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Development of Multi Component Loads, Torque and Temperature Measurement Device for Friction Stir Welding Process

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Development of Multi-Component Loads, Torque and Temperature Measurement Device for Friction Stir Welding Process

by

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Table of Contents

CHAPTER 4: RESULTS & DISCUSSION 80

List of Tables

List of Figures

List of Symbols

General

q	Energy
$\dot{q}$	Energy rate
R	Radius (general)
r	Radius
S_n	Cone slant height
A	Cross sectional area
d	Depth
h	Height
l	Length
ν	Poisson ratio
θ	Angle
μ	Coefficient of friction
$COHE$	Sliding resistant coefficient
ω	Angular speed
ρ	Density
k	Thermal coefficient
c_p	Heat capacity
T	Temperature
F	Force component
N	Normal load
P	Pressure component
σ	Stress component
g	Gravitational acceleration
v	Linear velocity
τ	Torque

Electrical

P	Power
V	Voltage
I	Current
R	Resistance
E	Electrical potential
Ω	Impedance
emf	Electromotive force
α	Seedback coefficient
E_α	Seedback emf

List of patent, publication and seminar

1. Malaysia Patent Application. PI 2010003982, “A Method for Spot Welding and An Apparatus to Perform The Method.” I.P Almanar, Jauhari Tahir, Z. Hussain, Farkhan. August 24, 2010.
2. K, Jauhari T, Jamaluddin A, Zuhailawati H, and Indra P A. "Principle and Thermo-Mechanical Model of Friction Stir Welding." In *Welding Process*, by Kovacevic R, 1-26. Rijeka: Intech, November 21, 2012.
3. K, Jauhari T, Indra, P A, Zuhailawati, H.”Mathematical Model for Multi Component Forces & Torque Determination in Friction Stir Welding.” *Advanced Material Research*. 230-232 (2011): 1255-1259.
4. T.K Jauhari, I.P Almanar, H. Zuhailawati, “Mathematical Model for Multi-Component Forces and Torque Determination in Friction Stir Welding.” International Conference on Frontiers of Manufacturing Science and Measuring Technology. Dali, China. 2011.

Pembangunan Alat Pengukuran Komponen Berbilang Beban, Kilasan dan Profil Suhu bagi Proses Kimpalan Geseran Beraduk

Abstrak

Proses kimpalan geseran beraduk merupakan satu kaedah sambungan pepejal yang menggunakan sumber haba yang terhasil daripada kerja geseran mekanikal alat putaran terhadap bahan kerja, menghasilkan sambungan tanpa sebarang bahan pengisi. Sejak diperkenalkan, kimpalan geseran beraduk ini masih lagi berada di tahap awal berbanding kaedah sambungan lakuran konvensional. Asas proses kimpalan ini masih kurang mantap, kurang piawai garis panduan amalan dan keadaan operasi optimum bagi penggunaan bahan tipikal serta ketidakupayaan untuk mengaitkan pembolehubah proses terhadap sifat hasil sambungan. Asas kajian ini adalah berkenaan dengan prinsip kerja mekanikal proses kimpalan melalui kaedah pengukuran bagi mendapatkan manfaat hasil penambahbaikan sifat mekanikal sambungan. Kajian ini membentangkan analisa parameter kimpalan melalui sistem metrologi yang mengukur komponen dinamik dan kuasi statik daya dan kilas berbilang 3 dimensi yg dikenakan sambil merangkap butiran suhu yang terhasil. Ukuran daya dan kilas mewakili tindak balas beban mengemukakan kesan terhadap sifat fizikal sambungan berdasarkan pembolehubah parameter kimpalan. Tambahan, model matematik diterbitkan bagi menganggar proses kimpalan berdasarkan sifat bahan tergantung suhu dan bagi mengesahkan sistem metrologi. Prinsip mekanik sentuhan diadaptasi ke dalam model dengan mengambil kira prinsip geseran Coulomb dan prinsip ubah bentuk plastik. Seterusnya, pemindahan haba yang berlaku dalam sistem dikaji melalui kerja experimen. Hubungkait ukuran beban dan kilas terhadap suhu yang terhasil menunjukkan keupayaan untuk mengawal pembolehubah prosess. Sistem metrologi ini dengan jelas mengaitkan kawalan parameter dan tindak balas proses kimpalan, seterusnya menunjukkan sistem yang dibangunkan boleh diadaptasi kepada jenis bahan yang berbeza berdasarkan sifat bahan tergantung suhu bahan tersebut bagi julat pembolehubah parameter yang berbeza.

