CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

1. INTRODUCTION

Rapid advancements in technology have led to demand of low cost, lightweight and high strength materials and forced researchers to explore more on composites, which are capable of fulfilling the evolving needs of industries [Tri Dung, 2020]. Many times, as a matter of demand of applications, metal-matrix composites become first choice of researchers as well as industries. Among light weight materials, Zinc-aluminium (ZA) alloys possess high strength, low density, moderate mechanical (tensile strength and hardness) properties, high corrosion resistance, low cost, easy availability and good cast ability, hence, it becomes one reliable option for many applications especially in automobile, military, and aerospace sectors [Pola et al., 2020]. ZA alloys may serve well as replacement in various applications over their conventional counterparts like copper alloys, aluminium alloys, bearing bronze etc., due to their excellent bearing (high wear resistance and low coefficient of friction) properties in normal atmospheric conditions [Morgan et al., 1985]. ZA alloys have already been used for automotive components such as toothed gear, clutches, gear houses etc. Based on elemental compositions, Zn-Al based alloys are categorised and termed as ZA alloys. Industrially important members of ZA family are ZA8, ZA12 and ZA27. These families are categorized based on Al content (8 to 27 wt. %) along with other minor elements such as copper (Cu), manganese (Mn), silicon (Si) etc. With increase of aluminium content from 8 % to 27 %, strength of these alloys also increases.

Zinc-Aluminium containing 25-27 wt.% Al i.e. ZA27 possesses high strength and also has better properties than those of ordinary cast aluminium alloys. Significant cost reduction has been observed when ZA alloys replace conventional Cu-Al based alloys and Brass. Low cost and good performance makes ZA alloys a better choice especially for bearing or bushing applications over bronze-based bearings [Lo et al., 1992, Khair et al., 2004]. It has been found that at elevated temperature (above 200^0C) ZA base materials show poor mechanical properties, which restricts the use of these materials in many applications. To enhance elevated temperatures mechanical properties, various reinforcements in the form of oxides, borides, carbides or intermetallic have been used. Researchers have also observed that addition of second phase particles in ZA alloy based composites, also improves mechanical and wear properties of composites. It has also been suggested by various researchers that reinforcements of hard particles in base matrix also increases thermal stability and load bearing capacity in sliding wear test [ZQ et al., 2001, Murphy et al., 1992]. Various researchers also studied the effect of hybrid reinforcements on ZA alloy-based composites like quarry dust –Silicon carbide (SiC), SiC/Graphite (Gr), fly ash/SiC and Al_2O_3 + SiC etc. and observed better mechanical as well as tribological properties than the base alloy. They also observed enhanced characteristics at elevated temperature. However, in most of the cases increase in strength and fracture toughness is observed at the expense of percentage elongation [Folorunso et al., 2019, Bobic, 2004].

To explore the full potential of composites, it is essential to understand the different types of composites and their fabrication techniques. Coming sections explore composites types, fabrications techniques and effect of varying parameters on morphological, mechanical and tribological properties of composites:

1.1 Types of Composites

There are certain criteria to term any material as composite. It should consist of two or more physically and/or chemically distinct phases properly assigned according to type phase with an interface detaching them. The final product should have innate properties which are not anticipated by any of the component as separate entity [Chawala, 2001]. Based on matrix materials, composites are grouped as:

1.1.1 Polymer matrix composites (PMCs)

Polymer matrix composites (PMCs) are also called fiber-reinforced polymer (FRP) composites and it consists of polymer resin (high molecular weight reinforced plastic) as the matrix medium with fibers as the reinforcement. Such kind of materials makes it possible to obtain variety of composites and can be manufactured in large amount. PMCs possess good properties even at room temperature and are easy to fabricate at low cost. There are various kind of materials used as reinforcement in PMCs such as glass fiber, carbon fibers and aramid fibers. Various techniques have been developed for manufacturing PMCs. Processing of PMCs can be simplified by dividing it into two categories i.e. Thermoset based composites and Thermoplastic based composites. For manufacturing of Thermoset matrix composites, number of techniques like Hand lay-up spray techniques, Filament winding techniques, Pultrusion, Resin transfer moulding technique, Autoclave based methods etc. are available and they are frequently being used. For manufacturing of Thermoplastic based composites, various techniques such as Injection moulding technique, Film stacking, Diaphragm forming, Thermoplastic Tape laying, etc. are frequently being used [Rajak et al., 2019, Majidi, 2000]. However, use of PMCs is posing environmental challenges as it leads to generation of hazardous air pollutants (HAPs) and generation of hazardous (HW) and solid wastes [Sands et al., 2001].

1.1.2 Ceramic matrix composites (CMCs)

Monolithic ceramics generally possess significant stiffness and strength even at elevated temperatures. But poor toughness is the bottleneck and leads to manufacture ceramics matrix composites to enhance the toughness to make them useful for high temperature applications. In CMCs, the ceramics are used as matrix and short fibers or whiskers of SiC, BN, and ZrB_2 etc are used as reinforcement. CMCs can be manufactured using Liquid phase sintering, hot pressing or hot iso-static pressing, cold pressing, sintering and reaction bonding processes etc [Tarik et al., 2021]. Despite exhibiting excellent properties, high fabrication cost, high energy requirements and difficult post processing such as machining on these types of composites are major concern and restrict mass utilizations of CMCs [Gavalda et al., 2019].

1.1.3 Metal matrix composites (MMCs)

As its name suggests, MMCs are composites where matrix is generally ductile metal/alloy and continuous in nature. Matrix may consist of particles, short fiber or whisker in the form of reinforcement like SiC, Al_2O_3, TiC, ZrB_2, TiB_2, TiO_2 etc. Such composites materials can be used at elevated service temperature than their original counterparts. Reinforcements may improve the mechanical (tensile, compressive and hardness) properties as well electrical conductivity and simultaneously can provide dimensional stability, however, there are certain exceptions. MMCs have found very wide applications due to variety in combination of properties. There are various metallic materials used as metallic matrices for MMCs i.e. Aluminium alloys, Magnesium alloys, Copper alloys, Zinc alloys etc. Various processing techniques have been used to manufacture MMCs. Some of them such as Liquid state processes, Infiltration methods, Solid state processing find wide applications in industries [Evan et al., 2003, Chawla, 1998].

