triangular. As can be seen from the **Table 9.1** maximum tensile strength is achieved with triangular pin tools. Badarinarayan et. al. (2009) concluded that static strength of welds made with triangular pin is twice as compared to welds made with cylindrical pin tool. Tensile strength is less for square pin tool later on increases for circular pin tool and is reached maximum for the rectangular pin tool. Welds made with rectangular pin tools were the weakest. ANOVA of the tensile shear fracture load revels that the percentage contribution of tool pin profile for tensile shear fracture load is 75%, which makes it most significant input parameters for friction stir spot welding affecting tensile shear fracture strength.

9.1.3 Effect of Tool Rotational Speed on Tensile Strength

In the present investigation, three levels of tool rotational speed that were studied are 900 RPM, 1400 RPM and 2100 RPM. From the **Table 9.1** it can be easily understood that the maximum tensile strength was obtained at low tool rotational speed. As there is any increase in tool rotational speed the tensile shear fracture strength of the specimen is decreased. Maximum tensile strength was achieved at lowest level of tool rotational speed i.e. 900 RPM. It was also observed that the effect of tool rotation speed is more at lower speeds whereas the effect is considerably less at higher tool speeds. ANOVA of the tensile shear fracture load revels that the percentage contribution of tool rotational speed for tensile shear fracture load is 23%, which makes it second most significant input parameters for friction stir spot welding affecting tensile shear fracture strength.

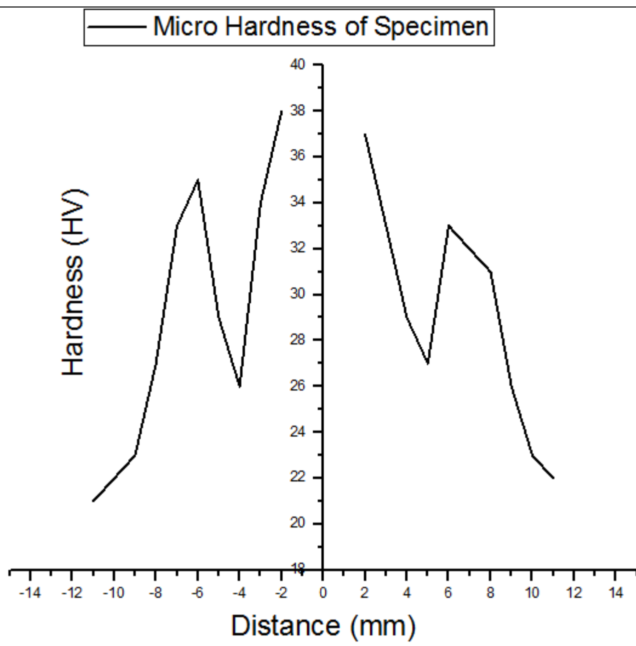
9.1.4 Effect of Dwell Time on Tensile Strength

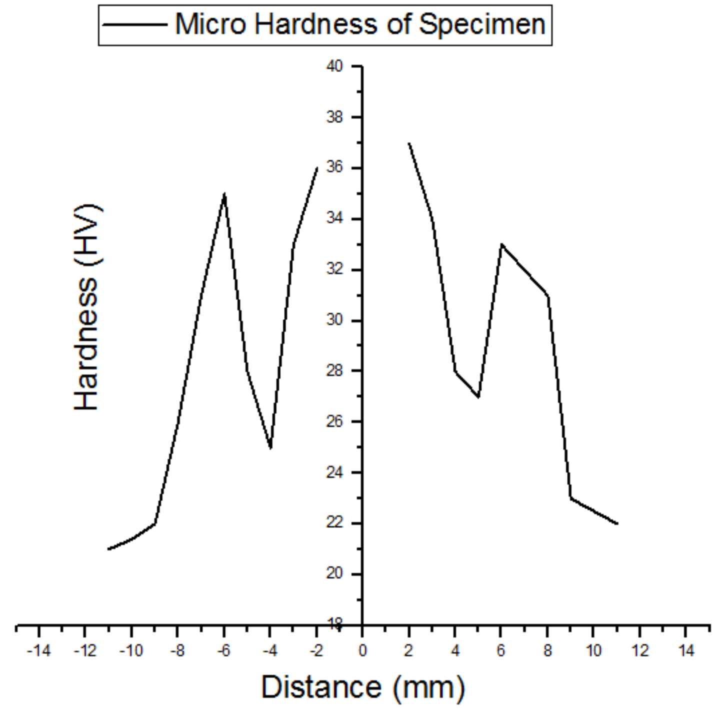
Literature reveals that dwell time is the least studied FSSW input process parameter. It is major contributor of heat input in FSSW process. Therefore its effect on FSSW process output quality characteristics was explicitly investigated. The effect of dwell time on the tensile shear fracture load is least of all the input process parameters. ANOVA of the tensile shear fracture load revels that the percentage contribution of dwell time for tensile shear fracture load is 0.4%, which makes it least significant input parameters for friction stir spot welding affecting tensile shear fracture strength. Tensile shear fracture load increases almost insignificantly with increase in dwell time.

