Chapter 01: Introduction

1.1 Preamble

The present chapter discusses composites materials, Friction Stir Processing (FSP) and Friction Stir Welding (FSW) techniques. The respective sections elaborate on the working principle of individual processes and their application. Apart from this, the chapter discusses the need for research.

1.2 Composites Materials

The current situation of an emerging trend and varying technology creates a need for introducing novel materials having required properties with low cost (Prabu, Karunamoorthy, Kathiresan, & Mohan, 2006). The superior thermal, mechanical and physical properties of composite materials, attracts various industries (Patel, Pandey, & Rao, 2011). From various historical examples such as the Iron Pillar of Delhi (Wranglen, 1970), weapons such as Mongolian bows, Damask sword and Japanese sabers (Gay, 2014), it can be said that composite materials are not new to humankind (Aleksendric & Carlone, 2015). It can be said that composite materials are derivative of conventional materials (Inegbenebor, Bolu, Babalola, Inegbenebor, & Fayomi, 2015). In composites, reinforcement materials either in the form of fibers or in the form of particles are inserted into conventional materials/alloys (i.e. matrix material). The addition of reinforcement particles will ultimately enhance the properties of conventional materials (Gay, 2014). There exists sufficient literature which states the use of composite material or development of special purpose composite material (Zhang, Duan, Zhu, & Yin, 2017; Jani, Kumar, Khan, & Kumar, 2016; Srivatsan, 1995; Lloyd, 1994).

There exist three different types of matrix material i.e. polymer matrix, mineral matrix and metal matrix (Hull & Clyne, 1996). Similar to this reinforcement can be classified as particulate, discontinuous fibers and continuous fibers reinforcement (Taha, 2001). Metal Matrix Composites (MMC) are composites that generally consist of two parts i.e. matrix and reinforcement. The matrix part of the composite consists of light weight metal or alloys and the reinforcement phase consists of different metals, or organic compounds or ceramic materials (Chawla & Chawla, 2006). Among various types of MMC, particulate reinforced MMC is most commonly used. It consists of light weight alloys such as magnesium, aluminium, titanium etc in the matrix phase. These alloys are reinforced with oxides, carbides, bromides, nitrides or silicate precipitates (Kaczmar, Pietrzak, & Wlosinski, 2000). Among various MMC, Aluminium Matrix Composite (AMC) draws the attention of various industries such as aerospace industries, automobile industries, aircraft industries, marine industries, nuclear energy industries and many more (Goni, et al., 2003; Suresh, Mortensen, & Needleman, 1993; Liu, et al., 2016; Jayabalakrishnan & Balasubramanian, 2018). Depending upon the reinforcement particles, AMC possesses properties such as better thermal conductivity, lower coefficient of thermal expansion, lower density, higher stiffness, better dimensional stability with excellent strength to weight (Kunze & Bampton, 2001; Rino, Chandramohan, & Sucitharan, 2012). Although these composites possess admirable properties, their industrial application is restricted. The industry ready composite must have a uniform distribution of reinforcement, maximum wettability, minimum porosity and avoid chemical reaction (Hu, Zhao, & Li, 2016; Verdian, 2010). A few of the applications of MMC are as follows:

Airplanes Panels	Aircraft Structures	Landing Gears
Fuselage	Shafts for Automobile	Pistons
Electronic Packages	Automobile Disc Brakes	Missile Panels
Cylinder Liner	Tanker Armor	Storage Batteries
Electrical Contacts	Neutron Shield in Nuclear Reactor	Marine Structures

Out of several fabricating techniques such as powder metallurgy, centrifugal casting and in-situ casting, the stir casting process is most frequently implemented. Stir casting process has proven to be an efficient technique with comparatively lower complexity. However, it should be noted that cast composites will tend to have several casting defects such as voids and groves. Along with this, the resulting cast composite may have issues related to agglomeration/cluster or settling of reinforcement particles. Thus post casting, it becomes necessary that the fabricated composites undergo several processing techniques such as hot/cold rolling, annealing and many more (Parikh, Badgujar, & Ghetiya, 2019). Out of several conventional techniques, solid state processing technique i.e. Friction Stir Processing (FSP) has gained more popularity for resolving several casting defects, altering microstructural properties and enhancing mechanical properties. The subsequent section provides the background of the FSP process.