In last decade, a new category of metal-matrix composites has come-up, which may have two or more reinforcement in a single matrix and is termed as hybrid composites. Hybrid composites acquire wide range of properties in each aspect as compared to conventional composites, which contains single reinforcement. The most attractive property of hybrid composites is that in tensile stress conditions, failure is usually non catastrophic [Yegireddi et al., 2019, Prabhuram et al ., 2010].

This can be understood from above discussion MMCs can have wide diversity in applications due to larger scope of variation in properties, easy availability of raw materials, simple fabrication methods and above all these are more environment friendly relative to other types of composites. Following section briefly discuses different preparation techniques and reinforcements and their effect on MMCs:

1.2 PREPARATION TECHNIQUES OF MMCs

MMCs can be produced either through *exsitu* or *insitu* techniques. In *exsitu* processes second phase to be reinforced is already available and is added to solid or liquid state matrix. While in *insitu* process second phase to be reinforced is generated by chemical reaction between suitable inorganic salts and matrix material [Zhang et al., 2007].

In *exsitu* process, the second phase reinforcement particles are mixed in the melt by mechanical stirring. Stirring leads to formation of vortex in the melt and results in homogeneous distribution of reinforcement particles. The process can be performed either in open or inert atmosphere. After completion of homogenization the melt is poured into preheated mould and allowed to cool in atmospheric conditions [Zhang et al., 2007].

In the *insitu* process different inorganic salts are used to synthesise the reinforced particles. The reactant salts are preheated in an electric oven and charged into molten metal/alloy at desired reaction temperature. During ignition, the salts react exothermically to form product. *Insitu* reinforcement can be carried out through processes such as Direct metal reaction (DMR), rapid solidification processing (RSP), Reactive hot pressing (RHP), Reactive squeeze casting (RSC), Mechanical alloying (MA), Reactive spontaneous infiltration (RSI) etc.

The feasibility of fabrication routes includes the cost of the fabrication, simplicity of the process, and effect on the characteristics of composites. Varying preparation methods have their advantages and disadvantages, according to desired needs, the suitable method can be opted. MMCs can be prepared by many methods but the most popular methods are liquid state and solid-state fabrication methods. The liquid state fabrication method for MMCs is fairly simple and less costly as compared with solid-state. Through Powder metallurgy technique, nano particles and grain boundary strengthening capability are well exploited. Powder metallurgy route is preferred when high precision and complex products are needed [Jiang et al., 2005, Guel et al., 2009, and Casati et al., 2014].

Some of the liquid state and solid-state fabrication techniques are discussed below in brief:

1.2.1 Liquid State Processing Techniques

1.2.1.1 Stir casting technique (SCT)

It is one of the most commercially used technique to fabricate MMCs. Ray (1969) had reinforced the particles of alumina into Al melt through stirring molten Al alloys and accommodating the ceramic powders. Nageswaran et al. (2018) used stir casting technique to fabricate Copper metal matrices reinforced with TiO_2 and Graphite (Gr) and reported that it produces more homogeneous reinforcement with improved dispersion over conventional stirring technique and it is also more economical. Better wettability between second phase particles and matrix results in improved homogeneity. Raju et al. (2018) have used stir casting technique to fabricate Al-Cu alloy and copper powder as reinforcement and reported that for fabrication of MMCs liquid stir casting is more reliable. The reinforced powder is dispersed in the Al-Cu alloy matrix but it is not alloyed. Luo (1995) has reported that SCT is more suitable for fabricating composites upto 30 volume % (vol.%) fraction of reinforcement. Balaji et al. (2015) have successfully used SCT for fabricating Al7075 with 6 wt.% SiC as reinforcement and they achieved uniform distribution of particles into matrix through this technique. Das et al. (2016) successfully used SCT to fabricate Al-Cu alloy with TiC as reinforcement and reported that the dissemination of fine TiC particulates was uniform throughout the matrix.

1.2.1.2 Compocasting

Wettability of reinforcement particles and matrix material is essential to enhance properties. Compocasting offers solution to reduce the problems of wettability [Rosso, 2006]. In Compocasting process, first alloy is melted and later temperature is reduced to semisolid state. In this region particle reinforcement takes place, and it averts gravity separation and diminishes their agglomeration [Ejiofor et al., 1997]. Gladston et al. (2017) used Compocasting technique and successfully prepared AMC reinforced with rice husk ash (RHA) and reported that through use of this technique, they enhanced wettability and admission of particle into Al alloy. Bobic et al. (2014) prepared Aluminium alloy as matrix and SiC as reinforcement and reported that this technique saves energy and enhances tribological properties. Sevik et al. (2006) have prepared composite using Al- Si alloy with Al_2O_3 reinforcement and reported that porosity in Compocasting can be reduced using die casting method.

1.2.1.3 Liquid infiltration

In this technique penetration of fiber array by liquid metal occurs. One of the disadvantages of the technique is that it doesn’t provide proper wetting of ceramic reinforcement [Champion et al., 1978]. Ibrahim et al. (2014) prepared W-Cu composite and reported that it is difficult to produce such composite via conventional sintering route and successfully fabricated the W-Cu composite with incorporation of the liquid phase sintering (LPS) and the liquid infiltration (LI) methods and found a congruent microstructure nearly without any pores. Zenga et al. (2014) have prepared carbon/carbon (C/C)–Zr–Ti–C composites using LI technique and reported that increase in the reaction temperatures, leads to lessening in the terminal density of samples. They also reported that enhanced initial holding time results in high final density and controlled height of infiltration melt were controlled by diffusivity of composite.