9.1.5 Results of Micro Hardness

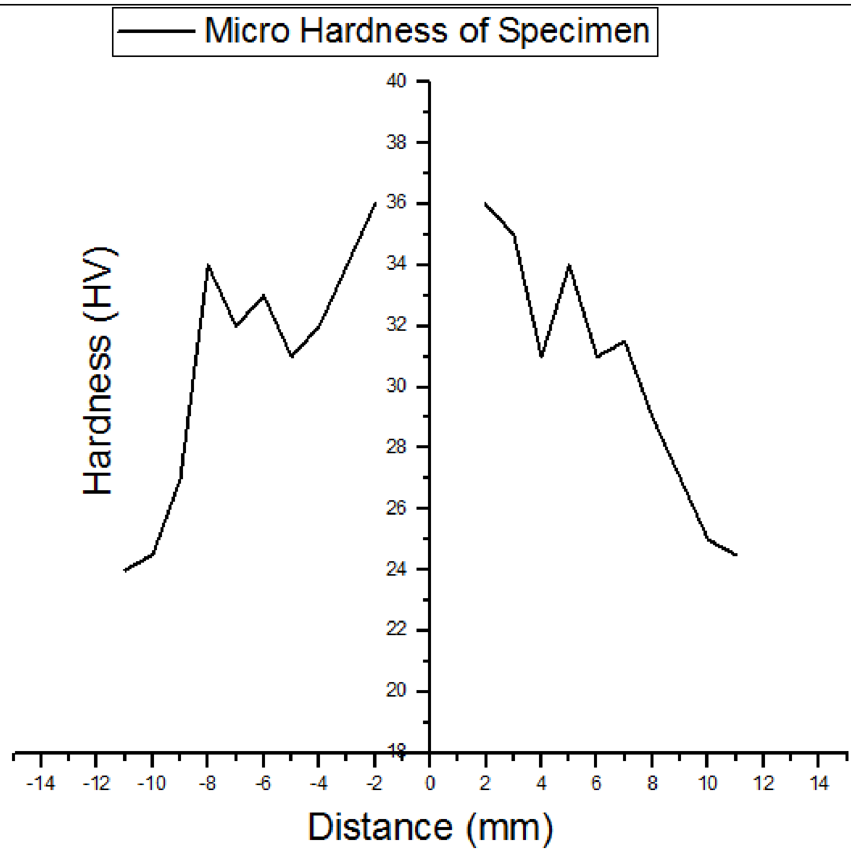
The hardness across the cross section of the weld (along the width) was measured using Micro Hardness Tester HV-1000B. The specimen cut along its weld zone for micro hardness testing. The testing was conducted using indentation load of 300 gf and a dwell time of 12 seconds. The readings were taken for the upper plate and were recorded at an interval of 1 mm on both sides of the weld hole. The readings were taken at mid thickness of upper plate i.e. 3mm from top of plate. Scatter graphs were plotted from data obtained from this testing. The different micro hardness graphs are shown below in **Table 9.3.**

Table 9.3: Different Micro Hardness graphs for Specimen

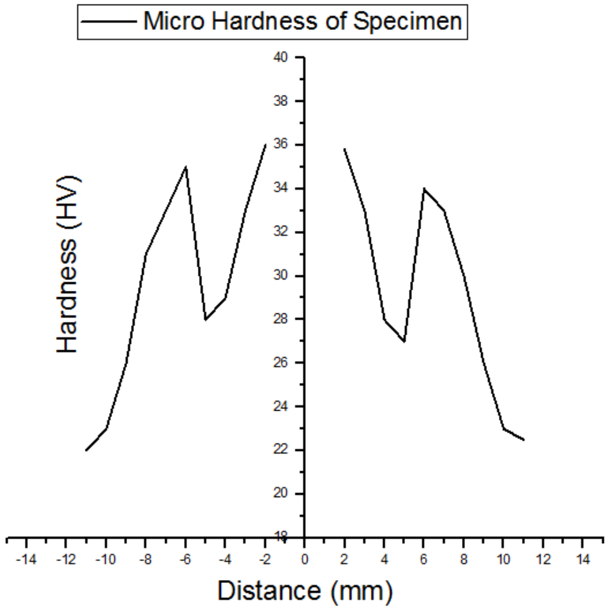
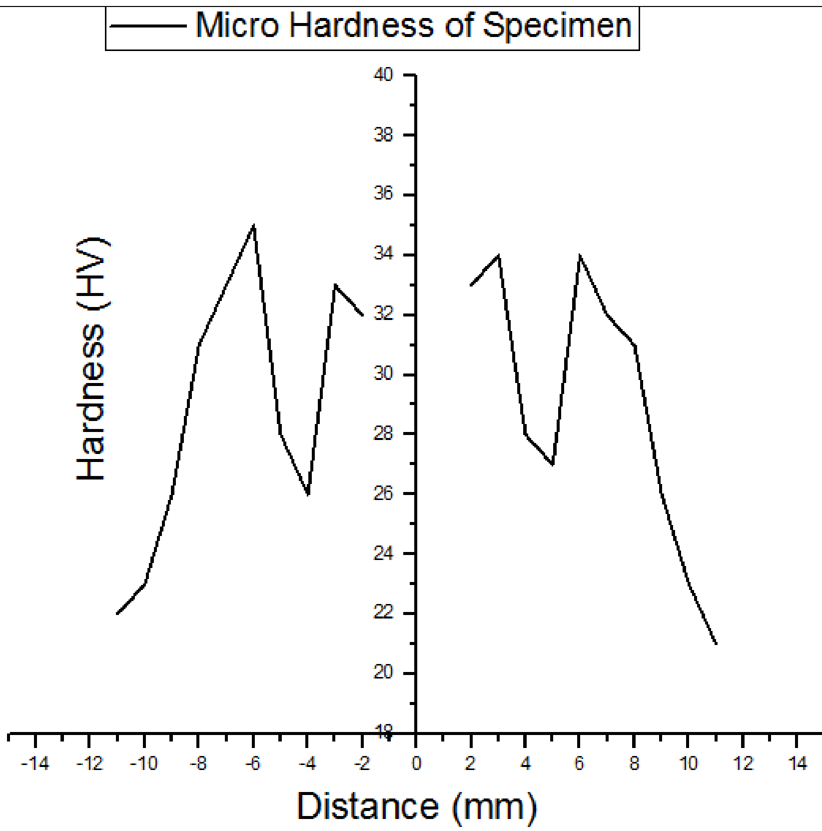
Specimen