Development of Multi Component Loads, Torque and Temperature Measurement Device for Friction Stir Welding Process

Abstract

Friction stir welding process is a solid state joining method that utilizes heat source from mechanical friction work of a rotational tool exerted on work material, producing joint without the use of filler material. Since its introduction, friction stir welding is still at infant stage compared to conventional fusion joining method. The welding process fundamental is still not well established, lack in standard practicing guideline and optimum operating conditions for typical material application as well as inability to definitively relate process variables to the produced joint properties. The basis of this study is regarding to the mechanical work principle of the welding process, which is devised through measurement method as a mean to look for the possible benefits of improved joint mechanical properties. This study presents the analysis of welding parameters responses via a metrology system which measure the dynamic and quasi-static multi components three dimensional loads, torque exerted and to capture the corresponding temperature profile. The measured loads and torque represent the acting reaction forces suggesting its influences on joint physical properties based on welding parameters variables. In addition, a mathematical model is derived to approximate the welding process based on the work material temperature-dependent material properties, employed to validate the metrology system. Contact mechanic principle is adapted into the model accounting both Coulomb's friction and plastic deformation principle. Proceeding, heat transfer within the system is studied through experimental work. The relationship of the measured loads and torque with the corresponding temperature shows the possibility to control the process variables. The metrology system explicitly correlates the controlling parameters and their reaction to the welding process thus shows that the developed system is adaptable to different materials based on their temperature-dependent material properties, for a range of different welding variables.

CHAPTER 1: INTRODUCTION

1.1 Friction stir welding

Friction stir welding is a solid-state welding process that gained much attention in the research as well as manufacturing industry since its introduction in 1991 (Thomas, et al., 1991) and (Dawes & Thomas, 1995). For about 20 years, friction stir welding has been used from high technology applications such as aerospace to automotive till high precision application such as micro welding.

The main feature of a solid-state welding process is the non-melting of the work material which allows a lower temperature and a lower heat input welding process relative to the melting point of material being joined. This is advantageous over the conventional fusion welding where excessive high heat input is required to melt the work material. Much less heat input required for friction stir welding process is being translated into economic benefits, safer than conventional methods and comparatively less complicated welding procedures. The friction stir welding make it possible to join light weight and difficult to join material such as aluminium alloy, magnesium alloy, copper and titanium alloys rather than using conventional welding. The clear advantages have greatly influence the increased usage of these materials in structural applications (Hwang, et al., 2008) and (Kim, et al., 2010). In addition, friction stir welding also make possible to produce sound weldment in 5000 and 7000 series aluminium alloys that are not possible to be welded using conventional methods.

Friction stir welding process provides proven good quality and strong weldment with lesser number of equipments, eliminates the use of filler metal and improved weldability. Due to these factors, friction stir welding has successfully been employed to the aerospace, automobile and ship building industry (Nicholas & Kallee, 2000). The need to further understand and improve friction stir welding process continues to propagate in many applications.

1.2 Role of friction stir welding in manufacturing industries

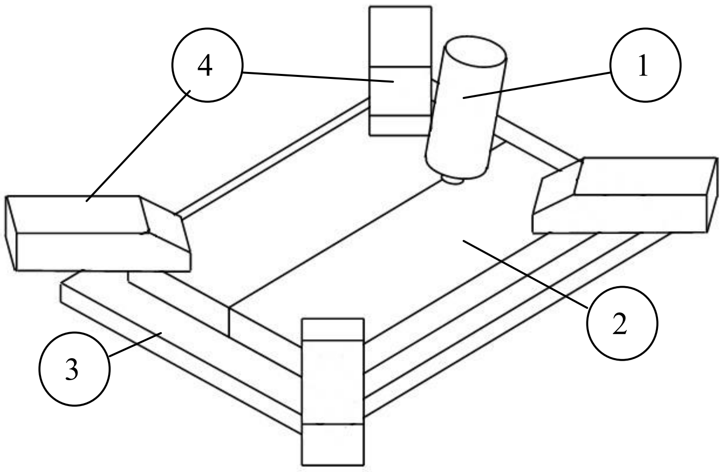
Interestingly, friction stir welding process is gaining pace in manufacturing industries, best for its economic benefit apart from environmental concern as well as the ability to be adapted in advance automation system such as robotic. Friction stir welding process is very prominent in aluminium components and panel fabrications with highly rated technology readiness level (TRL) (Smith, et al., 2003).

Friction stir welding is an applicable technique adapted for rail cars to fabricate floor panel part of a Type 700 Shinkansen or bullet train. It is also widely used in friction stir welded aluminium roof, side wall and floor panel for suburban train and other more recent commuter or express rail cars. This is due to its low distortion, larger weldment product and panel size output, prefabricated panels as well as tailored blanks and joints (Kumagai & Tanaka, 2001), (Kallee, et al., 2002). The advantages are also being shared in marine application when it is first commercially used for ship building in 1996 with the ability to joint thick panels, sandwich and honeycomb panels and corrosion resistance material panels. It is well favoured for performing butt join in comparison to conventional arc welding application which also turns out to be significantly viable in terms of low labour cost and shorter welding cycle time (Delany, et al., 2007). The other important application of friction stir welding process is to the aeronautical and aerospace industries where aluminium alloy is used as primary material for their construction. The process enables manufacturers to completely replace the riveted joints and assemblies of lapped and abutted configuration that are used mainly for fuselage sections, propellant and fuel tanks of commercial air carrier as well as space launch vehicle (Arbergast, 2006). Thus, the process allows total elimination of thousands of rivets usage which result in better quality, stronger and lighter joints at reduced assembly cost. Meanwhile in automotive application, friction stir spot welding (FSSW), a recent innovated process of friction stir welding (FSSW) is introduced to replace conventional resistive spot welding (RSW) in the transition of aluminium alloy application for panels in domestic and commercial vehicle. Aluminium application in automotive industry is chosen for its prefabricated and tailored panel, strength-to-weight ratio, reducing fuel consumption, recyclable material as well as marked reduction in production cost. This has compelled car manufacturers to use the same concept not only for the body panels, but for other part as well (Kallee, et al., 2005).

