CHAPTER 2
LITERATURE REVIEW

2.1 INTRODUCTION

This chapter presents a brief on the most prominent literature that contributed to this research study. The evolution of process governing phenomenon, conceptual understanding, gradual advancements, pros and cons of the various studies and attempts made to address those issues and the motivation for this research were comprehensively presented.

2.2 INTERLAYER CONCEPT IN FRICTION WELDING

Elliot et al. (1981) firstly reported that diffusion bonding and friction welding can be applied directly or with the introduction of an interlayer material at the contact interface. It has been suggested that improved weld properties can be achieved by introducing an interlayer between the contacting substrates prior to the friction welding operation. Hartwig et al. (1977) showed that interlayer materials have been applied during dissimilar friction welding of aluminum and steel base materials. This study had been carried by several researchers whose focuses were on evaluating the effects of interlayer selection on joint mechanical properties (Kouptsidis, 1977; Dunkerton, 1982a; Sassani et al., 1988). Maldonado et al. (2001) discussed the formation of brittle FeAl and Fe$_2$Al$_5$ intermetallics on dissimilar MMC/AISI 304 stainless steel friction welds. In the case of dissimilar MMC/Ag/AISI 304 stainless steel friction welds, circular silver
nanoparticles with dimensions ranging from 10 to 20 nm and Ag₃Al intermetallic were obtained. Further, the same group examined the influence of softened zone width and hardness (yield strength) on the notch tensile strengths of dissimilar welds using finite element modelling (FEM).

Zhang et al. (2012) performed electron beam welding of aluminum alloy and steel with Ag interlayer. Seam morphology, structure and mechanical properties of the joints were investigated with different action positions of the electron beam spot. The results revealed that with the rise of the beam offset to the silver side from the interface between silver and steel, the seam morphology was improved, and the porosity in the Ag interlayer perished. A layer composed of Ag₂Al and Al eutectic was formed at the interface between silver and aluminum and became thin and spiccato as the beam offset increased. Maldonado et al. (2001) additionally examined the influence of welding parameters, reinforcing particle chemistry and shape, matrix condition and silver interlayers on particle fracture during similar and dissimilar friction welding of aluminum-based metal-matrix composite (MMC) base material.

Chander et al. (2013) presented an overview of friction welding of AISI 304 and AA 6061 and the corresponding impact of electroplated interlayers on the weldment. Chen (2010) reported the creation of a friction stir weld between a magnesium-based alloy workpiece and an aluminum-based alloy workpiece. An interlayer composition was placed at one or both of the friction stir engagement locations or faying surface weld location. The interlayer in which the interlayer composition consists essentially of a mixture of an adhesive, and one of the materials or material combinations selected from the group consisting of: 1) silver, tin, and zinc; 2) silver and tin; 3) copper and tin; 4) zinc; 5) copper, tin, and alumina; 6) alumina; 7) aluminum and alumina; and 8) carbon and tin, as powder.
Friction stirring the magnesium-based alloy workpiece and the aluminum-based alloy workpiece with a friction stir tool primarily employs the friction stir engagement location and penetrates the workpieces to each faying surface weld location. The action of the friction stir tool also causes at least a portion of the adhesive to cure and to bond the magnesium-based alloy workpiece and the aluminum-based alloy workpiece together.

Chen et al. (2012) investigated the laser penetration welding of a steel-on-aluminium overlap configuration with Ni-foil interlayer. The steel-on-aluminium overlap configuration prevented the formation of intermetallic compounds inside the fusion zone. A new intermetallic compound Al0.9Ni1.1 was discovered to have formed between the fusion zone and Al alloy, in addition to FeAl3, compared to a joint with no Ni-foil interlayer. The Ni-foil interlayer improved the metallurgical reaction at the interfacial zone, which decreased the microhardness of interfacial intermetallic compounds and enhanced the toughness of the joint. The tensile property of the joint with Ni-foil interlayer is higher than that of the joint without Ni-foil interlayer.

Ambroziak et al. (2007) asserted that metals such as titanium, vanadium, zirconium, niobium, molybdenum and also tantalum and tungsten must be protected from the effects of oxygen, nitrogen and hydrogen at elevated temperatures. For this reason, they noted with interest that both from the innovative and practical points-of-view, the possibility of using the process of friction welding to produce joints in these materials should be investigated. The authors reported on the pseudo alloy of tungsten of D18 type, an alloy produced by a powder-metallurgy method of sintering tungsten grains, which forms the matrix (95% by weight), with the bonding phase formed by Ni-Fe alloy.
2.3 MECHANICAL TESTING AND METALLURGICAL EXAMINATION

Taban et al. (2010) carried out inertia friction welding to create joints between a 6061-T6 aluminum alloy and a AISI 1018 steel using various parameters. The authors stressed that the joints were evaluated by mechanical testing and metallurgical analysis. Microstructural analyses were reported to have been done using metallographic, microhardness testing, scanning electron microscopy (SEM), energy dispersive spectroscopy (EDS), X-ray elemental mapping, focused ion beam (FIB) with ultra-high resolution SEM and transmission electron microscopy (TEM) in TEM and STEM modes. They reported the results of the analyses to show the fact that joint strengths on the order of 250 MPa could be achieved. In addition, failures were seen in the plasticized layer on the aluminum side of the joint. Further, bond lines were characterized by a thin layer of formed Al–Fe intermetallic. This intermetallic layer averaged roughly 250 nm thick and compositionally appeared related to the FeAl and Fe$_2$Al$_5$ phases.

Uzun et al. (2005) carried out the joining of dissimilar Al 6013-T4 alloy and X5CrNi18-10 stainless steel using friction stir welding (FSR) technique. The microstructure, hardness and fatigue properties of friction stir welded 6013 aluminium alloy to stainless steel were investigated. Optical microscopy was used to characterize the microstructures of the weld nugget, the heat affected zone (HAZ), and thermo-mechanical affected zone (TMAZ) and the base materials. The authors reported the results, claiming that FSR could be used for the joining of dissimilar Al 6013 alloy and X5CrNi18-10 stainless steel. Seven different zones of the microstructure in the welding were reported as follows: (1) parent stainless steel; (2) HAZ in the stainless steel at advancing side of weld; (3) TMAZ in the stainless steel at advancing side of weld; (4) weld nugget; (5) TMAZ in the Al alloy at retreating side of
weld; (6) HAZ in the Al alloy at retreating side of weld; and (7) parent Al alloy. A good correlation between the hardness distribution and the welding zones were observed. Fatigue properties of Al 6013-T4/X5CrNi18-10 stainless steel joints were found to be approximately 30% lower than that of the Al 6013-T6 alloy base metal.

Fazel-Najafabadi et al. (2011) used lap joining method to join a 304 stainless steel plate with that of a CP-Ti by friction stir welding technique. Stainless steel was selected as the top member. Sound dissimilar joints were achieved using an advancing speed of 50 mm/min and rotation speeds in the range of 700–1100 rpm. A region of vortices of bimetallic weld of 304 stainless steel and CP-Ti was formed in the lap joint fabricated using the highest applied tool rotation speed; this was associated with plasticizing of both members with the aid of a double-shoulder tool. It was further stated that due to complex material flow, mechanical interlock features were shaped that consisted of extruded stainless steel into the plasticized titanium region. A maximum shear strength value of ~119 MPa was achieved; this was found to be close to that of CP-Ti. The lap joint was strengthened by the formation of vortices of bimetallic weld of 304 stainless steel and CP-Ti and mechanical interlock features at joint interface due to complex materials flow.