1.3 Friction Stir Processing (FSP)

This solid state surface processing technique follows the principle of Friction Stir Welding (FSW) (USA Patent No. GB9125978A, 1991) and was first reported by Mishra et al. (2003). FSP has proven to be a capable technique that modifies the microstructure and mechanical properties of surface composites. Working of FSP involves penetration of non-consumable rotating tool having shoulder and pin in the workpiece. The transverse motion and stirring action generated by the rotating tool will result in the processing of the material (Ma, 2008; Mishra, Mahoney, McFadden, Mara, & Mukherjee, 2000). The stirring action results in plastic deformation which will initiate dynamic recrystallization. Initialization of dynamic recrystallization will lead to refined microstructure. Most frequently it has been observed that FSP has been implemented for the fabrication of surface composites. Figure 1.1 represents the different steps involved in the fabrication of surface composites using FSP. The first step shown in Figure 1.1 indicates the machining of the groove on the surface of the workpiece material. Once the machining of the groove is completed, the groove will be filled or packed with reinforcement materials before performing FSP. In the third step, a pinless rotating tool will be provided transverse motion along the groove which will close the groove. Finally, the workpiece material will undergo a second pass with a rotating tool having a pin during which refinement of matrix and reinforcement particles will occur.

However, advancement in the last few decades shows the development of several methods using which the reinforcement particles can be introduced into the matrix phase during FSP. Some of the commonly implemented methods for introducing the reinforcement particles are (Sunil, Reddy, Patle, & Dumpala, 2016):

- Groove filling method: Groove having predefined dimensions is machined on the surface of the matrix material. Followed by machining, secondary phase particles are introduced in the groove. After filling the groove, FSP is performed on the groove.

- Groove filling and closing method: As per the previous method a groove is created and secondary phase particles are introduced in the groove. After filling, the groove is closed by a pinless FSP tool. After closing the groove, FSP is performed with a tool having a pin.

- Hole filling method: Instead of machining groove, small holes are drilled on the matrix surface. Secondary particles are introduced in those holes and then FSP is performed. The same has been represented in Figure 1.2.

- Hole filling and closing method: Similar to the groove filling and closing method, the hole filled with secondary phase particles is first closed by performing FSP using the pinless tool and then FSP is performed using a tool having a pin.

- Sandwich Method: In this method laminates or layers of reinforcement phase are used. The secondary phase is placed between the two matrix materials and a sandwich type of arrangement is made. On the performance of FSP, the reinforcement phase will get dispersed throughout the matrix.