Since its introduction, friction stir welding application has matured significantly with widespread use of wide range of aluminium alloys for structural applications and the process is compatible to be used in ferrous, stainless steel, nickel, copper and titanium alloys. However, only a small percentage of world welding and joining market has implemented the process. It is still relatively underutilised and this is varied among industries, university researches, collaborations and other niche applications. In Malaysia, it is still at the infant stage. With all the challenges to joints wide variety hard to weld materials and configuration, the motivation of the application and adaptation of this noble technology in manufacturing is not only to meet quality joints, but for the economic value and also for its environmental friendliness.

1.3 FSW configuration and process

Friction stir welding configuration consists of (1) cylindrical rotating tool, (2) two or more work materials of similar or dissimilar material combinations (3) backing fixture and finally (4) clamping or holding fixture as schematically shown in Figure 1.1. The rotating tool design consists of a combination of two cylinder of a specific radius ratio known as shoulder and smaller radius pin or probe, where the height of the pin or probe is usually more than half of the work material thickness but not equal to its overall thickness. The most common rotating tool design is as in Figure 1.2.



1. Rotating tool
2. Work materials
3. Backing
4. Clamp

Figure 1.1: Friction stir welding configuration schematic

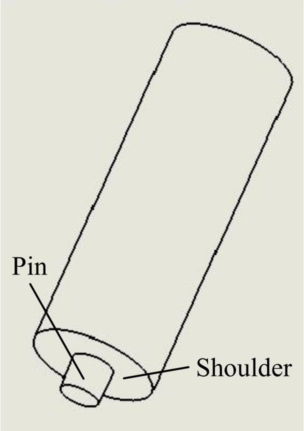


Figure 1.2: Common friction stir welding rotating tool design

The work materials to be joined may be arranged as such as common practice welding configuration but the most common configurations used in friction stir welding are abutted and lapped. Through these configurations, it has the capability to join thick plate without the need for special and additional preparation prior to the welding process. Meanwhile, the backing fixture functions to provide opposing support to the work material against the process loads and at the same time to contain the generated heat within the work materials. The most crucial part of the friction stir welding configurations is the clamping or holding fixture, where insignificant clamping of the work materials configurations may fail to counteract the load exerted from the friction stir welding process and thus causes welding failure at the welding line and defects in the weldment.

Friction stir welding process involves four phases which are (1) plunging phase, (2) dwelling phase, (3) welding phase, and finally (4) exit or retract phase. The whole friction stir welding process phases of an abutted work material configuration is illustrated in Figure 1.3.

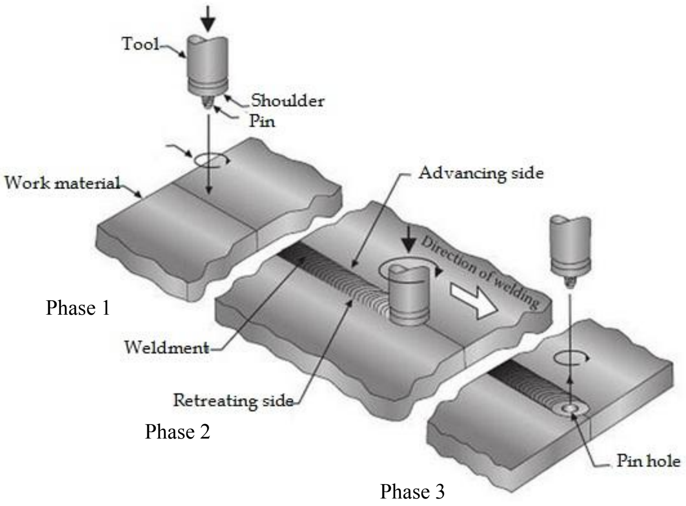


Figure 1.3: FSW process phases; 1) Plunging, 2) Dwelling, 3) Welding and 4) Exit (American Welding Society, 2007)

Briefly, the process starts initially with rotating tool pin or probe thrusting onto the configured work material under a constant axial load to generate mechanical friction heat. This process will continuously increases the temperature at the immediate contacting surface of the rotating tool and work material, maintained until the temperature increased to a temperature that causes the work material to soften, plasticized and significantly lose its strength. Consequently, these conditions allow the rotating tool to penetrate to a certain depth of usually almost but not equal to the thickness of work material. The plasticized material is subjected to displacement by the rotating tool probe or pin plunge, effectively being flashed out together with a portion of the generated heat, thus introducing new immediate lower temperature and harder surface of work material. This mechanism further explains the transient heat generated through pure mechanical frictional work at the rotating tool-work material contact interface. The end of the plunging phase is signified by the sound contact of the rotating tool shoulder with the immediate work material surface.