Winiczenko et al. (2012) explained on the ductile cast iron–austenitic stainless steel, ductile cast iron–pure Armco iron and ductile cast iron–low carbon steel welds, using the friction welding method. The tensile strength of the joints was determined using a conventional tensile test machine. Moreover, the hardness across the interface of materials was measured on metallographic specimens. The fracture surface and microstructure of the joints were examined using either light stereoscope microscopy as well as electron microscopy. In this case, scanning electron microscopy (SEM) and transmission electron microscopy (TEM) were
applied. The results of the analysis showed that the joint had the tensile strength compared to that of basic material. In case of ductile cast iron, it is possible to reach the tensile strength equals even 700 MPa. It was concluded that the process of friction welding was accompanied with diffusion of Cr, Ni and C atoms across the ductile cast iron–stainless steel interface. This led to increase in carbon concentration in stainless steel where chromium carbides were formed, the size and distribution of which was dependent on the distance from the interface.

Malarvizhi et al. (2011) fabricated a AA2219 aluminium alloy square butt joints without filler metal addition using gas tungsten arc welding (GTAW), electron beam welding (EBW) and friction stir welding (FSW) processes. The effects of three welding processes on the tensile, fatigue and corrosion behaviour were studied. Microstructure analysis was carried out using optical and electron microscopes. The results showed that the FSW joints exhorted superior tensile and fatigue properties compared to EBW and GTAW joints. It was also found that the friction stir welds showed lower corrosion resistance than EB and GTA welds. This was mainly due to the presence of finer grains and uniform distribution of strengthening precipitates in the weld metal of FSW joints.

Dong et al. (2012) experimentally carried out lap joining of aluminum alloy sheets to galvanized steel sheets by gas tungsten arc welding (GTAW) with Al–5% Si, Al–12% Si, Al–6% Cu, Al–10% Si–4% Cu and Zn–15% Al filler wires. Different amounts of Si, Cu and Zn were introduced into the weld through different filler wires. The effects of alloying elements on the microstructure in the weld and tensile strength of the resultant joint were investigated. It was found that the thickness of the intermetallic compound (IMC) layer decreased and the tensile strength of the joint increased with the increase of Si content in the weld. It was reported that the thickness of the
IMC layer could be controlled as thin as about 2 μm and the tensile strength of the dissimilar metal joint reached 136 MPa with Al–12% Si filler wire. It was further stated that Al–Si–Cu filler wire could result in thinner interfacial layer than Al–Cu filler wire, and fracture during tensile testing, which occurred in the weld for the former filler wire but through the intermetallic compound layer for the latter one. A Zn-rich phase was formed in the weld made with Zn–15% Al filler wire. Moreover, the Zn–Al filler wire also generated thick interfacial layer containing a great amount of intermetallic compounds and coarse dendrites in the weld, which led to a weak joint.

Chen et al. (2012) investigated the lap joints of TC1 Ti alloy and LF6 Al alloy dissimilar materials were fabricated by friction stir welding and corresponding interface characteristics. Using the selected welding parameters, excellent surface appearance formed, but the interface macrograph for each lap joint cross-section was different. With the increase of welding speed or the decrease of tool rotation rate, the amount of Ti alloy particles stirred into the stir zone by the force of tool pin decreased continuously. Moreover, the failure loads of the lap joints also decreased with an increase in welding speed and the largest value was achieved at a welding speed of 60 mm/min and tool rotation rate of 1500 r/min, where the interfacial zone can be divided into 3 kinds of layers. The microhardness of the lap joint showed an uneven distribution and the maximum hardness of HV 502 was found in the middle of the stir zone.

Andrzej et al. (2010) investigated the friction welding of a dissimilar-metal joint in titanium and tungsten pseudo alloy, in which sintered tungsten grains and alloy Ni–Fe formed respectively. The aim of the investigations was to determine which microstructures occurred in the titanium–tungsten pseudo alloy joint and which interlayers ensure that there were no brittle structures in it. The friction welding process was found to
proceed differently than in the case of titanium–tungsten joints. Stable Ti–Fe–Ni–W intermetallic phases with cracks propagating in them would occur in the joint zone. Proper interlayer of copper on the tungsten pseudo alloy side and vanadium on the titanium side were selected. Joints with tensile strength of 410 MPa were obtained.

Cavaliere et al. (2006) investigated the mechanical and microstructural properties of dissimilar 2024 and 7075 aluminium sheets joined by friction stir welding (FSW). The two sheets, aligned with perpendicular rolling directions were successfully welded; successively, the welded sheets were tested under tension at room temperature and the mechanical response with respect to the parent materials was analyzed. The fatigue endurance (S–N) curves of the welded joints was achieved, since the fatigue behavior of light welded sheets was the best performance indicator for a large part of industrial applications; a resonant electro-mechanical testing machine load and a constant load ratio \( R = \sigma_{\text{min}}/\sigma_{\text{max}} = 0.1 \) was used at load frequency of about 75 Hz. The resulted microstructure was due to the FSW process studied by employing optical and scanning electron microscopy either on ‘as welded’ specimens and on tested specimen after rupture occurred.

Aval et al. (2011) investigated thermo-mechanical behavior and micro-structural evolution in similar and dissimilar friction stir welding of AA6061-T6 and AA5086-O. First, the thermo-mechanical behaviors of materials during similar and dissimilar FSW operations was predicted using three-dimensional finite element software, ABAQUS, then, the mechanical properties and the developed microstructures within the welded samples was studied with the aid of experimental observations and model predictions. It was found that different strengthening mechanisms in AA5086 and AA6061 result in complex behaviors in hardness of the welded cross-section where the hardness variation in similar AA5086-O joints mainly depends on
recrystallization and generation of fine grains in weld nugget, however, the hardness variations in the weld zone of AA6061/AA6061 and AA6061/AA5086 joints are affected by subsequent aging phenomenon. Also, both experimental and predicted data illustrated that the peak temperature in FSW of AA6061/AA6061 was the highest compared to the other joints employing the same welding parameters.

Esmaeili et al. (2011) experimentally investigated the effect of friction Stir welding parameters on mechanical and metallurgical properties of aluminum 1050/brass (70%Cu–30%Zn) joints. Optical microscopy, SEM, X-ray diffraction analysis and EDS analysis were used to probe microstructures and chemical compositions. In order to examine mechanical properties, besides hardness test, tensile strength of the welds was measured. The main parameters investigation were the tool rotational speed, offset, welding speed, and depth of the sinking pin. The maximum ultimate tensile strength of the joint reached in the reported study was 80% of the base metal (aluminum). Results showed that the optimum parameters will yield a defect-free joint arisen from a suitable material flow and a narrow multilayer intermetallic compound at interface in addition to a composite structure in the stir zone which all result in a strong joint. Also, by leaving the optimized condition, occurrence of large brass fragments and welds defects lower weld strength besides shifting fracture path from interface to the stir zone. Also, according to the results, using low rotation speed was accompanied by the disappearance of interfacial intermetallic layer, whereas fast rotation will thicken this layer. Moreover, severe mechanical twining is observed in TMAZ of brass, which led to high values of hardness in this region.

Moreira et al. (2009) carried out a mechanical and metallurgical characterization of friction stir welded butt joints of aluminium alloy 6061-T6 with 6082-T6. For comparison, similar material joints made from each one of
the two alloys were used. The work included microstructure examination, microhardness, tensile and bending tests of all joints. An approximate finite element model of the joint, taking into account the spatial dependence of the tensile strength properties, was made, modeling a bending test of the weldments. This study showed that the friction stir welded dissimilar joint presented intermediate mechanical properties when compared with each base material. In tensile tests, the dissimilar joint displayed intermediate properties. For instance in the hardness profile, the lowest values were obtained in the AA6082-T6 alloy plate side where rupture occurred, and in the nugget all type of joints presented similar values.