P= Square; R= 900 RPM; T= 30 sec

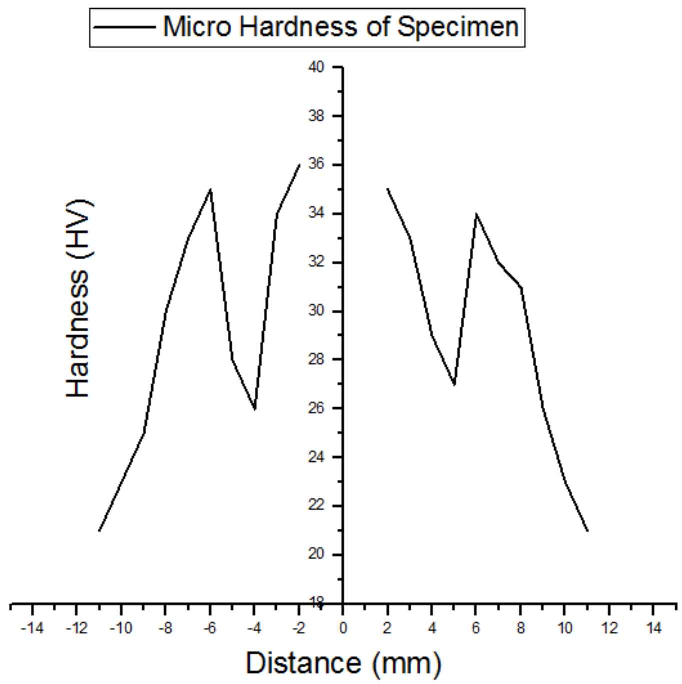


P= Square; R= 1400 RPM; T= 45 sec

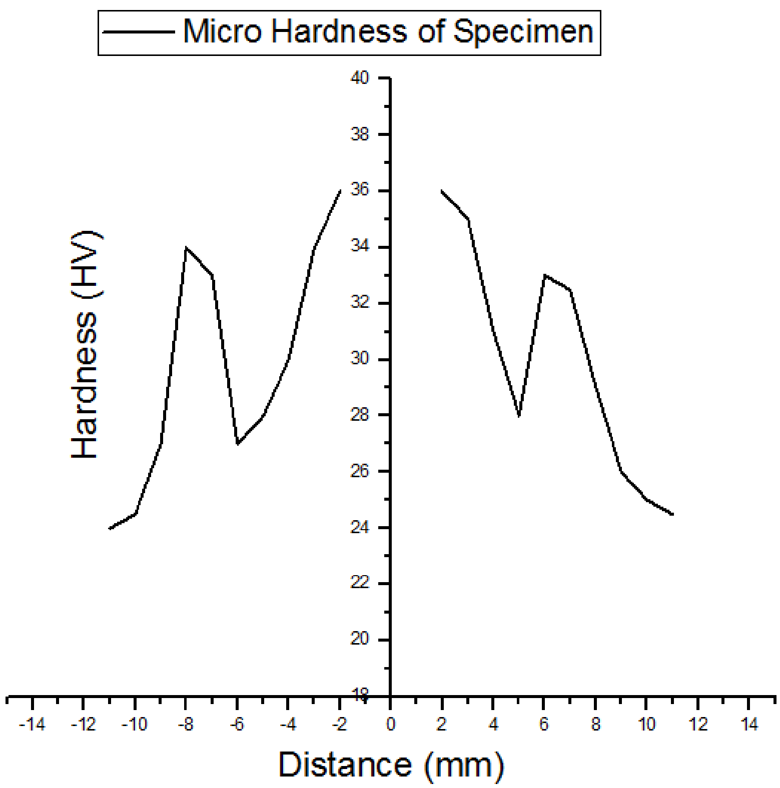


P= Square; R= 2100 RPM; T= 60 sec

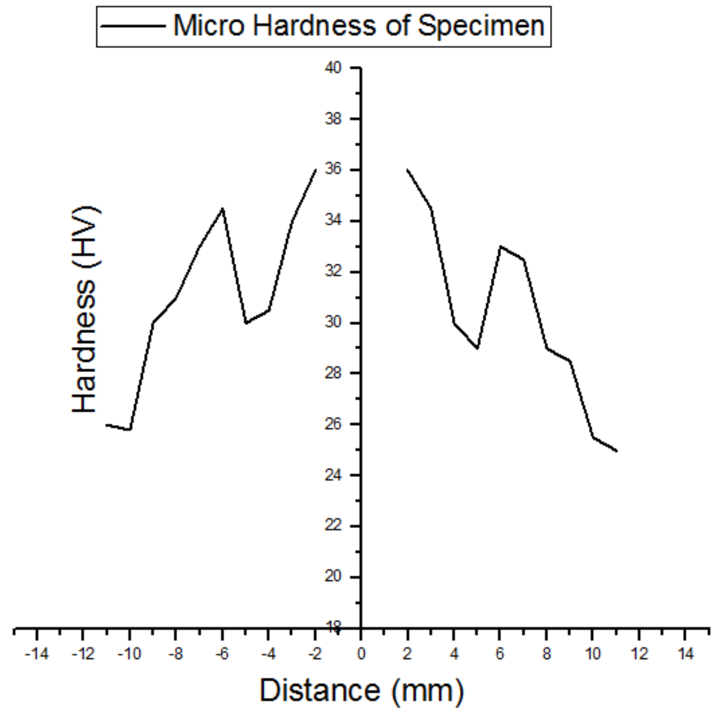

P= Circular; R= 900 RPM; T= 45 sec

P= Circular; R= 1400 RPM; T= 30 sec



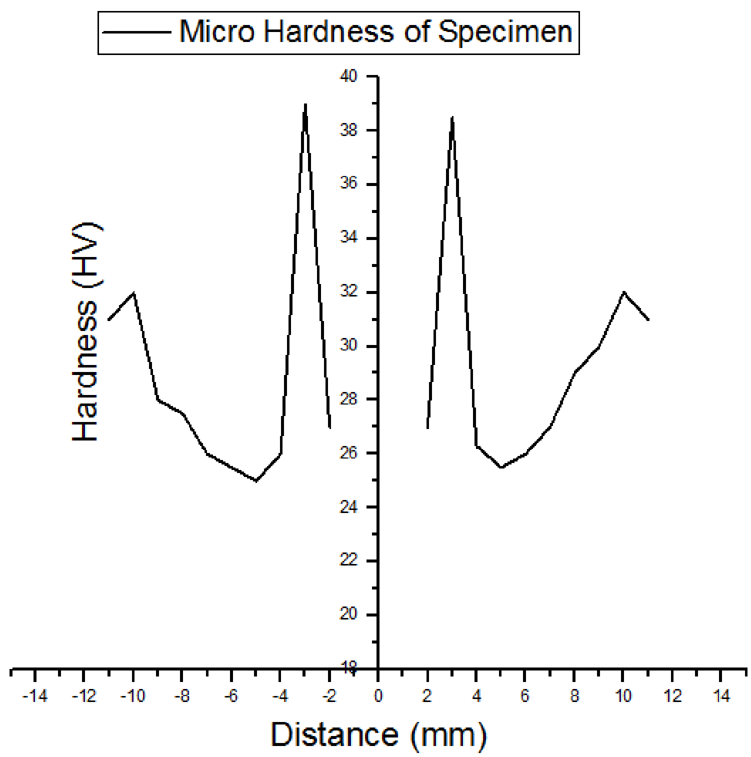
P= Circular; R= 2100 RPM; T= 60 sec



P= Triangular; R= 900 RPM; T= 60 sec



P= Triangular; R= 1400 RPM; T= 30 sec



P= Triangular; R= 2100 RPM; T= 45 sec

9.1.6 Effect of Process Parameters on Micro Hardness

The Vickers hardness profiles in the mid thickness of the upper plate of specimens are shown in **Table 9.3**. According to the profile of Vickers hardness, the distribution of Vickers hardness was found to be more or less symmetric with respect to the center of keyhole of the welds made at all given processing parameters. The Vickers hardness profile of the specimens showed a W-shaped appearance. The welds have higher Vickers micro hardness in the stir zone than the base material. The hardness value is highest in the stir zone, in the vicinity of the weld keyhole. Hardness value first decreases while moving away from the stir zone and then again increases after some distance. Hardness value starts to stabilize after 10 mm from the weld center. Maximum value of Vickers hardness is 39 HV which is for weld joint by triangular Tool pin profile, tool rotational speed 2100 RPM and dwell time of 45 sec.

9.1.7 Results of Micro Structure Testing

The microstructure of the welded specimen was observed using a Axio microscope. The model used in this study is ZESIS Axio Microscope as shown in **Fig. 6.13.** the aim of microscopic investigation was to study the breakage of specimen after tensile testing and study their behaviour.

