ADAMA SCIENCE AND TECHNOLOGY UNIVERSITY

SCHOOL OF MECHANICAL, CHEMICAL AND MATERIAL ENGINEERING

PROGRAM OF MANUFACTURING ENGINEERING

OPTIMIZATION OF FRICTION WELDING PARAMETERSFOR WELDMENT OF ALUMINIUM-COPPERELECTRICAL CONNECTOR

By

WorkuMamuyeYilma

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Advisor:

Dr. B K Singh

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Approved by board of examiners:

1. Solomon Dhufera___ ____________________ __________________

Chairman, dep't Graduate Committee Signature Date

2. Dr.BK Singh_____ _________________________________

Advisor Signature Date

3.__________________ _________________________________

Co-advisor Signature Date

4. Dr.DesalegnWogaso_____________________ __________________

Internal Examiner Signature Date

5.Dr.TeshomeMulatie__ ________________ ___________________

External Examiner Signature Date

DECLARATION

I certify that the research work titled "***optimization of friction welding parameters for weldment of aluminium-copper electrical connector***" is my own work. The work has not been presented elsewhere for assessment. Where material has been used from other sources it has been properly acknowledged/referred.

Graduate:WorkuMamuye

Signature: _______________Date: ________________

Advisor: Dr.BK Singh____ Signature: ________________ Date: _______________

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The most rewarding achievement in my life, as I approach middle age, is the completion of my M.s.c thesis.

Before all GOD and his BLESSED MOTHER; has given me strength in my work.

I would like to take this opportunity to express my immense gratitude to all those persons who have given their invaluable support and assistance. In particular, I am profoundly indebted to my supervisorDR. B K SINGHwho was very generous with his time andknowledge and assisted me in each step to complete thethesis. The research for this thesis was financially supported by a postgraduate studentship from Adama science and Technology University.

I'd include those who helped including my advisor, friends, and colleagues. It is also appropriate to thank for friendly support, so I'd also include my friends in town and family members.

Notwithstanding all of the above support for this project, any errors and/or omissions are solely my own.

I love my family. This thesis is dedicated to them.

ABSTRACT

Friction welding of aluminium and copper has wide application in electrical transmission in production of bimetallic (lug) or connectors. Theuse of dissimilar metal connector is to prevent high electrical loses due to contact resistance, and mechanical contact between aluminium and copper is not permanent in their application due to environmental degradation due to dissimilar metal contact.Problem such as galvaniccorrosion between two metals in mechanical contact is saviour and it is technically distractive in application of connectors in electrolytic or humid environments; hence fiction welding of the two metals solves the problem by introducing technically acceptable joint between the two metals by eliminating occurrence of electrolytic action between dissimilar metal contacts.

Tensile strength of the connectors is very important to withstand stress caused bytemperature and heat and mechanical force in application. Electrical resistance behaviour is also highly important. Friction welding process is generally used for welding dissimilar metals such as aluminium and copper and process parameters are significant effect on the forth mentioned tensile strength and electrical resistance properties of the connectors. Optimization of process parameters of friction welding process is needed to obtain desired response as mentioned above.

Therefore the aim of this research is to optimize process parameters that give best electrical resistance and tensile strength properties of the weldment. Optimization of welding parameter that gives two performances characteristics such as tensile strength and electrical resistance are successfully optimized. In optimization processGRAY RELATIONAL ANALYSIS, ANOVA and TAQUCHI method are used. Vertical drilling machine is used for friction welding process and the machine is 1.7 KW power and rotational speed of 3060 RPM. The optimization of the process parameters of the friction welding i.e. RPM, friction pressure, and friction time is conducted.The obtained optimum setting for two performance output characteristics such as strength and electrical resistance is:friction time at 20 (second-MAXIMUM), friction pressure 117 (Mpa-MAXIMUM) and speed (1050 RPM-MINIMUM). Furthermore based on two performance study friction pressure is basic parameter that determines the desired responses.

Key words: Friction welding,Dissimilar metal connector, Gray relational analysis, Electrical resistance, Mechanical strength.

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CHAPTER 1 INTRODUCTION

1.1.Historical development of friction welding

It was an old idea to join metals together utilizing the heat generated at the interface by friction.Some applications and patents were dated back to the turn of the century.However, scientific study was not started until 1956 after CHUDIKOV(Uday, 2010) had reviewed the old concept and successfully demonstrated the possibility of achieving high quality butt welds between metal rods. Intensive research effort has been launched since then by VILL (Uday, 2010) and others in the U.S.S.R in order to understand the process from scientific view point.

The process was introduced to the U.S.A. in 1960 and at the American machine and foundry(Uday, 2010).CHENG did some pioneering work on parameter analysis and the thermal aspects of friction welding (Lockwood, 2002).Friction welding as a method of joining was first patented in the 1890s by an American named BEVINGTON(Uday, 2010). References are also known which indicate that the ‘spin welding’ of plastics was carried out in the 1930s–1940s. However, its impact for welding metals become dormant until 1956 when the process was advanced significantly by Soviet workers. Further time elapsed before the process was introduced into the UK and USA in the early 1960s (Uday, 2010).

1.2.Optimization of friction welding process parameters

Friction welding is a solid state welding process for joining two similar or dissimilar materials. It is used widely throughout many manufacturing processes where high production rates are required. Friction welding conditions are generally selected on the basis of past experience or study. However, establishment of a method to decide the conditions in response to the phenomena which occur during friction welding is needed.This is because the optimum welding conditions vary for each welding machine.

Effective simulation software was given in the simulation of friction welding process for specific geometries (Sahin M. , 2004). The simulation process was specific for single geometry and for one material. This shows that friction welding process variables should be-optimized for specific application when it is needed. There is no general rule of friction welding parameter setting that work for every application. This clearly shows the process is dependent on many conditions such as machine, material, application requirement and so on. For each machine it is necessary to produce design of experiment and optimization(Sahin A. Z., 1998). Selection of best process parameter for each machine individually needs time and capital. The technique to satisfy this problem is using design of experiment tools to optimize process parameters.

1.3.Statement of the problem

When joining dissimilar metals such as copper and aluminium, problems such as brittle inter-metallic compounds are created in the joint. As such, the friction welding parameters and their settings must be carefully selected to achieve strong welds and minimize rejects. Operating at non optimum process condition may result in undesirable output such as (Rosli, 2015).

- ❖ partial destruction and involvement of inter-metallic layer which reduces the strength of the weldment;
- ❖ non-uniform heating of the cross section of the welded specimens and non-uniform joint between the specimens due wrong election of process parameters;
- ❖ increase in the overheating of the metal in wrong selection of process parameters and hence affect the joint interface and performance of the weldment directly or indirectly to the strength and physical property, Electrical property and weld structure;

Optimum parameter selection can minimize the effect of these problems. This study therefore optimizes process parameters such as strength and resistance for its application in electrical connector.

The problems with selection of other welding process of these metals are, first there is a case to generate an inter-metallic compound and involvement of the other metal flake in the interface of the materials Second, in the case of metals with very different melting points or flow stresses, it is difficult to be welded, because only the metal with lower melting point softens and the material with higher melting point cannot decrease the flow stress (TSUJINO, 2016)**,**(Bhamji, 2012)**,** (Rosli, 2015)**,** (Sahin M. , 2010).

Certain physical properties of copper and aluminium, like the high electric and thermal conductivity, enable their common application in electric power, and other areas, in the form of bimetals. The necessity for joining copper and aluminium is important for electric conductors or cable endings.Joining elements, used for connecting copper and aluminium cables, was mostly made by creating a mechanical contact between the two metals, that is ,by folding them or bolting of the two metals. Poor joining method in Al/Cu joints is unreliable in the long time. The reasons for this are the followings:

- The weakening of the joint during its use at higher temperatures which is caused due to different linear Al and Cu thermal expansion coefficients.
- A large transient electrical resistance at the interface, which is one of the problem of a joint based on the mechanical type of connection.
- Occurrence of galvanic action due to the mechanical contact between copper and aluminium which is a series problem in the electric transmission failure.

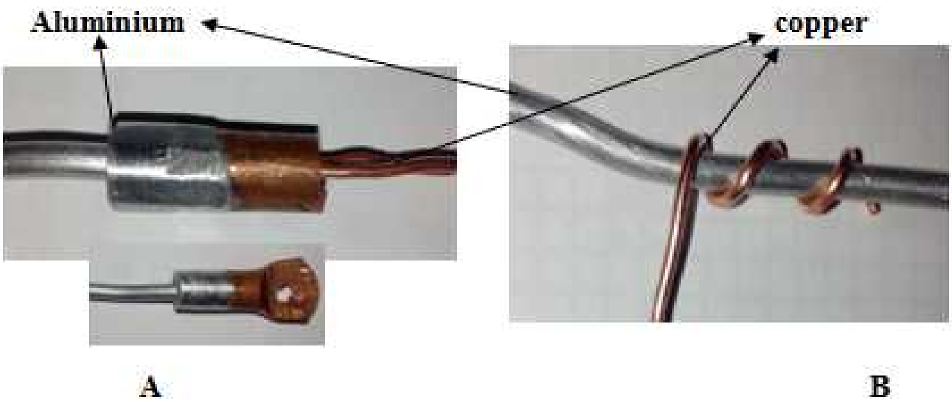


Figure 1.1The use of elctrical connector B)Withowt using conector indicates the usual connection problem.

Galvanic corrosion is failure process when two dissimilar metals are in contact in electrolyteenvironment. Theenvironment such as air-moisture, salt-moisture is the electrolytic medium for the galvanic corrosion to take place. The material that is in electrolytic series far apart is galvanic couples. When the two metals are in contact in electrolytic medium the metal with low galvanic potential corrodes and the metal with high galvanic protection ability will not harmed by the corrosion. When aluminium and copper are mechanically contact in electrolytic environment aluminium is severely corroded and failure from the aluminium side resulted and the mechanical contact is destroyed due to galvanic action. Galvanic corrosion problem can be solved by using friction joint materials when the dissimilar materials are welded by friction and this will prevent occurrence of electrolysis between the metal contacts. Unlike mechanical contact between the two metals friction welding is very efficient method to eliminate galvanic action in electrical contacts between dissimilarmaterials such as aluminium and copper.

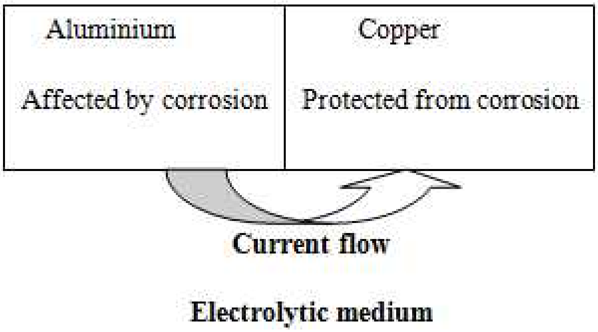


Figure 1.2 Galvanic corrosion between aluminium and copper mechanical contact

Thus, bond with better performance between Al and Cu is achieved with an inter-diffusion of the solid-state atoms. The procedure, with which such a connection is formed, is called friction welding. When aluminium and copper are in contact in air, the aluminium can be expected to be attacked severely by galvanic corrosion. It is advisable to use a friction welded bi-metallic lug; to prevent galvanic corrosion in electrical connections between aluminium-copper terminals (Bhamji, 2012).

Based on the problem mentioned above; this thesis is aimed to perform welding experiment to weld copper and aluminium metals and study process parameters for the desired outputs such as electrical resistance and tensile strength, which are much related with the above problem statement described in this section. Generally the aim of this study is to perform process parameter optimization for desired output based on the design experiments and give the optimum parameters for future application and future work.

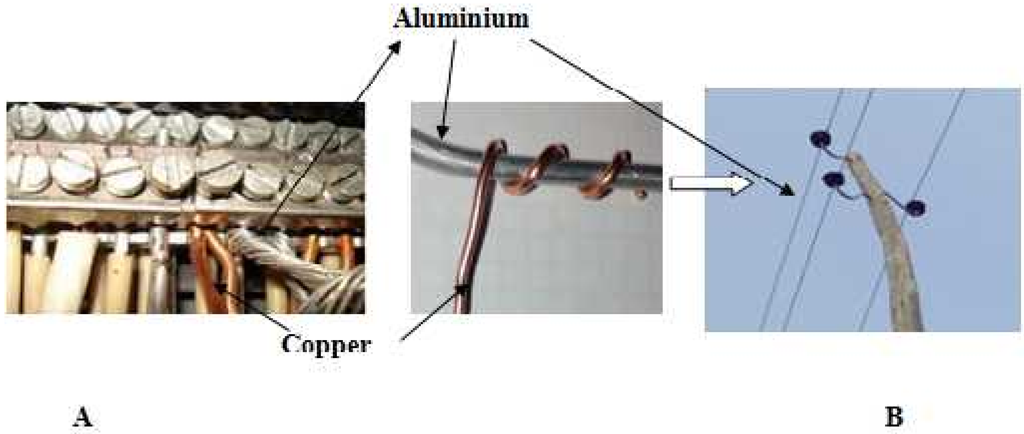


Figure 1.3A) Example of poor electrical connections ; B) Electrical distribution line

1.4.General and specific objective

Based on the problem statement the following description is given to describe the specific and general objectives of the study.

1.4.1. General objective

The main objective is to optimize the process parameters of friction welding for two outputs characteristic. The two output measures are electrical and mechanical properties for selected process parameters for special friction welding design in drilling machine. The optimised process parameters are presented as best results of process parameters for the output parameters (Tensile strength and electrical resistance of joint interface). Finally present the best setting of process parameters for friction welding process for specific outcomes (tensile strength and electrical resistance) for the intended application in electrical connectors.

1.4.2. Specific objective

- Develop friction welding setup on conventional drilling machine.
- Conduct friction welding experiment.
- Microscopic observation of joint region and specify the structural differences at the joint interface.
- Present final model electrical connector and show how to use to it.

1.5.Limitation of the study

The drilling machine used in this study is not designed for friction welding process. Friction welding setup design on drilling machine results many limitations such as vibrations, Measurement and control problems. The study is therefore limited to use advanced friction welding machine. Special friction welding machine consists of control systems, pressure and temperature measurement systems and additional systems to eliminate disturbance of the process during the process of friction welding. In the availability of this difficulties and lack of available machine the study is successfully demonstrated and studied the process parameters. In spite of the useful method used for conducting experiment the following are main limitations in measurement and test procedures.

1.5.1. Limitation to the resistance measurement

Resistance measurement is not specially designed for resistance measurement in small amounts. The resistance measurement previously carried out by using advanced resistance measurement systems which uses micro level accuracy. The resistance in this particular research is performed indirectly from relationship between current and voltage drop measurements. The fineness of the output result is controlled by two input parameters as stated above. In spite of the measurement uncertainty the study eliminate fluctuation and disturbance by using appropriate resistance measurement technique which is called Kelvin four wire resistance test method which is in detailed discussed in literature and methodology chapters. The measurement uncertainty based on four wire resistance is listed as follows:

- Inclusion of the resistance of bulk material into the contact resistance
- Instrument errors which may be occurred due to temperature variation
- Fineness or precision of the instruments used in the measurement

1.5.2. Limitations to the standard electrical test

Standard electrical test are available for testing the electrical properties when the connectors are used in practical environments. Examples of electrical measurements are current burst test, résistance test etc. These tests are conducted to check the performance of connectors in application. In this study only the prototype is made with suitable electrical and mechanical properties for the aim of to optimize process parameters for best result in the selected method and application. In spite of performing the standard electrical test the study is focused to justify the selection of process parameters and the test results are important for future study. It is also justified that the obtained results are meet the requirements of electrical connector’s interims of application modelling of connectors. In general the following points are summarized the limitations of the study.

- The method and machine is only used for specific project.
- The measurement systems should be computerised for eliminating high disturbance in measurements, one of the limitations of this study is using computerized and synchronized measurement system in friction welding process.
- The model is presented, but the connector is not practically tested in electrical application.
- Electrical measurements such as resistance test are indirect method of testing and there is measurement uncertainty.

1.6. Scope of the study

The scope of the study is to study the input process parameters such as friction pressure, friction time and rpm for the desired output parameters such as strength and electrical resistance. Optimizations of process parameters of friction weldments of aluminium and copper materials which are used for electrical transmission application are studied. The study only focuses on the material type specific for the study. The size and method is also specific for this study.

Generally materials of copper and aluminium EC grade material are used. The dimension and the shape of the workpieces are limited and the machine is also specific for this study. Selections of process parameters are chosen based on the size and shape of the material used and there is deference between process parameters from other study. Basic process parameters of friction welding are RPM, Friction pressure, Friction time, Upset pressure and Upset time. From this it is clearly viewed that the scope of process parameters are limited for this study. The process parameters for this study include three parameters such as RPM, Friction pressure and Friction time.

1.6.1. Scope in application

The result from this study is used in electrical connection systems. The use of electrical connection involves using bimetallic friction welded connectors for connecting two electrical lines. The application of connection involves using connector's terminal ends and cables to be connected. The other application includes the use of these connectors for reducing installation complexity when connections are removed and inserted frequently.

Generally the result from this study is used for mass production of aluminium and copper bimetallic connectors in electrical power transmission applications. The process parameters that are optimized in this research are used for production of bimetallic connectors from the selected materials in this study. On the other hand the selected material and size of the workpiece is special for application of connectors that are small in size.