Arivazhagan et al. (2011) investigated the microstructure and mechanical properties of AISI 304 stainless steel and AISI 4140 low-alloy steel joints by gas tungsten arc welding (GTAW), electron beam welding (EBW) and friction welding (FRW). For each of the weldments, detailed analysis was conducted on the phase composition, microstructure characteristics and mechanical properties. The results of the analysis showed that the joint made by EBW has the highest tensile strength (681 MPa) than the joint made by GTAW (635 Mpa) and FRW (494 Mpa). From the fractographs, it was observed that the ductility of the EBW and GTA weldment were higher with an elongation of 32% and 25%, respectively, when compared with friction weldment (19%). Moreover, the impact strength of weldment made by GTAW was higher compared to EBW and FRW.

Chen et al. (2011) asserted that nanostructured oxide dispersion strengthened (ODS) Fe-based alloys manufactured by mechanical alloying (MA) are generally considered to be promising candidate materials for high-temperature applications up to at least 1100 °C because of their excellent creep strength and good oxidation resistance. However, a key issue with these alloys is the difficulty in using fusion welding techniques to join components
due to oxide particle agglomeration and loss in the weld zone and the
disruption and discontinuity in the grain structure introduced at the bond. In
their study, the evolution of microstructure was comprehensively studied in
friction stir welds in a ferritic ODS alloy. Initially, electron backscattering
diffraction (EBSD) was used to analyze the grain orientation, the grain
boundary geometries and recrystallization behaviour. It suggested that
deformation heterogeneities were introduced during the friction stirring
process which facilitated the onset of recrystallization. Transmission electron
microscopy (TEM) and scanning transmission electron microscopy (STEM)
were used to observe the effects of the friction stir welding (FSW) process on
the grain structure and the distribution of $Y_2O_3$ and other particles in the metal
substrates in the FSW and adjacent regions, after the alloys had been
recrystallized at temperatures up to 1380 °C for 1 h in air. The results showed
that fine-equiaxed grains and a uniform distribution of oxide particles were
present in the friction-stirred region but that the grain boundaries in the parent
metal were pinned by particles. Friction stirring appeared to release these
boundaries and allowed secondary recrystallization to occur after further heat
treatment. They concluded that the FSW process appears to be a promising
technique for joining ferritic ODS alloys in the form of sheet and tube.

Gaafer et al. (2010) investigated the mechanical and microstructural
characteristics of friction stir welded AA7020-O Al plates. The influence of
the tool rotational and welding speeds and such characteristics was studied.
The friction stir welding (FSW) was conducted at tool rotational speeds of
1120, 1400, and 1800 rpm and at welding speeds of 20, 40 and 80 mm/min. It
was found that increasing the tool rotational speed and/or reducing the
welding speed increases the primary Al phase grain size as well as the size of
the precipitates at the center of the stirred zone (SZ). The tensile
characteristics of the friction stir welded tensile samples depend significantly
on both the tool rotational and welding speeds.
Hu et al. (2012) investigated a large-diameter thin-walled aluminum alloy tube which was produced by friction stir welding combined with spinning, and the tube’s microstructure and mechanical properties. The microstructural heterogeneity of the friction stir welded joint was significantly improved by severe plastic deformation, which resulted in the generation of a fine-grained structure and uniform distribution of second-phase particles in the weld and base material. The weld region of the tube showed similar microstructure and mechanical properties to that in base material.

Sirong et al. (2010) investigated the microstructures and mechanical properties of the welded joint. The AZ31B magnesium alloy sheet added with 0.5 wt. % Ce was welded with friction stir welding (FSW). The results showed that the microstructures in the weld nugget zone were uniform and with small equiaxed grains. The grains in the heat-affected zone and the thermo-mechanical affected zone were coarser than those in the base metal zone and the weld nugget zone. The ultimate tensile strength of AZ31B magnesium alloy added with 0.5 wt. % Ce was 270.41±4.48 MPa, and its elongation to fracture was (17.71±0.60)%. The ultimate tensile strength of FSW joint was 237.97±2.53 MPa, and its elongation to fracture was 6.63±0.60%. The fracture locations of FSW joint were in the heat-affected zone. The ductile fracture was the main fracture mode. The ultimate tensile strength of the sample along the direction of the weld was 270.02±1.45 MPa, and its elongation to fracture was (17.08±0.39) %. The microhardness in the weld nugget zone was slightly lower than that in the base metal. The microhardness in the thermo-mechanical affected zone and heat affected zone was lower than that in the weld nugget zone. The microhardness increased from the surface to the bottom of the weld.

Kostka et al. (2009) investigated the microstructure of the interface between Al alloy and Mg alloy joined by friction stir welding when
characterized using electron microscopy. The intermetallic compound reaction layer had a thickness of about 1 μm and consisted mainly of fine-grained Al$_{12}$Mg$_{17}$ phase. Further, nano size-grained Al$_3$Mg$_2$ inclusions in close proximity to the Al$_{12}$Mg$_{17}$ layer appeared in the Al alloy.

Arora et al. (2010) experimentally carried out the characterization of microstructure evolution in friction stir welded aluminum alloy by optical microscopy (OM) and transmission electron microscopy (TEM) and electron backscatter diffraction (EBSD). The weld nugget consisted of very fine equiaxed grains and experienced dissolution of nearly half of metastable precipitates into the matrix during welding. Thermomechanically-affected zone (TMAZ) also experienced dissolution of precipitates but to a lesser extent whereas coarsening of precipitates was observed in heat-affected zone (HAZ). Grain boundary disorientation measurements using EBSD indicated continuous dynamic recrystallization as the underlying mechanism for the fine equiaxed nugget grains. The yield and tensile strength of the weld decreased with comparison to base material. But due to the decrease of grain size and the dissolution of second phase precipitates, an increased Charpy energy value was observed in the weld nugget.

Sun et al. (2012) experimented with the technique of successful application of a flat spot friction stir welding technology to aluminum alloys; this technique was expanded to the spot lap welding of 1 mm thick mild steel. It revealed that sound joints could be successfully obtained with smooth surfaces and without any internal welding defects. Two welding strategies based on the welding parameter could be used to obtain the welds that fractured through plug failure mode at high shear tensile strength. One way is to weld the sheet at low heat input in the first step and the second step is used to generate large stir zone and flatten the sample surface. However, the microstructure in the stir zone was not homogeneous and a coarse columnar
grain structure formed at the bottom of the stir zone. Another way was to make the stir zone penetrate into the lower sheet during the first step and the second step was only aimed to flatten the sample surface. In this case, the total heat input could be reduced and the microstructure of the stir zone can be remarkably refined. The sound joints fractured along the circumference of the stir zone and reached about 6600 N during the shear tensile tests.

Chen et al. (2009) examined the microstructure and tensile properties of joints. The Al–Si alloy and pure titanium was lap-joined using friction stir welding technology. The maximum failure load of joints reached 62% of Al–Si alloy base metal with the joints fractured at the interface. X-ray diffraction results showed a new phase Ti$_3$Al$_3$ formed at the interface. The microstructure evolution and the joining mechanism of aluminum–titanium joints were systematically discussed.

Wei et al. (2012) conducted friction stir lap welding on soft/hard metals. A welding tool was designed with a cutting pin of rotary burr made of tungsten carbide, which made the stirring pin possible to penetrate and cut the surface layer of the hard metal. Magnesium alloy AZ31 and stainless steel SUS302 were chosen as soft/hard base metals. The structures of the joining interface were analyzed by scanning electron microscopy (SEM). The joining strength was evaluated by tensile shear test. The results showed the flower-like interfacial morphologies with steel flashes and scraps, which formed bonding mechanisms of nail effect by long steel flashes, zipper effect by saw-tooth structure and metallurgical bonding. The shear strength of the lap joint falls around the shear strength of butt joint of friction stir welded magnesium alloy.