(a) Square Tool Profile | **(b) Circular Tool Profile** | **(c) Triangular Tool Profile**

Fig. 9.3 Micro Structure of Specimen broke after Tensile Testing

Fig. 9.3 shows the micro structure of friction stir spot welded specimen after broken out by tensile testing. From **Fig. 9.3(a)** this specimen is welded by using square tool and easily seen the ductile fructure on the welded edge of the specimen. **Fig. 9.3(b)** this specimen is welded by using circular tool and it is easily seen from the figure that edge having less surface damage. **Fig**.

9.3(c) this specimen is welded by using triangular tool and it is easily seen that fracture is very bad, because welding by triangular tool is very good so it requires higher tensile force for weld breaking.

Fig. 9.4 shows the micro structure of friction stir spot welded specimen top sheet welded with the square tool at 1400 RPM rotational speed and 45 sec dwell time. As form **fig. 9.4** it is cleary seen that the weld edge is quite rough with higher surface irrugalarities.

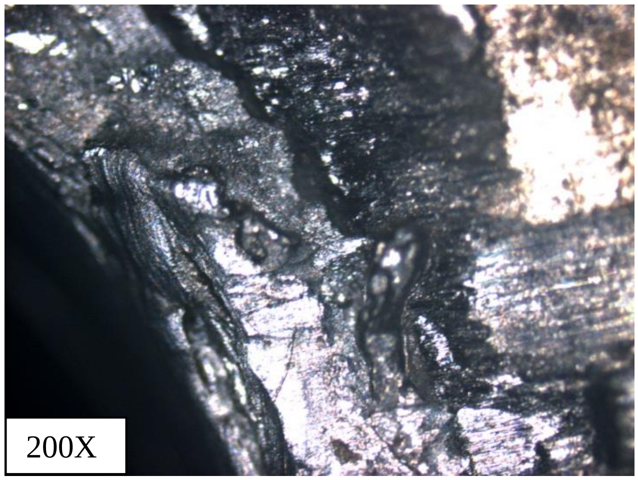


Fig. 9.4 Micro structure of FSSW with square tool at 1400 RPM rotational speed and 45 sec dwell time

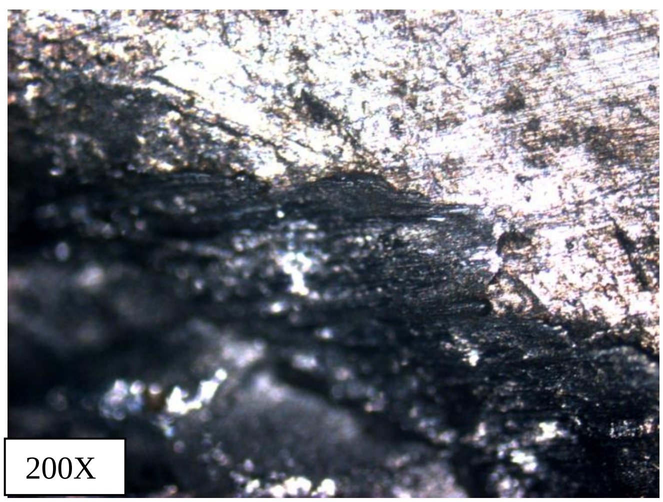


Fig. 9.5 Micro structure of FSSW with circular tool at 1400 RPM rotational speed and 45 sec dwell time

Fig. 9.5 shows the micro structure of friction stir spot welded specimen top sheet welded with the circular tool at 1400 RPM rotational speed and 45 sec dwell time. As form **Fig. 9.5** it is cleary seen that the weld edge is quite smooth with very less surface irrugalarities.