Figure 1.4 Model bimetallic connector A) Design for two side bolt and B) Design for one side bolt

1.6.2. Scope in design, and test

As presented in limitations of the study the study is limited to test resistance variations due to the process parameter selection. The study is not intended to manufacture or to test the output result is capable of meeting standard test methods. The presented resistance test is for experimental analysis of process parameters and feasibility of the process parameters to optimize the friction welding process. Therefore the future studies in needed to standardise the method and test the output result for approval in electrical application.

1.7. Significance of the study

In application point of view the outcome from this study may be significant for electric power utility in Ethiopia. Power saving and utilizing available power by using special electrical connection systems such as using bimetallic connectors are essential. Industrial cable connections and electrical sub stations are use connectors such as in this research (aluminium and copper bimetallic connector).Interims of significance the usage of bimetallic connector are very important.In electrical connections of industries, machineries, electrical stations and substations, house hold electrical connections,distribution lines are all use electrical connectors that are technically efficient and energy saving in their application. The use of connectors for power connection is not limited interims of power saving, there are other advantages of using electrical connectors such an advantage is simplicity of installationof electrical connections, elimination of spark and overheating of the connection, galvanic corrosion between dissimilar metal contact all are significant advantages of using such type of electrical connectors . Performance of dissimilar electrical connectors is its ability to perform electrically stable and mechanically strong in operation. To meet this requirements optimum process parameter should be determined for the desired output result.

CHAPTER 2 LITERATURE REVIEW

Related with friction welding process several researchers are studied deferent ensues such as tensile strength of weldments in relation with process parameters such as RPM, Friction pressure and friction time and other parameters such as electrical resistance properties and intermetallicformation. The following sections are tried to present the study by deferent researchers' interims of deferent aspects of friction welding process. Relatedensues with friction welding of aluminium and copper are its process parameters effect on tensile strength and electrical resistance behaviour. The other important study is the micro-structuraldifferences and the nature of intermetallicformation, its impact in the tensile strength and electrical resistance properties of the joint material.

2.1.Processes parameter optimization

Study was conducted in the local aluminium and copper bimetallic lug production. The material was aluminium and copper standard electrical transmission materials. The process parameters are selected from samples in the production line. The objective of the study was to avoid disturbance to the actual production line, the source of data was the relevant historical process information extracted and analysed with ANOVA(Rosli, 2015).

In the study no special process was conducted and that was the main drawback of the study. Full factorial design of experiment was used for analysis. The response was to optimize process parameters for strength of the weldment. The parameters were rotational speed friction pressure and friction time. Total number of eight experiments was conducted. The response measurement was conducted three times; this was strong side of the study which eliminates the uncertainty of response measurement due to the availability of large amount of data. Rotational speed at high level (1450 Rpm), friction pressure at low level (39.2 Pa) and friction time at low level (4 s) was give optimum result for mechanical strength according to(Rosli, 2015). In this study multi performance optimization such as electrical resistance and strength simultaneously are not given and this is an open question for future study.

Study of friction welding process of aluminium 96.7% and copper 99.9% was conducted by using continues friction welding process. Drive motor 4 kW power and 1,410 rpm was selected in the process.Friction time, friction pressure and upset pressure are process parameters and tensile strength was the response parameter. Generally 10 experiments are performed in deferent combination of parameters. Tensile strengthmeasurement was also conducted for 10 experiments.Upset time and rotational speed was maintained constant at (15 s and 1410 RPM respectively).Optimum welding parameters was found as; (60 MPa max) for friction pressure, (120 MPa max) for upset pressure and (2.5 secondlow) based on statistical analysis performed. This study included many input process parameters and it was the main advantage of the study. The main drawback was it did notoptimize the result for multi performance characteristic as mentionedin the previous study. This study also pointed out that the level of intermetallic formation is the main reason for the decrease of the tensile strength. According to this study we can maximize the strength by selecting optimum setting of process parameters (Sahin M. , 2010).

2.2. Joint strength

Materials of aluminium-copper dissimilar metal friction welding were conducted to show the relationship between process parameters and tensile strength of the welded part. The process parameter was duration of welding, frictional pressure and rotational speed. Full factorial analysis by the technique of design of experiment was used to study the effect of process parameters. Friction welding model experiment was designed consisted of rotation chuck, stationary chuck, hydraulic system and stopping system. The result of the investigation showed that process parameter individually has no effect on tensile strength, but the combination of the process parameters has significantly affected the quality of the weld.Tensile properties was improved for a particular thickness of intermetallic layer, the thickness of the intermetallic layer was increased with speed of rotation and reduced with friction pressure(Yilba, 1995).

In this literature the outer is studied friction welding process parameters for better tensile strength. According to the outer tensile strength of friction welding process is depend on the combination of process parameter and the values and setup of the process parameters. In other words controlling one process parameter such as speed or pressure does not improve tensile strength. From this review it can be important to note only process optimization is possible when design of experiment is conducted for process parameter. And also it is important to note friction welding process parameter optimization reduces the formation of intermetallic compounds which is the major factor for reduction of the tensile strength of the weldment produced by friction welding process.

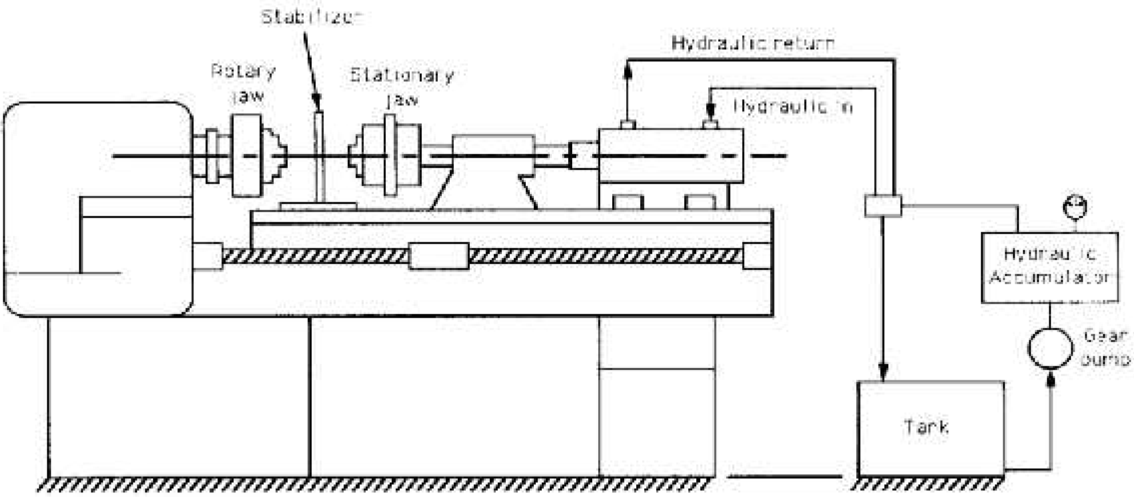


Figure 2.1Friction welding setup(Yilba, 1995)

It was clearly indicated that increase in the thickness of the intermetallic layer reduces the tensile strength. Generally the study was showed strength decreased due to involvement of intermetallic compound(Yilba, 1995).

2.3. Electrical property

Experimental analysis was conducted to investigate the tensile and resistance property of aluminium and copper electrical materials.Material specification was (AA 1050 to C101) friction welded by linier friction welding method. Size of the linear friction welding samples was 50×12×50 mm with a weld interface of 50×12 mm.The process parameters that were varied in this study were frequency of oscillation, amplitude of oscillation and friction pressure.A forge pressure of 75 MPa was used, which was applied for a period of 5 s. A burn-off distance of 2 mm was used in the study. For resistance the test methods used was voltage drop test. The voltage was measured across the weld interface in deferent distance from the weld line.For resistance test a 400 amp direct current (DC) was passed through a welded sample that was 4.5×12 mm in cross-section. For the conducted resistance test approximately 0.2 mV potential drops can be resolved by gradually adjusting the current input. Generally in this experiment, very small resistance change was detected in all welded samples. This shows all welds have very small electrical resistance. The main limitation of this study was only linier friction welding process examined. Rotational friction welding was not examined and the process was not optimized for multi-responsecharacteristics such as, electrical resistance and tensile strength simultaneously.

2.4.Intermetalic compounds

Study conducted in continues drive friction welding of aluminium and copper the author investigated the intermetallic formation between the materials listed(Wei, 2016). The materials were copper and aluminiumbars specifications Cu (99.9%) and Al (99.1 %). The specimens were machined with a dimension of 20 mm diameter in welding part and 14 mm diameter in clamping part. Welding machine of 40 KN capacity at constant friction force (19.1 MPa), forge force (31.8 MPa) and speed of rotation (1900 rpm), and varying friction time as 2 s, 4 s, 6 s and 8 s was used in the process. Temperature was detected by infrared thermometer. Metallographic characterization employing scanning electron microscopy (SEM) and X-ray diffraction (XRD) technique was used to analyse the microstructure and composition respectively. The outer presented the result in figures as shown below:

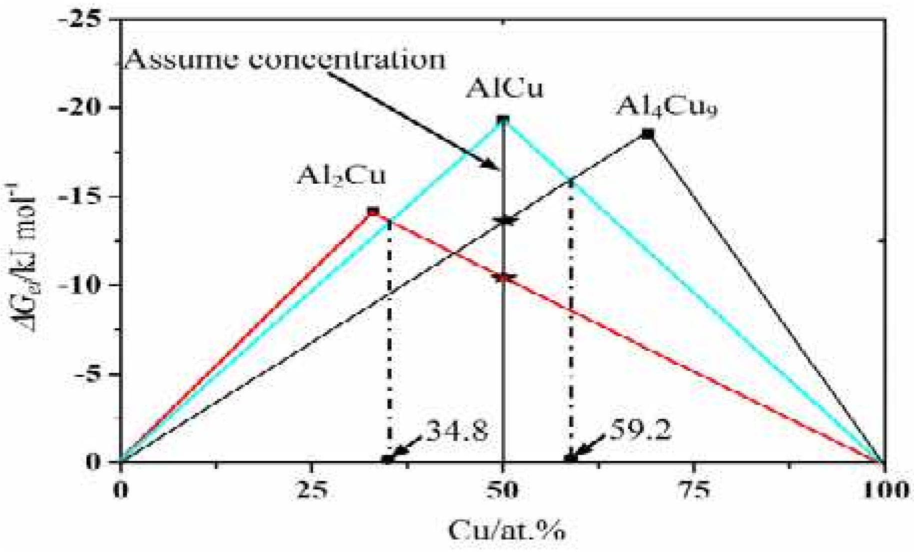


Figure 2.2Effective Gibbs free energy changes of formations (Δ_{Ge}) for Cu–Al compounds under different concentrations(Wei, 2016)

From this investigation temperature was main parameter for study of microstructure, interdifusion and intermetallic phase formation. Based on the result the temperature in the interface was predicted as 375-450 degree centigrade.The effective Gibbs free energy change of formation model was used to predict the Al–Cu compound formation, the model showed that Al_2Cu (Al side) and Al_4Cu_9 (Cu side) appeared first. Intermetallic compound layer with a thickness of 0.7 μm~10 μm was visible from the SEM examination and the thickness and interfacial temperature was shown increased when friction time increased. Also it was proved that intermetallic phases Al_2Cu and Al_4Cu_9 were identified in all samples in view of the XRD and EDS analyses.

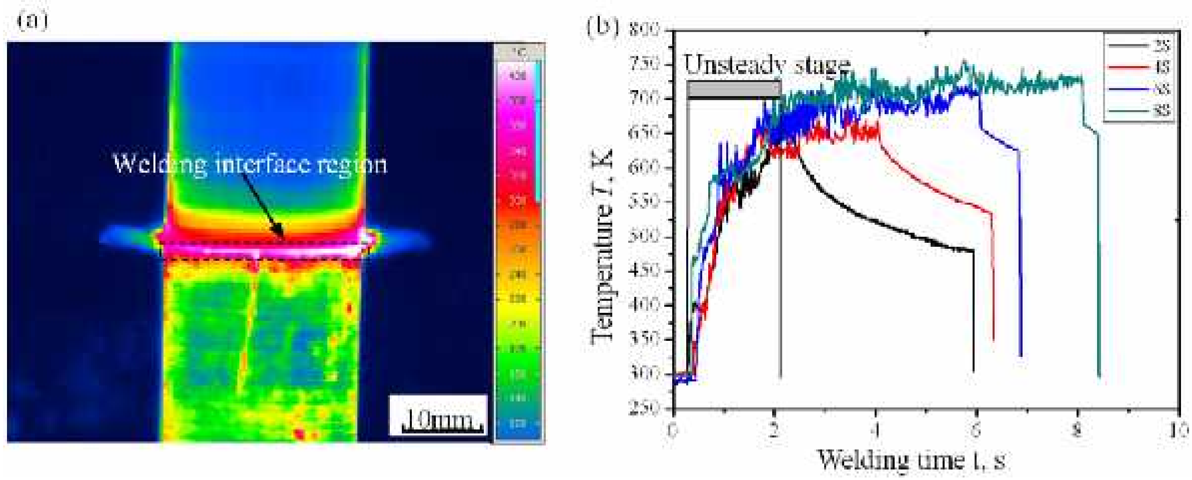


Figure 2.3 Actual CDFW process of Al–Cu tubes: (a) The location of the welding interface region in a typical infrared thermal image, and (b) variation in the maximum surface temperature of the welding interface region with different welding time(Wei, 2016)

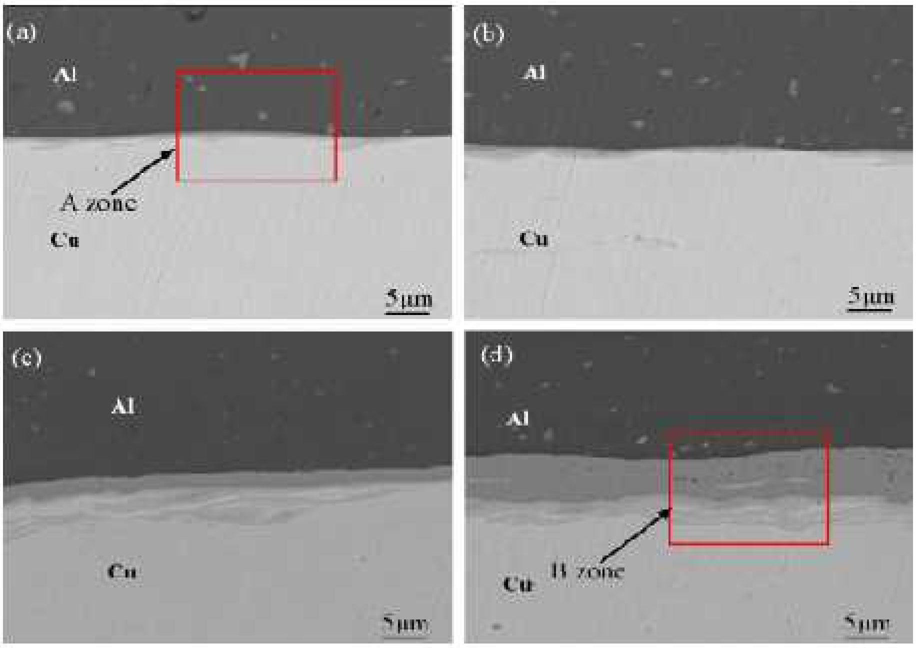


Figure 2.4SEM micrographs of the interfacial regions at friction time: (a) 2 s, (b) 4 s, (c) 6 s and (d) 8 s(Wei, 2016).

Novel radial Friction stir welding was conducted to investigate the nature of intermetallic compounds present in the weld interface of bimetallic tube investigated. The materials used were inner and outer tubes Cu (T2) and pure Al (AA1060), respectively.Both Cu and Al tubes were 70 mm in length, 17 and 20mm inner diameter, and 1.5 and 2 mm wall thickness, respectively.The tubes were sectioned perpendicularly to the welding direction for micro-structural examinations. Welding parameters were RPM (95, 300, 600, and 950), welding speed 15mm/min, dwell time 2sec and retracting speed60mm/min(Li, 2017).

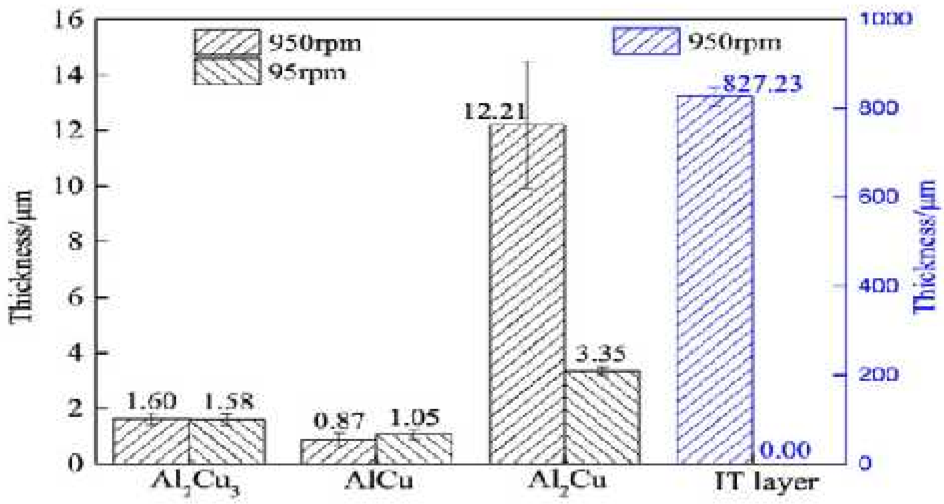


Figure 2.5The thickness of various layers under different rotational speeds(Li, 2017)

In the process when welding is performed at 950 rpm the temperature was reached 590 degree centigrade. At this temperature the study reported that aluminium was melted because of lowering of melting temperature of solid solution formed. In this report the author selected 950 and 95 degree centigrade for further analysis. According to the study at 950 RPM three layers were formed layer-1 leyer-2 and layer-3. The study was also indicated formation of intermetallic compounds Al_2Cu,Al_2Cu, and Al_2Cu_3 at deferent locations based on XRD diffraction pattern. It was showed that when RPM increased thick intermetallic layer was formed. Particularly the author was suggested that higher heat input and longer holding time are conducive to improving the interdiffusion of atoms. The micro-hardness of reaction layer reaches 154 HV at 95 rpm and 280–290 HV at 950 rpm, which is higher than that on the Al and Cu base metal due to the formation of intermetallic compound(Li, 2017).