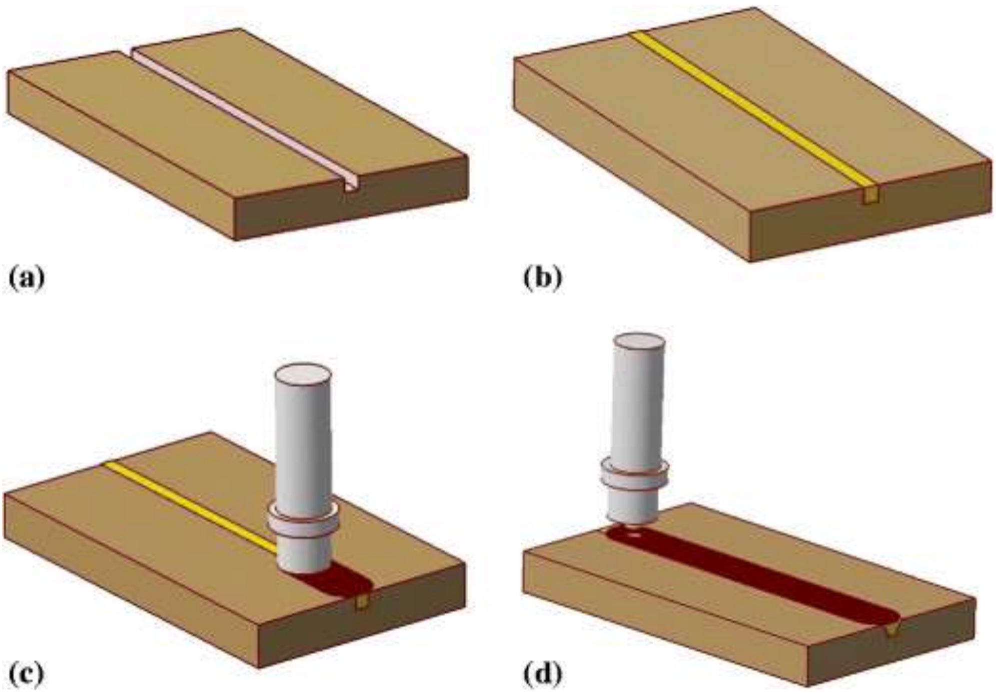

Figure 1.1 Step involved in the fabrication of surface composites using FSP (a) machining of groove, (b) compacting the grove with reinforcement particles (c) clapping pass and (d) stirring pass (Sathiskumar, 2013)

The rotation and transverse of the tool will generate plastic deformation which tends to shear the plasticized material from Advancing Side (AS) to the Retreating Side (RS). The AS is the side, where the tool transverse direction and tool rotation direction will be same. Whereas on RS, the tool transverse direction will be opposite to the tool rotation direction. Apart from this, FSP results in modification of mechanical and metallurgical properties of the processed region, without affecting the unprocessed region (Patel, Badheka, & Kumar, 2016). Noteworthy applications of FSP are surfacing, casting modification, powder processing, obtaining superplasticity, channeling and surface composite fabrication.

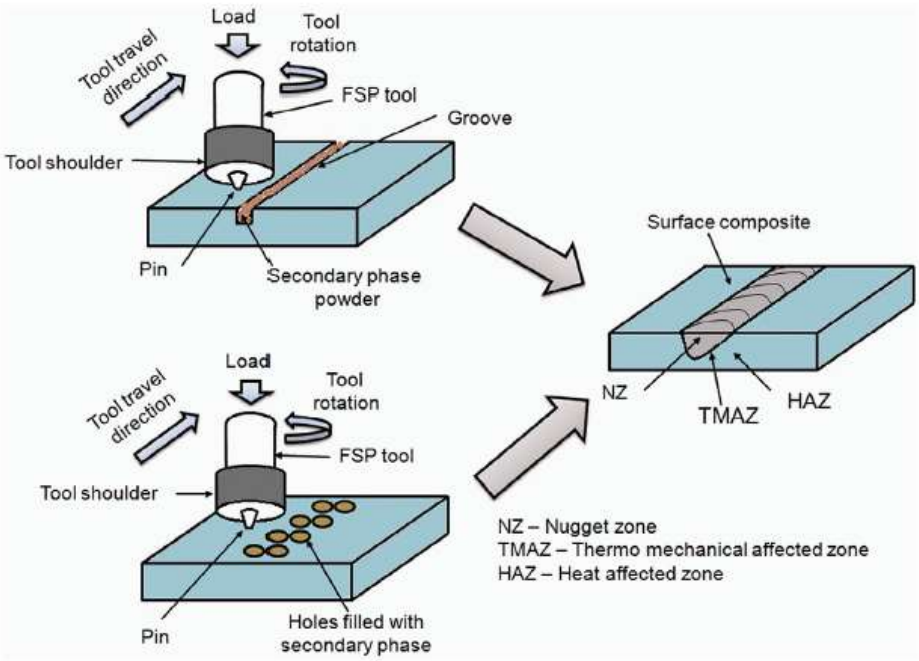

Figure 1.2 Methods for adding secondary particle phase in the matrix (Sunil, Reddy, Patle, & Dumpala, 2016)