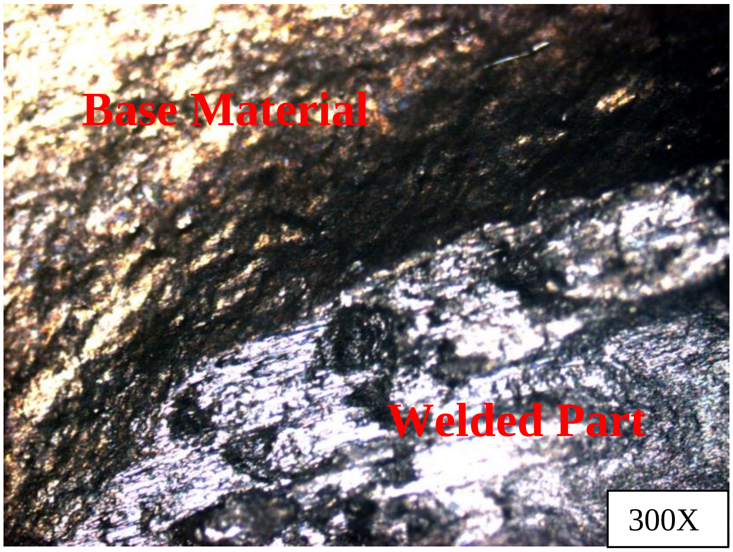


Fig. 9.6 Micro structure of FSSW with square tool at 900 RPM rotational speed and 45 sec dwell time

Fig. 9.6 shows the micro structure of friction stir spot welded specimen top sheet welded with the square tool at 900 RPM rotational speed and 45 sec dwell time. As form **Fig. 9.6** it is cleary seen that the welded part micro structure is changed from the base material, it is because of the force and heat generated during the welding.

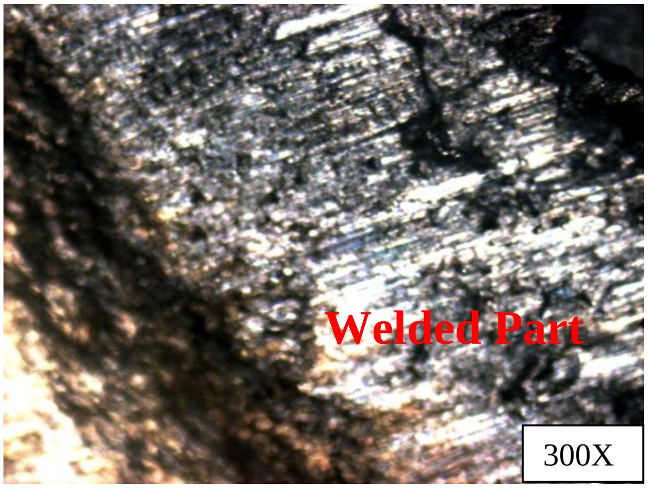


Fig. 9.7 Micro structure of FSSW with circular tool at 900 RPM rotational speed and 45 sec dwell time

Fig. 9.7 shows the micro structure of friction stir spot welded specimen top sheet welded with the circular tool at 900 RPM rotational speed and 45 sec dwell time. As form **Fig. 9.7** it is cleary seen that the welded part micro structure is changed from the base material, it is because of the force and heat generated during the welding.

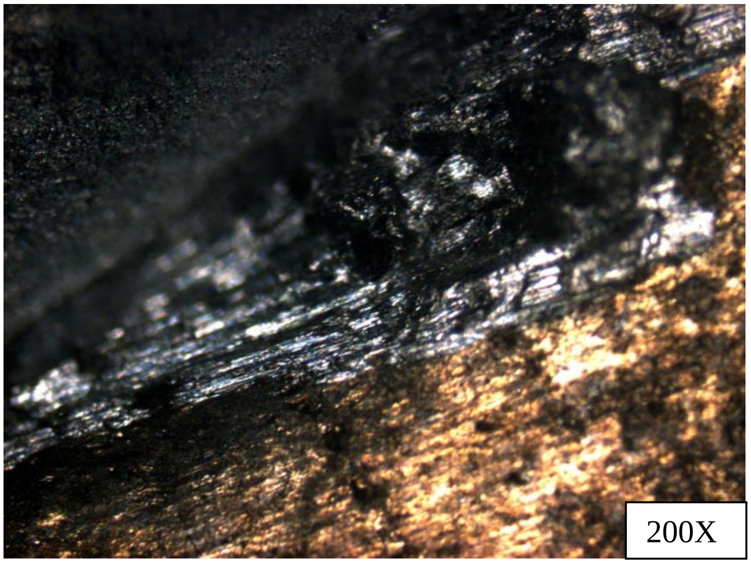


Fig. 9.8 Micro structure of FSSW with triangular tool at 900 RPM rotational speed and 45 sec dwell time

Fig. 9.8 shows the micro structure of friction stir spot welded specimen top sheet welded with the triangular tool at 900 RPM rotational speed and 45 sec dwell time. As form **Fig. 9.8** it is cleary seen that the welded part micro structure is changed from the base material, it is because of the force and heat generated during the welding.

Fig. 9.9 shows the micro structure of friction stir spot welded specimen top sheet welded with the triangular tool at 1400 RPM rotational speed and 45 sec dwell time. As form fig. 9.9 it is cleary seen that the micro structure of welded part quite smooth with havin fine structure, it is because of the high tool rotational speed.