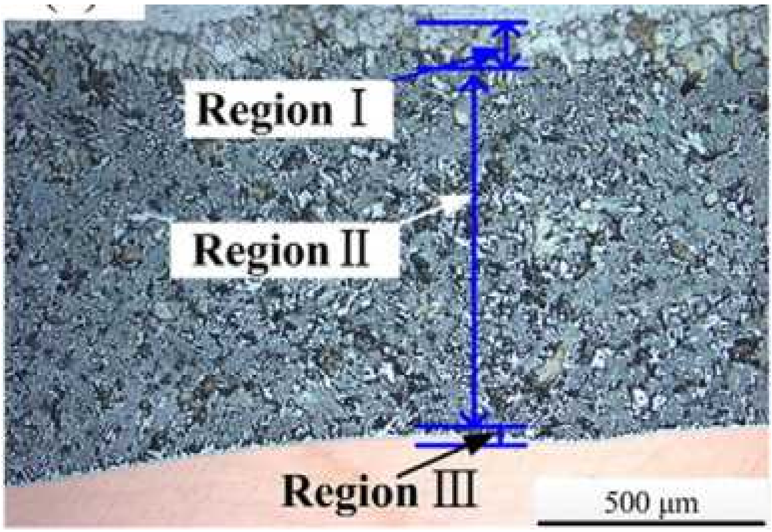


Figure 2.6Interface morphology of Al/Cu bimetallic tubes produced at 950 rpm(Li, 2017).

The study was also investigated the shear strength behaviour at deferent rotational speeds. The shear strength reaches 73 MPa when the rotational speed was 95 rpm, which is 62.2% higher than that obtained at 950 rpm. In fact, the major factor influencing the joint strength is the intermetallic layers thickness formed at the Al/Cu interface. The author also cited that it is well known that the strength of joint decreased with the increase of the intermetallic layers thickness. It is also cited that intermetallic formation in friction welding process is higher than in diffusionannealing(Li, 2017).

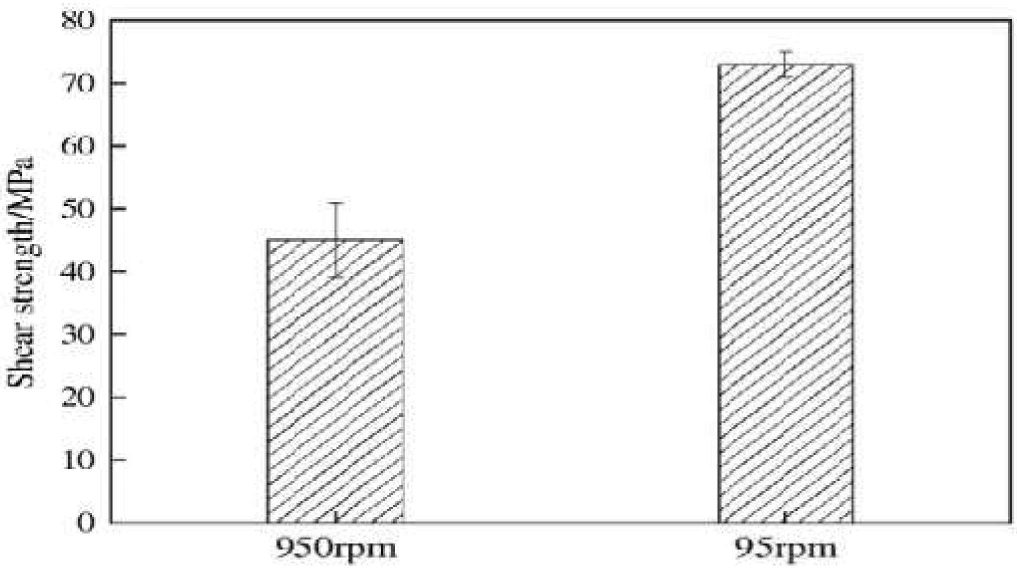


Figure 2.7 Strength variation at deferent rotational speed(M and Taheri, 2001).

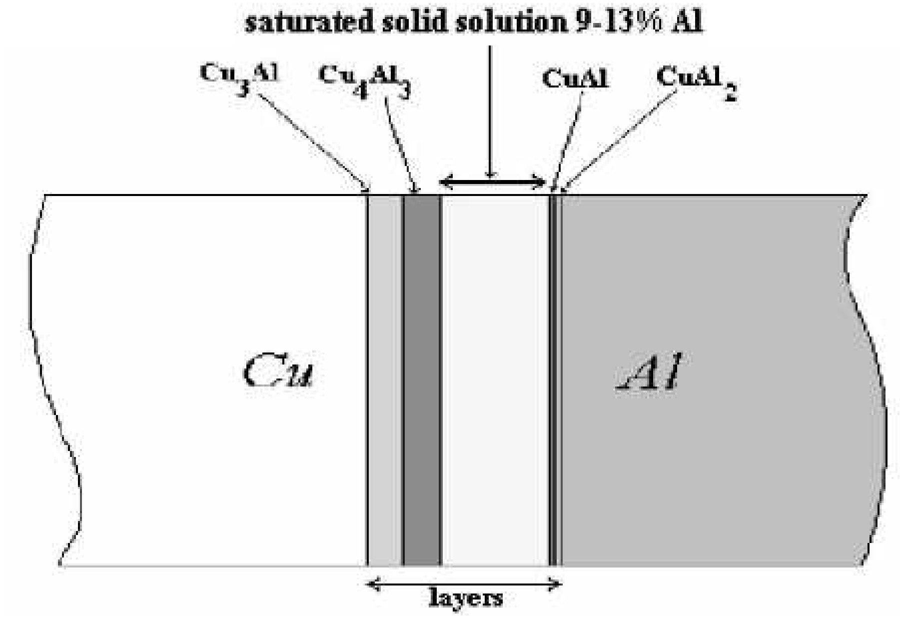


Figure 2.8 Schematic figure of intermetallic compounds and solid solution layer detected by EDX analysing(M and Taheri, 2001)

General report showed that welding of aluminium and copper by conventional welding techniques is difficult due to the deference in physical properties of the two materials. Advanced welding technology which is called friction welding is one of the processes used to weld the twomaterials. In friction welding process there are several intermetallic compounds that are appeared to decreases the weld strength. The compounds are very brittle and have low strength than the copper and aluminium. Theseintermetallic are also formed due to the thermal effect and the diffusion process during the welding process. Deferentintermetallic compounds are produced at deferent stage such as below350 degree centigrade and above 400 degree centigrade(Papkala, 2006). Thus the control of temperature is very important for limited formation of intermetalliccompounds. Onthe other hand the control of the processing parameters is also very essential to control the heat generated during the friction welding process. Based on this concept the strength of the weldment produced is essentially controlled by the amount of intermetallic formation and hence it is also determined by the processing parameters.

2.5.Intermetalics electrical property

Conductivity of intermetallic compounds is about oneseventh of the conductivity of copper or one fifth of theconductivity of aluminium, indicating that due to theformation of these compounds the total conductivity reduces highly.The decrease in the conductivity is doe to increasein the intermetallic width.Based on the report obtained from the outers presentation joint has an accepted quality if its conductivity value placed within the first part of the figure shown below where the thickness of intermetallic layers is below 2.5 micron(M and Taheri, 2001).

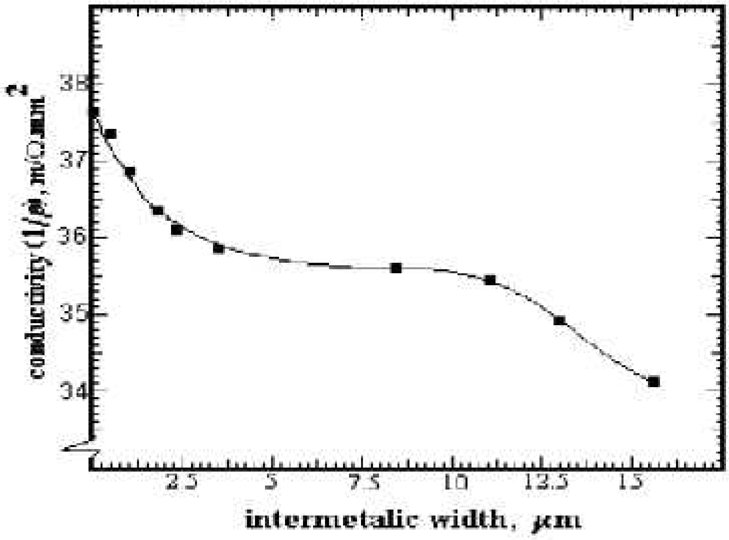


Figure 2.9Variation of conductivity with intermetallic width(M and Taheri, 2001)

According to the outer the theoretical values of resistivity of bimetal for parallel current are calculated from the following equation(M and Taheri, 2001).

$$\frac{1}{\rho_{el}} = \frac{v_{\mathrm{Al}}}{\rho_{\mathrm{Al}}} + \frac{v_{\mathrm{Cu}}}{\rho_{\mathrm{Cu}}} \quad \text{--------} \ (1)$$

From the above equation, where: resistivity of aluminium is, 0.0276V.mm /m resistivity of copper is, 0.0165V.mm /m; theoretical resistivity of bimetal is, 0.0246V.mm /m; volume fraction of aluminium is, 50.82; volume fraction of copper is, 0.18. In the absence of intermetallic compounds the theoretical value of bimetal conductivity (inverse of resistivity) is equal to 40.65 m/V.mm, while the maximum actual measured value is equal to 37.61 m/V.mm. According to the report by the outer, the deviation from theatrical calculation maybe incurred due to the inherent resistivity of the bond that is not considered in the theoretical calculation in the report (M and Taheri, 2001)

Electrical property such as resistance of Aluminium-copper joined by diffusion annealing was studied by(Won-Bae and Bang, 2005). The study uses four wire resistance measurement techniques which were previously used for resistance measurement. The aim of the study was to investigate the resistance variation due to the intermetallic formation during the diffusion annealing by temperature. The schematic presentation of the resistance measurement is shown in the figure below. The technique was used 3mm gap between the potential probes.The equipment and parameters were (0.1 micro ohm)preseason ohmmeter, constantcurrent in (m-amp), and voltage drop in (m-V). The result from the study is summarized below in schematic taken from the report reviewed.

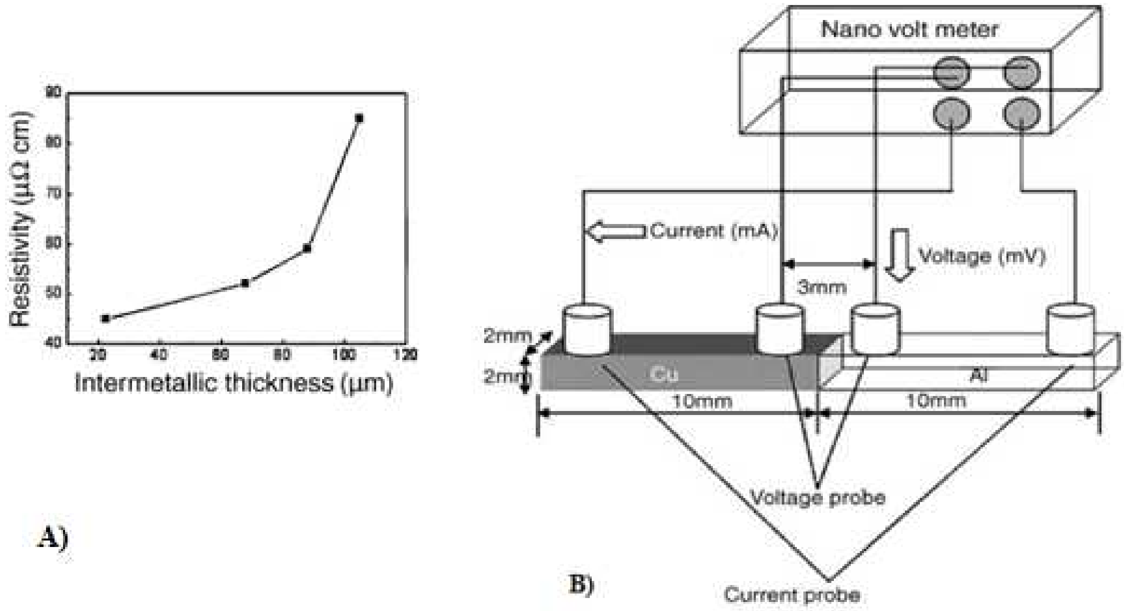


Figure 2.10 A) Relationship between intermetallic thickness and resistivity B) Four wire resistance measurement setup(Won-Bae and Bang, 2005)

CHAPTER 3 MATERIAL AND METHODOLOGY

3.1.Friction welding process

Traditionally, friction welding is carried out by moving one component relative to the other along a common interface while applying a compressive force across the joint. The friction heating generated at the interface softens both components, and when they become plasticized, the interface material is extruded out of the edges of the joint so that clean material from each component is left in place of the original interface (Uday, 2010). The relative motion is then stopped and a higher final compressive force may be applied before the joint is allowed to cool. The key to friction welding is that no molten material is generated and the weld being formed is in the solid state reported by the literature. In rotary friction welding, which has been used commercially since the 1940s, one component is rotated around its axis while the other remains stationary according to the same report taken from the outer or literature. For welding, the two components are brought together under application of pressure reported by (Uday, 2010)

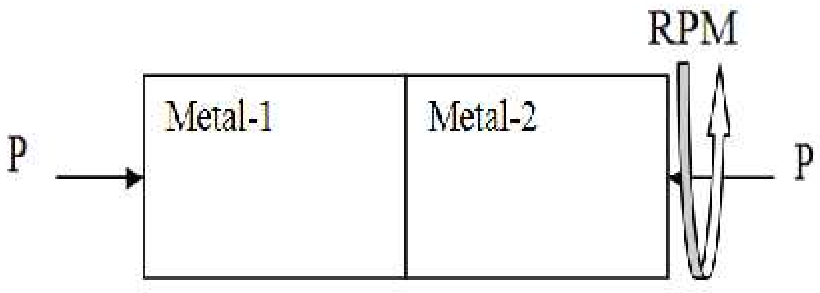


Figure 3.1Friction welding basic process

3.2.Direct drive friction welding process

In direct drive friction welding there are three basic parameters this are friction time, friction pressure and rotational speed (Maalekian, 2007).The relationship between deferent parameter is simply described in graphical. The basic process of direct drive friction welding can be categorized in three stages.

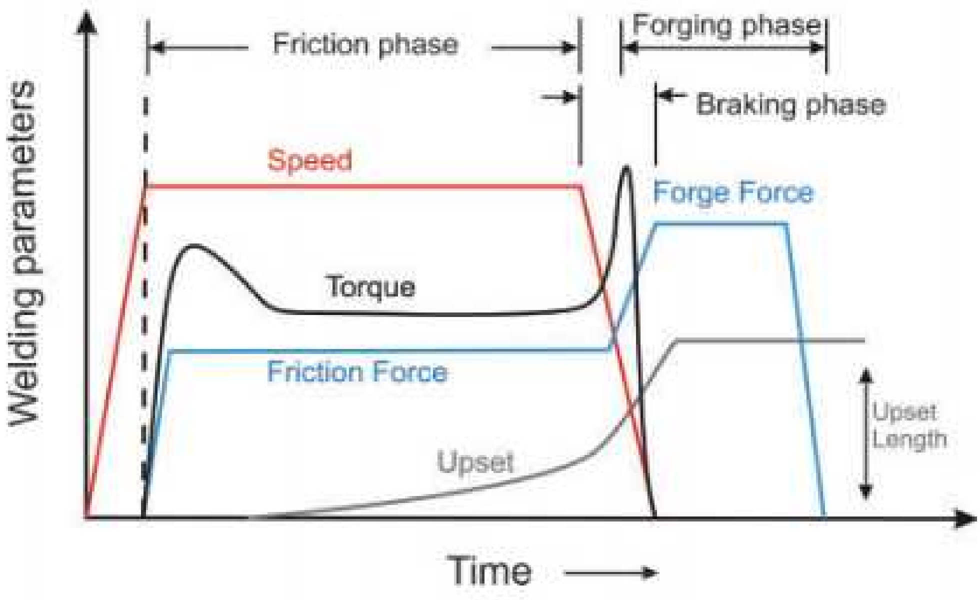


Figure 3.2Schematic variation of welding parameters with time for direct drive friction welding process(Maalekian, 2007)

In the first stage the torque rises at some value. The torque decreases to the equilibrium stage. In the second stage the torque remains constant. In the third stage the torque peak (increase to some value) and gradually decreases after the peak.In direct drive friction welding, most of the time two stage friction forces is applied; however, one stage friction force is sometimes used, particularly in research work(Maalekian, 2007).The welding heat is developed during friction and heating stage and the weld is consolidated and cooled during the forging stage(Uday, 2010).