1.2.2 Solid State Processing Techniques

1.2.2.1 Powder metallurgy technique

Many researchers reported the fabrication of MMCs through powder metallurgy technique. It provides various combinations of unique properties produced by sintering of powders, which is one of the most highlighted advantages of Powder metallurgy (PM) technique. Improvement in properties can be achieved using fine particle size which leads to uniform microstructure [Sluzalec, 2015]. Casati et al. (2014) have prepared Al matrix composite reinforced with alumina and reported that through PM technique nano particles and grain boundaries strengthening capability can be achieved. Bharat et al. (2018) have used PM route for synthesis of pure matrices of Al, reinforced with ceramic beryllium aluminium cyclosilicate (Beryl) particulates and successfully fabricated Al – beryl composite. They also reported that PM is an appropriate process for fabrication of very precise components with variety of shapes. Ponraj et al. (2017) prepared copper matrix composite with graphene as reinforcement through PM route and reported that through PM route there was homogeneous distribution and good interfacial bond between Cu and Graphene nano sheet was achieved.

1.2.2.2 Diffusion bonding

Diffusion bonding is most utilized solid-state techniques which is used for fabrication of similar or dissimilar metals. In this technique, fabrication of composites takes place due to inter diffusion of atoms between metallic surfaces. Diffusion bonding offers utilization of diverse materials and in this process, fiber direction and volume fraction can be easily controlled. In diffusion bonding technique there is disadvantage of long processing times, elevated temperature and pressure. Due to this, diffusion bonding technique is expensive and mostly used to fabricate complex shape products [Attar et al., 2015]. Diffusion bonding technique is also used to produce mono-filament reinforced metal-matrix composites [Kandpal et al., 2014].

Reinforcement also plays an important role in MMCs properties as discussed in next section:

1.3 EFFECT OF REINFORCEMENT ON THE PROPERTIES OF MMCs

Reinforcement in a matrix doesn't need to be in the form of long fibers, it may be in the form of whiskers, continuous fibers, sheets, particles, short fibers, or flakes. Reinforcement type, shape, and size play a vital role in varying properties of the composites. Chawla, (2001) has categorized the reinforcement based on some parameters and is given in Table 1.1.

Table 1.1 Type of reinforcement based on aspect ratio and size (Chawla, 2001)

Type	**Aspect ratio**	**Diameter in µm**	**Examples**
Particles	1-4	1-25	SiC, Al_2O_3, BN, B_4C
Short fibers or whisker	10-1000	0.1-25	SiC, C, Al_2O_3, Al_2O_3 + SiO_2
Continuous fiber	>1000	3-150	SiC, Al_2O_3, C, B, W

MMCs mostly consist of a ductile matrix reinforced with hard fibers or particles. Metals such as Beryllium, steel, & tungsten and ceramics like Alumina (Al_2O_3), silicon carbide (SiC), silicon nitride (SiC), boron carbide (B_4C), boron nitride (BN) may be used as continuous fibres, however whiskers and particulates of the ceramics mentioned can also be used as discontinuous reinforcements [Chappell, 1998]. Researchers have used various reinforcements in Zn-Al based metal matrix composite according to the desired property. It has been found that wettability between matrix and particle reinforcements affects the strength of the composites. They have also suggested an improvement in properties through continuous fiber reinforcements as they are highly anisotropic and can bear maximum tensile strength in fiber direction and it varies according to volume fraction from axial to the transverse direction [Owoeye et al., 2019]. Bobic et al., (2004) have studied the effect of particle reinforcement in Zn-Al alloy and found improvement in mechanical as well as tribological properties.

The fracture toughness of composite is another desired property and it mainly depends upon the size, orientation, and distribution of the reinforced phase. The addition of ceramic reinforcement mostly degrades the toughness of metal matrix composite. So, for increasing the toughness of MMCs, fibers with a low density of critical flaws and high *insitu* strength should be used else they act as crack initiators. McDanels et al., (1985) have shown that high toughness can be achieved by using scrubbed matrix powder, through proper mixing and augmenting mechanical work during fabrication. Crowe et al., (1986) have found that particle reinforcement is better than short fiber reinforcement for fracture toughness of MMCs.

The creep property is influenced by the melting point of metal alloys and reinforcement. If the reinforcement and metal alloys have the same melting point they will fail together in creep. So, for enhancing the creep property of MMCs, ceramic materials used as reinforcement must have high melting point [McLean et al., 1985]. It has been also found that the steady-state creep can be achieve using discontinuous fiber and particulate reinforced MMCs [Williams et al., 1986]. Fatigue strength is also one of the requirements of industries for applications of products that involve long term cyclic loadings. MMCs show higher fatigue strength than unreinforced alloys. For fatigue property the matrix- reinforcement is important. Williams et al., (1986) found that unbonded intermetallic particles were fatigue crack-initiation sites. The fatigue property can be enhanced through using improved wetting properties of particles or whiskers. The damping property of heterogeneous materials are more significant rather than homogeneous materials. So MMCs are mostly preferred in the case where noise reduction or vibration reduction is necessary because the fundamental property of damping is the dissipation of energy. Mishra et al., (1986) have found that the effective damping property can be achieved through some mismatch in CTE of reinforcement and matrix material. G Gautam et al., (2015) have used ZrB_2 as reinforcement in Al alloy to prepare composite and concluded that UTS, YS, and hardness of composite increase continuously through an increase in vol.% of ZrB_2 in alloy and it increases up to 3 vol.% and at this composition, the composite exhibits the maximum improvement in strength.