1.4 Weldability of MMC

For several applications, the strength of aluminium is not sufficient. Thus, it is normally alloyed with various alloying materials such as copper, manganese, magnesium, zinc and silicon. Depending upon the alloying material and their weight percentage the aluminium alloys are divided into different series. AMC are the composite in which aluminium alloys are reinforced with various reinforcement particles such as nitrides, oxides, bromides, carbides and ceramic particles. Depending upon the type of reinforcement, the AMC possess various excellent properties. During the last three decades, AMC has attracted many industries due to their excellent properties. It has been noticed that industries related to aerospace, automobiles, aircraft and many more goals to reduce the weight of the structure (Kunze & Bampton, 2001). AMC have the capability to meet the goals of these industries. The only drawback associated with AMC is: due to the presence of reinforcement particles the weldability of these composites reduces significantly. By adopting fusion welding it is difficult to achieve defect-free joint. Various drawbacks that are associated with fusion welding of AMC are (Storjohann, et al., 2005):

- It results in incomplete mixing of aluminium alloy and reinforcement particles
- It results in porosity as large as 100 µm in the nugget zone
- The excess eutectic formation
- The formation of undesirable deleterious phases such as Al_4C_3

Some literature also states that the joining of composites using the conventional welding process is not reliable. Commonly implemented techniques for welding AMC are vacuum brazing (Zhang, Quan, & Wei, 1999), ultrasound assisted soldering, electron beam welding (Peng, et al., 2011; Storjohann, et al., 2005), transient liquid phase bonding (Cook & Sorensen, 2011), laser welding (Wang, Chen, & Yu, 2000; Bassani, Capello, Colombo, Previtali, & Vedani, 2007; Mao, Lu, Wang, Qin, & Zhang, 2014), diffusion welding (Liu, Liang, Jie, & Miao, 2003), gas tungsten arc welding (Mao, et al., 2012; Huang, et al., 2017), braze welding (Zvolinskii, et al., 1995), tungsten inert gas welding (Xuan, Gu, Zhong, & Sun, 2010), ultrasonic brazing (Zhao, Yan, & Fu, 2009) and metal inert gas welding (Garcia, Lopez, Bedolla, & Manzano, 2003). Niua et al. (2006) performed laser welding of AMC and it was observed that even after appropriate selection of welding parameters, the strength of the joint was around 70% of base metal. The reaction between reinforcement particles SiC and aluminium in a molten pool reduces the strength which results in the formation of the brittle joint. Zhang et al. (1999) performed vacuum brazing of SiC reinforced AMC and reported weak bonding quality for SiC/Al interface and it was observed that the strength of joint decreases if the volume percentage of SiC increases. The result also showed that for a constant volume of SiC, the strength of the joint decreases if the particle size of SiC increases.

By using these convention welding techniques, it is difficult to obtain desire joint properties. Joining of MMC using conventional joining process promotes the undesirable reaction between matrix and reinforcement phase. This deleterious reaction will result in the formation of the brittle joint. To eliminate the formation of brittle joints, the melting of these composites during the joining process must be avoided. Thus, to join such composites, FSW process can be implemented. FSW performs joining of these workpiece without melting and thus it is also termed as a solid state joining process. Storjohann et al. (2005) performed a comparison of fusion and FSW of Al 6061-20% Al_2O_3 and Al 2124-20% SiC separately. Conventional fusion welding processes such as gas tungsten arc welding, electron beam welding and laser beam welding were not able to generate successful welds. During fusion welding of Al-SiC composite, it was observed that reaction between Al and SiC results in the formation of Al_4C_3 which eventually reduces the strength of joint. On the other side, it was observed that both the composite was successfully welded using FSW. Through careful control of heat input and process parameters in FSW, the defects associated with the fusion welding process can be reduced. The parameter such as welding speed, rotational speed, tool shoulder diameter, tool design, axial force and weight percentage of reinforcement affects the material flow behavior during FSW process. The welding temperature and rotation of the tool also influence the particle size, shape and distribution in the weld zone (Zhang, Quan, & Wei, 1999).