The outer are reported that the friction welding process is generally complex process and there are number of parameters that need to be considered in friction welding process. Basically main process parameters of friction welding process are friction pressure, friction time and RPM. Other process parameters are upset pressure and upset time which are not considered in this study. Therefore this study considers three basic process parameters such as friction pressure, friction time and RPM. The process is also very similar with the basic friction welding process and it is proved that the process can be performed easily on drilling machine and it is shown in the following sections in experimental setting and experimental procedure in detail.

3.2.1. Direct drive friction welding machine

With direct drive friction welding machines, one of the work-pieces to be welded is clamped in a vice or chuck. The other work-piece is held in a cantering chuck that is mounted on a rotatable spindle. The scientific report from(O'Brien, 1997) is summarized as the spindle is driven by a motor through a single or variable-speed drive. To make a weld, the rotating work piece is thrust against the stationary work-piece to produce frictional heat at the contact surfaces as illustrated in Figure 3.1 taken from the same reference. The combination of speed and pressure raises the contact surfaces to a suitable temperature and deformation (upset) occurs. Rotation is then stopped and the pressure is maintained or increased to further upset the interface and complete the weld. A typical weld cycle is illustrated in figure 3.2 by(Maalekian, 2007). The machine spindle can be driven directly by a motor and allowed to stop under its natural deceleration characteristics and the retarding torque exerted by the weld (O'Brien, 1997).

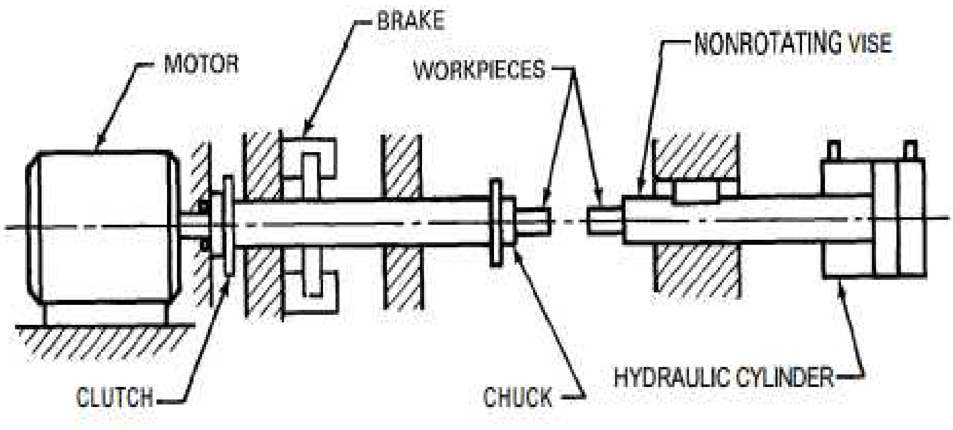


Figure 3.3Basic arrangement of a direct drive welding machine (O'Brien, 1997)

A typical friction welding machine consists of the following components (O'Brien, 1997):

- Head
- Base
- Clamping arrangements
- Rotating and upsetting mechanisms
- Power supply
- Controls
- Optional monitoring devices

From the report by (O'Brien, 1997)890 N to 275 tons (250 metric tons) maximum forge force in direct drive friction welders and up to 2250 tons (2040 metric tons) maximum forge force in inertia friction welders are available. Agiven machine can generally make welds which have a faying area range of eight to one. For example, a 30 ton (27 metric tons) maximum forge force machine can make welds in bar stock ranging from 13 mm diameter to slightly less than 38 mm diameter mild steel according to the report by (O'Brien, 1997).

Based on the basic friction welding machine requirement this research is intended to design the friction welding setup in drilling machine. As pointed in this section the friction welding machine consists of several components such as control system, drivesystem, and clamping systems. The designed friction welding setup in drilling machine is similar with the basic friction welding machine. The setup is presented in detail in experimental setup and experimental procedure in this chapter. The setup designed for this study is generally consists of stoppingsystem, clampingsystem, rotating and manual pressurising mechanism, measurement devices attached on the system. By including these systems it is possible to design friction welding setup on the drilling machine as presented in detail in experiment setup and procedure sections in this chapter.

3.3.Friction welding process parameters

3.3.1. Heating time

For a particular application, heating time is determined during the set-up or from previous experience. Excessive heating limits productivity and wastes material. Insufficient time may result in uneven heating as well as entrapped oxides and cause unbonded areas at the interface. Uneven heating is typical of friction welds in a bar stock. Near the centre of a rotating bar, the surface velocity may be too low to generate adequate frictional heating. Hence, thermal diffusion from the outer portion of the faying surface must take place to ensure a sound bond overall. for example friction time should be held as short(5 sec) as possible for AISI 304L austenitic stainless steel rod (12 mm diameter) and AISI 4340 steel couple to get good strength of the joint. From the review the outer cited that time is second significant factor for orbital friction welding process(Maalekian, 2007).

3.3.2. Speed

The choice of speed is depend on the type of material, size of the material, higher speed lead to maximum generation of heat. The amount of heat is also affects the nature of recrystallization of the joint material. The increase of intermetallic formation is also due to the increased heat of welding process. In addition to that the range of speed selection is also related with the type of material and its mechanical and physical properties.

Appropriate selection of speed is very essential for the desired quality of the weld. For example for AISI 304L austenitic stainless steel rod (12 mm diameter) and AISI 4340 steel couple high rotational speed(2500 rpm) leads to narrower heat affected zone (Ozdemir, 2005) which shows the variation of selection of the speed of rotation. In similar study of orbital friction welding process speed is very significant process variable and it is also suggested that speed is very substantial parameter for linier and rotational friction welding(Maalekian, 2007).

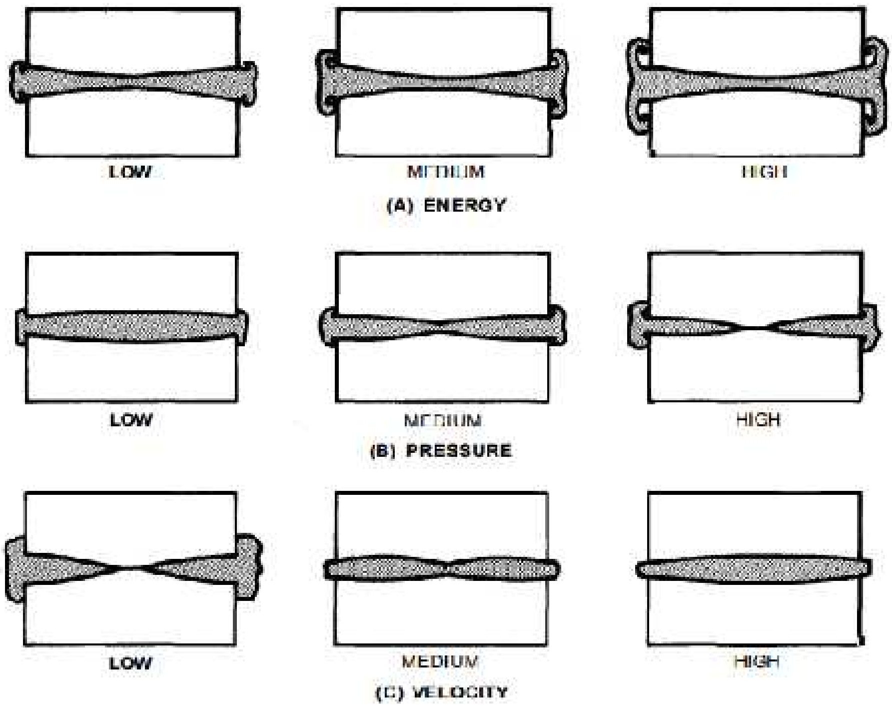


Figure 3.4Relationship between heating time and heating pressure for mild steel with continuous drive friction welding (O'Brien, 1997)

3.3.3. Pressure

The selection of pressure is also wide range based on the application and the desired response. The pressure controls the temperature gradient in the weld zone, the axial shortening and the power required for driving the workpieces. The specific pressure is depend up on the material type to be joined and the geometry of the work pieces. Friction pressure must be high ingeneral to hold the friction surfaces to the large contact to eliminate the oxidation of the materials in the welding process.

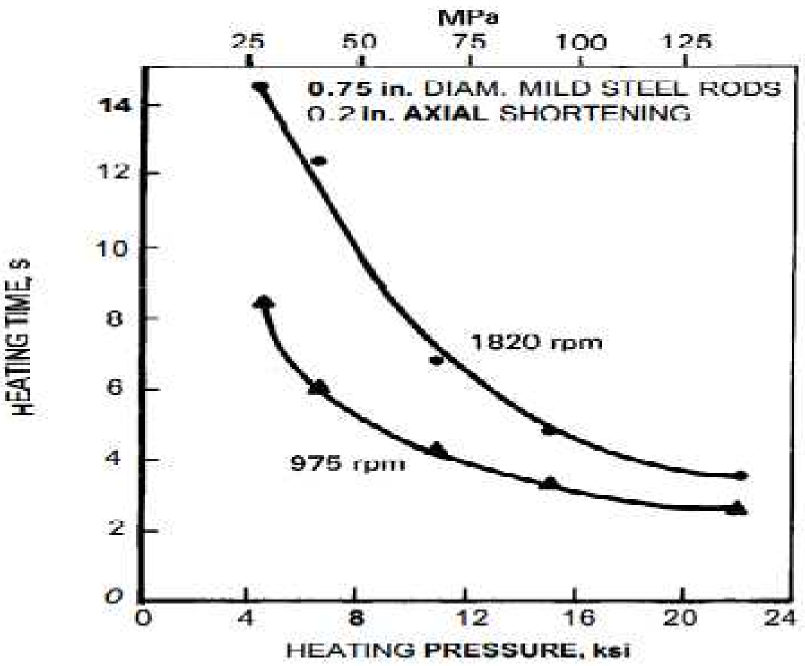


Figure 3.5Effect of welding variables on the heat pattern at the interface and flash formation of inertia welds (O'Brien, 1997)

For less speed and less pressure the result is less heating and low axial shortening in general. In orbital friction welding the outer suggested that pressure has less significant for weld quality(Maalekian, 2007).

3.4. Process parameter selection

RPM, friction pressureand friction time are the three parameters chosen for friction welding process. Based on statistical analysis simplified L9 design of experiment is used. Output parameters are electrical resistance and strength of the element. The parameter selection is difficult task and it is entirely dependent on the machine conditions. The following table 3.1 shows the selection of the parameters.

Table 3.1Input parameter selection for the friction welding process

Process parameter	Low	Medium	High
RPM	1050rpm	1550rpm	3060rpm
Friction Pressure	78 Mpa	97Mpa	117 Mpa
Friction time	5 second	15 second	20 second

Table 3.2Parameter assignment

Parameter	Low	Medium	High
RPM	Low(-1)	Medium(0)	High(+1)
Pressure level	Low(-1)	Medium(0)	High(+1)
Time of welding	Low(-1)	Medium(0)	High(+1)

3.5.Material selection

The selection of material is based on the desired application related to electrical power transmission. The selected materials are electrical materials copper and aluminium electrical conductors. Based on the friction welding requirements the materials are prepared for welding process by suitable surface preparation such as machining of contact surfaces. Other aluminium materials are available but they are not the alloy type for electrical application. The EC grade aluminium and copper electrical conductor materials are selected to meet the required electrical and physical properties required for specific application for electrical power transmission.

3.6. Workpiece preparation

The aluminium and copper metal are prepared into pieces of rod. The work piece length is dependent with the machine and the fixture dimensions.Buckling of the work piece is difficult problem that need to solve. The buckling problem is solved by minimizing the length of the work piece. The other problem is the off entering of the work piece from the axis of rotation. The main reason of centring problem is the machine rigidity or vibration of the machine during operation at maximum rpm and maximum pressure.

The diameter of the work pieceis 8mm and 9.5 mm for (copper and aluminium respectively. The workspaceimageis shown in the figure below. To enhance the welding process diameter of copper should be smaller than aluminium. Inaddition to that work piece surface should be very flat and smooth to enhance the friction heat.

Figure 3.6The workpiece

The work piece should be straight to eliminate the vibration of thework piece on its axis of rotation. For aluminium thermal expansion expands the material from the weld area and large axial shortening cause the decrease in the length. To compromise loss of material and axial shortening proper length should be given for aluminium.

Lathe machines used for surface preparation, the circular part is face and turn to reach the final dimensions. No additional surface cleaner solution is used in surface cleaning; this is because the surface is free of dirt when it is machined.

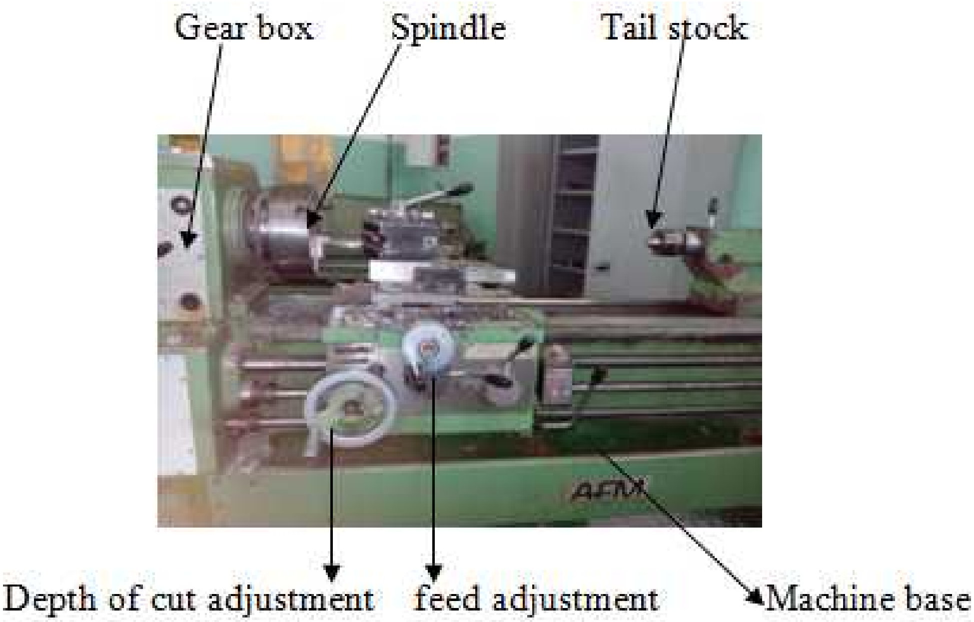


Figure 3.7Lathe machine (Manufacturing engineering machine shop)

3.6.1Material property

The materials selected for this study have several properties including electrical property, mechanical property and they have specific alloy percentage used for electrical type copper and aluminium materials. The summarized mechanical property, electrical property and alloying element percentage contribution is given in the following tables for aluminium and copper EC grade materials.

Table 3.3Copper material data

Size(mm)		8mm	
Standard/specification		ASTM B49/ISBN 1977	
.Sr. No	Parameters	Specification	
		DUCAB	ASTM B49
1	Oxygen(ppm)	200-400	100-165
2	Surface oxide(angstrom	Max.500A	Max.750A
3	Diameter variance(mm)	±0.38	±0.38
4	Conductivity %IACS	> 101 IACS	Min.100
5	Elongation%	> 40	Min.30
6	Tensile strength(N/mm	>220-240	--
7	Surface	Smooth surface	Smooth surface
CHEMICAL ANALYSIS			
Element	ASTM B49	BSEN 1977	
Selenium	2 ppm	2	
Tellurium	2 ppm	2	
Bismuth	1 ppm	2	
Group total(Se+Be+Ti)	3 ppm	3	
Antimony	4 ppm	4	
Arsenic	5 ppm	5	
Tin	5 ppm	-	
Lid	5 ppm	5	
Iron	10 ppm	10	
Nickel	10 ppm	-	
Sulphur	15 ppm	15	

Silver	25 ppm	25
Total impurities(max.in.ppm)	65 ppm	65
Copper%	99.98%	
Co+Fe+Si+Sn+Zn+Ni maximum- 20 ppm		

Table 3.4Aluminium material data

Standard/Specification		ASTM H14/1350		
Size(mm)		9.5		
Tensile strength(Mpa)		103-138		
Elongation % min (250 mm gauge length)		15		
Resistivity Ω[illegible]n .max		0.028080		
Equivalent volume of conductivity % IACS.min		61.4		
Element %	DAC specification		ASTM B233	
	min	Max	min	Max
Aluminium	99.7		99.5	
Silicon		0.1		0.1
Iron		0.2		0.4
Zinc		0.02		0.05
Gallium		0.02		0.03
Vanadium + Titanium		0.02		0.02
Copper		0.05		0.05
Manganese		0.01		0.01
Chromium		0.01		0.01
Boron		0.05		0.05
Arsenic		0.009		-
Heavy elements(Cd+Hg+Pb)		0.0095		-
Other elements each		0.03		0.03
Other elements total		0.1		0.1

3.7.Optimization method

Gray relational analysis TAKUCHI and ANOVA is used to optimize multiple output performance. Optimization of multiple performance characteristic such as resistance and mechanical strength is conducted.

For the multi-performance characteristic optimization the following process of calculation are performed.

- The normalization of the process output data.
- grey relational coefficient calculation from the normalized data
- Gray relational grade calculation from gray relational coefficients and obtaining the optimized parameter setting from gray relational grades.
- Analysis of variance (ANOVA) of the final simplified single output from the gray relational analysis grade.
- Confirmation test.