1.3.1 ZrB_2 as Reinforcement

Among ultra-high temperature ceramics (UHTCs), Zirconium diboride (ZrB_2) has relatively low density (6.09 g/cm^3), low thermal expansion, and high elastic modulus, which makes it a suitable material for reinforcements. ZrB_2 has a hexagonal crystal lattice and with the presence of free electrons in Zr-Zr, bonds provide high electrical and thermal conductivities. B-B bonds elevate the stiffness, hardness, and chemical inertness properties. The strong Zr-B bonds increase the melting point of ZrB_2. In addition to its high melting point, ZrB_2 has a combination of exceptional characteristics such as chemical inertness against molten metal and slags, retention strength at high temperatures, erosion and corrosion resistance in adverse atmospheres, high thermal and electrical conductivities, and great thermal shock resistance. ZrB_2 is also reported to be favourably resistive to plasma arcs and sparks. The formation of ZrB_2 composites depends on the characteristics and intrinsic properties of additives and raw materials. The composites morphology, purity, size of particles, surface areas, etc, are important factors that influence the product's properties [Sonber et al., 2011]. Although the characteristics of ZrB_2 composites can generally be modulated during the production process, they are mainly determined by engineering the steps and ingredient properties. Accordingly, it is important to study the synthesis routes of ZrB_2 based composites comprehensively. Such types of studies may provide a detailed understanding of the effect of the utilized material in manufacturing processes and the potential properties of the final product [Xie et al., 2008, Sun et al., 2021]. Xin et al., (2010) studied the effect of ZrB_2 reinforced on Zn-Ni alloy and showed improvement in the strength and fracture toughness due to excellent interfacial bonding between ZrB_2 particles and Zn-rich matrix.

Zn-Al based MMCs are easy to fabricate and exhibit comparable properties with the material used in various applications, especially in the automobile sector. In the next section a brief discussion of Zn-Al based composite is given, also the role of ZrB_2 as reinforcement particles is explored:

1.4 Zn-Al (ZA) BASED METAL MATRIX COMPOSITES

Zinc is one of most abundant and earliest found elements on earth and also a significant amount of Zn is recycled. Primary Zn is mainly used for die casting alloy production. Research data reveals that about half of the consumed Zn is utilized for galvanizing the steel and restricting corrosion. Zn is frequently used as an alloying element in Al, Cu, Mg, etc. Recently, Zn-based alloys are investigated as a promising alternative to iron and magnesium as new biodegradable material used as bioimplants [Pola et al., 2020]. Zn and Al are one of the most abundantly available materials on earth and the alloys of Zn-Al possess a high strength-to-weight ratio, which attracted researchers to explore a combination of both. Zn-Al based composites are being used in different sectors and have found wide applications, special attention in components related to automobile, structural, marine, etc.

Zn-Al based alloy is mostly used in die casting, plain bearing, clutch, car body, cylinder blocks, ornaments, etc. Zn-Al based alloys are also utilized in the construction field to produce roofing, downspouts, gutters, flashlight reflectors, parts for lamps, etc. Recently Zn-Al alloy-based extrusion and forging components have also been developed [Goodwin, 2018]. Zn-base alloys provide a variety of properties which makes them suitable for die-casting manufacturing and, in general, for foundry technologies. Low energy and resource consumption due to lower melting point and long working life. Also, Zn-Al based material system exhibits high fluidity, which results in the filling of complex mold cavities and easy fabrication of very thin sections [Kubel, 1987]. Zn-Al alloy exhibits high thermal conductivity and a high tensile & yield strength. The alloys are corrosion resistant and non-sparking, which improves safety and longevity. Components made with Zn alloys are recyclable and environmentally friendly, which helps to reduce waste sent to landfills [Bobic et al., 2005].

Researchers have found that Zn-Al based composites show comparatively more or equivalent mechanical and tribological properties to Cu-based alloys. They offer a more aesthetic appearance owing to their easily palatable, wear and corrosion resistance resulting in a good surface finish. However, their performance degrades at elevated temperatures due to which these are mostly utilized for small non-structural applications such as automotive, hardware, electric/electronic devices, clothes, toys, sports, ornaments, etc. For instance, parts like safety belt blocks, locking mechanisms, wiper motor housings, cylinder locks, some electronic connectors, handles, tap systems, zippers, belt buckles, spring adjusters in bikes, costume jewelry, and appliances, etc. are made from zinc-base alloys. Table 1.2 gives some important applications of Zn-Al based alloy in various industries.

Table 1.2 Application of Zn-Al based alloy

Applications	**References**
Die casting	Lynch, 2001 and Murphy et al., 1984
Roofing, Downspouts, Gutters, Flashlight reflectors, Parts for lamps	Pola et al., 2020
Plain bearings	Pascoe , 1983
Gears, crankcase for model engines, seat recliner, emergency ladder bracket assembly, Optical checkout reader, automotive engine mounts, motor mount, steering column bushing and locks, throttle linkage parts I-wheel hubs and drive sprockets (belt and chain drive), truck doors latch assembly etc.	Gross , 1987

From the above discussion, this can be inferred that Zn-Al based alloys have wide applications and require a detailed understanding of their morphological, mechanical, and tribological behavior to fulfill the growing needs of industries. So, for further understanding of the behavior of Zn-Al alloy and its composites, morphological, mechanical, and tribological studies have been discussed in the below section:

1.4.1 Morphological Behaviour

Microstructural studies of literature have been done to reveal the behavior of Zn-Al alloy based composites to provide a better understanding of changes in structure. Through review of literatures available, it has been found that researchers have used two different types of Zn-Al based alloy. Some of the researchers have used only alloy of Zn and Al and used nomenclature of Zn-Al or Al-Zn and ZA etc [Miroslav et al., 2009, Gervais et al., 1985, Kanth et al. 2019] while others have taken Zn, Al and some amount of copper and termed as ZA8, ZA12, ZA27, etc [Jayaprakash et al., 2018, Milhaichuk, 1983 and Folorunso et al., 2019]. The selection of proper etchant to see the microstructure plays a very vital role. So exact selection of etchant becomes essential and it depends on the composition of the alloy. Savaskan et al., (1986) studied the optical microstructure (OM) of Zn-Al alloy. It consists of Al-rich phase (α phase exists as dark regions), Zn-rich phase (β phase exists as lighter phase) and the dendrites enclosed by α+ β eutectic (mostly exists as grey regions). While the OM of ZA27 alloy unveils the dendritic structure consisting of primary α dendrites enclosed by eutectoid α+ β and metastable ε phase [Prasad, 2000]. This provides the difference between phases present in ZA alloy and ZA27 alloy. In ZA alloy the phases are α, β, and α+ β while in ZA27 due to the presence of Copper (Cu) there is another metastable ε phase present which may be an alloy of copper and zinc, which was not formed in case of ZA alloy [Li, 2014, and Zhu, 2004]. Savaskan et al., (1987) studied the effect of aging at 150°C on the microstructure of Zn-Al alloy and found that the alloy consists of an Al-rich α phase, Zn-rich β phase, and eutectoid of α+ β. Due to aging there is a slight change in dendrites cores but coarsened the decomposed β phase.