Miao et al. (2007) experimented by joining the nanostructured ferritic alloy (NFA) MA957 by friction stir welding (FSW) and electro-sparked deposition (ESD) welding. Transmission electron microscopy (TEM)
and small-angle neutron scattering (SANS) characterization studies showed a uniform fine-scale equiaxed ferrite structure with a high dislocation density and slightly coarsened nm-scale particles in the joint region of the FSW weld compared to the base metal. Microhardness and tensile measurements on the FSW showed a modest reduction in the strength of the joint compared to the as-processed MA957. In contrast, the ESD-welds contained considerable porosity and the nm-scale particles dissolved or coarsened significantly, resulting in a larger degradation of the joint region strength.

Khodir et al. (2008) focused on the microstructure and mechanical properties of dissimilar joints of 2024-T3 Al alloy to 7075-T6 Al alloy produced by friction stir welding. Effects of welding speed and fixed location of base metals on microstructures, hardness distributions, and tensile properties of the welded joints were investigated. SEM-EDS analysis revealed that the stir zone contained a mixed structure and onion ring pattern with a periodic change of grain size as well as a heterogeneous distribution of alloying elements. The maximum tensile strength of 423.0 MPa was achieved for the joint produced at welding speed of 1.67 mm/s when 2024 Al alloy was located on the advancing side.

Chung et al. (2011) studied the dissimilar butt welded joint of reduced-activation ferritic/martensitic steel (RAF/M) F82H and austenite stainless steel (AISI304 (SUS304)) by friction stir welding. The effect of the position of the steels and tool plunging was considered in order to prohibit the mixing of the F82H and SUS304. When the dissimilar butt welding was performed such that the F82H plate was on the advancing side and the tool was plunged on the F82H side, defect-free joints could be successfully fabricated. Optical microscopy and EDX analysis were used to characterize the dissimilar joint microstructures and the interface. It was confirmed that the dissimilar joint formed no mixed structure and inter-metallic compounds.
Shang et al. (2012) experimented by joining the AZ31B Mg alloy and 6061 Al alloy using cold metal transfer (CMT) welding with pure copper (HS201) as the filler metal. The microstructure of Mg/Al CMT weld joint was studied by means of optical microscopy, scanning electron microscope (SEM), energy dispersive X-ray (EDX), X-ray diffraction (XRD). Results showed that dissimilar metals of Mg/Al could be successfully joined by CMT under proper processing parameters. The bonding strength of the joint was 34.7 MPa. A variety of Al–Cu intermetallic compounds, i.e. AlCu, CuAl₂, Cu₉Al₄, presented in the fusion zone of Al side, and Cu based solid solution was generated in weld zone, while Cu₂Mg and Al–Cu–Mg ternary eutectic structure was formed in the fusion zone of Mg side. The micro-hardness in the both sides of fusion zones increased sharply, which were 362 HV in Mg side and 260 HV in Al side. The joint was brittle fractured in the intermetallic compound layer of the fusion zone of Mg side, where plenty of Cu₂Mg intermetallic compounds were distributed continuously.

Zhang et al. (2007) stressed that the clear zigzag-line pattern on transverse cross-sections can be used to explain the formation mechanism of the weld nugget when friction stir welded AZ31 magnesium alloy without any other insert material is used as mark. It provided a simple and useful method to research the joining mechanism of friction stir welding. The rotation speed was kept at 1000 r/min and the welding speed changed from 120 mm/min to 600 mm/min. The macrostructure on the transverse cross-section was divided into several parts by faying surface. The results showed the shape and formation procedure of the weld nugget change with the welding speed. There were two main material flows in the weld nugget: one is from the advancing side and the other is from the retreating side.

Zhang et al. (2011) investigated two types of FSSW, normal FSSW and walking FSSW, which are applied to join 5052-H112 aluminum alloy
sheets with 1 mm thickness. They also studied the effect of the rotational speed and dwell time on microstructure and mechanical properties. Friction stir spot welding (FSSW) is a newly-developed solid state joining technology. The lower sheet material underneath the hook did not flow into the upper sheet due to the concave surface in the shoulder and groove in the anvil. The hardness profile of the welds exhibited a W-shaped appearance and the minimum hardness was measured in the HAZ. The results of tensile/shear tests and cross-tension tests indicate that the joint strength decreases with increasing rotational speed, while it was not affected significantly by dwell time. At the rotational speed of 1541 rpm, the tensile/shear strength and cross-tension strength reached the maximum of 2847.7 N and 902.1 N, corresponding to the dwell time of 5 s and 15 s. Two different fracture modes were observed under both tensile/shear and cross-tension loadings: shear fracture and tensile/shear mixed fracture under tensile/shear loadings, and nugget debonding and pull-out under cross-tension loadings. The performance of the welds played a predominant role in determining the type of fracture modes.

Dressler et al. (2009) experimented by joining titanium alloys TiAl6V4 and aluminium alloy 2024-T3 successfully by friction stir welding. Microstructure, hardness and tensile strength of the butt joint were investigated. The weld nugget exhibited a mixture of fine recrystallized grains of aluminium alloy and titanium particles. Hardness profile revealed a sharp decrease at titanium/aluminium interface and evidence of micro-structural changes due to welding on the aluminium side. The ultimate tensile strength of the joint reached 73% of AA2024-T3 base material strength.

Kim et al. (2006) investigated the effect of the welding speed and the rotation speed on the microstructure in the stir zone by measuring the Si particle distribution in the ADC12 alloy. The stir zone had fine recrystallized
grains without dendritic structures, and the eutectic Si was uniformly dispersed in the stir zone. The size of the Si particles was statistically determined in the stir zone using image processing. The number of finer Si particles, which was formed by stirring of the tool probe, increased during the FSW. Finer Si particles were distributed more in the bottom than in the other regions, though the size of the Si particles in the base metal was the same in all the regions. The size of the Si particles decreased with increasing welding speed. However, it was not significantly affected by the rotation speed.

Bilici et al. (2012) investigated the effects of the welding parameters on static strength of friction stir spot welds of high density polyethylene sheets. Friction stir spot welding parameters affect the weld strength of thermoplastics, such as high density polyethylene (HDPE) sheets. For maximizing the weld strength, the selection of welding parameters is very important. In lap-shear tests, two fracture modes were observed; cross-nugget failure and pull-nugget failure. The tool rotational speed, tool plunge depth and dwell time were determined to be important in the joint formation and its strength. The joint which had a better strength fails with pull-nugget failure morphology. Weld cross section image analysis of the joints were done with a video spectral comparator. The plunge rate of the tool was determined to have a negligible effect on friction stir spot welding.

Yan et al. (2010) investigated a dissimilar friction stir welding between 5052 Al alloy and AZ31 Mg alloy with the plate thickness of 6 mm. Sound weld was obtained at rotation speed of 600 r/min and welding speed of 40 mm/min. Compared with the base materials, the microstructure of the stir zone is greatly refined. Complex flow pattern characterized by intercalation lamellae was formed in the stir zone. Microhardness measurement of the dissimilar welds presents an uneven distribution due to the complicated microstructure of the weld, and the maximum value of microhardness in the
stir zone is twice higher than that of the base materials. The tensile fracture position locates at the advancing side (aluminum side), where the hardness distribution of weld shows a sharp decrease from the stir zone to 5052 base material.