1.5 Friction Stir Welding (FSW)

FSW is a solid state joining process that was invented at The Welding Institute (TWI) of Cambridge, UK (USA Patent No. GB9125978A, 1991). The peak temperature during the welding process remains almost less than 80% of the melting point of base metal. It uses a third body non-consumable tool to join two flaying surfaces. FSW tool consists of two parts: shoulder and profiled pin. Various part of FSW tool is shown in Figure 1.3. The welding tool serves two purposes: heating of workpiece and generates stirring action which provides movement to the material for producing joint. The contact of the pin with the workpiece will result in the generation of heat due to friction which ultimately softens the material. The contact of the shoulder with the workpiece increases the frictional heat, expands the zone of softened material and constrains the deformed material (Mishra & Ma, 2005).

The welding process can be divided into four periods i.e. plunge-in period, dwell period, welding period and plunge-out period. In the plunge-in period, the rotating tool is inserted at the flaying surfaces of the workpiece such that the bottom surface of the shoulder comes in contact with the top surface of the workpiece. The second step involves a dwell period in which the rotating tool is provided a dwell of predefined time. By providing dwell, the rotating tool will plastically deform the workpiece material present in its vicinity. After completion of the dwell period, the rotating tool is provided a feed in the transverse direction. The rotation of the tool will transfer the plasticized material from the leading edge to the trailing edge of the tool and is forged by intimate contact of the tool shoulder resulting in solid state joining (USA Patent No. GB9125978A, 1991). After completion of the welding process, the tool is plunge-out from the workpiece leaving a hole in it. Figure 1.4 shows the schematic diagram of the welding process.

Figure 1.3 Friction Stir Welding Tool (Meilinger & Torok, 2013)

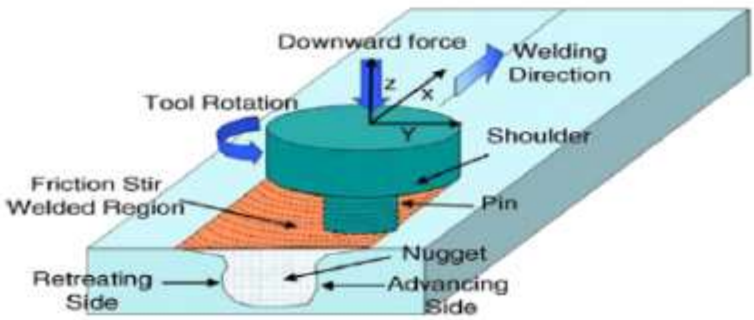

Figure 1.4 Schematic of FSW process (Mishra & Ma, 2005)

The quality and soundness of weld joint depends upon various process parameters which ultimately affect the material flow. For sound weld, control over several process parameters such as tool rotational speed, welding speed, shoulder diameter, axial force, the tilt angle of tool and tool geometry becomes necessary. The tool geometry includes the profile of shoulder, profile of pin, pin length, pin diameter, the ratio of tool shoulder diameter to pin diameter (Periyasamy, Mohan, Balasubramanian, Rajakumar, & Venugopal, 2013; Mohamadreza, Abbas, & Sipro, 2011). The stirring of material, mixing of material and heat generation is taken care of by rotational speed. The welding speed controls the appearance of generated weld. The axial load maintains the contact conditions and helps in the generation of frictional heat between the tool and workpiece. Macrostructure of various pilot experiments are analyzed and a range of parameters are selected such that the macrostructure is free from defects such as pinhole, tunnel defects, crack, voids, surface groove and surface galling. Reported macrostructure and microstructure are divided into four zones according to the thermomechanical histories experienced during the welding process. This division depends on the material flow generated by the tool during the welding process. Various zones that can be observed in weld joint are shown in Figure 1.5. In Parent Material (PM) the deformation of material will not occur. However, the material under this zone might have experienced thermal histories, but these thermal histories will not alter the microstructure and mechanical properties of material. Close to PM is the Heat Affected Zone (HAZ), in which the material has experienced the thermal cycle. These thermal cycles tends to modify the microstructure and/or mechanical properties. However, in this region, no plastic deformation occurs. Thermo-Mechanically Affected Zone (TMAZ) is the zone in which the welding tool will plastically deform the material. Also, the heat generated due to friction will exert some influence on the material. However, in this region recrystallization of material doesn’t take place. Weld zone (WZ) or Weld Nugget (WN) sometimes also referred to as Stir Zone (SZ) or Nugget Zone (NZ) is the region that will undergo fully recrystallized and refers as the zone which was previously occupied by tool pin. Similar to FSW, material processed using FSP will also be characterized by these four different zones.