Many researchers studied the effect of reinforcements on the microstructure of Zn-Al alloy and suggests grain refinements of the matrix due to particle reinforcements. Some of the researchers have studied the effect of Al_2O_3 on ZA27 alloy and observed that composites exhibit mostly similar structures as an alloy with refined grains due to better bonding between matrix and reinforced particles. Homogeneous dispersion of particles from casting route while spheroidal and nodular structure have been observed via powder metallurgy route respectively [Prasad et al., 2000, Mitrovic et al., 2007, Bobic et al., 2003, Bozic et al., 2011]. Even some of the researchers have used a combination of reinforcement like Al_2O_3 and SiC, Gr and SiC, SiC and ZrO_2 or C, etc and concluded that due to the smaller size of particles they are more prone to form a cluster and comparatively bigger size are favorable for uniform distribution [Bobic et al., 2004, Kiran et al., 2013 and El- Khair et al., 2011].

Liu et al. (2013) and Babic et al., (2009) have studied the effect of heat treatment on the optical microstructure of ZA27 alloy and suggested that as solution temperature increases, α (Al-rich) and β (Zn rich) phases dissolve slowly into η phases and after solution treatment at 365°C for 1 h, the microstructure is mainly composed of the supersaturated η phase with little dark Al-rich α phases along the grain boundaries and microstructure became more homogeneous and a refined grain structure was obtained. These refinements in grain occur due to the presence of a second-phase particle. The reinforcement particles act as nucleation sites which further restrict the growth of grain boundaries. Also, it was observed that as the size of the particle decreases, clustering took place and the grain refinement takes place in mostly all the fabrication routes.

Li, (2014) has studied the effect of TiB_2 particles on ZA27 alloy. He observed that the TiB_2 particles were pushed into the interdendritic region of the α- Al rich phase and led to matrix grain refinements. Folorunso et al., (2019) have also revealed a similar result with dendritic structure and homogeneous distribution with particle reinforcements.

This can be concluded from the above discussion that particle reinforcements cause refinement of matrix grain. However, finer particle size may lead to clustering.

1.4.2 Mechanical Characteristics

In the recent past Zn-Al have shown very promising and attractive results, especially with some reinforcements. In this section, the mechanical properties of ZA based composites have been studied in reference to hardness, tensile strength, ductility etc. Folorunso et al., (2019) have synthesized a composite of ZA27 alloy reinforced with second phase quarry dust (particle size <38 μm) and silicon carbide particles (particles size 30 μm) via stir casting route and achieved approximately 32% and 80% improvement in hardness and strength value respectively at 10 wt.% of reinforced particles. They have suggested that this improvement may have taken place due to resistance to surface plastic deformation offered by hard particles and composite offers enhancement in crack movement resistance and fracture.

Fatile et al., (2017) have prepared ZA27/ZnO composite via double stir casting route and revealed that at 4 wt.% addition of ZnO, there has been approximately 28% increase in hardness and 35.5% increase in ultimate tensile strength (UTS) of composite at the cost of loss of ductility in order of 24%. While, further increase in reinforcements from 4% to 5% lead to the reduction of hardness as well as in UTS. This reduction in strength may have taken place due to aggregation of particles and saturation of grain boundaries. Similar results have been observed by Mazahery et al., (2013) in A354 alloy and nanocomposite. Chen et al., (2015) have taken Zn-Al-Cu matrix and TiB_2 as reinforcement particles (particles size 0.2 to 1.5 μm) and processed them via melt reaction techniques and achieved approximately 17% increment in hardness while 13% in UTS with reduction in elongation of approximately 4% at 5% addition of TiB_2. They have also compared the result with some other reinforcements which suggested a similar result and concluded that this increment in strength would have taken place due to small reinforcements particles which act as a hindrance for movement of dislocation and also suggested that mismatch of coefficient of thermal expansion (CTE) also played a vital role in strengthening.

David et al., (2018) have synthesized ZA27/TiC composite via liquid metallurgy route and achieved ~17% increment in hardness at 10 wt.% of TiC. Bobic et al., (2004) have synthesized Zn-Al composites reinforced with Al_2O_3 and SiC using Compocasting and concluded that synthesis using Compocasting transforms the dendritic structure to non-dendritic structure, also smaller particle size and uniform distribution provide better mechanical characteristics both at room and elevated temperature. Sharma et al., (2002) have presented the effect of aging parameters on mechanical characteristics of ZA27/aluminide MMCs and suggested that due to aging mechanical properties as well as electrical resistivity of composite have increased and it may have taken place due to solid solution strengthening caused by precipitation formation and transformation. They also suggested that aging kinetics increased due to the addition of second phase particles. Dama et al., (2017) synthesized ZA27/B_4C composite via stir casting route and observed the increment in hardness and UTS, ~ 60% and ~30% respectively. Researchers have done a comparative study of Zn-Al based alloy with conventional alloys like steel, phosphor bronze, and SAE 660 bronze and found that despite being lightweight, Zn-Al based alloy shows similar mechanical behavior. Table 1.3 presents the nomenclature used for different alloys. Fig. 1.1 presents the density and hardness of different alloys [Murphy et al., 1983, Lee et al., 1987].