At this moment, the rotating tool is allowed to dwell for a period of time causing the temperature at the contact interface to increase further, up to its hot working temperature. The heat generated from the mechanical frictional work is greatly dependent to the relative increase of contact surface area as well as the relative speed. The heat generated causes the affected area under the shoulder to expand considerably. Phenomenally, the heat causes the work material closed to the immediate contact to lose its strength and becoming plastic. Once this condition is reached, thin soft material layer is produced and would stick to the dynamic rotating tool surface and being forced to be displaced along. Instantly the heat generation mechanism is partially turned to plastic dissipation heat generation. It is explained by the energy dissipated from the internal shearing of different velocity between displaced soften work material layer to static more solid surface. Ideally, intermittent heat generation mechanisms due to the mechanical friction work and the plastic dissipation take places because of the transient heat generation and transfer effects as well as the material ability to regain its strength as heat is lost to the ambient. In addition, the other role of these mechanical frictional work and plastic dissipation mechanisms are to induce soft material displacement and causes the stirring action or severe material deformation which later produce the amalgamated joint.

The dwelling phase is followed by welding phase. After the local temperature of work material under the rotating tool approaches its hot work temperature or soft enough to be stirred and displaced, the rotating tool is moved transversely along the welding line. This traverse motion caused the plasticized soft material at the leading edge of the rotating tool being squeezed and sheared through a small slit formed by the displaced soft material at the side or lateral of the tool, preferably in the direction of rotational tool rotation. The displaced soft material is then deposited to the gap at the trailing edge left by the once occupied rotating tool pin or probe. The soft plasticized material is forcedly displaced by the rotating tool along its rotating direction under a closed encapsulation of harder solid work material wall and rotating tool shoulder. The soft material is forged to the trailing edge in layers forming weld nugget. At each traverse increment of the rotating tool motion, the displacement of soft plasticized work material to the trailing edge will introduce new solid, lower temperature work material at the leading edge. Thus it reintroduces mechanical friction work heat generation mechanism prior to plastic deformation mechanism and continuously repeating the heat generation process all over again at each traverse displacement of the tool. This produces cyclic transient heat generation, takes part throughout the welding phase and strongly affected by the combination of the rotational tool rotation and traverse speed. Recap, during the welding phase, the plasticized material is subjected to displacement, extrusion and shearing mechanisms facilitated by the rotating tool rotation, thrust and transverse movement under cyclic heat generation mechanisms along the welding line and finally consolidating welding nugget at the trailing side.

At the end or exit phase, the rotating tool is retracted away from the work material leaving a cylindrical hole mark that once occupied by the rotating tool pin or probe. For cosmetic reason, the cylindrical hole may be filled with filler material at the end of the process but the most common method used is by introducing dummy material prior the exit phase. Dummy material is of the same material used for the work material to be weld and placed at the end of welding line. The rotating tool is allowed to traverse to and exit within the dummy material which later is cut away leaving good surface finish. Though, this cosmetic issue would remain in the application of innovated friction stir spot welding.

These process phases in friction stir welding are dependent to one another to produce a good amalgamated weldment and are strongly affected by the welding parameters. The assurance of good weldment is determined by proper control of varying measureable welding parameters such as the rotational speed, axial plunge force and torque, traverse speed, tool geometry and orientation in the form of generated heat energy. Similar to other conventional welding methods, heat energy notably determines the quality of the joint.

1.4 Recent advancement in friction stir welding

Since the last two decades, there are considerably vast lab and industrial work done on friction stir welding process which leads to the emerging advancement of new materials application and combinations, process improvement, tool designs, welding configurations, tailored blank application and adaptation to automation. Though, the most important innovation in the process itself is its variations; (1) High speed friction stir welding, HS-FSW, (2) Ultrasonic stir welding, USW, (3) Thermal stir welding, TSW, (4) Friction stir spot welding, FSSW, (5) Friction stir joining, FSJ, (6) Friction stir processing, FSP, and (7) Friction bonding, FB (Schwart, 2011).

The recent advancement shows the introduction of high-speed friction stir welding aiming at reducing process forces by the means of the increasing heat generation rate. This reduction in forces is to realize the idea of permitting manual handheld welding work. HS-FSW process is also designed to achieve lighter and portable device or equipment. This will make possible to be handheld and eliminate the need for rigid fixturing of the work material and rotating tool.

Ultrasonic stir welding is another variation of the process where ultrasonic energy is used to assist in initial heat generation. The objectives are to reduce process forces and welding time. The major boost of USW is it reduces dependency on rotating tool shoulder to generate heat and instead, make use of coupled ultrasonic vibration to further agitate the rotating tool at the contact interface and amplifying the mechanical friction effect.