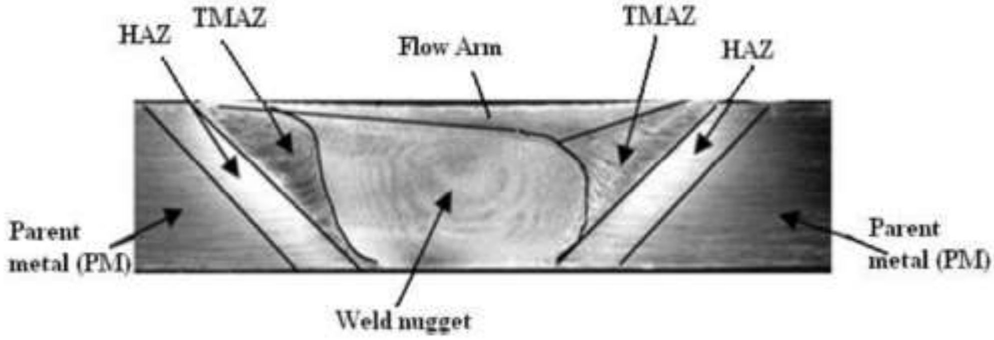

Figure 1.5 Various microstructural regions in the transverse cross-section of a friction stir welded material (Mahoney, Rhodes, Flintoff, Spurling, & Bingel, 1998)

1.6 Motivation

Considerable progress has been achieved for the development of MMC so that it can be used in an effective manner. AMC is one such type of MMC which possess characteristics such as light weight, higher strength, better manufacturability, low cost and many more. Literature shows that AMC fabricated using the stir casting process tends to have a homogenous distribution of reinforcement particles. However, the cast composites reveal several defects such as agglomeration of reinforcement particles, casting defects such as voids and groves and particles free regions. These defects can be avoided by conventional post processing techniques. The present investigation considers FSP for altering microstructural properties and improving mechanical properties of cast composites. So far, existing literature reveals implementation of FSP for manufacturing surface composites and not for the processing of cast materials/composites.

A substantial amount of work has been performed on similar FSW of light alloys such as aluminium alloys, magnesium alloys and many more. The studies performed on aluminium alloys include investigation of macrostructure and microstructure of weld joint, mechanical properties of weld joints, the consequence of welding process parameters on resulting characteristics of weld joint, the effect of tool pin profile, single-objective and multi-objective optimization of process parameters, development of mathematical models for predicting specific properties, thermal and thermomechanical analysis. Also, the available literature reflects that a considerable amount of work has been performed in the direction of joining dissimilar alloys using the FSW process. Comparatively, very little literature is available related to the joining of AMC using the

FSW process. The available literature reflects the joining of AMC which are manufactured using few grades of aluminium alloys (such as AA 6061, AA 2009 and AA 7005). Most of the performed work focuses on microstructure analysis, mechanical properties and fatigue properties of welded joints, the effect of tool pin profile, tool wear during welding process and effect of reinforcement particles on microstructure and mechanical properties of joint. However, very few research works showcase the consequence of FSW process parameters on the weld joint characteristics. Considering the current status, it can be said that AMC can be manufactured by considering different grades of aluminium alloys (such as AA 2014, AA 2024, AA 5083, AA 6063, AA 6082, AA 6351 or AA 7075) in the matrix phase. Moreover, further studies are required for investigating the effect of process parameters and weight percent of reinforcement particles on various properties such as macrostructure, microstructure and mechanical properties of the welded joint.