Table 1.3 Nomenclature of different composition of Zn-Al based alloy

Composition of Zn-Al-Cu- Si (in wt. %)	**Nomenclature**
69.9-27.1-3-0	A1
60.1-38.-1.9-0	A2
56.-35.6-0-8.4	A3

Note*- as: as cast, ht: heat treated

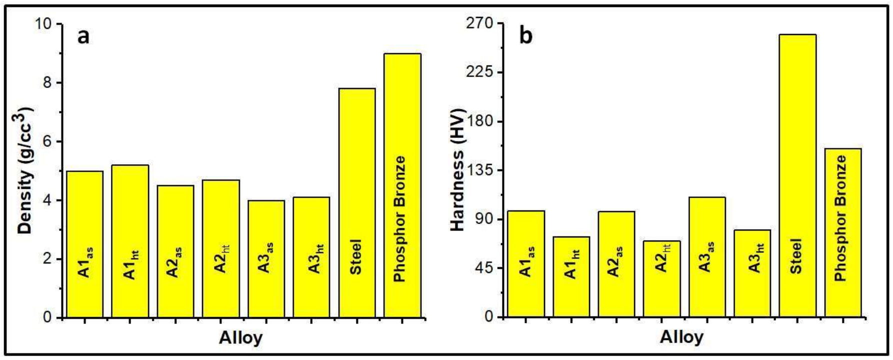

Fig. 1.1 Comparative properties of different alloys (a) Density (b) Hardness [Murphy et al., 1983 and Lee et al., 1987]

1.4.3 Tribological Characteristics

Before discussing the tribological behavior of Zn-Al based composites, it is essential to understand the basics of tribology. Tribological properties are expressed in terms of wear and friction.

1.4.3.1 Wear

It is the phenomenon of material removal of one or both the mating surfaces when one solid surface is in relative motion against a counter/mating body either in sliding, rolling, or reciprocating conditions. Wear phenomena is observed on the mating surface; however, it depends on the surface as well as bulk characteristics of the materials in contact. Mostly wear of material is a negative phenomenon, however, in many cases wear is used also as required phenomenon [Bhushan, 1999].

Wear mechanism is categorized based on surface contact medium available etc. however, in this section, types of wear relevant to present study are introduced. Wear and friction process depends on various parameters which have also been discussed later in the next sub section;

Adhesive wear: It is a common type of wear and occurs when surfaces of similar material interact with each other and the material removal takes place due to adhesive bonds between mating surfaces. The influence of adhesion reduces as the surface is contaminated by the absorbed gases or oils. Solid surface meets at the interface through asperities interaction which gets deformed during the motion and generates the fragments. These fragments could be transferred from one surface to another surface or may be removed as wear particles [Bhushan, 1999].

Abrasive wear: This type of wear takes place between two surfaces when the hard asperities of one surface or hard particles on the surface or from an external source interact with the soft counter surface. These hard asperities or particles cause plastic deformation, cracks, and grooves in the soft surface during motion. The removal of material due to plastic deformation may occur in different modes such as plowing, cutting, or wedge formation [Bhushan et al., 1985, Hawk, 1997].

Chemical (corrosive) wear: This type of wear takes place when mating surfaces are in sliding motion in the presence of a corrosive environment such as the presence of lubricants. The favorable condition for such wear is a corrosive environment imposed by chemicals, high temperature, and high humidity. If the test is carried out in the presence of air, then it is called oxidative wear due to the presence of oxygen which acts as a corrosive medium in the air **[**Bhushan, 1999, Dwivedi, 2010**]**.

1.4.3.2 Influence of operating parameters

The varying parameters which influence the wear rate of materials are applied load, sliding distance, sliding velocity, operating temperature, humidity, etc. Researchers have revealed that with increasing applied load the wear rate increase for Zn-Al based alloy and composites due to the delamination of the surface, third-body wear, formation of grooves, etc. At low load, mode of wear is mostly mild and the nature of debris is dominated by oxides, however, at high loads nature of wear changes to severe, and oxidative-metallic debris with the dominance of metallic fragments is observed. However, with the sliding velocity wear behaves differently. Sliding velocity increases the surface temperature which enhances the oxidation process several folds. The oxide layer reduces the metal-to-metal contact and decreases the wear rate initially and with increasing sliding velocity till a certain value, reaches a minimum value. However, with further increase in sliding velocity, the oxide layer breaks leading to the gross material transfer and a sharp increase in wear rate [Mohan, 2006].

Another mechanism responsible for the decrease in wear rate is termed as glaze layer. This layer is the sintered wear debris that comes out due to the tearing of the oxide layer under high temperature and pressure [Rajaram et al., 2010]. If the same experiment is conducted under a vacuum, it exhibits a higher wear rate because any type of contamination including oxygen is unavailable, which could have restricted metal to metal contact [Bhushan, 1999].

1.4.3.3 Friction and laws of friction

Friction is the force that resists or opposes the relative sliding or rolling motion between two surfaces. Several factors affect the basic mechanism of friction such as the physical, chemical, and mechanical properties of the materials. At the microscopic level, the mechanism includes the adhesive forces between contacting surfaces, the interaction of asperities, plowing of one surface by the other harder surface, debris due to the fragmentation of the surface or by the fracture of the oxide film and environment [Bhushan, 1999; Mohan et al., 2015].

1.4.3.3.1 Stages of friction

The coefficient of friction (COF) depends on various factors such as adhesion, plowing, deformation, and third body particles during motion. COF lies in six stages in the course of sliding distance. In the first stage, the friction force does not show more variation and remains almost steady. The plowing component of the friction (μ_{plow}) dominates in this region. The adhesive component doesn't have much significance due to surface contamination. In the second stage, friction force increases because adhesive forces become prominent with time, however, there is a sharp increase in frictional force in the third stage. The increased COF is due to the increase in the number of wear particles and also due to increased adhesion as a result of oxide removal from the contacting surface. In addition, asperities on the surface may also contribute to frictional force. In the fourth stage, the friction force does not show any change because the number of wear particles and the adhesion remains almost constant. In the fifth stage, friction force decreases due to the reduction in plowing and asperity deformation. This kind of condition is achieved due to mirror smooth surface as a result of asperity removal. Finally, in the sixth stage, the friction force remains constant due to the same surface finish of both surfaces. However, in reality, mirror-smooth surfaces cannot be achieved as wear particles are always present. During sliding motion between the hard and soft surfaces, the wear particles are entrapped at the interface and there is hardly any change after the fourth stage and the frictional force remains constant [Sin et al., 1979, Mohan, 1989].