Different from USW, thermal stir welding decouples heat generation from mechanical friction of conventional friction stir welding and instead, emphasized external induction heating to increase work material temperature at the welding spot or welding line. Though, induction heating may ultimately increase the rate of heat generation but the implication is that, it reduces the strain rate of the plastic deformation, a prevalent characteristic in friction stir welding. Reduced strain rate will significantly affect the final welding properties (Ding, et al., 2006).

The most common variation of all is the friction stir spot welding, which is well known to be used in transportation industries to replace rivet and as well as adhesive joining method. Though this method produces cosmetic defect in the form of pin hole created by the rotating tool, the weldment has sufficient mechanical strength for joining method (Gerlisch & North, 2006).

While all friction stir welding variants are dedicated for metallic material, friction stir joining method is dedicated for joining thermoplastic materials. It has been used for polypropylene, polycarbonate and high density polyethylene materials (Mishra & Ma, 2005). The advancement of FSJ method may possibly makes way for mechanical joining method involving plastic matrix composite.

Friction stir processing is a unique non-joining method variant of friction stir welding where it utilizes the friction and stirring process, alters the work material microstructure to be super fine, modified with improved physical properties and at the same time suppressed defects such as porosity and short crack (Abergast et al., 2001). The introduction of foreign particle into base material during FSP creates new near quality to metal matrix composite structure and thus improving the material properties. This provides a new platform to produce improved future materials.

The consequent of FSP method emerges as a modified method of friction bonding that allows bonding of overlapping thin plates through locally modified microstructure. The process utilizes less stirring effect due to the short pin geometry and thus differs from common friction stir welding method.

The majority of these friction stir welding variants methods stress on their ability to increase welding time and at the same time to reduce forces exerted from the welding process. The other purpose of these methods is to provide means of producing joining method involving different type of materials and configurations. More or less, these methods share the same mechanism of mechanically manipulating soften work material and the formation of almagamated weldment at the trailing edge.

1.5 Problem statement

Even though friction stir welding method has been around since 1992, the process is still being considered immature in the sense of its fundamental principle and still lacking of standardized operating procedure that can be accepted and adapted in industrial practices. In comparison, friction stir welding is not widely available in general application rather than conventional fusion joining methods especially in automotive industry due to shorter process cycle and conventional heat generation mechanism. The true understanding of friction stir welding process is still far-reaching; understanding the physics and nature of the process, lacking of standards guideline and practice, optimization of the process for typical material application as well as not suitable for small to medium scale robotic or manual handling.

1.6 Research objectives

This current work is proposed to look at the possible benefit that can be gained from the features of friction stir welding and its variations, through process measurement. Specific objectives are summarized as follow;

1. To develop a measurement system for measuring process parameter response during friction stir welding process of abutted aluminium alloy work material, compatible to standards mechanical test.
2. To find the physical mechanism of the friction stir welding process and its effects towards the work material both through theoretical and experimental work
3. To study the parameters involved in the friction stir welding process that is to be used for optimum condition for joining various metals.

1.7 Thesis organization

Chapter 2 present literature reviews on friction stir welding method which mainly emphasized on the heat generation and temperature-dependent material properties response to mechanical work. Chapter 3 present proposed mathematical model of the process, design approach for the holding fixture and data acquisition system, parametric study and model validation through experiment. Chapter 4 present the results analysed obtained from previous chapter, discussed the presented results in detail and answer questions arise from the study. Chapter 5 concludes findings achieved in the research, the proposed future work, improvement and recomendation.

CHAPTER 2: LITERATURE REVIEW

2.1 Friction stir welding work principle

The working principle of friction stir welding has been described and elaborated by many researchers (Hwang, et al., 2008), (Kim, et al., 2010), (Frigaard, et al., 2001), (Ravichandra, et al., 2001), (Schmidt, et al., 2004) and (Schmidt & Hattel, 2008). To understand the working principle of the friction welding process, it is best to appreciate the physics related to the process heat generation mechanisms. As described in Chapter 1, friction stir welding process started with the initial mechanical friction between the thrusting rotating tool and the immediate surface of the working material. The plastic dissipation heat generation mechanism soon takes over the mechanical friction as the immediate work material is sheared and plasticized into layers close to the rotating tool surface. The detail of the study is regarding the welding process heat generation mechanisms, the nature of the process thermodynamic, the friction stir welding joining mechanisms and its characteristics, welding process variables and previous research works are discussed in this chapter.

2.1.1 Friction heat generation

Mechanical friction work is initiated when rotating tool surface is in contact and sliding with the immediate stationary surface of work material under a normal load, introducing velocity difference between the dynamic rotating tool and the static work material surface. Thus this combination introduces mechanical friction work and subsequently, heat. Fundamentally, mechanical friction work has been described based on the Amonton’s laws. The law firstly explained that the friction between two separate bodies is directly proportional to the normal load applied, where the coefficient of friction is a constant variable and temperature dependent at static condition, known as static friction. At dynamic condition, the coefficient of friction is considered as kinetic friction where the contact condition is non-sticking or sliding. The second explanation of the law is that the friction force is not dependent on the apparent area of the separated and in contact bodies (Popov, 2010).