Kurt et al. (2011) stated rotary friction welding is one of the most economical and efficient production methods for joining similar and dissimilar materials. It is widely used with metals and thermoplastics in a wide variety of aviation, transport, and aerospace industrial component designs. Individually, mild steel to mild steel and copper to copper are normally easy to weld by fusion welding methods, but the joint of mild steel to copper can be extremely difficult due to the differences in the two materials’ melting temperature, density, strength, and thermal conductivity. Thus, these kinds of problems can be eliminated by a solid-state friction welding technique. The authors sought to understand the friction welding characteristics of mild steel-bronze dissimilar parts. The study looked into the influence of process parameters, which includes friction pressure, upsetting pressure, and upset time on the axial shortening, hardness, microstructure, and tensile properties of the welds. The optimum parameters for upset time, upset pressure, and friction pressure necessary for welding were obtained. Finally, the obtained mechanical properties results were commented on in the light of optical microscopy.

Joining of aluminum to steel is generally difficult because of the differences between their physical and chemical properties. Both alloys have incomparable melting points, thermal conductivity, coefficient of linear expansion and heat capacities, as reported by Cardarelli (2008).
Considering the phase diagram of Al–Fe system from Baker (1992), the low solubility of iron in aluminum promoted the formation of brittle intermetallic compounds such as Fe2Al5, FeAl3, in the weld zone. As a result of such difficulties, especially the formation of thick intermetallic layers, creation of a strong joint between aluminum and steel sounds impossible or very difficult by using common fusion welding techniques.

The much advancement made in the weldability of materials used in the engineering applications through friction welding has increased the importance of the use of dissimilar materials such as aluminum, magnesium, copper and steel in the applications such as automotive and aerospace areas. Thomal et al. (1991) as well as Dawnes and Thomas (1995) initially reported on the process for aluminum alloys and later on, dissimilar materials.
Mishra and Ma (2005) presented the detailed investigations on the difficulty of making high-strength materials with fatigue and fracture resistant welds in aerospace aluminum alloys, such as highly alloyed 2XXX and 7XXX. These have long inhibited the wide use of welding for joining aerospace structures. These aluminum alloys are generally classified as non-weldable, because of the poor solidification microstructure and porosity in the fusion zone. Also, the loss in mechanical properties as compared to the base material is very significant. These factors make the joining of these alloys by conventional welding processes unattractive. Some aluminum alloys can be resistance welded, but the surface preparation is expensive, with surface oxide being a major problem.

Cam and Mistikoglu (2014) reported on the microstructures and mechanical properties of friction stir welded Al-alloys existing in the open literature, which were discussed in detail. The correlations between weld parameters used during FSW and the microstructures that evolved in the weld region and thus mechanical properties of the joints produced were also crucial in determining the resultant product of the weldment materials.

Bhamji et al. (2010) reported on the joining of metals by linear friction method. FW was considered to be the most significant development in metal joining in a decade and is a ‘‘green’’ technology due to its energy efficiency, environment friendliness, and versatility. As compared to the conventional welding methods, FW consumes considerably less energy. No cover gas or flux is used, thereby making the process environmentally-friendly. Li et al. (1999) reported on the microstructural behavior due to the welding of aluminum alloys. The joining does not involve any use of filler metal and therefore any aluminum alloy can be joined without concern for the compatibility of composition, which is an issue in fusion welding. When
desirable, dissimilar aluminum alloys and composites can be joined with equal ease.

Furthermore, FW of dissimilar alloys/metals has attracted extensive research interest due to potential engineering importance and problems associated with conventional welding. FSW is generally identified as a new welding technology that can be used to weld dissimilar alloys and metals. Li et al. (2000) reported on the friction stir welding process of aluminum alloy 2024 to silver. The residual microstructure and the phenomena related to the grain growth and crystallization behavior of the aluminum alloy and the copper plates were discussed in detail. The material flow and microstructure in the friction stir butt welds of dissimilar aluminum alloys were reported by Ouyang and Kovacevic (2002).

Kazi et al. (2001) reported on the friction stir welding and process in which a few studies have been undertaken to friction stir weld dissimilar aluminum alloys, copper alloys or aluminum alloys to other. The weld efficiency was observed to reduce if a very hard aluminum alloy was stirred with a very soft aluminum alloy. However, most of these studies were previously focused on material flow visualization, and no optimum FW parameters and tool geometry were identified and was reported by Li et al. (1999) in the dissimilar materials systems. The resultant welds were usually with an unwelded seam, large open (void) zones, and oxide inclusions at the root of plates. Furthermore, it was reported that the locations of two dissimilar alloys exerted a significant effect on material flow pattern and the resultant weld quality.
2.4 THERMAL ASPECTS OF FRICTION WELDING

The temperature distribution in friction welds is determined by factors such as the power input, the thermo physical properties of the adjoining base materials and by flash formation. A key problem during modeling of the friction welding process is in obtaining an accurate description of the heat generated at the bondline.

Yeong-Maw Hwang et al. (2008) experimentally investigated to explore the thermal histories and temperature distributions in a work piece during a friction stir welding (FSW) process involving the butt joining of aluminum 6061-T6. They found that successful welding processes are achieved by appropriately controlling the maximum temperatures during the welding process. By help of regression analysis they found that second-order polynomial curve is best fit the experimental temperature values in the width direction of the work piece. The Vickers hardness test was conducted on the welds to evaluate the hardness distribution in the thermal-mechanical affected zone, the heat affected zone, and the base metal zone. Tensile tests are also carried out, and the tensile strength of the welded product is compared with that of the base metal.

Hamilton et al. (2008) developed a thermal model of friction stir welding that utilizes a new slip factor based on the energy per unit length of weld. The slip factor is derived from an empirical, linear relationship observed between the ratio of the maximum welding temperature to the solidus temperature and the welding energy. The thermal model successfully shows the maximum welding temperature over a wide range of energy levels but the temperature for low energy levels for which heat from plastic deformation dominates was accurately found. The thermal model supports the hypothesis that the relationship between the temperature ratio and energy level is characteristic of aluminum alloys that share similar thermal
diffusivities. The thermal model was used to generate characteristic temperature curves from which the maximum welding temperature in an alloy may be estimated if the thermal diffusivity, welding parameters and tool geometry are known.

Andrzej (1990) defines that Friction welding is a complicated process, which involves the interaction of thermal, mechanical and metallurgical phenomena. A finite element model to simulate this coupled process is developed to represent the workpieces and surface contact conditions. Predictions of the temperature distribution, thermal expansion and thermo-plastic stresses are obtained from this model. Comparison of the analytic results to test data are presented and discussed.

Ming-Liang Zhu et al. (2010) conducted the tensile and impact behavior of dissimilar weld joints of newly developed rotor steels 23CrMoNiWV88 and 26NiCrMoV145 at various temperatures below 350 °C. Homogeneous microstructures and asymmetrical micro-hardness along the dissimilar welding joint were observed. With the increase of temperature, strength decreased which was associated with the increased plasticity, and fracture location changed from weld metal (WM) to intermediate pressure (IP) base metal (BM) at around 300 °C. Compared to the homogeneous impact specimen with two fracture zones at fracture surface, a combined quasi-cleavage and ductile fracture mode with three zones was observed at the fracture surface of the dissimilar weld joint when the testing temperature was in the range of 0–40 °C. The occurrences of separated zones were mainly ascribed to the multi-layer welding process and thus improved the impact toughness of the welding joint.