3.7.1. Optimization formula

Table 3.5Gray relational analysis formulas(Hasani, 2012),(Lin, 2004)

Equation	Meaning of the symbols
$x_i(k) = \frac{y_i(k) - \min y_i(k)}{\max y_i(k) - \min y_i(k)}$	Normalizing Higher is the better x_i(k)=the value after gray relational generation y_i(k)=the smallest value of y_ik for the kth responce Maxy_i(k)=is the largest value ofy_i(k)= for the kth response.
$x_i(k) = \frac{\max y_i(k) - y_i(k)}{\max y_i(k) - \min y_i(k)}$	Normalizing Lower is the better
$\xi_i(k) = \frac{\Delta_{\min} + \zeta\Delta_{\max}}{\Delta_{0i}(k) + \zeta\Delta_{\max}}$	$\xi_i(k)$=the grey relational coefficient ζ=distinguishing coefficient If all the parameters are given equal preference, is taken as 0.5

	Deviation sequence Δ_{0i}=absolute value of $x_0(k) - x_i(k)$ Δ_{min}=absolute value of $x_0(k) - x_j(k)$=smallest value of Δ_{0i} Δ_{max}= absolute value of $x_0(k) - x_j(k)$=largest value of Δ_{0i}
$$\gamma_i = \frac{1}{n}\sum_{k=1}^{n} \xi_i(k)$$	γ_i=Gray relational grade n=number of process responses
$$SS_T = \sum_{j=1}^{p} (\gamma_j - \gamma_m)^2$$	SS_T = total sum of the squared deviation γ_j=total mean of gray relational grade
$$\hat{\gamma} = \gamma_m + \sum_{i=1}^{q} (\bar{\gamma}_i - \gamma_m)$$ $$CI = \hat{\Phi} \pm \sqrt{F_{\alpha;1;fe} \times V_e \times \left(\frac{1}{n_{eff}} + \frac{1}{r}\right)}$$	$\hat{\gamma}$ =estimated total mean grey relational grade γ_m = Total mean of the grey relational grade $\bar{\gamma}$=Mean of the grey relational grade at the optimal level q=Number of cutting parameters that significantly affect the multiple performance characteristics CI=Confidence interval

3.8.Experimental equipments

3.8.1. Hydraulicpressure gage

The load or the pressure on the system is possible to measure based on the drilling machine construction itself .Under the spindle opening it was placed pressure gage which indirectly séance the pressure level on the work piece.Friction welding of the two workspaces requires the application of pressure in deferent levels. The piston pressure is applied; the pressure coming from the hydraulic piston directly transferred to the work piece. And the piston pressure is measured by the pressure gauge attached directly in the piston assembly. The actual pressure on the sample is calculated and presented in the following table 3.1.

3.8.2. Stop watch

The time duration friction welding is measured by using external stop watch. Friction time is the time required when the workspaces are rubbing together until welding ends and the spindle rpm stops rotating. In each experimental run time is recorded accordingly for the number of experiments. The duration is from (5-20) minimum and maximum respectively.

Figure 3.8Stopwatch for recording the duration level of the friction welding process.

3.8.3. Infrared thermometer

The infrared thermometer shown in the figure is representing the methodin which the temperature is recorded in remote sensing design. For each process temperature data is taken and the average temperature for the process is calculated and presented. The temperature increases from initial to final stage of the process. The maximum temperature is 190 degree centigrade. Near the interface the temperature is maximum and decreases when it is far from the weld interface.

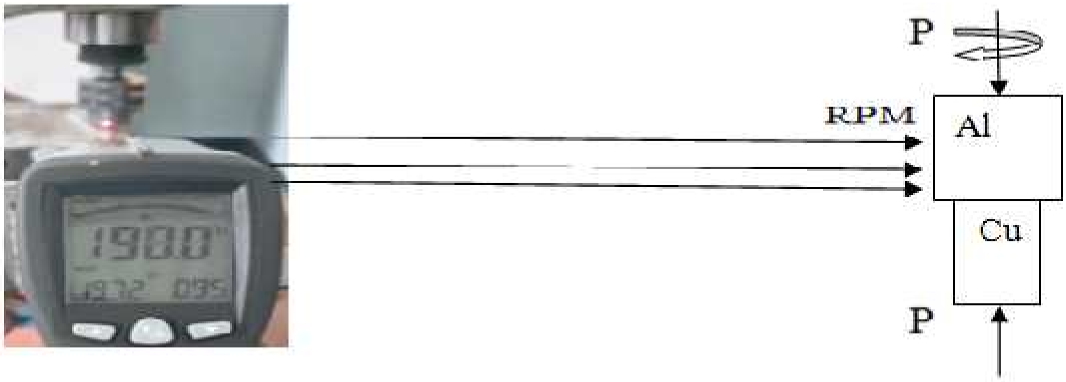


Figure 3.9Infrared thermometer remote temperature sensing system

3.9.Experimental setup

In this psrticular study vertical driling machine is used forfriction welding process.The machine specification is 3060 RPM, 1.7 KW hource power.Detail machine setup is presented in figure 4.3.workpiece holding and hydraulic presure gage is shown clearly in the figure.the hydraulic oil aded cylinder and piston is placed as shown in the arow.the upward force force is aplied from the downward table and it is directly transfered to the workpiece area.the force is also transfered from the workpiece to the presure gage.the presure gage sence the force/presure aplied to the hydraulic oil inside the piston cylinder arangment.the figure shows the picture of the piston cylinder and the presure gage.for each experiment the presure gage reads the presure on the workpiece from (78-117Mpa),this presure is converted by relating the force aplied to with the workpiece area.

A) Lower workpiece holder **B) Upper workpiece holder**

Figure 3.10 Workpiece holders

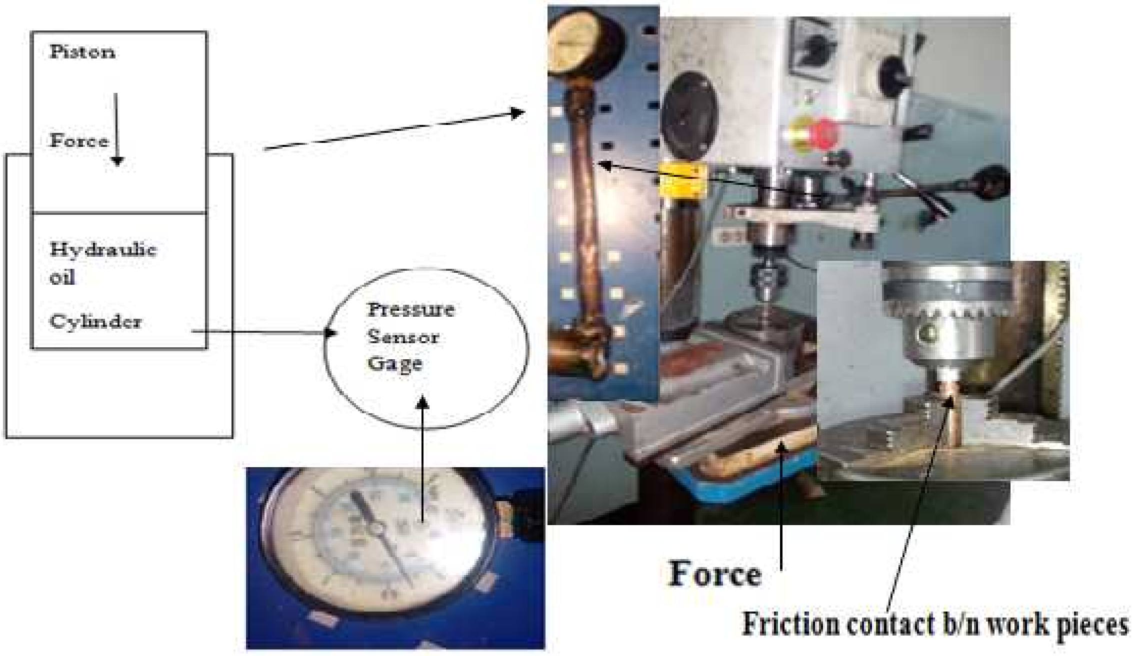


Figure 3.11Friction welding setup

4.9.1. Experimental procedure

First the drilling machine is rotated to some speed. Then the work pieces are frictionally contact each other with the application of gradual pressure from the table of the drilling machine. The pressure is indicated in the gage setup as shown in figure 5.4. The work pieces are allowed to friction for specified time when the pressure is applied. The machine spindle stopped when the material is plasticized and constant pressure applieduntil removal of the sample. The speed the pressure and the time are recorded for each experiment. The measurement methods for these parameters are presented in the previousdiscussion.

In the folowing figure 3.12 each components are presentied with arow showing the actual placement of the devices and components which are esential in this welding experiment. The workpiece copper and alumnium in their corect location on the clamping ,the atached presure gage the machine control unit such as suden stoping and rotational speed changer are all clearly seen in the figure.

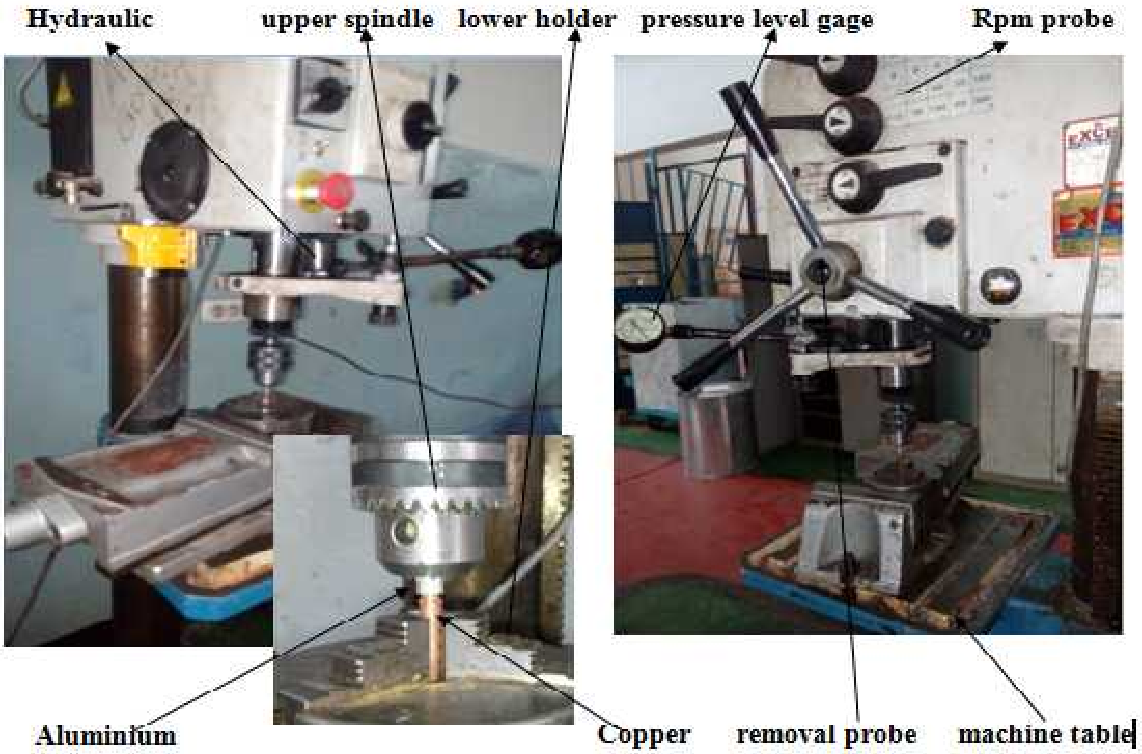


Figure 3.12Experimental setup

4.9.2. The weldment

Weldment of aluminium and copper on drilling machine is shown in the figure below.The experiments are performed in series by recording the friction time the RPM and the friction pressure. Eachweldment is performed in specified parameter value. The next stage is to perform tensile strength and resistance test on each specimen. Each specimen has length of 10 cm and diameter of copper and aluminium is 8 and 9 mm respectively.

In figure 3.13 the presentation of the weldments produced from friction welding experiment is given. The figure shows the actual friction welding experiment result with no size reduction the initial weldments and the figure shows the size reduced and extra material during the welding process removed are all given in the same figure. From this figure it is important to note that the final friction welding tensile specimen is used directly from the initial weld sample itself, this is because with the same diameter the ultimate tensile strength is not affected by the length and shape of the specimen its only effect is on its elongation which is not considered in this study which is only the aim is to determine the ultimate tensile strength of the weldment.

Figure 3.13Results of nine samples friction welding of aluminium and copper from the experiment performed on the drilling machinewith deferent parameter seting with final finished weldment

It is clearly seen that to check the ultimate tensile strength of the weldment it is possible to use tensile test machine by directly griping on the opposite side of the specimen on the tension force pull of the tensile test machine. Figure 3.13 is also clearly shows the extra material removed or machined weldment is shown. This machined weldment is used for producing the electrical connector as given in chapter one in this document or in the appendix section of this document.

4.10.Tensile strength test

Tensile test machine is used to measure the tensile strength of the friction welds .The machine has 10 KN tensile test machine .it is available at BELAYAB CABLE FACTORY. After the tensile load is known from the test machine the strength can be calculated by dividing the load by the work piece area. For example for experiment no 8 the tensile force is 5.07 KN and the work piece area is 50.24mm square. And tensile strength is force divided by area and it is obtained as 100.915Mpa.

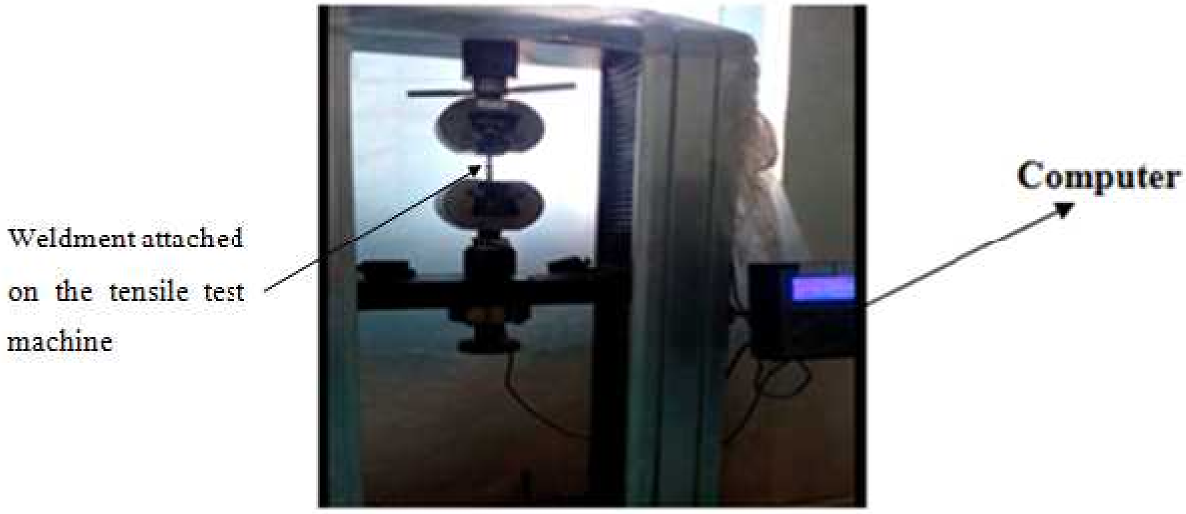


Figure 3.14 Tensile test machinecapacity of 10 KN

4.11.Electrical measurement

The contact resistance is defined as the ratio the voltage across the contact to the current flowed through a closed pair of contacts. In figure 3.10, there is an interface between the metal 1 and metal 2 which is contact resistance. The current, I, which coming from the current source flows through this interface, can be read from a current meter. And then the voltage drop across the interface can be read from a voltage meter as, U. Then the contact resistance value R_x can be calculated by the following equation(Min, 2005).

$$R_x = \frac{U}{I} \quad ---(2)$$

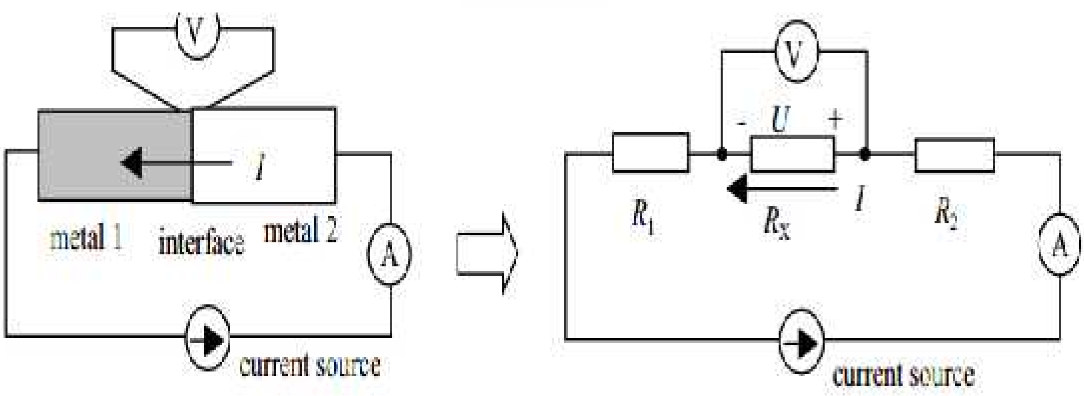


Figure 3.15Circuit diagram of kelvin plank 4- wire resistance test (Min, 2005)

There are 4 kinds of reason to induce the measurement uncertainty when measuring contact resistance(Min, 2005):-

- The definition of contact resistance is not perfect. The voltage drop across the contact includes the voltage drop of the bulk, inevitably. So the voltage-measuring terminals should be connected as closely as possible to the contact area under test. This will help to prevent the voltage drop, which is caused by the test leads and bulk resistance, from being added into the measurement.
- The oxide film and dust between pairs of contact have been changing with heat. The conductivity of contact has been changing with the temperature uncertainly.
- The stress on the contact could influence the area of contact, and then influence the value of contact resistance. The stress changed with temperature, air pressure humidity and time.
- Some measurement uncertainties of contact resistance have been also caused by measurement instrument.