1.7 Objectives

The objectives of the present study are:

a) To manufacture AMC with different weight percent of reinforcement particles and investigate the effect of weight percent of reinforcement particles on microstructural, mechanical and tribological properties of manufactured composites.

b) To enhance the microstructural properties of fabricated AMC using FSP. Investigating the effect of process parameters and comparing the microstructural and mechanical properties of as-cast composites with processed composites.

c) To investigate the tribological properties of as-cast and processed composites and evaluate the effect of FSP (i.e. rotational speed and transverse speed) and weight percent of reinforcement particle on wear rate and coefficient of friction.

d) To perform FSW of AMC and investigate the effect of weight percent of reinforcement particles on resulting microstructural and mechanical properties of the welded joint. Comparing weld joint properties with that of as-cast composites.

1.8 Methodology

For fulfilling the objectives of the present study, the following methodology will be adopted:

- Manufacturing of AMC with different weight percent of reinforcement particles. For the present investigation, AMC will be fabricated by reinforcing Silicon Carbide (SiC) in AA 2014 grade aluminium alloy.

- The manufactured composites will be evaluated based on microstructure, mechanical and tribological properties. The microstructure will be evaluated using Optical Microscopy (OM) and Scanning Electron Microscopy (SEM). Mechanical properties such as tensile strength, hardness and elongation of the composite will be measured. A comparative study between microstructure, mechanical and tribological properties of aluminium alloys and AMC will be conducted based on which the effect of the addition of reinforcement particles will be evaluated.

- Performance of pilot experiments to determine the range of process parameters for processing of manufactured composites. Considered process parameters for FSP will be rotational speed, transverse speed and tool tilt angle. Final experiments will be performed by considering process parameter which successfully processes composites without any visual defects.

- Mechanical and metallurgical characteristics of processed composites will be studied and obtained microstructure will be correlated with mechanical properties. Comparison will be carried out between mechanical and metallurgical results of as-cast and processed composites.

- To understand the tribological behavior with the variation in weight percent of reinforcement particles in as-cast composites, a pin-on-disc wear test will be performed. To understand the effect of FSP, the wear test of processed composites will be performed under the same condition and the obtained results will be compared with as-cast composites.

- FSW of fabricated AMC will be attempted and characteristics of welded joint will be investigated for microstructure and mechanical properties.

- Thesis writing.

The flow chart of methodology is shown in Figure 1.6.