Cao et al. (2005) conducted an experimental study to determine if the maximum temperature in the workpiece can reach the lower bound of the melting temperature range and trigger liquation during friction stir welding
FSW) of aluminum alloys as some computer simulations had suggested. Alloy 2219, which is essentially a binary Al-Cu alloy, was selected as the material for study because of its clear lower bound of the melting temperature range, that is, the eutectic temperature 548°C. In addition to FSW, gas metal arc welding (GMAW) of alloy 2219 was also conducted to provide a benchmark for checking liquation in FSW of alloy 2219. The microstructure of the resultant welds was examined by both optical and scanning electron microscopy. It was found that in GMAW of alloy 2219, q (Al2Cu) particles acted as in-situ micro sensors, clearly indicating the onset of liquation by reacting with the surrounding aluminum matrix and forming distinct composite-like eutectic particles upon reaching the eutectic temperature. In FSW, on the other hand, no evidence of q-induced liquation was found as the welds contained q particles alone and no eutectic particles, suggesting that the eutectic temperature was not reached during FSW. However, in most friction stir welds large q particles were observed, some exceeding 100 μm and even 1 mm in length as compared to the normal q particles of only about 10–15 μm in length in both the base metal and the weld, that is, the stir zone or nugget. The large q particles appeared to have formed during FSW from agglomeration of fractured q particles and the smaller ones of the q particles in the workpiece. No apparent correlation between the extent of agglomeration and the welding condition was found.

Sharma et al. (2012) worked at a high strength Al–Zn–Mg alloy AA7039, which was friction stir welded by varying welding and rotary speed of the tool in order to investigate the effect of varying welding parameters on microstructure and mechanical properties. The friction stir welding (FSW) process parameters have great influence on heat input per unit length of weld, hence on temperature profile which in turn governs the microstructure and mechanical properties of welded joints. There exits an optimum combination of welding and rotary speed to produce a sound and defect-free joint with
microstructure that yields maximum mechanical properties. The mechanical properties increased with decreasing welding speed/ increasing rotary speed i.e. with increasing heat input per unit length of welded joint. The high heat input joints fractured from heat-affected zone (HAZ) adjacent to thermomechanically affected zone (TMAZ) on advancing side while low heat input joints fractured from weld nugget along zigzag line on advancing side.

Dinaharan et al. (2012) asserted that inadequate development of fabrication methods restricts the applications of new families of aluminum matrix composites (AMCs). They further stated that friction stir welding (FSW) is a potential candidate to join AMCs without any defects associated with conventional fusion welding processes. The primary objective of his work was to apply FSW process to join AA6061/ (0, 5 and 10 wt. %) ZrB2 in-situ cast composites and evaluate the joint properties. The composites were prepared by reacting inorganic salts K2ZrF6 and KBF4 with molten aluminum and joined using a FSW machine at a tool rotational speed of 1150 rpm, welding speed of 50 mm/min and axial force of 6 KN. The joints showed the presence of various zones such as weld zone (WZ), thermomechanically affected zone (TMAZ) and heat-affected zone (HAZ). The weld zone was characterized with a homogenous distribution of ZrB2 particles. The stirring action of the tool resulted in fragmentation of several clusters present in the parent composite. The weld zone exhibited higher hardness than that of the parent composite. The tensile strength of welded joints was comparable to that of parent composites. The wear resistance of the composites improved subsequent to FSW.

Friction welding can also be used because the energy is produced due to friction, resulting in a low heat input and narrow HAZ. Hard or brittle intermetallic interlayers are not easily produced, which can decrease the weld quality. Moarrefzadeh (2012) reported on the heat affected zone in friction
welding process. It was reported that the thermal effect of friction welding that specially depended on the friction type and temperature field in workpiece. This is the main key of analysis and optimization of the process. Brazing is a liquid-phase process that uses a fusing material to connect two different materials. Diffusion bonding requires a high vacuum or heating equipment; therefore, it is more expensive and has restricted applications. Mechanical interlocking or mechanical fasteners are methods that lack ductility; therefore, stress concentration is easily produced in the connection points (such as bolt joints or rivets), which may lead to fractures. The microstructure and crystallographic texture spanning the soft region at the thermomechanically affected zone/heat-affected zone (TMAZ/HAZ) boundary of a friction stir weld in 2519 Al were reported by Fonda and Bingert (2004) in which a systematic investigation was carried out to determine their contributions to the properties of that region. It was confirmed that the microstructure was shown to be the primary cause of softening at the TMAZ/HAZ boundary.

Friction welding results in plastic deformation and temperature rise within and around the welded zone. Smith et al (1999) as well as Bendzsak and Smith (2000) proposed a thermo-mechanical flow model in which the principles of fluid mechanics were applied. It assumed viscous heat dissipation as opposed to frictional heating. This model used tool geometry, alloy type, tool rotation speed, tool position and travel speed as inputs and predicted the material flow profiles, process loads, and thermal profiles. It was indicated that three quite distinct flow regimes were formed below the tool shoulder. These are: (a) a region of rotation immediately below the shoulder where flow occurred in the direction of tool rotation, (b) a region where material is extruded past the rotating tool and this occurred towards the base of the pin, and (c) a region of transition in between regions (a) and (b) where the flow had chaotic behavior. Knowledge of temperature distribution
in the vicinity of the welded bond is significant in the assessment of physical processes in the area of welding. The temperature gradient and plastic thermal deformations determine microstructural changes, diffusion phenomena and mechanical properties of the finished product. Unfavourable thermal and stress effects are intensified when materials of different heat and mechanical properties, like Al₂O₃ and Al, are bonded.

Uzun et al. (2005) investigated the microstructure, hardness and fatigue properties of friction stir butt welded 4 mm thick aluminum 6013-T4 to X5CrNi18-10 stainless steel. They successfully obtained sound joints and characterized several distinct regions of dissimilar welds such as HAZ and TMAZ in both base metals; however, they did not investigate the effect of process parameters on the mechanical properties of joints. Watanabe et al. (2006) investigated the effect of tool rotation speed and pin-position on the tensile strength of 2 mm thick 5083 aluminum alloy and mild steel sheets. Tanaka et al. (2009) analyzed the effect of rotation speed on temperature rise and joint strength of 7075-T65 aluminum alloy and mild steel at the condition of constant welding speed, and the effect of heat input on the formation of intermetallic compounds and resultant tensile strength was investigated.

Many aluminum alloys are strong by virtue of precipitation hardening through natural or artificial ageing from the solution-treated condition. Yukata et al. (1999) reported on the heat associated with welding changes in the microstructure of the material. This can be seen from the below Figure 2.2. HVmin and HVmax represent the hardness in the solution-treated and precipitation hardened states. The effect of welding is to cause a drop in hardness from HVmax towards HVmin as the peak temperature experienced increases, curve (a), Figure 2.2. This is because precipitates will coarsen and reduce in number density in regions remote from the heat source, and will re-enter solution when the peak temperature is sufficiently high. Grong (1997)
reported that some re-precipitation may occur during the cooling part of the thermal cycle, resulting in a hardness value beyond HV\text{min}, curve (b), Figure 2.2.

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{figure2_2.png}
\caption{A schematic diagram showing dissolution and re-precipitation in age-hardenable aluminum alloys}
\end{figure}

The ultimate result is the continuous line with a minimum in hardness somewhere in the heat-affected zone, due to the competing effects of dissolution and re-precipitation. But in contrast, Svensson et al. (2000) reported about the age hardenable AA 6082, where a minimum hardness occurs in the HAZ, and friction welding of non-hardenable AA 5082 results in uniform hardness across the weld.