Due to this points mentioned above, there is measurement uncertainty. However the Kelvin planks four wire resistance test method is very good and approximate method employed for measuring contact resistance in small amount.

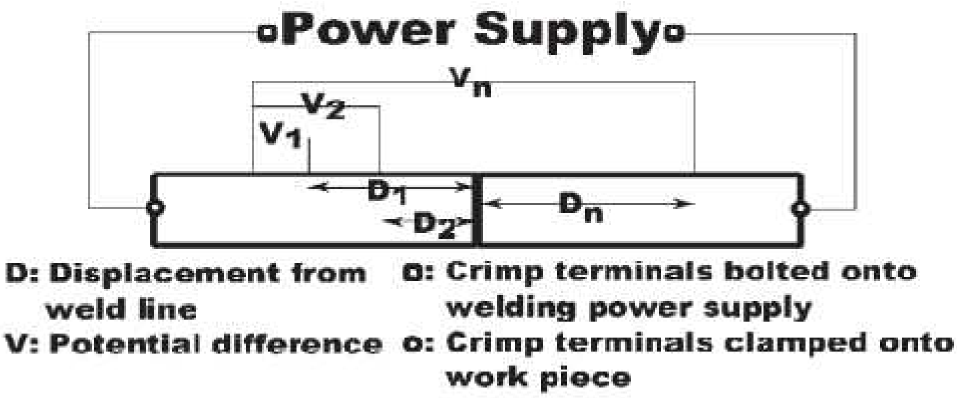


Figure 3.16Electrical resistance measurement(Bhamji, 2012)

3.11.1. Sample preparation for electrical measurement

Total of nine weldments are produced for electrical test. The weldment is reduced from the original size to 7 mm diameter. All the samples are equal in diameter; this is because the resistance electrical property varies when the size is deferent. The sample preparation is done as usual on lathe machine by turning the original weldment. The electrical measurement that is needed to be conducted is resistance variation between the weldments when constant current pasestherough the weldments the voltage drops and resistance is found from voltage drop and constant current flow inside the weldment. The resistance across the weldment is performed by using Kelvin four wire resistance test procedure as shown in figure 4.8. The resistance is found from the voltage drop test when constant current is passed through the weldment. Similar procedure is performed in all the weldments shown in figure 4.9.the result is presented in the next chapter for discussion

Figure 3.17Samples for electrical resistance measurement

3.11.2.Experimental setup for resistance measurement

Sample is prepared for the resistance measurement. All the samples are equal in diameter and each has diameter of 5mm.No matter to the sample length because small portion of the sample is used.The resistance measurements are shown. The circuit is designed based on the voltage drop principle and Kelvin four wire test method(Min, 2005). The test is performed by adjusting the current amount in three levels. This is done because of the voltage drop is minimum and to get significant voltage drop the current level is adjusted for three stages to get the final reading. The step increase of the current is100 m-amp,2000m-amp and 10000 m-amp. The voltage is resolved from the voltmeter at 2000 m-amp and based on this current level the resistance are calculated from the equation below.

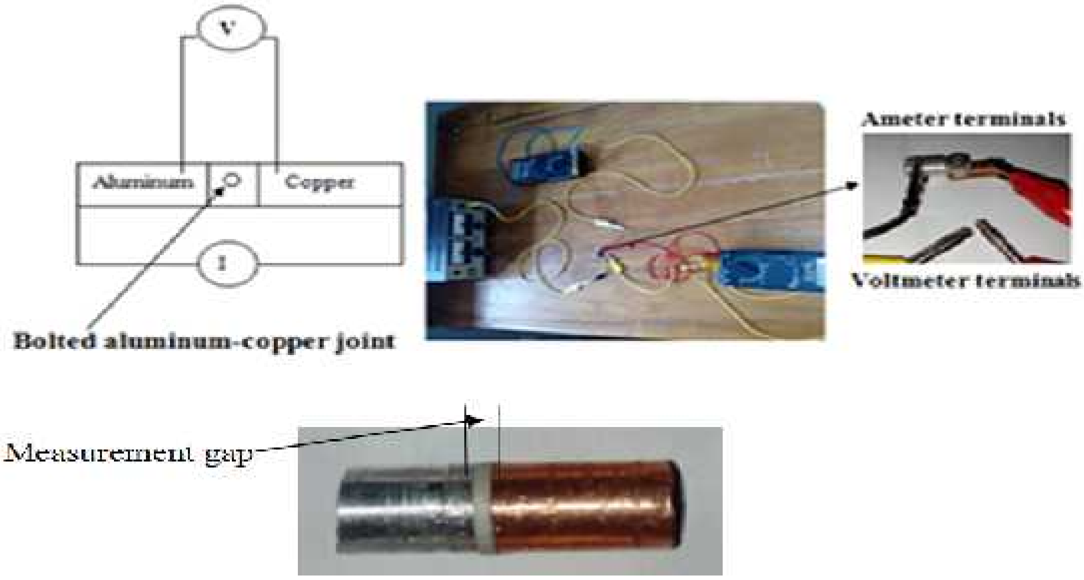


Figure 3.18 Resistance measurement circuit

The advantage of four wire resistance measurement technique is its ability to measure the contact resistance correctly and do not include the resistance of the wire connected to the contact probe (Milenko, 2007). This is because no current is flowed through the voltage measuring wire and on the contact probe due to no current flow no voltage drop exist due to the wires and the contact probes.

Currently micro ohmmeter precision of 0.01micro ohm is available and probe spacing 1mm current of 10Amp can be used to measure small resistance (Milenko, 2007). Measurement of resistance has many disturbances as presented in the literature chapter of this study. it is reported that the accuracy of the resistance value is mainly depend on the inclusion of the bulk material resistance and inclusion of resistance by other factors such as dislocation, porosity at the interface and resistance variation due to temperature change. From the literature reported in chapter two it is fact that the resistance of the intermetallic compound formed during the welding process is very much higher than the resistance of the bulk material itself. Due to the thickness of intermetallic compound formed is very small in thickness in micro-meter level the resistance resulted from intermetallic is very small which has very small effect on the friction welded specimen. And it is possible to produce specimens with approximate precision from the first wedment and test with the available equipment.

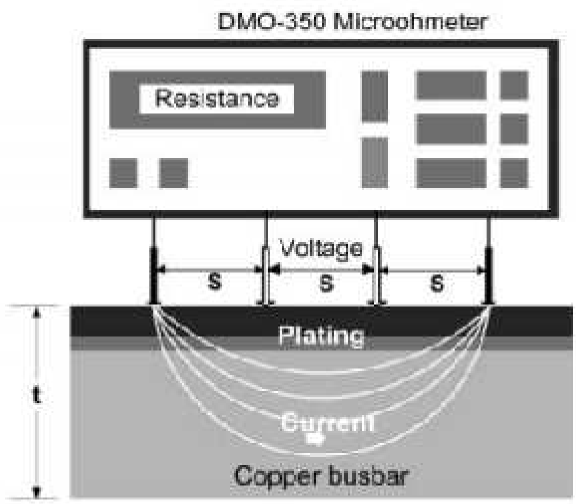


Figure 3.19Four-probe resistance measurements assembly (Milenko, 2007)

Figure 3.20Digital voltmeter and ammeter

V= I R ((Kuphaldt, 2006)------------ (3)

Where:

V=voltage drop

I=current inside the test specimen

R=measured resistance from current and voltage drop

3.12.Microscopic observation

Optical microscope is used to seejoint structure. The surface is firstly made smooth before the specimen is observed under microscope. The observation is used to see the micro structure of the joint interface region. Joint layer is tried to see by performing specific sample. The process of sample preparation is as follows:

- Mounting with mounting machine
- Grinding with deferent size grinding pepper.
- Polishing with polishing machine repeating polish and dry with high speed compressed air
- Etching with chemical reagents such as (KELLERS) reagent found from materials engineering lab for aluminium side,aluminium and copper interface etchant by 2.5 g Fe Cl_3 powder with 5 ml distilled water, and copper etched by 25 ml HCl,2.5g Fe$Cl_3$and 50 ml distilled water. All reagents are reacted in ordinary room temperature. The mounting schematic is observed in the figure below.

Table 3.6Etchant chemicals used for microscopic surface preparation.

NAME OF ETCHANT	REAGENTS	APPLICATION
KILLERS		aluminium surface etching
Al-Cu Interface etchant	by 2.5 g Fe [illegible]owder with 5 ml distilled water	interface surface etching
Copper etchant	25 ml HCl,2.5g Fe [illegible]nd 50 ml distilled water	copper surface etching

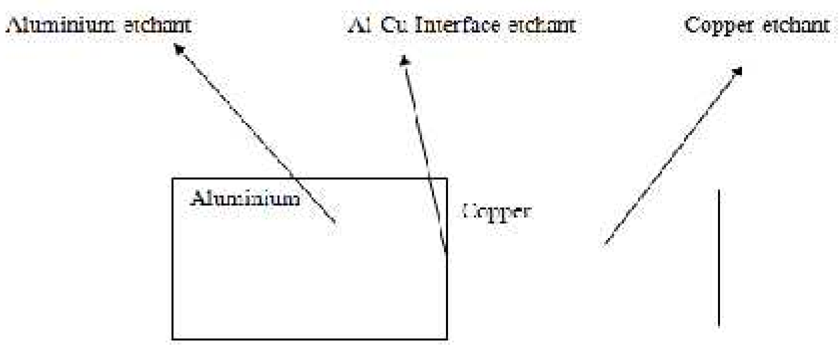


Figure 3.21Deferent parts of the specimen etched by chemical

CHAPTER 4 RESULT AND DISCUSION

In this chapter the results and the finding is discussed. The resistance and tensile strengthis presented and the optimization of these process parametersusing gray relational analysis and ANOVA are presented.

4.1.Tensile strength and electrical resistaancemeasuremnt results

Based on the MINITAB software L9 design of experiment is selected. Three factors RPM,friction pressureand frictiontime is used and the values of the parameter are presented in detail in table 4.1.

To obtain the tensile strength the tensile force is divided by the area of the weldment. The tensile test machine records the tensile force and by dividing this force by the area the tensile strength is calculated and presented in table 4.1 below.

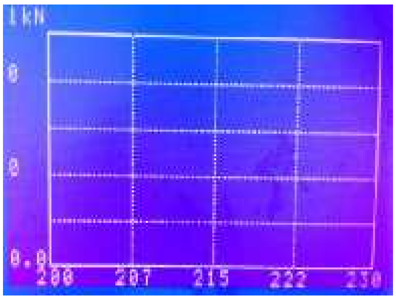
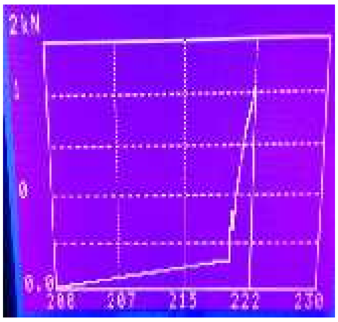
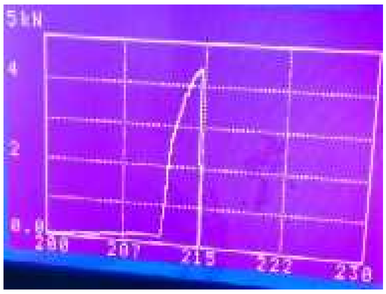
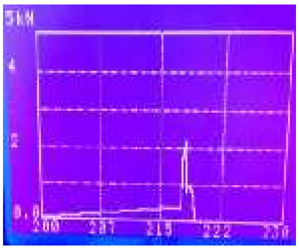
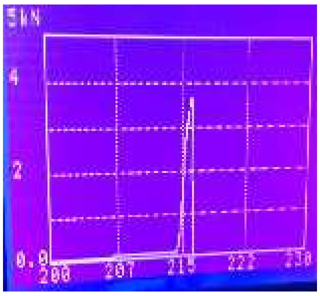
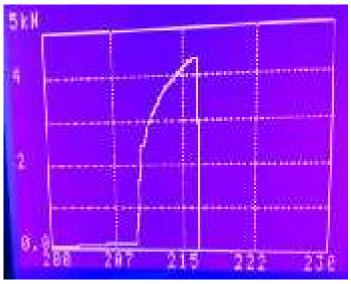
Resistance is in ohm is obtained from the current and voltage values on ammeter and multimeter presented in the material and methodology chapter. The voltage is the value of the potential drop across the test specimen (welding interface). On the other hand the current value is the constant current supplied by the system to the test specimen and flowing through it constantly. Finally as stated before the resistance is easily obtained by dividing the voltage drop to the current and it is given in table 4.1 below.

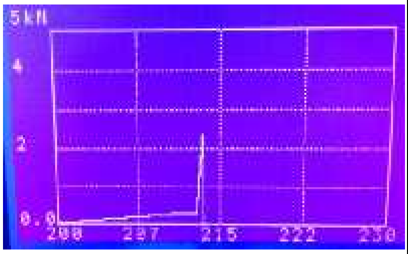
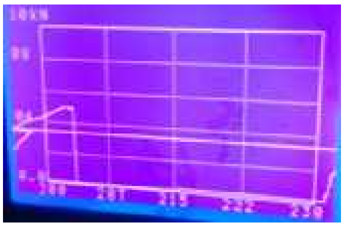
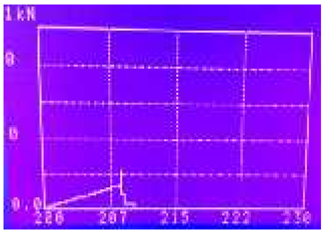
Table 4.1Tensile strength and resistancemeasurement results

EXP Run	Friction time	Friction Pressure	RPM	Ultimate Tensile strength Mpa	Load at Breakage (KN)	Resistance (Ohm)	Average Temperature in degree centigrade
1	5	78	1050	1.393	0.07	2.5×10 [illegible]	40.39
2	5	97	1550	32.444	1.63	1.5×10 [illegible]	39.18
3	5	117	3060	87.978	4.42	1.5×10 [illegible]	110.13
4	15	78	1550	43.789	2.2	1.5×10 [illegible]	67.48

5	15	97	3060	72.651	3.65	2×10[illegible]	65.42
6	15	117	1050	86.783	4.36	1.5×10[illegible]	65.84
7	20	78	3060	47.373	2.38	1.5×10[illegible]	95.62
8	20	97	1050	100.915	5.07	1.5×10[illegible]	52.34
9	20	117	1550	4.378	0.22	1×10[illegible]	120.7

Table 4.2Result of tensile test

Experiment 1	Experiment 2	Experiment 3
No graph for small load  Peak=0.07 KN Ultimate tensile strength=1.393Mpa	 Peak=1.63 KN Ultimate tensile strength=32.444MPa	 Peak=4.42 KN Ultimate tensile strength=87.977Mpa
Experiment 4	**Experiment 5**	**Experiment 6**
 Peak=2.2 KN Ultimate tensile strength=43.789Mpa	 Peak=3.65 KN Ultimate tensile strength =69.665Mpa	 Peak=4.36 KN Ultimate tensile strength =86.783Mpa

Experiment 7	Experiment 8	Experiment 9
 Peak=2.38 KN Ultimate tensile strength =47.372Mpa	 peak=5.07 KN Ultimatetensile strength =100.915Mpa,Area of workpiece=50.24square- mm	 Peak= 0.22 KN Tensile strength =4.378Mpa Ultimate tensilestrength=Ultimate(peak load)/area of workpiece

4.2.Gray analisis of multiperformance optimization

Normalization of the data is presented in table 4.2 based on the normalization formula presented in chapter 3.For normalizing the data, there are two deferent case. The first case is the response is optimized for larger value. The other case is the response is optimized for smaller value. In this case the tensile strength is optimized for larger value and the resistance is optimized for lower value.

Table 4.3Normalization of the response

Experimental No	Ultimate Tensile Strength After data processing (normalizing)	Resistance After data processing (normalizing)
Reference sequence	1.000	1.000
1	0.000	0.0000
2	0.312	0.6666
3	0.87	0.6666
4	0.426	0.6666
5	0.716	0.3333
6	0.858	0.6666
7	0.462	0.6666

8	1	0.6666
9	0.03	1.0000

Table 4.4Deviation sequence

Experimental run	Ultimate Tensile strength After data processing (normalizing)	Resistance After data processing (normalizing)
Deviation sequence	$\Delta_{0i}(1)$	$\Delta_{0i}(2)$
1	1	1.0000
2	0.688	0.3334
3	0.13	0.3334
4	0.574	0.3334
5	0.284	0.6667
6	0.142	0.3334
7	0.538	0.3334
8	0	0.3334
9	0.97	0.0000

From table 5.3 the resistance variation is very negligible from one experiment to another. Non variable measurement result of resistance indicates the electrical resistance is not the variable response for the process. From the measurement result the variation of the resistance is very small when the process is varying from one to the other input parameter thus another additional response is needed for optimization. In application point of view if resistance is the only important response needed for final output then any combination of process parameter yield good weldments of negligible resistance. In this study resistance and tensile strength of the weldment is equally important and the two performance optimization of process parameter is essential and needed to obtain best process parameter.