1.4.3.3.2 Friction of materials

According to earlier understanding continuous welding and fracture of the surface was the responsible mechanism for sliding friction, but later studies suggested that plastic deformation is the main mechanism that occurs due to the adhesion of surface asperities [Bowden et al., 1950]. However, further studies added knowledge in this area and suggested other contributory factors to friction.

Adhesion takes place due to the inter-atomic attraction of contacting surfaces. Atomic bonds are formed due to force of attraction resulting in adhesion. During sliding motion, old adhesive bonds break, and new bonds are formed. The contribution of adhesive forces to COF is denoted as μ_{ad}. If the surfaces are not contaminated, then force due to adhesion is more which contributes to COF in a larger way. Contaminated surfaces exhibit low adhesive force and their contribution to overall COF is nominal. There are several factors such as crystal structure, surface conditions, applied load, contact duration, the temperature at the contact point, etc., which affect the adhesion between surfaces [Bowden et al., 1950, Bhushan, 1999;]. Plowing of the softer surface takes place, when, it comes in contact with hard asperities/particles of the other surface. During sliding contact, asperities of the hard surface interact with the asperities of the soft surface and plow them away, contributing to an increase in COF. The contribution of plowing to friction is denoted as μ_{plow}. Studies have shown that the plowing component depends on the slope of plowing asperity, asperity geometry, and also on the presence of loose particles [Rabinowicz, 1965, Sin et al., 1979].

During sliding if asperities are not plowed away but deformed then they contribute as elastic (μ_e) and plastic (μ_p) components of asperity deformation (μ_{asp}) and finally to COF

[Bhushan et al., 1991]. During sliding sometimes particles from an internal or external source are entrapped between surfaces as a third body and contribute to overall COF. The contribution of the third body in COF is denoted as μ_{part} [Suh, 1986].

Friction is also affected by the properties of contacting materials and operating parameters such as sliding velocity, applied load, temperature, and environmental conditions. If sliding surfaces are under a normal environment then the friction is lower due to contamination, but under a vacuum, surfaces remain clean causing a higher coefficient of friction. In normal atmospheric conditions, surfaces get oxidized as they are exposed to oxygen present in the air, but with an increase in normal load oxide layer breaks, and the friction increases. Variation in friction with sliding velocity is also observed. At the lower sliding velocity, the friction is low due to the oxide layer formed on the surface, but this layer gets damaged with an increase in sliding velocity, and the coefficient of friction increases. Test temperature may also affect the coefficient of friction. In the case of material having a low melting point, the material melts due to localized heating and forms a layer of low shear strength causing COF to decrease [Whitehead, 1950; Bhushan 1999; Mohan et al., 2015].

Extensive research has been done on tribological characteristics of Zn-Al based alloy and composites and it has been found that such types of alloys possess excellent tribological characteristics and can replace various conventional alloys and composites based on Al, Cu, and steels. Researchers have also suggested that such alloys have excellent bearing characteristics (high wear resistance and low COF) and can be a better replacement for steel and phosphor bronze [Lee et al., 1987, Kumar 2018, Babic et al., 2010]**.** Murphy et al., (1984) have fabricated Zn-Al based alloy and composites via chill casting with varying Al, Cu, and Si and also bring out the effect of heat treatment. They have suggested that the wear behavior of alloy containing Si is close to or superior to that of cast iron and phosphor bronze. This enhanced wear behavior is attributed to the presence of discrete Si particles in the Zn-Al matrix. Other researchers have reported similar results. Some of the researchers reported that Zn-Al type alloys have better bearing characteristics than conventional SAE660 Bronze which is one of the most preferred materials especially in bearing application in automobiles industries [Murphy et al., 1984, Lee at al., 1987, Marczak et al., 1973].

This can be concluded that Zn-Al based alloy exhibits good wear characteristics and can be a potential replacement for conventional bearing materials. Chen et al., (2015) have revealed that the addition of 5% TiB_2 leads to ~77% reduction in wear while ~ 40% reduction in coefficient of friction (COF). They have suggested that this decrease in wear and COF may have taken place due to a good interfacial bond between particles and matrix and the homogeneous distribution of particles in the matrix. A similar result has been reported by many other researchers [Thakur et al., 2001, Ramesh et al., 2011, Kumar et al., 2008]. Folorunso et al., (2019) have observed 60% less wear by reinforcement of 10 wt.% second phase particles of quarry dust and SiC. Kumar (2018) fabricated the composites via ultrasonic stir casting technique and studied the effect of reinforcement of SiC and Gr in ZA27 alloy on wear characteristics. They used the Taguchi method to study the wear characteristics and found that hybrid composite manifests very less wear as compared to alloy while optimum results were achieved at sliding speed (1.5 m/s), load (40 N), and sliding distance (500 m). Kumar et al., (2006) have studied the effect on wear characteristics of garnet reinforced (0-20 wt.% in an interval of 5 %) ZA27 composite using pin on disc and varying sliding speed from 1.25 m/s to 3.65 m/s and load from 50 N- 250 N suggested that in case of change in sliding speed the wear loss was reduced due to reinforcement of garnet particles and observed ~ 60-65% reduction in wear loss at 20 wt.%. However, in the case of load variation 70-80% reduction in wear loss and 26-35% reduction in COF. They have recommended that at a certain value of applied load i.e., a transitional occurrence takes place causing unexpected rise in the wear rate.