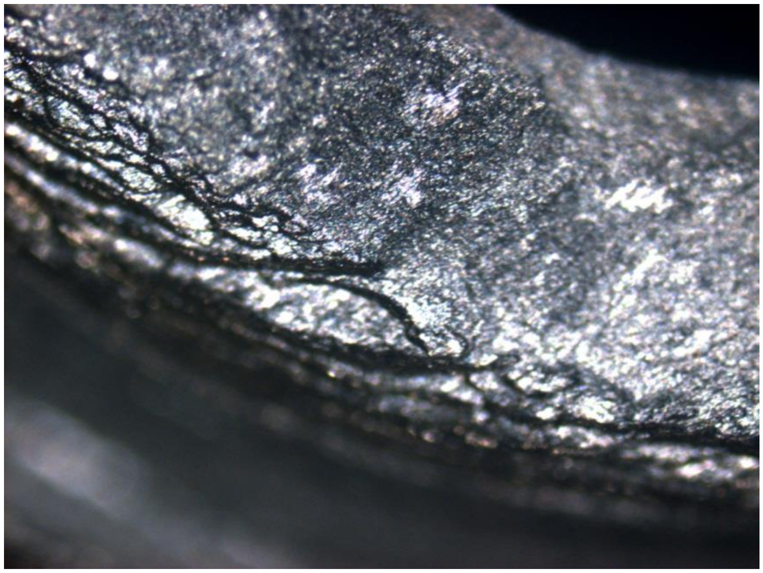
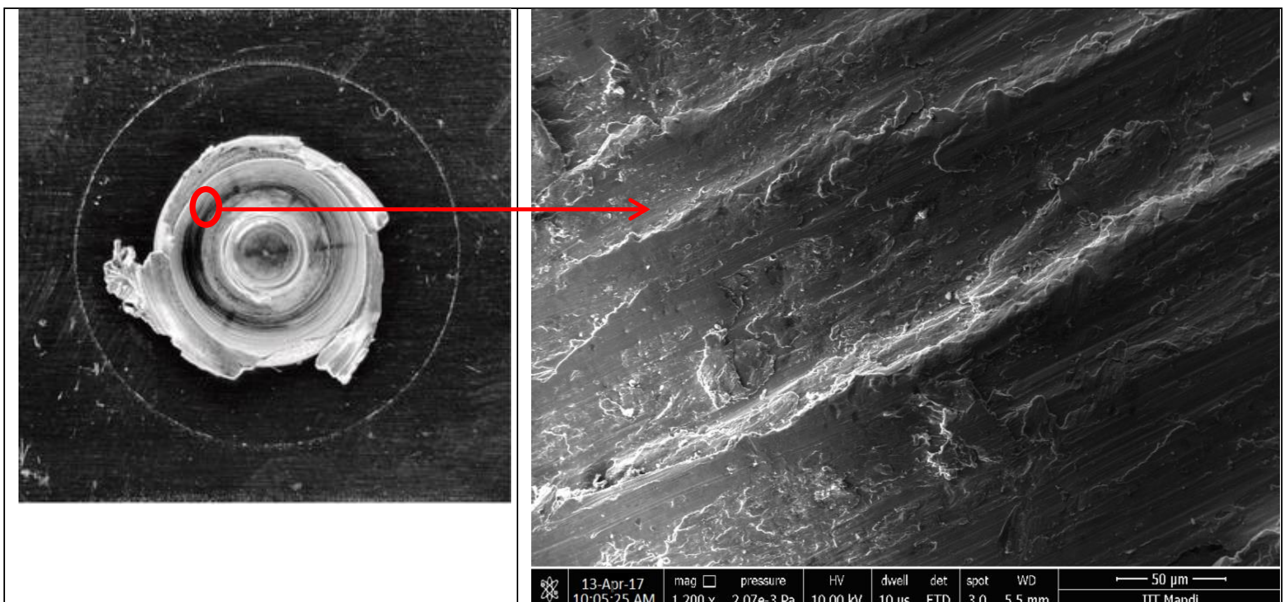


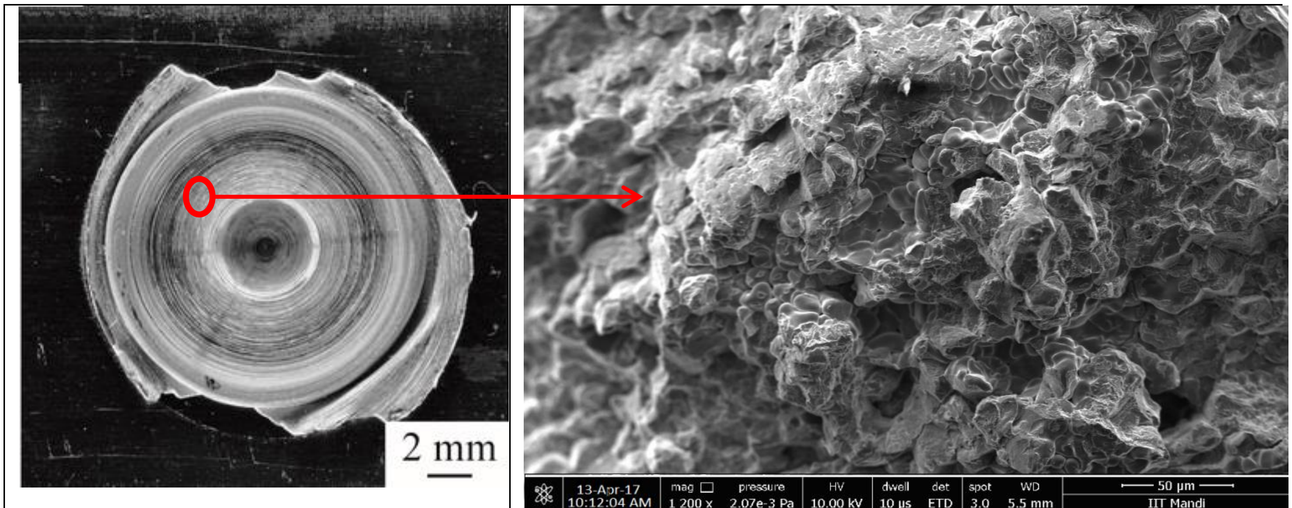
Fig. 9.9 Micro structure of FSSW with triangular tool at 1400 RPM rotational speed and 45 sec dwell time



(a)	(b)

Fig. 9.10 Scanning Electron Microscope of FSSW with triangular pin tool at 2100 RPM rotational speed and 45 sec dwell time