Table 4.5Gray relational coefficient and Gray relational grade

Experimental No	Gray relational coefficient		Grey relational grade $\gamma_i = \frac{1}{n}\sum_{k=1}^{n}\xi_i(k)$	Rank
	P $\xi_i(1)$	R $\xi_i(2)$		
1	0.3333	0.3333	0.33330	9
2	0.4208	0.5999	0.51035	8
3	0.7936	0.5999	0.69670	2
4	0.4655	0.5999	0.53270	7
5	0.6377	0.4285	0.53310	6
6	0.7788	0.5999	0.68935	3
7	0.4816	0.5999	0.54075	5
8	1.0000	0.5999	0.7999	1
9	0.3401	1.0000	0.67005	4

From the result presented in table 5.4 tensile strength is varying throughout the experiment. This clearly shows that tensile strength of the weldment is largely influenced by the process parameter. from the above discussion the maximum tensile strength is at experiment no 8 which indicates that the process parameter selection is very important for obtaining good weldment quality overall. In this analysis the electrical resistance and the tensile strength are simultaneously combined to obtain best parameter for improvement of both output responses. Gray relational results presented in tables 5.2 through 5.3 are the analysis process and result for two desired outputs optimization of the responses presented in the previous discussion.

In the table 4.4 the larger the gray relational grade represents the higher the relational between the variables and the lower the gray relational grade is less relational between the variables. From the table 4.4 experiment no 8 is the most powerful relation between the output parameters. In this analysis multi objective optimization is converted to single gray relational analysis in table 4.4 shown. From the gray relational analysis we can optimize the multi performance of two output parameters such as resistance and strength. The gray relational grade is analysed based on main effect plot to get the optimum parameter settings for multi performance as shown above.

4.3.Main efect plot of gray relational grade

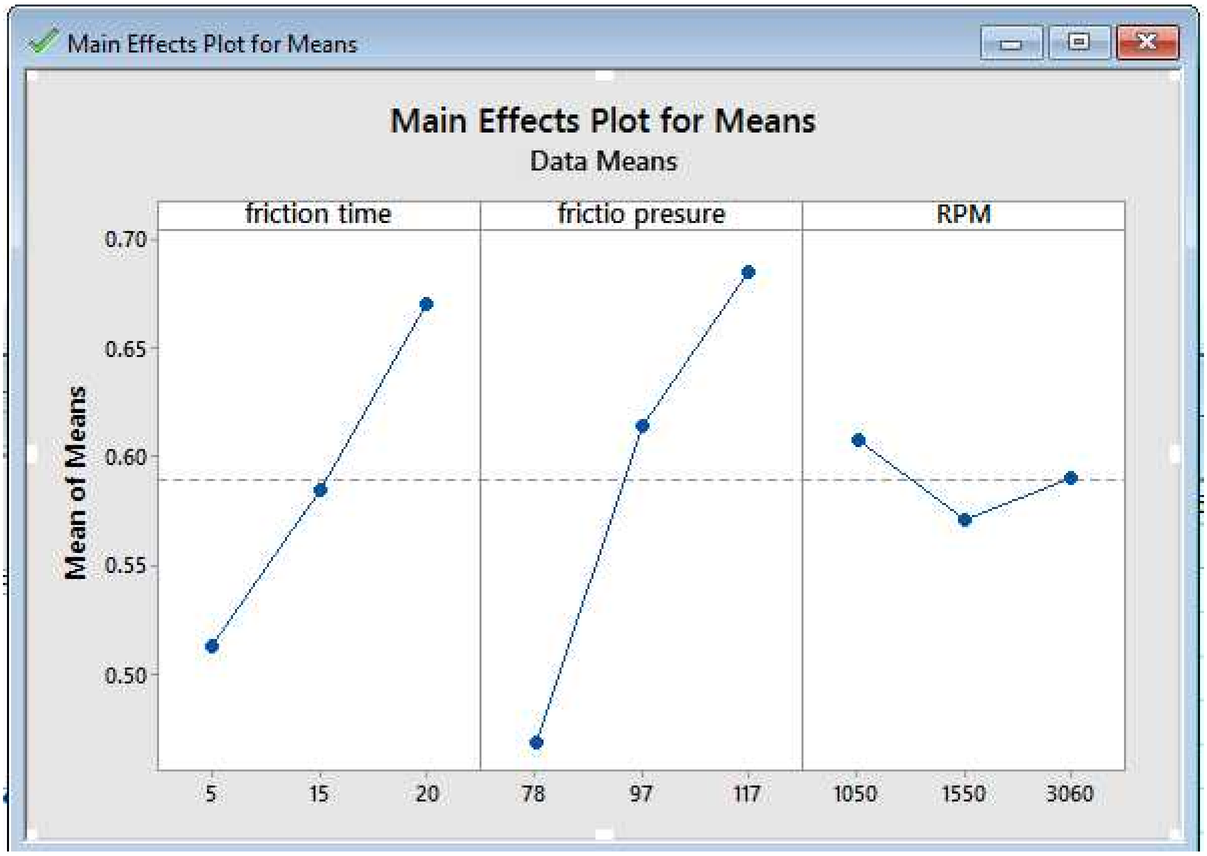


Figure 4.1TAKUCHI/ANOVA analysis main effect plot of gray relational grade

Table 4.6Response table for means

Level	friction time	fraction pressure	RPM
1	0.5134	0.4689	0.6075
2	0.5850	0.6144	0.5710
3	0.6702	0.6853	0.5902
Delta	0.1568	0.2164	0.0365
Rank	2	1	3

NOTE: Total mean of the gray relational grade which is 0.5896.

Optimal level of the process parameters based on the above discussion is friction time is 20 (s), friction pressure is 117 (Mpa)and 1050 (RPM) based on main effect plot.Rotational speed at high level (1450 Rpm), friction pressure at low level (39.2 Pa) and friction time at low level (4 s) was give optimum result for mechanical strength according to(Rosli, 2015).The result from this analysis is very deferent from the result from literature.The deference in the result may be from two reasons. The optimization for present case is for two performance strength and electrical resistance simultaneously, but from the literature the response is for strength.Form table 5.5 the friction pressure is pressure is most important parameter and RPM is the second important parameter. Friction time is the list important parameter for two response performance (strength and electrical resistance).

4.4.ANOVAanalisis

Table 4.7Analysis of variance for gray relational grade

Source	DF	Adj SS	Adj MS	F-Value	P-Value
friction time	2	0.036956	0.018478	0.90	0.525
frictiopresure	2	0.073050	0.036525	1.79	0.359
RPM	2	0.002000	0.001000	0.05	0.953
Error	2	0.040894	0.020447		
Total	8	0.152900			

The percentage contribution of the input parameters is shown in table 5.7 and ANOVA analysis. The result shows the higher percentage contribution for the process is friction pressure which is 48% and the next contribution is from the friction time which is 24% and RPM has very small contribution for the process which is 1.333%.

From a weld quality standpoint, speed is not generally a critical variable; that is, it can vary within large range without affecting the quality of the weld. For example, a spindle speed of 600 RPM can be used to weld steel products of to 50 to 101 mm diameters.For certain dissimilar metal continuations, low velocities (and their shorter heating times) can minimize the formation of brittle intermetallic compounds. In practice, however, heating time (for a given amount of upset) is usually controlled by varying the friction welding pressure(O'Brien, 1997).

4.4.1. Friction pressure

When the pressure increased from low to high the friction heat increases. On the other hand at given rpm when pressure is very low the friction heat is also very low. Friction heat is very crucial for the joining process; this is because heat is used to facilitate the interdifusion or migration of atoms from both materials in friction welding(Milenko, 2007).Basically friction welding is solid state welding processes because the workpiece is not melted like fusion welding process, only the metal is plastically softened below the melting temperature. The process takes place in to three stages (1) Heating stage (2) Welding stage and (3) Forging stage. The first heating stage is used to heat the metal to particular temperature well below the melting temperature. In welding stage the metals are welded together by migration (diffusion) of atoms from one another.

Frictional heat is the heat source in this type of welding process and the heat is generated when the metals are rubbing together with high pressure application. The amount of pressure is deferent varied from the type of metals and the size of the workpiece. Pressure value of 97-117Mpa is used in this study and the value is also much related with the literature. Generally the amount of the pressure is determined by the metal type, the parameters such as friction time, speed and also the size of the workpiece. The process of friction welding can be performed successfully using drilling machine or lathe machine with good performance, but the processes is very sensitive to the parameter variations and due to this reason practical friction welding is usually performed on computerized friction welder machine and it is easy to control process parameters such as pressure in this special machine.

4.4.2. Friction time

Increasing the friction time increases the temperature between the workpiece during friction stage. The decrease in friction time decreases the temperature between the interfaces. Theheats generated between the surfaces are essential for migration of atoms from one workpiece to another. Small friction time is generally suggested in fiction welding process this is because of the formation of intermetallic compounds at larger friction time. In this study friction time is 20 second which is suggested for the desired response such as resistance and strength to be optimised. The value of friction time is generally deferent according to the process parameter combinations. For example large friction peruse results low friction time to heat the metal to the required temperature and vise-versa.in general speaking from the result obtained, the friction time selected in this study is well related with the literature and it can be seen from the literature review chapter in this document.

In general heating time decreases with increase of friction pressure and also it decreases when speed increases at constant pressure. Sufficient heating time may be required for heating the centre of the workpiece because of low velocity at the centre surface. Sufficient time is required for transferring the heat from the outer surface to the centre of the workpiece.

4.4.3. Speed

Low friction pressure and low rpm may result slow heating, on the other hand large friction pressure and low rpm results effective and uniform heating between the workpiece. High rpm results large delay time to stop the rotating spindle. Thedelay affects the weld quality in two ways. The first is by gradually destroying the weldment the other hand it produces high amount of flash from aluminium material. In general speed is not critical variable for quality of weldment, but the amount of speed is determined by the friction pressure and friction time. If sufficient friction pressure and friction time is selected then speed is not critical variable for the process. The result from this study also support the result obtained in literature in the selection of speed. One of the uniqueness of this study is the selection of material is special which is not previously studied and the size of the workpiece used is small when it is compared with other literatures. Finally it is very important to state that optimization of friction welding of aluminium and copper electrical materials for two performance is especially needed for special applications in connectors and other electrical transmission components. The result from this study is also special importance in practical application of friction welding process.

4.5.Confidence interval and confidence level

Confidence interval for the predicted mean of the grayrelational grade on the confirmation experiment is given by the following equation. The confidence interval is the interval of upper and lower bonds which shows the gray relational grade of the confirmation test must be between the confidence interval with 95 % confidence.

The calculated value of the confidence interval is (CI=0.7659±0.17578) which is upper limit=0.94169 and lower limit=0.59012.the confirmation test gray relational grade must be between the interval in order to justify the result.

The gray relational grade of the confirmation experiment is between the CI which proved the result obtained in. Based on the CI result the mean of the gray relational grade for confirmation experiment is 95 % chance to be between the CI (0.94169- 0.59012).

From 95% confidence test it can be possible to predict the output result of the process for mass production of weldments. The forecast in mass production is performed in two deferent ways. one if the chance of the mean of the output gray relational grade is between the 95 % confidence interval, then we can predict the quality of the weldment based on the 95% confidence level. On the other hand is if we can predict the quality of the weldment with 95% confidence then we can estimate the defect in mass production. If we perform the above very important decisions then the next is to minimize the defective weldments out of large number of mass production. The actual importance of this study is approved when mass productions of weldments are performed in large scale for application point of view.

4.6. Confirmation test

The expected mean of the gray relational grade at optimum settings is calculated from the following equation which is stated in methodology chapter. It is helpful to predict the mean value of the gray relational grade at optimum parameter setting. Expected mean of the gray relational grade at optimum setting is calculated as 0.7659 and it is the expected mean value of the gray relational grade at the optimal setting.

When the process is performed for confirmation test the process should be expected to result the desired ultimate strength closer to the best output in the array of experiments initially yield maximum ultimate strength value. The procedure to confirm this design result for optimum desired output result is the final achievement from the study. Also further work is needed to optimize the disturbance from the machine vibration; machine quality and other factors that will disturb process output are neglected, and not considered in the analysis. By considering the above limitations the result of confirmation test can be used to justify the result obtained, experiment performed and analysis procedure from this study.

Based on the above discussion the results obtained are very important in the decision making for process performance and selection of process parameters. This is important in two reasons the first is it reduce the defect in mass production the other is it minimize the effect of process parameter variation on the quality of the weldments or the products when it is used in another applications such as electrical connectors, circuit connectors etc.

Table 4.8 Summary of optimization result

Output parameter	Gray theory prediction	Confirmation test Fiction time 20second Friction pressure117MPa Speed 1050RPM
Load(KN)		5.502
Resistance(ohm)		1×10[illegible]
Gray relational grade	0.7659	0.73439
Improvement in grey relational grade = 0.053 CI=Confidence interval=Upper limit=0.94169,Lower limit=0.59012 Gray relational grade of confirmation test is 0.73439 which is between the confidence interval; hence it is justified the result.		

4.7. Microscopic observation

Microscopic observation is performed to see the structure of the weld interface and locate deferent regions of the weld interface. The aim is to compare the microscopic image with other images in the literature.

Joint interface

Figure 4.2 Sample for microscopic view

4.8.Result of microscopic view

As shown in the microscopic image solid solution between aluminium and copper is clearly seen. The formation of solid solution is the result of high friction and heat. Aluminium is highly affected by friction and heat than copper because of high wear resistance of copper than aluminium. It is difficult to see the grain structure of the solid solution formed because of low magnification of the optical microscope. It is expected that the solid solution formed and heat affected and highly deformed part of the material have deferent structure and composition. Determining the composition of deferent parts is not the scope of this study.

Mixing zone

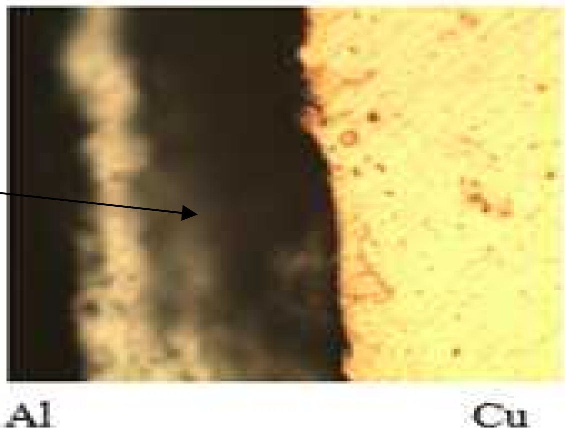


Figure 4.3 Microscopic view

4.8.1. Microscopic view of joint interface

Deferent regions of the interface of the specimen are clearly visible. Mixing region, joint region and friction zone are visible from microscopic view. The mixing zone is the region which is shown in letter B which indicates at this region the intermixing of copper and aluminium exist. Joint zone is near to copper which shows the joint exists at the copper very end and it is represented by letter B. The friction zone indicated by letter A represents the friction affected aluminium side because of low hardness of aluminium.

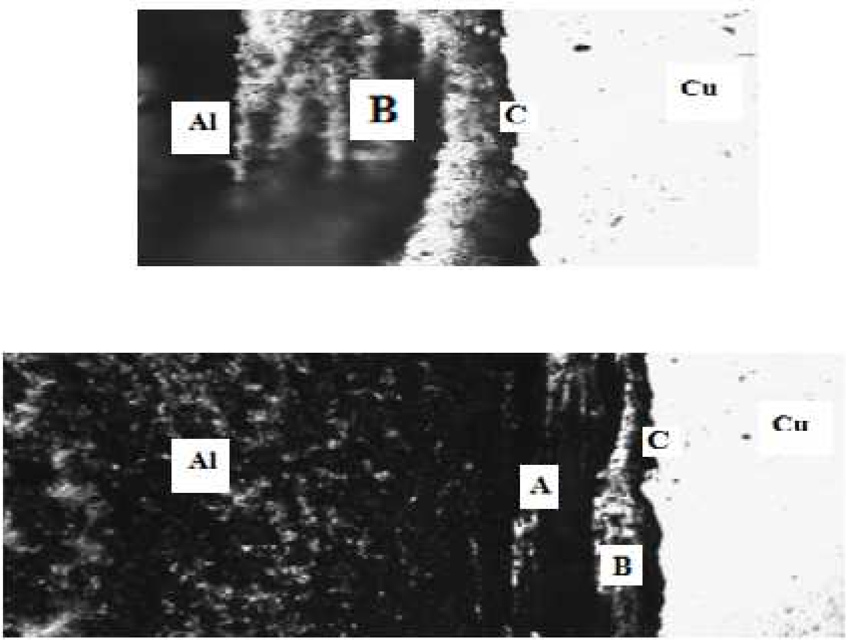


Figure 4.4A) Friction zone, B) Mixing zone and C) Joint zone, the figure shows the interface structure of the Al/Cu frictional joint at optimal parameters

4.9.Result of temperature measurement

The measurement of temperature is performed by using infrared thermometer at welding surface. The recorded temperatures for given experimental run are taken to be the average of the values recorded at one single welding cycle. The maximum temperature recorded is 190 degree centigrade, also the maximum average temperature is 120.7 degree centigrade and this is at experimental run number nine where maximum tensile strength is occurred.

4.10. Result of hardness values of the weldment

The harness value of the weldment at optimal parameter is presented in order to determinehardensof joint interface and bulk material in both side of the weld interface. The result from the hardness measurement is performed at deferent distance selected at deferent locations from both sides of the weld interface.