HV denotes the Vickers hardness number adapted from Grong (1997). This general scenario may be complicated by the effects of deformation in FW as described for the specific example of AA 2219 as reported by Nair et al. (2007). AA 2219 is a copper precipitation-strengthened alloy containing about 6.3 wt\% Cu, which because of its
strength and toughness at low temperatures, is used for containing liquified gases for rockets of various kinds. It is frequently supplied in the T87 condition, meaning that it has been solution treated cold–worked (10% reduction in rolling) and artificially aged. It can be welded using arc processes but this result in a reduction in the cross-weld strength because the proof strength of the fusion zone decreases to about 140 MPa compared with the 370 MPa of the plate. The former can be increased to between 220–275 MPa using pulsed GTAW or pulsed electron beam welding techniques because this promotes finer grains in the fusion zone.

Chen and Kovacevi (2004) studied the feasibility of joining Al 6061 to AISI 1018 steel. They reported the effect of pin-position on the temperature distribution and microstructure of weld zone at constant tool rotation and traverse speed. Lee et al. (2006) examined the type of intermetallic compounds produced in the reaction layer between friction stir welded 6056-T4 Al alloy and 304 austenitic stainless steel. Due to the nature of FSW process, with correct selection of welding parameters, no melting of base alloys is expected. Thus, the formation of intermetallic compounds decreased noticeably.

Recent experimental and computational works have provided significant insight about several interesting features of material flow in friction welding and the joining process. Nandan et al. (2008) reported on the process, weldment and the micro-structural properties of friction welded aluminum, magnesium, copper, titanium alloys and steel. Thomas et al. (1999) reported on the feasibility of steel welding as the friction-welding of steels had not progressed as rapidly as far as aluminum is concerned due to the following reasons.
i) The material from which the tool is made has to survive much more strenuous conditions because of the strength of steel;

ii) There are also numerous ways in which steel can be satisfactorily and reliably welded;

iii) The consequences of phase transformations accompanying FSW have not been studied in sufficient depth; and

iv) The variety of steels available is much larger than for any other alloy system, requiring considerable experiments to optimise the weld for a required set of properties.

Threadgill and Johnson (2004) mentioned that FW would become a commercially attractive method for the fabrication of ships, pipes, trucks, railway wagons as well as hot plate and that this assertion had not yet come to fruition. That the application of FW to steels is premature is emphasised by the fact that with few exceptions, only elementary mechanical properties have been characterised; most reports are limited to simple bend, tensile and hardness tests. Thomas et al. (1999) proposed these welding processes for steel. The authors noted that for serious structural applications of the type proposed above it would be necessary to assess fracture toughness and other complex properties in greater depth.

Thomas et al.’s (1999) results provided a typical temperature profile behind a friction-stir weld on steel as illustrated in Figure 2.3. The maximum temperature reached was less than 1200°C and the time \( t_{85} \) taken to cool over the range 800–500°C was about 11 s.

Lienert et al.’s (2003) report stands as an example for a manual metal arc weld with a heat input of about 1.3 kJmm\(^{-1}\).
Therefore, the metallurgical transformations expected on the basis of cooling rates alone are not expected to be remarkably different from ordinary welds. However, there are certain major qualifications to this statement. Since the peak temperatures reached are much lower than in arc welds, the part of the HAZ which becomes fully austenitic will be smaller in dimension and with a finer austenite grain size. The latter helps avoid detrimental transformations, for example to untempered martensite, by reducing the hardenability of the steel. It should therefore be possible to weld high carbon-equivalent steels using FSW than would be possible for arc welding processes. Indeed, examination of the data for the mild steel designated alloy 2 was estimated at about 335°C using the method described
by Maynier et al. (1978). The TMAZ should become fully austenitic at some stage of its thermomechanical history. It is likely that the severe deformation in this zone causes the austenite to recrystallise, perhaps repeatedly, prior to its transformation during subsequent cooling. This can result in a finer and consequently somewhat harder microstructure than the HAZ, consistent with the hardness behaviour. The situation for the FSW ferritic stainless steel (Alloy 1) is different, in that the heat-affected zone is harder than the TMAZ. The reason for this is not clear from the limited microstructural evidence presented by Thomas et al. (1999).

Mishra and Ma (2005) suggested that for materials with high melting point such as steel and titanium or high conductivity such as copper, the heat produced by friction and stirring may be not sufficient to soften and plasticize the material around the rotating tool. Thus, it is difficult to produce continuous defect-free weld. In these cases, preheating or additional external heating source can help the material flow and increase the process window. On the other hand, for materials with lower melting point such as aluminum and magnesium, cooling can be used to reduce extensive growth of recrystallized grains and dissolution of strengthening precipitates in and around the stirred zone. Bienvenu and Koutny (1991) reported on the solid-state diffusion bonding of aluminum foils.

Khandkar et al. (2003) examined the important role played by the boundary conditions at the bottom surface and reported that for FSW of AA6061-T651 plates, an overall convective heat transfer coefficient of $1000 \text{Wm}^{-2}\text{K}^{-1}$ might be appropriate for the bottom surface of the workpiece if the backing plate is not considered. However, they observed that when a stainless steel backing plate is taken into account, a variable gap conductance would be appropriate for the work-piece/backing-plate interface, and recommended an average gap conductance somewhat less than 5000
Wm\(^{-2}\)K\(^{-1}\). They suggested that significant variations in the heat transfer rates can occur depending on the specific experimental conditions and recommended determining the rate experimentally. Since the accuracy of the computed temperature field depends on the value of the heat transfer coefficient, the uncertainty in the heat transfer coefficient can significantly affect the reliability of the computed temperature field.

Significant improvement in the reliability of the model predictions were suggested by Nandan et al. (2007) and they achieved it by determining the uncertain parameters, such as the heat transfer coefficient using a limited volume of experimental data. This approach has been tested for FSW of dissimilar aluminum alloys.

However, joining of aluminum to steel is not easy for the following reasons:

- Much higher melting point of steel compared to aluminum.
- Difference of the thermal expansion coefficients between steel and aluminum.
- The very tenacious superficial oxide film on aluminum alloys, which interferes with the achievement of a metal-to-metal contact at the interfaces.
- Formation of brittle intermetallic compounds (IMC).

Schbert et al. (2001) reported on the formation of a thick and brittle Al-Fe intermetallic compound (IMC) layer at the welding interface and degradation of strength of the base materials because of additional adverse thermal effects. The most serious problem is the formation of brittle intermetallic compounds (Fe\(_x\)Al\(_y\)) resulting from the reaction of Al with Fe. In particular, fusion welding involves the formation of large amounts of
intermetallic compounds in the weld metal because steel and aluminum are mixed in the liquid state and thus has been considered to be unsuitable for fusion welding. Lee et al. (2005) showed that controlling the formation of IMC layers is important for obtaining a reliable joint.

In contrast, the formation of the intermetallic compound in solid-state welding can be controlled by selecting suitable bonding parameters, since the creation of the IMC is controlled by diffusion of reacting elements in the solid state. For this, many investigations have been reported of solid-state bonding of aluminum alloy to steel. Friction welding is a process most widely used for joining of dissimilar metals because of its high productivity and reliability of the joint performance, in addition to the controllability of the formation of the IMC layer.

As suggested by Tylecote (1968), however, the formation of the Al-Fe intermetallic compound at the interface causes a serious reduction of the joint strength. Wallach and Elliot (1981) suggested by reviewing previous publications that a reduction of the joint strength occurred when the thickness of the IMC layer exceeded about 1 μm. They also suggested that the Mg addition to the aluminum alloy enhanced the growth of the IMC layer and reduced the joint strength, while the Si addition retards the growth of the IMC layer and improves the joint strength. Since then, many papers have reported about the effect of the IMC layer on the solid-state bonded joint of aluminum alloy to steel. It is generally accepted that the effect of a brittle IMC layer on the mechanical properties of the joint becomes more serious, as its width increases. The joint strength decreases almost linear with an increase of the thickness of the IMC layer.