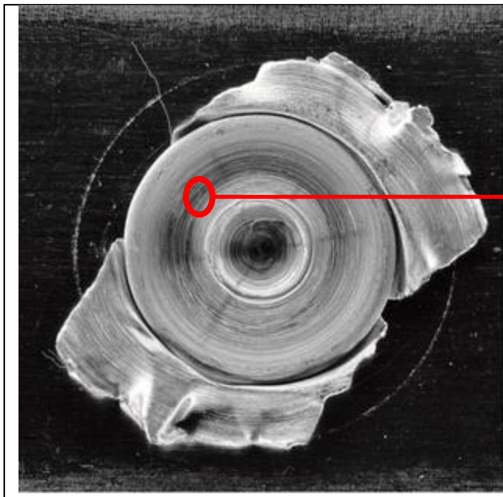
Fig. 9.10 shows the scanning electron microscope of friction stir spot welded specimen top sheet welded with the triangular pin tool at 2100 RPM rotational speed and 45 sec dwell time. As form **fig. 9.10(a)** it is cleary seen that the flash level is excessive because of the triangular tool and high tool rotational speed. **Fig. 9.10(b)** shows the surface of the friction stir spot welded part morphology.



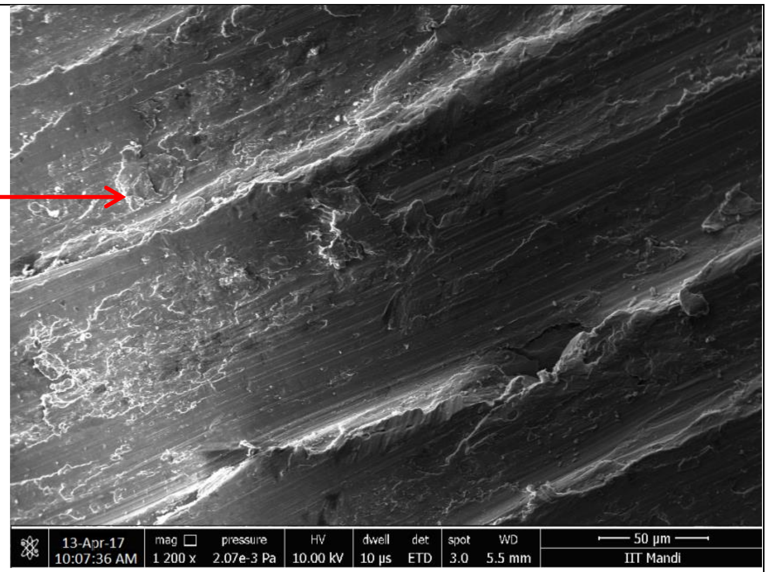
(a)	(b)

Fig. 9.11 Scanning Electron Microscope of FSSW with circular pin tool at 1400 RPM rotational speed and 60 sec dwell time

Fig. 9.11 shows the scanning electron microscope of friction stir spot welded specimen top sheet welded with the circular pin tool at 1400 RPM rotational speed and 60 sec dwell time. As form **fig. 9.11(a)** it is cleary seen that the flash level is excessive because of the triangular tool and high tool rotational speed. **Fig. 9.11(b)** shows the micro structure of the friction stir spot welded part morphology.



(a)



(b)

Fig. 9.12Scanning Electron Microscope of FSSW with square tool at 1400 RPM rotational speed and 60 sec dwell time

Fig. 9.12shows the scanning electron microscope of friction stir spot welded specimen top sheet welded with the square tool at 1400 RPM rotational speed and 60 sec dwell time. As form **fig. 9.12(a)** it is cleary seen that the flash level is excessive because of the triangular tool and high tool rotational speed. **Fig. 9.12(b)** shows the surface of the friction stir spot welded part morphology.

CHAPTER 10

CONCLUSIONS AND FUTURE SCOPE

10.0 OVERVIEW

In present chapter the results are thoroughly analyzed and optimal process parameters for FSSW of Aluminium 6061 alloy are selected. The chapter is divided into four main parts. The first contains discussion on the tensile behavior of FSSW joint. The second part discusses about the micro hardness of FSSW joints respectively. The third part contains the conclusions. Scope for future work is detailed in the last part.

10.1 Discussion of Tensile behavior of FSSW joint

The results in previous chapter clearly shows that tool pin profile is the most significant parameters in deciding the tensile behavior of the friction stir spot welded Aluminium 6061 plates. Maximum tensile shear fracture load of 2446 kN was achieved for specimen of having friction stir spot welding at triangular tool profile, 900 RPM tool rotational speed and dwell time of 60 sec, whereas minimum tensile shear fracture load of 1523 kN was achieved for specimen of having friction stir spot welding at square tool profile, 2100 RPM tool rotational speed and dwell time of 60 sec. Three tool pin profiles were investigated in present study. The profiles chosen for experimentation were square, circular and triangular. As can be seen from the **Table 9.1** maximum tensile strength is achieved with triangular pin tools. Tensile strength is less for square pin tool later on increases for circular pin tool and is reached maximum for the rectangular pin tool. Welds made with rectangular pin tools were the weakest. ANOVA of the tensile shear fracture load revels that the percentage contribution of tool pin profile for tensile shear fracture load is 75%, which makes it most significant input parameters for friction stir spot welding affecting tensile shear fracture strength. In the present investigation, three levels of tool rotational speed that were studied are 900 RPM, 1400 RPM and 2100 RPM. From the **Table 9.1** it can be easily understood that the maximum tensile strength was obtained at low tool rotational speed. As there is any increase in tool rotational speed the tensile shear fracture strength of the specimen is decreased. Maximum tensile strength was achieved at lowest level of tool rotational speed i.e. 900 RPM. It was also observed that the effect of tool rotation speed is more at lower speeds whereas the effect is considerably less at higher tool speeds. ANOVA of the tensile shear fracture load revels that the percentage contribution of tool rotational speed for tensile shear fracture load is 23%, which makes it second most significant input parameters for friction stir spot welding affecting tensile shear fracture strength. Literature reveals that dwell time is the least studied FSSW input process parameter. It is major contributor of heat input in FSSW process. Therefore its effect on FSSW process output quality characteristics was explicitly investigated. The effect of dwell time on the tensile shear fracture load is least of all the input process parameters. ANOVA of the tensile shear fracture load revels that the percentage contribution of dwell time for tensile shear fracture load is 0.4%, which makes it least significant input parameters for friction stir spot welding affecting tensile shear fracture strength. Tensile shear fracture load increases almost insignificantly with increase in dwell time.