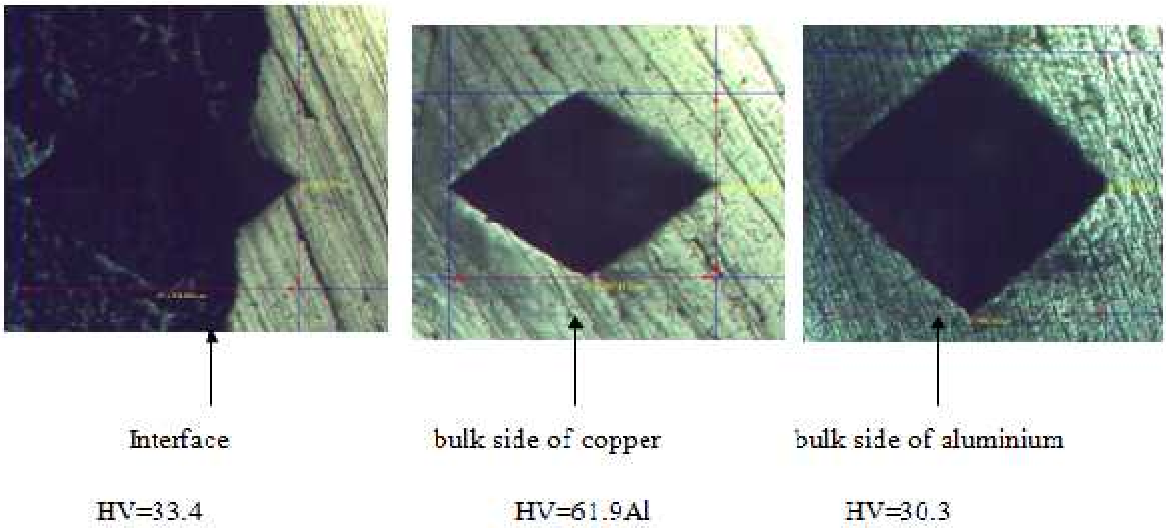


Figure 4.5 Hardness measurement at different locations of weldment welding parameter at the resulted optimum setting obtained

Based on the result of hardness measurement the hardness of copper and aluminium material is not affected by the heat generated by the process in both sides of the bulk material. In fact the hardness of copper is higher than aluminium and the measurement result of vhikers hardness test also reveals this fact. The other important result is that the hardness at the weld interface is deferent from the hardness of both materials of copper and aluminium. This deferent result at the weld interface is may be due to the solid solution or the mixing zone shown in the microscopic view. In general from the hardness measurement and from optical microscope result it is not possible to judge the formation of intermetallic compounds and so it is needed to perform XRD and other techniques to analyse and prove the formation of intermetallic compounds. In fact the result from literature presented in chapter two suggest that at deferent temperatures it can be possible to have the formation of intermetallic compounds. The formation of intermetallic compound is a function of temperature and exposure time. And based on the result obtained from this study temperature up to 190 degree centigrade are recorded and this recorded temperature is may be sufficient for the formation of some type of intermetalliccompound.

CHAPTER 5 CONCLUSION AND RECOMMENDATION

5.1.Conclusion

In thisstudy detail experimental task is carried out including friction welding process setup on drilling machine. Experimental setup for resistance test, process parameter selection, and measurement systems for process parameters were performed in detail. Friction welements of aluminium and copper are friction welded on the designed setup and test of Presses parameters are also performed.

The main objective of this study the two performance optimization of friction welding process is conducted successfully. The desired responses are strength and resistance. The process of optimization uses the combination of TAGUCHI design of experiment, ANOVA and gray relational analysis procedures. Minitab software is used in the analysis of variance and main effect plot.

Based on the optimization analyses the process parameters are optimized. Thetwo performance optimized parameter setting is obtained and it is Friction time 20 (s), Friction pressure is 117 (Mpa) and 1050 (RPM). Verification experiment is also performed based on the optimized setting and obtained best results. The optimization result indicated that Pressure is significant for the two-performance output such as resistance and strength.

In order to test the predicted results, confirmation experiment is performed at optimum conditions. The mean of relational grade for the confirmation experiment is 0.7343 which is in the range of 95% confidence interval. Hence, the model is justified based on the confirmatory test which shows if experiment is conducted the electrical resistance and tensile strength of the weldment is in the range between the confidence interval. The confirmation test is also justified that the selected process parameters give best result of tensile strength and resistance as expected from the output.

From the multi objective optimization it could be concluded that:

- ❖ Friction pressure is significantly important input parameter fortwo-performance characteristic such as tensile strength and electrical resistance

- Multi-performance optimized parameter setting is obtained and it is presented as friction time is 20 (second MAXIMUM), friction pressure is 117 (Mpa MAXIMUM) and 1050 (RPM MINIMUM).
- The 95% confidence level proved that the gray relational grade for confirmation test is between the CI and it is closer to the best result which indicates the optimization is successfully works

5.2.Recomendation

Based on the experiment and analysis the following points are recommended:

- Welding of aluminium and copper presented in this study should be performed with process parameter friction pressure 117 Mpa friction time 25 second and 1050 RPM to get two performance good result for response parameters. The response parameters are resistance and tensile strength of the weldment.
- It is advisable to use bimetallic connectors in power transmission and the result from this process is then used for application in electrical connectors. Electrical connector is produced from aluminium copper weldments through processing techniques such as machining and other process and this is not the objective of the study and it is simply for presenting the optimization result.
- For mass production of connectors from aluminium and copper weldments. Parameter selectionis very important for weldment tensile strength and electrical property of aluminium and copper friction welding process and production.

5.3.Future work

- Future work needed that the future study should be on the optimization of microstructure of the weldment.
- The corrosion resistance behaviour of aluminium and copper friction welding isimportant for future study.

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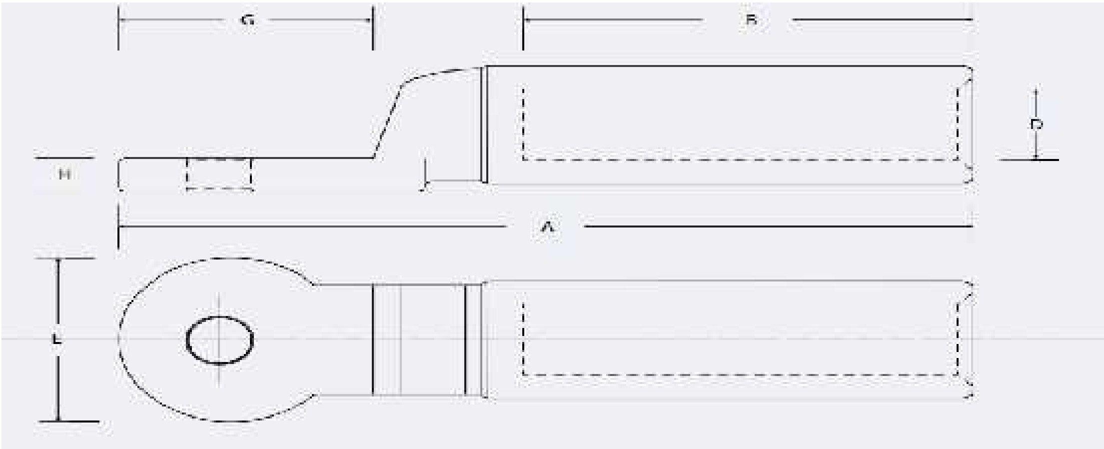
APPENDIX

APPENDIX-A:

STANDARD GEOMETRY OF AL-BARREL AND CU-STUD CONNECTOR

Standard geometry of Al-barrel and Cu-palm(ELECTRICAL CONNECTTORS PRODUCT CATALOG)



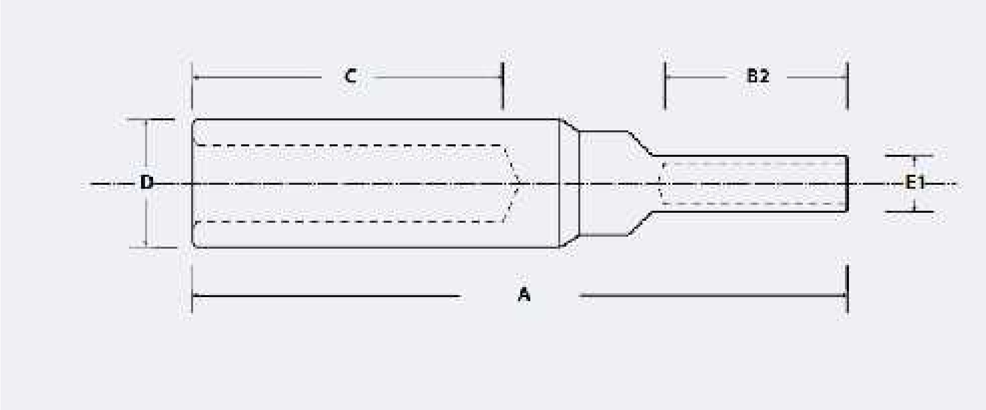
Specification (ELECTRICAL CONNECTTORS PRODUCT CATALOG)

Part No.	Cable Size	Stud Size (mm)	Dimensions (mm) A	B	D	E	G	H	A/F Hex Die (mm)
BL23B	23mm²	blank	75	30	7.5	22	21	4.5	9.0
BL23-8	23mm²	8	75	30	7.5	22	21	4.5	9.0
BL23-10	23mm²	10	75	32	7.5	22	21	4.5	9.0
BL23-12	23mm²	12	75	32	7.5	22	21	4.5	9.0
BL35B	35mm²	blank	80	32	8.5	22	21	4.5	9.0
BL35-8	35mm²	8	80	32	8.5	22	23	4.5	9.0
BL35-10	35mm²	10	80	32	8.5	22	23	4.5	9.0
BL35-12	35mm²	12	80	32	8.5	22	23	4.5	9.0
BL50B	50mm²	blank	80	32	9.5	22	23	4.5	13.2
BL50-8	50mm²	8	80	32	9.5	22	23	4.5	13.2

APPENDIX-B:

STANDARD GEOMETRY Al-BARREL AND Cu-BARREL

1) Standard geometry(ELECTRICAL CONNECTTORS PRODUCT CATALOG)



2) Specification(ELECTRICAL CONNECTTORS PRODUCT CATALOG)

Part No.	Nominal Cable Size		Dimensions AL (mm)			Dimensions Cu (mm)		A/F Hex Die (mm)	
	AL	Cu	A	C	D	B2	E1	AL	Cu
BLK300-35	$300mm^2$	$35mm^2$	130	60	35	40	11.5	28.4	9.2
BLK300-50	$300mm^2$	$50mm^2$	130	60	35	40	12.8	28.4	10.4
BLK300-70	$300mm^2$	$70mm^2$	130	60	35	40	14.7	28.4	11.5
BLK300-95	$300mm^2$	$95mm^2$	130	60	35	40	17.4	28.4	14.2
BLK300-120	$300mm^2$	$120mm^2$	130	60	35	40	20.0	28.4	16.5
BLK300-150	$300mm^2$	$150mm^2$	130	60	35	40	22.5	28.4	18.3

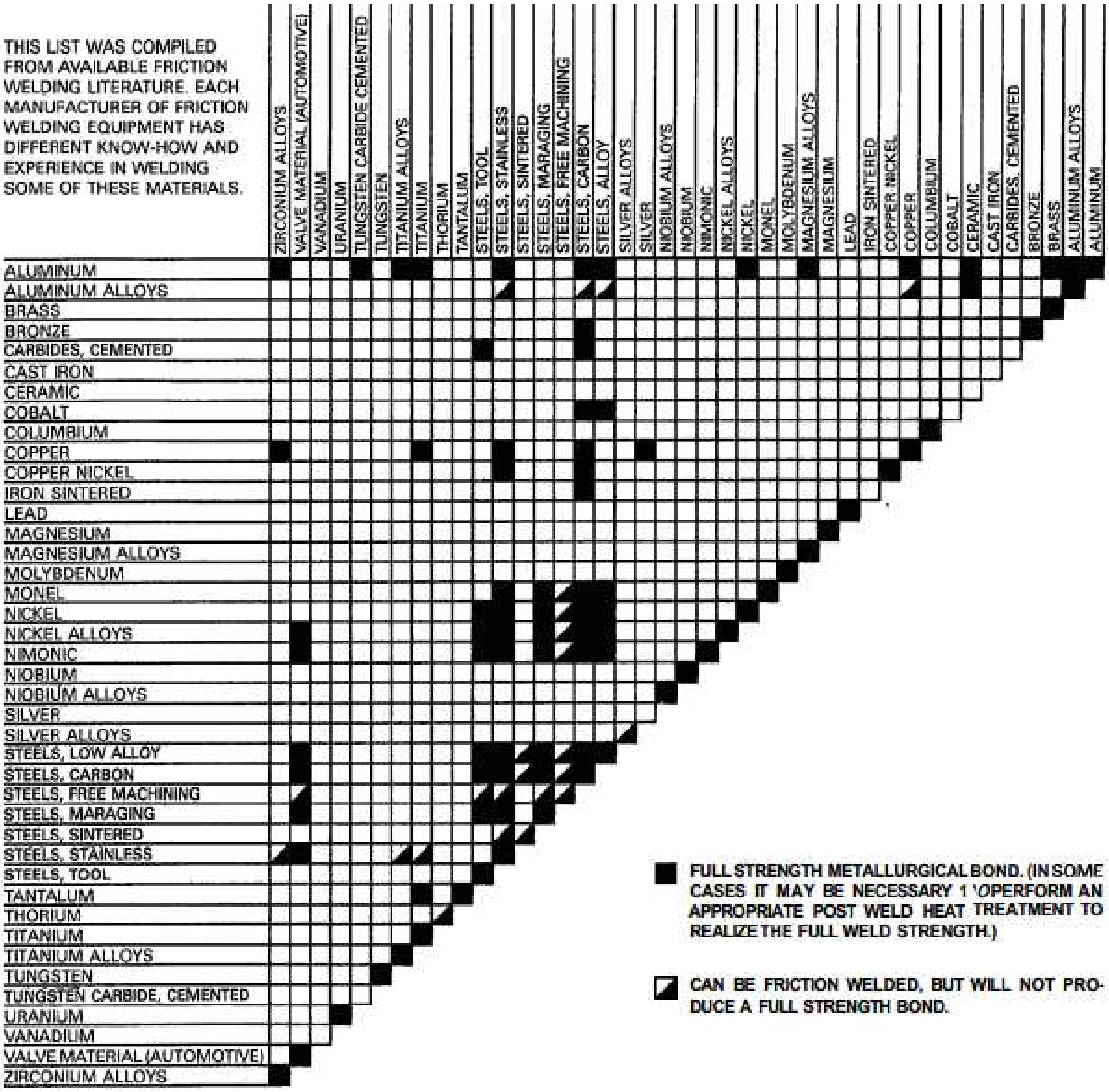
APPENDIX-C:

MODEL OF SMALL BIMETALLIC CONNECTOR

A)Copper palm -aluminium palm B) Copper palm -Aluminium barrel   A B Hole diameter =3mm  Diameter=8mm	Bolted clamp(electrically high resistance at the joint)  Diameter =8mm Hole diameter=3mm
Copper barrel –Aluminium barrel  Diameter =8mm	Three figures shows: the deference b/n the bolted connector and friction welded connection copper barrel - aluminium barrel 

APPENDIX-D:

FRICTION WELDED METAL COMBINATIONS (O'Brien, 1997)



APPENDIX-E:

STANDARD ELECTRICAL FORMULATION

- Current carrying capacity of conductor(CURRENT CAPACITY OF CABLE, 2018) is given by:

$$I = \sqrt{\frac{\Delta\theta}{R'T}} \text{(G.slade, 1990)}$$

Where;

I=conductor current, A (Amp)

R'=DC resistance of the conductor per unit length

ϴ=Maximum conductor operating temperature, in degree centigrade

Θ_a=Ambiant temperature in degree centigrad

Δϴ=Temperature deference $\Theta - \Theta_a$, in degree Kelvin

T=Thermal resistance per unit length between conductor and surrounding, K.m/W

- Dependence of resistance with size is given by:-

$$p = \frac{RA}{L} \text{(G.slade, 1990)}$$

Where;

p=specific resistance per unit length of the conductor

A=cross sectional area of the conductor

L=length of conductor

APPENDIX-F:

ANALYTIC METHOD OF CALCULATING SMALL RESISTANCE VALUE WITHIN SMALL THICKNESS

- Resistivity of aluminium=2.4 micro ohm.cm(G.slade, 1990)
- Resistivity of copper = 2.0micro ohm.cm(G.slade, 1990)
- Cross sectional area of bimetallic joint=A=0.542square.cm
- R= Summation of resistance of each part in series
- Thickness of intermetallic layer formed after diffusion annealing in furnace for 1 hour above 400 degree centigrade is s x=9 micro meter (G.slade, 1990)
- The resistivity of total interface; diffusion annealed in furnace is 18.5 micro ohm.cm (G.slade, 1990)
- Length of aluminium=Length of copper=1.5cm

R (Total resistance of bimetallic lug) is given by:-

R = $R_{copper}+R_{alumnum}+R_{interface}$=12.6267micro.ohm=$1.2\times10^{-5}$ohm

- R_{copper}=5.725micro ohm
- $R_{alumnum}$=6.87 micro ohm
- $R_{interface}$=0.0317micro ohm

Electrical resistance of mechanical contact:

Decrease of contact pressure Low High						
Resistance in ohm	Infinity	0.0126	0.0068	0.0045	0.001	0.0005