Generally, friction work is assumed based on Coulomb's dry friction model between solid bodies where, at the same time it conforms the Amonton's law. In the model, the mechanical friction work and heat generation relationship of sliding friction is explained by contact condition between hard and soft metallic material interaction. The interaction involves very small scale asperities at the immediate contact surface. As the normal force is acted on the rotating tool, it is being transferred and divided onto smaller area asperities resulted a very high contact pressure. Due to the relative velocity differences and the load per unit area, the dynamic mechanical work causes ploughing effect of the soft material by the hard materials' asperities, being agitated, deformed and finally broken releasing the stored energy in the form of heat (Sherwood & Bernard, 1984).

The released energy, a very high local thermal energy causes the immediate contact area temperature to rise, eventually transferred and stored into the rotating tool and the lump work material. The heat causes the work material to gradually soft, reduces its strength and deformed into soft material layer in between the rotating tool and the work material. The soften work material layer is later to be displaced by the rotating tool pin resulting new surface contact condition and promoting another cycle of mechanical friction heat generation.

2.1.2 Plastic dissipation heat generation

Plastic dissipation heat generation typically occurs at higher temperature resulting from mechanical friction heat generation mechanism at the dwelling phase where the work material is completely confined under the rotating tool. Through mechanical friction heat mechanism, the immediate work material temperature under the rotating tool is increased to a degree where the soften work material layer close to the rotating tool interface started to lose it strength, yielded, stick and move along with the rotating tool. This phenomenon increases the thermal softening effect and causes shears within the soft work material layers interfaces and causes the mechanical friction heat mechanism to diminish and at the same time introducing high strain rate plastic deformation. The mechanical friction heat generation mechanism is taken over by plastic dissipation heat generation mechanism, generated internally within the work material away from the rotating tool-work material interface (Ravichandra, et al., 2001), (Schmidt, et al., 2004) and (Nandan, et al., 2006).

Similar to any thermodynamic system, the friction stir welding process is susceptible to the nature of heat transfer. As the heat is being transferred out of the system, the plastically deformed material tend to recover its strength establishing new and lower temperature work material layers thus reinitiate mechanical friction heat generation mechanism (Schmidt & Hattel, 2008). At the welding phase, plastic dissipation heat generation mechanism is increased at the cost of the travelling rotating tool, shearing the work material to higher extend toward trailing edge and further increase the immediate work material temperature before reintroducing new contact condition and the mechanical friction heat generation mechanism cycle (Soundararajan, et al., 2005).

These heat generation mechanisms cycle keep on repeating throughout the welding process due to continuous instance of slip and stick contact conditions and plastic flow of the work material alternating boundary conditions at the material to rotating tool interface (Schneider, et al., 2006). Partly to the heat generation mechanisms, the other importance is that these high strain rate and thermal effects soften work material encompass at the trailing edge produce welding nugget and posture the main characteristic of the joint (Colligan, 2010).

2.1.3 Heat transfer

Simultaneously, the heat generated is constantly being transferred within the thermodynamic system; portions of heat are distributed within the work material, the rotating tool, the backing fixture and finally to the ambient. In depth, heat generated is subjected to three dimensional heat flows away from the heat source under boundary conditions; heat input and heat transfer at the rotating tool are indirectly coupled at the rotating tool to work material interface into the work material through heat conduction (Soundararajan, et al., 2005), and (Nandan, et al., 2006) and incorporated with conductive heat transfer effect around the pin in the deformation zone (Khandkar & Khan, 2001), (Schmidt & Hattel, 2005) and (Schmidt & Hattel, 2008). For the work material, convective and radiative heat transfers are considered for heat exchange at the top work material surface, past the shoulder peripheral (Nandan, et al., 2006) while at the same time only convective condition is considered for the bounding surfaces of work material (Khandkar, et al., 2003), (Soundararajan, et al., 2005). For the case of backing fixture, appropriate variable gap conductance is considered for work material to backing fixture interface depending on specific thermal contact resistance condition (Khandkar, et al., 2003) of temperature dependent (Shi, et al., 2003) or contact pressure dependent or surface contour of work material (Soundararajan, et al., 2005) or any of the combinations.

Ultimately 100% energy generated from mechanical work throughout the process is converted to heat and physical deformation with approximately 88% of the heat is conducted and distributed globally through the lump work material, backing fixture and else to the rotating tool (Schmidt & Hattel, 2008). Heat plays very significant relationship not only toward the physical success of the joint but also towards the temperature profile, heat transfer, internal strain and stress distribution during the friction stir welding process, towards weldment microstructure and residual stress of final weldment resulting properties which are strongly affected by the welding variables and temperature dependent material properties (Nandan, et al., 2008).