However, several authors have reported cases where friction welds of aluminum to steel fractured at the interface, showing lower strength than the base metal, even when the IMC layer was less than 1 μm thick. In this
regard, no clear explanation has been given for the controlling factor of the joint strength. In particular, aluminum alloys with a high Mg content have a lower joint efficiency and a narrower parameter window to obtain a high joint efficiency. Magnesium is therefore a very important element added to a variety of industrial Al alloys.

Although the formation of a certain amount of intermetallic phases is necessary to obtain a joint, an excess of these phases reduces the joint strength below practical usable values. It has been suggested that intermetallic phase formation at the joint interface is an essential requirement for the attainment of a satisfactory bond formation during dissimilar friction welding.

In addition to the above thermal change, there is a significant microstructural evolution, including grain size, grain boundary character, dissolution and coarsening of precipitates, breakup and redistribution of dispersoids, and texture. An understanding of mechanical and thermal processes during welding is needed for optimizing process parameters and controlling microstructure and properties of welds.

Friction welding process is classified by the American Welding Society (AWS) as a solid state joining process in which bonding is produced at temperatures lower than the melting points of the base materials (Maldonado-Zepeda, 2001). Friction welding as a solid state joining process has been considered as a potential process for joining a range of “difficult-to-weld” materials because of its inherent advantages, such as short welding time, minimal surface preparation, and ease of automation. The use of rotary friction welding was however limited to solid or tubular cylindrical sections because of the nature of energy delivery in this joining process. The linear friction welding process for non-cylindrical sections has been developed and used for some limited applications.
The difficulties in the welding of aluminum alloy with stainless steel by fusion welding processes have been a great challenge for engineering, because they result from hard and brittle intermetallic phases that are formed between aluminum and steel at elevated temperatures (Fe$_3$Al, FeAl, FeAl$_2$, Fe$_2$Al$_5$, and FeAl$_3$). The Fe-Al phases diagram shows the well-defined intermetallic phases (Banker and Nobili, 2002).

All heating responsible by the union is mechanically generated by friction between the parts to be welded. This heating occurs due to one part that is fixed, which is pressed on the other that is in high rotation. The friction between the surfaces makes possible a rapid temperature rise in the bonding interface, causing the mass to deform plastically and flows depending on the application of pressure and centrifugal force, creating a flash. With this flash, impurities and oxides are removed from the surface, promoting the creation of a surface with excellent physical and chemical adhesion. The increase of temperature in the bonding interface and the application of pressure on that surface originate the diffusion between the two materials, and hence their union.

The joints were cut in the transverse weld, embedded in an array of bakelite, polished and examined in the region of the interface on the aluminum and AISI 304 stainless steel sides, according to ASTM E3. Aluminum was attacked with Keller reagent and stainless steel with electrolytic acid oxalic 10% and examined under a microscope.

The photomicrograph of the junction between aluminum and stainless steel was taken in the central region of the sample with an increase of 100 X. The interface region was characterized by a straight line with some imperfections under the friction welding process. Both in the aluminum and stainless steel sides, microstructural changes were not observed near the interface region, as it occurred in fusion welding processes. All plastic
deformation resulting from the parameters used in the process occurred in the aluminum, due to the fact that this material has lower strength and lower hot forging temperature.

Gould (2012) conducted a review on the welding of aluminum alloys to steels and concluded that the resultant performance was strongly dependent on the formation of intermetallic phases. They further reported that with the bonding of aluminum to steel, a number of intermetallic phases such as FeAl, Fe3 Al and Fe2Al5 could be formed. They noted that results of prior investigations revealed that the formation of these phases are usually along the bond line of welds through interdiffusion. Gould (2012) added that with the growth of these intermetallic phases, the inherent low ductility in them leads to a situation in which the integrity of the joint is compromised. The author further commented that with cycle times shorter than 200-ms, there appeared to be a minimization of the intermetallic formation.

Gould (2012) further reported on an investigation carried out that the weld showed an effective heating time on the order of 700-ms. The author noted that this was significantly longer than 200-ms times that was earlier documented for intermetallic free joint formation. In a detailed analysis, the author commented that in several locations along the bond line, the scanning electron microscopy showed backscatter images with lighter for heavier elements, and darker for the lighter ones. It was declared that intermediate phases appeared in gray tones, which is a reflection of the composition of the particular intermetallic formed. A further insight on the experimental results, revealed by the author, showed that areas lacking an intermetallic between the aluminum and steel did not have sufficient incubation energy to occur. The author observed that in areas where nucleation occurred, growth appeared to have been largely down in the bond line instead of being into the bulk materials themselves.
Experimental results (Cam and Kocak, 2014) suggested that the high strain rate/high temperature deformation cycle that was applied in the course of joining the materials changed the metallurgical and mechanical properties of material immediately at and adjacent to the bond line during rotary and linear friction welding, and also within the weld zone in friction stir welding. Cam and Kocak (2014) further noted that the above mentioned process leads to metallurgical effects, which include:

i) The development of fine dynamically recrystallized equiaxed grains existing at the bond line, and occurring in all metal/metal joints. These fine grains, when compared with the larger grains having elongations of the joints, which are produced by gas metal arc welding (GMAW), confirm the diversity of these metallurgical effects;

ii) When age-strengthened base materials are welded, due to solution, overaging and reprecipitation, softened zone is formed (referred to as the strength undermatched area);

iii) New and sometimes brittle microstructural phases formation. An example is the strain-induced martensite in dissimilar joints including austenitic stainless steel;

iv) Formation of intermetallics in dissimilar metal joints; and

iv) Cracking, referred to as particle fragmentation when Al-based materials are welded; a case in point is the particle agglomeration in Fe-based superalloy MA 956 friction joints.
2.5 SUMMARIZING THE LITERATURE CONTRIBUTIONS

The studies reviewed discussed mechanisms/design principles/approaches/methodologies for the friction welding. A very little detail is available regarding the approaches for effective, if not optimal, design methodologies for friction welding with interlayer.

After sketching through the literature, it was observed that the literature on dissimilar welding with interlayers were inadequate. Moreover, there have been no concrete accessible documents. Added to this, the studies on Al MMCs to steel joining with experimentation, destructive and nondestructive evaluation, analysis on friction welding parameters’ interdependencies and finite element modeling and simulation for friction welding process with interlayers have not been reported in detail. Hence, the objective of the study aims at addressing this issue with a systematic approach.

The application of friction welding has largely been confined to similar materials or in few cases for dissimilar materials without interlayer. In general, the studies reported friction welding for non-ferrous materials. Although significant attention has been paid to friction welding and the issue of dissimilar material welding has gained limited attention of researchers, particularly, investigations relevant to interlayers for dissimilar welding is sparse in the literature. Aircraft and aerospace components are being made with materials such as stainless steel and aluminum. These materials, which can be difficult and many times impossible to weld with conventional methods, can be joined with the friction welding process. Aircraft/aerospace
Components friction welded include compressor rotors, fan shafts, cluster gears, landing gear components, bimetallic rivets and hook bolts, aluminum heat pipes, and cryogenic rocket components. In rocket engine assemblies aluminum-stainless steel joints are required for connection of aluminum valve components to stainless steel tubing. Considering the numerous advantages of friction welding process with interlayer, a proposal is undertaken to incorporate the interlayer in order to increase the bond integrity and reduce the HAZ. The demonstration of friction welding with various interlayers is an attractive alternative and is a pivotal attempt among competitors and the possibility of exploring technology transfer to industries would be the major benefit from this project outcome.