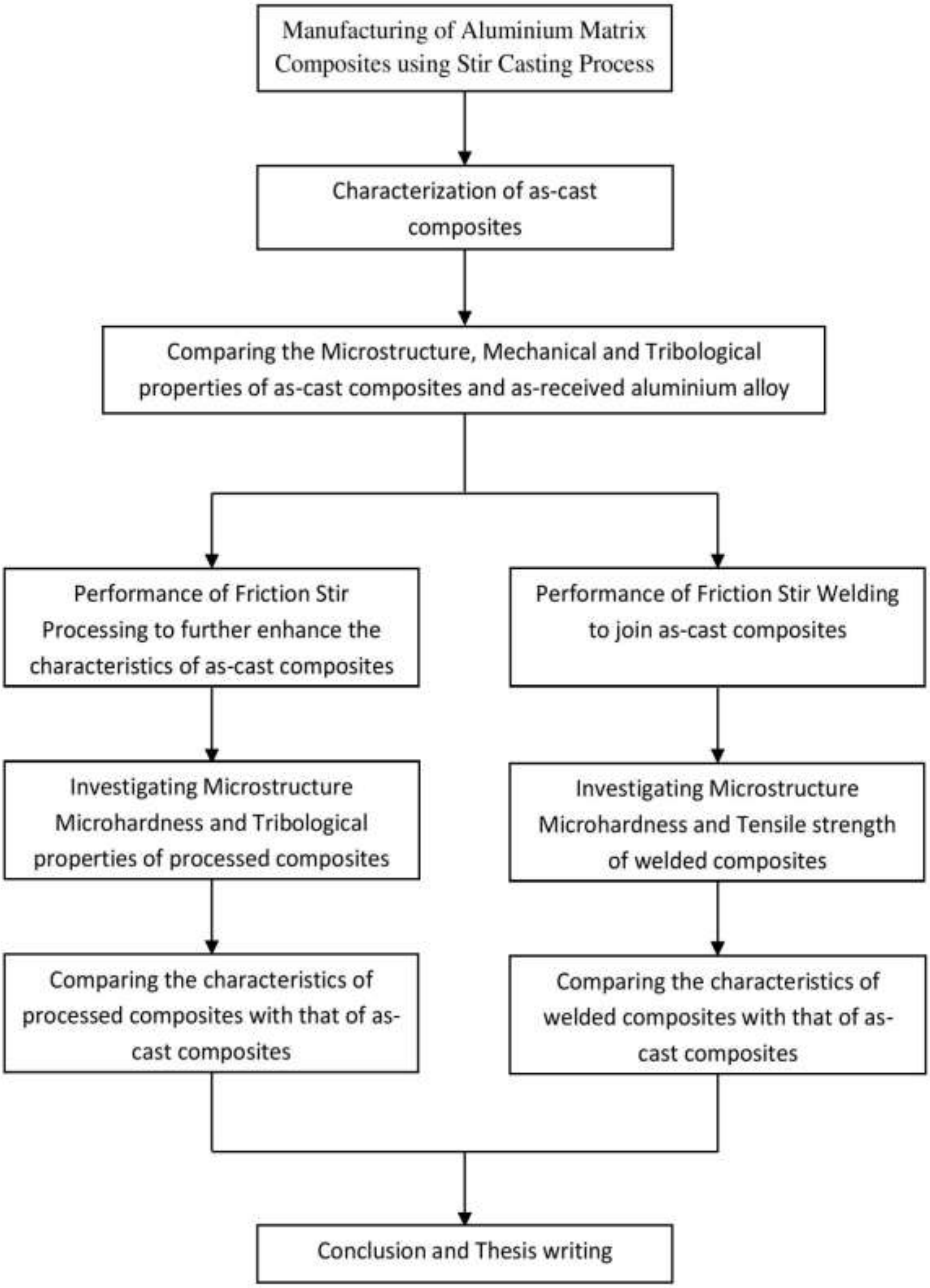

Figure 1.6 Flow chart of methodology

1.9 Thesis Organization

The thesis consists total six chapters. The first chapter gives brief introduction about composites materials and various techniques involved in manufacturing of composites. Apart from this, Chapter 01 also provide brief introduction about Friction Stir Processing (FSP) and Friction Stir Welding (FSW). Lastly, the chapter defines the objective of the present investigation and methodology to accomplish the defined objectives.

Chapter 02 presents the literature review in the research domain. Existing literature available in the field of stir casting process, FSP and FSW has been discussed and research gaps have been identified.

Chapter 03 reports the manufacturing of AA 2014 based MMC using stir casting process. Along with this, the chapter also presents the characteristics of manufactured composites. The microstructure, mechanical and tribological properties of composites has been presented and the same has been compared with characteristics of aluminium alloy.

Chapter 04 demonstrates the performance of FSP on stir cast composites. The effect of various process parameters on resulting microstructure, microhardness and tribological properties of processed composites has been presented. Lastly, the chapter represents the comparison of considered characteristics of processed composites and stir cast composites.

Chapter 05 narrates the joining of stir cast composites using FSW process. The microstructure and mechanical properties of welded composites has been discussed and the same has been compared with that of stir cast composites.

Chapter 06 focuses on the conclusion and recommendation on future work in the field of manufacturing, processing and welding of composites.