2.1.4 Friction stir welding mechanism

Weldment is produced in the course of welding phase where layers of materials are forced to move along with and around the rotating tool surfaces at a specific contact condition; fully sliding or partial sliding and sticking or fully sticking. The soft material layers motion are heavily deformed and driven by the rotating tool rotational direction, forced through the retreating side toward trailing edge and downward closed to the pin before finally being forged and deposited at the once occupied volume of the rotating tool probe or pin at the trailing edge under severe plastic deformation and strain (Schmidt & Hattel, 2005), (Nandan, et al., 2008) and (Arora, et al., 2009).

The mechanical torque of the rotating tool causes mechanical shearing to the immediate work material closed to the rotating tool, forcing soft work material layers to motion and strained, creating flows of fine material layers prior progression into weldment. The material flow motion or velocity is visually estimated through the grain size and shape, correlated to internal strain rate (Jata & Semiatin, 2000). The material flow and joining mechanisms are proposed by the region formed by the friction stir welding process or the material flow zones describing zones where shear layers are visibly distinguished by material characteristics, show the evident of non-melting but severely deformed soft material deposited into amalgamated weldment in layers and flowing manner.

2.2 Welding characteristics

Temperature profile and history of friction stir welding process are resembled by the distinct regions at the weldment characterized by discrete microstructure sizes, shapes and properties, produced by the significant thermal effect and plastic deformation. Under heat generation, lump effect and heat transfer, thermal profiles are spreaded out from the crown shapes heat source around the rotating tool to work material interface, dispersed toward the work materials surfaces and edges (Song & Kovacevic, 2003) and (Arora, et al., 2009). These regions are known as; 1) weld nugget, the product of plastic deformation due to the stirring effect deposited behind the rotating tool pin at the trailing edge, 2) thermo-mechanically affected zone (TMAZ) of internally sheared plastic deformation within the work material away from rotating tool to work material interface, 3) heat affected zone (HAZ) of structurally altered and thermally affected region due to intense temperature different between thermo-mechanically affected zone (TMAZ) and base metal temperature region, and 4) base metal of work material which is not physically affected by the thermal effect (Dong, et al., 2001).

Temperature profile portrayed direct relationship of the heat generation rate, the torque generated through the rotating tool, the loads exerted throughout the work material and the power consumed by the friction stir welding process. Both thermal and mechanical effect from heat generation and stirring effect engender welding characteristic in term of stresses, tensile and hardness properties. In regards, the rotating tool rotational and the traverse speed are interchangeably influence the temperature profile and affectively manipulate the material flow behaviour, weld material composition, microstructure orientation, strain, residual stress, thermal stress, hardness and strength of the welding (Elangovan, et al., 2008), (Moreira, et al., 2009) and (Tutum & Hattel, 2010).

2.3 Friction stir welding parameters

Independent process variables play significant effect on the friction stir welding process and control, entail the axial force, rotating tool rotational speed, tilt angle, tool traverse speed and tool geometry which includes pin and shoulder surface areas and ratio. The aforementioned variables strongly affect the heat generation rate, temperature profile within the work material, mechanical power required by the process, material evolution of the weldment and also the loads distributed within the work material. These factors are extensively studied to understand the mechanics of joining, process and final weld properties optimizations, where direct measurement are possible be done experimentally and predicted numerically.

It has been reported that rotational and traverse speeds have both direct and indirect influence to the final weldment. Its direct influences to the mechanics of joining suggesting degree of stirring based on the contact condition and multi component loads whilst its indirect influences to mechanical properties of the weldment is heavily influence by the combination of temperature exposure and tool design which at the same time, also facilitate stirring (Elangovan, et al., 2008). For a constant welding speed, low rotational speed induces low stirring effect and finally low heat generation rate while for a constant rotational speed, low traverse speed increases the exposure to heat source and vice versa but only to an extent. Extreme high rotational speed results too much heat while extreme high traverse speed results less heat, low stirring effect and increase travel resistance due to heavy loads on the rotating tool and hard work material at the leading edge where material is sheared to the lateral sides instead of moving around the rotating tool direction (Zhang & Zhang, 2009). Thus for any condition mentioned above, high friction stir welding process temperature ease material flow and finally reduce the multi component loads. Though, excessive heat from high heat generation rate or rotational speed or low traverse speed significantly reduces the mechanical properties of joint due to microstructure evolution of the regions exposed to excessive heat (Liu, et al., 2009). Albeit, the appropriate traverse and rotational speed below critical speeds might result optimum heat generation rate and reduced thermal exposure that produce good strength and hardness weld properties (Ren, et al., 2007) and (Patil & Soman, 2010).