10.2 Discussion of Micro Hardness of FSSW joint

The hardness across the cross section of the weld (along the width) was measured using Micro Hardness Tester HV-1000B. The specimen cut along its weld zone for micro hardness testing. The testing was conducted using indentation load of 300 gf and a dwell time of 12 seconds. The readings were taken for the upper plate and were recorded at an interval of 1 mm on both sides of the weld hole. The readings were taken at mid thickness of upper plate i.e. 3mm from top of plate. Scatter graphs were plotted from data obtained from this testing. According to the profile of Vickers hardness, the distribution of Vickers hardness was found to be more or less symmetric with respect to the center of keyhole of the welds made at all given processing parameters. The Vickers hardness profile of the specimens showed a W-shaped appearance. The welds have higher Vickers micro hardness in the stir zone than the base material. The hardness value is highest in the stir zone, in the vicinity of the weld keyhole. Hardness value first decreases while moving away from the stir zone and then again increases after some distance. Hardness value starts to stabilize after 10 mm from the weld center. Maximum value of Vickers hardness is 39 HV which is for weld joint by triangular Tool pin profile, tool rotational speed 2100 RPM and dwell time of 45 sec.

10.3 Conclusion

The following conclusions can be drawn from the present experimental investigation on the FSSW of Aluminium 6061 alloy.

- The increase in tensile strength of friction stir spot welded lap shear joints for particular input process parameters is because of grain refinement at crystallization temperature (0.6-0.7 times the melting point). The optimum heat input is necessary for maximum tensile strength, which is generated at optimum levels of input process parameters.
- The micro hardness profile across the FSSW region shows a W shaped appearance because different regions in the weld zone experience different amount of cyclic thermal load. Stir zone is the hardest region because it undergoes dynamic recrystallization induced by intense plastic deformation and high temperatures generated during FSSW process. Due to the effect of frictional heating, the grains in the heat affected zone get coarser than that of the parent material which leads to reduction in micro hardness value.
- The statistical analysis of FSSW process for tensile shear fracture load reveals that the tool pin profile has contribution of 75%, followed by tool rotational speed 23% and 0.4% dwell time.
- Tensile shear fracture load bearing capacity of the welds first decreases when switching from circular to square pin profile and then increases when switching to triangular profile. In case of circular and square tool pin, the rotation of the pin is symmetric in nature causing shear deformation of the material around the pin surface whereas due to the asymmetric geometry of square pin successive rotation of the pin is believed to enhance the plastic flow of the material in the vicinity of the pin in the radial direction.
- With increase in the tool rotational speed, the tensile shear fracture load bearing capacity of the welds decreases because heat input increases with increasing tool rotational speed, which gives rise to the growing grains and therefore decreasing joint strength.
- The effect of dwell time on tensile shear fracture load bearing capacity of the FSSW welds was not as significant as that of other parameters. Tensile strength increases insignificantly with increase in dwell time. Dwell time is required for heat input in FSSW.

10.4 Scope for Future Work

In the present study, only three parameters viz. Tool pin profile, Tool rotational speed and dwell time were investigated. Study of other process parameters like tool pin diameter, tool shoulder diameter, tool pin length, tool pin penetration, pin less tool, tool feed rate, different tool materials can be done. More extensive testing can be concluded to study the mechanical properties of the FSSW weld such as fatigue testing, cross tension testing etc. Highest temperature reached during the FSSW process can also be analyzed to study the effect of heat generation on the quality of weld. An economic evaluation of the processes along with other allied processes, both quantity and quality wise is further needed. The weld strength can also be tested at elevated as well as sub-zero temperatures, which may be useful in manufacturing of super critical equipment's like boilers, turbines etc.

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APPENDIX

FRICTION STIR WELDING OF ALUMINIUM ALLOYS: MECHANICAL PROPERTIES AND METALLURGICAL OBSERVATIONS

ORIGINALITY REPORT

%16	%7	%10	%8
SIMILARITY INDEX	INTERNET SOURCES	PUBLICATIONS	STUDENT PAPERS

PRIMARY SOURCES

Submitted to Lovely Professional University	Student Paper	%3
Submitted to IIT Delhi	Student Paper	%1
research.vuse.vanderbilt.edu	Internet Source	%1
Submitted to The University of Manchester	Student Paper	<%1
Submitted to Panjab University	Student Paper	<%1
Handbook of Manufacturing Engineering and Technology, 2015.	Publication	<%1
Submitted to Institute of Graduate Studies, UiTM	Student Paper	<%1

Badarinarayan, H.. "Effect of tool geometry on

8	static strength of friction stir spot-welded aluminum alloy", International Journal of Machine Tools and Manufacture, 200902 Publication	<%1
9	Karthikeyan, R., and V. Balasubramanian. "Optimisation and sensitivity analysis of friction stir spot-welding process parameters for joining AA 6061 aluminum alloy", International Journal of Manufacturing Research, 2012. Publication	<%1
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16	Bilici, M.K.. "Influence of tool geometry and process parameters on macrostructure and static strength in friction stir spot welded polyethylene sheets", Materials and Design, 201201 Publication	<%1
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18	Submitted to Indian Institute of Technology, Madras Student Paper	<%1
19	Shen, Zhikang, Xinqi Yang, Zhaohua Zhang, Lei Cui, and Tielong Li. "Microstructure and failure mechanisms of refill friction stir spot welded 7075-T6 aluminum alloy joints", Materials & Design, 2013.	<%1

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