Torque produced during the friction stir welding process depends heavily to the contact condition, rotating tool rotational speed, work material plasticity at the immediate rotating tool to work material interface, axial load exerted and the rotating tool design which are insensitive to the welding or traverse speed (Arora, et al., 2009), (Zhang & Zhang, 2009), and (Cui, et al., 2010). Any changes in the traverse speeds does not significantly affect temperature profile at constant rotating tool rotational speed compared to changes done in the rotational speeds. In addition, optimum rotating tool design influences the torque produced through the effect of sum of contact areas and contact conditions at the rotating tool to work material interface where it influences plastic deformation or strain work distribution, material transportation, process loads and work material temperature (Buffa, et al., 2006), (Elangovan & Balasubramanian, 2008), (Hattingh, et al., 2008), (Zhang, et al., 2009), and (Arora, et al., 2011). As temperature increases, work material temperature dependent shear stress plumps and no longer behave as solid thus reduces the torque at the rotating tool to work material interface and further reducing power and energy required to produce heat within the process. Sine qua non, good agreements of the welding variables offer sound and defect free joint properties while at the same time, economically profitable and productive.

2.4 Process modelling

This chapter discussed considerably vast works that has been made in pursue to understand the physical process that influences the variables associated to the friction welding process using empirical as well as numerical models for heat generation, material interaction and material flow. The models are based on the assumption of different contact conditions and heat generation mechanisms of the friction stir welding process at specific welding variables. Based on the fundamental of the friction stir welding process, welding phases portray the crucial stages involve the initiation and the progress of heat generation due to the mechanical work of the rotating tool that carries through.

2.4.1 Thermal model

Heat generation is modelled based on the torque required to rotate a circular shaft relative to the work material surface at coefficient of friction variables, pressure distributions and the assumption of 100% conversion of the shearing work to heat where the net power required is proportional to the tool rotational speed as well as the shoulder radius i.e. $q \approx \omega R$ (Frigaard, et al., 2001).

Mechanical friction work principle used for heat generation model is coupled with plastic dissipation work principle and the nature of heat transfer mechanisms to model three-dimensional heat and material flow based on temperature dependent coefficient of friction and temperature dependent pressure distribution for aluminium alloys (Dong, et al., 2001). In detail, three-dimensional visco-plastic flow and heat transfer has been investigated through solving the equations of conservation of mass, momentum and energy by considering heat source due to mechanical friction heat generation at the rotating tool to work material interface or due to the plastic dissipation heat generation away from the tool to work material interface or due to the combination of these two heat generation mechanisms (Ulysse, 2002), (Buffa, et al., 2006), (Nandan, et al., 2006) and (Nandan, et al., 2007).

The model is defined by the contact area, the rotating tool pin and shoulder ratio, the material shear stress, the spatially variable coefficient of friction, the angular velocity and the exerted normal pressure acted on the work material surface. The model is then validated through comparison of the numerically computed heat generation, peak temperature and the total torque exerted on the rotating tool to experimental result. Contact conditions, described as sliding, sticking or partial sliding or sticking or simply slip factor is derived experimentally, determined by the plunge force and torque from the welding process is adapted. The slip factor yield a proportional relationship between plunge force and heat generation where Coulomb's friction law is applied to describe the shear forces at the interface (Schmidt, et al., 2004) and (Colegrove, et al., 2007). Slip factor is also used to observe the welding energy and temperature, utilizing torque based heat input (Hamilton, et al., 2008). These works allow the prediction of the welding temperature from the transverse speed, rotating tool angular speed and the applied force. Eventually, fully coupled thermo-mechanical model with adaptive boundary conditions which applied both thermal and mechanical model is used to predict transient temperature profile, active developed stresses as well as the three-dimensional force components (Soundararajan, et al., 2005).

2.4.2 Model validation

The force and temperature measurement experiments were conducted under different welding parameters for model verification by differing the transverse and the rotating tool angular speed whilst maintaining the constant vertical force. The result is later used for the calculation of the heat input into the rotating tool and work material. In relation, mechanical model is developed to take account the effect on material such as the listed material properties; plasticity properties, thermal expansion, thermal stress, cooling effect, stress stiffening, stress distribution, material strain, residual stress as well as thermal history of the process (Chen & Kovacevic, 2003) and (Chen & Kovacevic, 2006).

Mechanical effect is visualised theoretically as material flow model to simulate the friction stir welding process effects on the soft material flow and join mechanism (Fratini, et al., 2006), (Zhang, et al., 2007). Theoretical representation of the mechanical effect is validated through the physical experimental work to highlights the particular material strain, its distribution and flow around the rotating tool, at the leading and trailing edges of advancing and retreating side as well as the actual bond that takes place in the friction stir welding process. Thus, the thermo-mechanical model shows the importance of the three-dimensional loads and torque exerted by the rotating tool to determine the best and optimized parameter for the friction stir welding process of any materials through statistical studies. The model is greatly related to the final weldment mechanical and welding process properties such as residual stresses, welding process temperature, final weldment tensile strength and productivity related variables such as welding speed, power consumed by the friction stir welding process and the rotating tool life. Proceeded, welding power is modeled to determine the overall heat input for the welding process based on the traverse speed and tool rotational speed as well as the effect on the work material properties. The model is calculated from the spindle torque through the relationship of the