However, the transition loads for the composites were increased than that of unreinforced alloy, and it also rises with the increase in garnet particle content. Researchers have suggested that ceramic reinforcement delays the transition from mild to severe wear by elevating either the load or speed at which transition occurs [Kumar et al., 2011, Terry et al., 1990]. Babic et al., (2010) have brought out the effect of graphite on tribological behavior of ZA27 alloy, where they fabricated ZA27/2 wt.% Gr composite via Compocasting route and studied the tribological characteristics using a block on disc under the dry and lubricating condition both. They have suggested that at varying speeds and varying loads in all the combination, reduction in wear rate due to graphite reinforcement**.** Khan et al., (2018) studied the effect of SiC on Zn-Al composite under high-pressure conditions, with use of pin on disc tribometer for analysis of wear characteristics and suggested that reinforcement of SiC particles enhanced the hardness but led to a decrease in density. The wear rate also declines with the rise in abrading distance for all conditions. This reduction in wear is due to the insertion of SiC particles. As load increases, wear rate also increased but the rate of the increase in wear is maximum for the base alloy followed by 5 wt.% and 10 wt.% SiC. They have also observed that COF decreases with the increase in test duration and maximum is observed for alloy followed by composite reinforced with 5 wt.% and 10 wt.% respectively.

It can be inferred from the literature that in most cases, the composite possesses superior wear resistance than that of alloys due to the strong bonding of the particle. The predominance of one or more processes such as capping, clogging, shelling and attrition, results in decreasing cutting efficiency of the abrasive and brittle fragmentation, affected the wear response of the specimens significantly under a given set of experimental conditions. Attrition plays a vital role in decreasing the rate of abrasion [Prasad et al., 1995 and 1997]. Also, this can be observed that frictional heating of the Zn-Al based matrix leads to an increase in COF and this may be due to penetration of the abrasive particles in the samples. Reduction in the severity of penetration due to reinforcement of the hard particles leads to a decrease in COF and as load increases depth of penetration may increase leading to a higher wear rate [Prasad, 2002]. Girish et al., (2011) have also fabricated the ZA27/Graphite via liquid metallurgy route and with varying wt.% of Gr from 0 to 10 wt.% in the interval of 2 and used POD techniques to investigate the tribological characteristics. They have observed an improvement in wear characteristics in the range of 20-30% with reinforcement of 10 wt.% of Gr on varying load and sliding speed and suggested that 4-6 wt.% reinforcement of Gr gives optimum results. They have also shown results for other properties like hardness, thermal conductivity, diffusivity, and mechanical damping values of composites and found that at a higher temperature, these properties are adversely affected with an increase in reinforcing percentage indicating the need to optimize Gr as per the designer's requirement.

1.5 ORIGIN OF THE PROBLEM

Tribological studies can contribute to enhanced sustainability in terms of reduction in CO_2 emissions through improvement in working life cycle of the product and reducing frictional losses. Researchers have given the alternative methodology for savings of 1.68–2.59 gigatons (GT) of CO_2 eq/year with increasing the longevity based on a materials stream of 6.64 GT. From a socio-ecological point of view, reduced wear can lead to doubling the utility value with the same resource consumption resulting in a gross reduction in CO_2 and greenhouse gas emissions [Woydt, 2021]. Hamilton et al., (1966) have suggested a reduction in CO_2 emission by improving tribological performance through improving surface topography. They introduced microcavities in the material for applications involving use of lubricants which helps in the reduction of COF and thus an overall reduction in frictional losses. Conventional bronze-based materials are mostly used for tribological applications, especially in automobile and machinery applications. However, low strength-to-weight ratio of bronze and higher energy requirements during processing due to higher fabrication temperatures motivated researchers to look for alternative materials. Composite materials are found to be suitable alternative materials for applications that cannot be catered to by conventional materials due to the possibility of fine tuning material properties based on use of different material combinations. Several different composite materials are available which exhibit good strength, high modulus of elasticity, and offer better thermal stability [Savaskan et al.,2008, Geng et al., 1993, Rohatgi et al., 2013, Anderson, 2016].

Various new processing routes for fabrication of composites have been developed over time (discussed in section 1.2). Stir casting is a simple and flexible processing route which has been commonly used to fabricate composites. Stir casting techniques are cost effective and thus used for production of large sized components and in mass production [Ulhas et al., 2017, Chou et al., 1985]. In the previous section, it has been discussed that to prepare the composites, reinforcement is done both in *exsitu* and *insitu*. However, *insitu* reinforcements provide advantages of a clear interface, homogeneous distribution, good interfacial bonding, and better wettability among reinforcement and matrix which help in the improvement of mechanical and tribological properties [Pramod et al., 2015].

Zn-Al alloys are being used in industries in various forms owing to their excellent fluidity, and castability [Goodwin, 2000]. Researchers have reported that Zn-Al based alloys offers several advantages such as better strength and wear properties, low fabrication temperature, and cost over conventional Al-based alloy and copper (Cu) based alloys. The low weight-to-strength ratio makes it suitable for foundry alloys over Al and Cu-based alloys and has been examined as potential replacements for bearing materials [Karni et al., 1994]**.** Tribological properties of composite materials are affected by numerous factors such as shape and size, nature, and type of reinforcement and matrix micro constituents, the nature of interfacial bonding between reinforcement and matrix, and the content of reinforcement [Min et al., 1985]**.** As per a study carried out by Lee et al., (1987), Zn-Al alloys were found to have more dimensional stability, as well as less wear, as compared to phosphor bronze. Another researcher has reported improved wear property by replacing Cu with Si and addition of Strontium (Sr) which modifies the microstructure structure of Zn-Al alloy [Jian et al., 1993]. Prasad et al., (1996) analyzed the tribological behavior of Zn-Al alloy and reported improved wear properties, over that of conventional Pb-Sn based bronze.

The use of lubrication in machinery mainly reduces friction coefficient among mating surfaces, reduces wear loss, and provides a cooling effect. Research data reveals that ~ 17 to 19% of the total energy produced is lost due to mechanical friction [Ali et al., 2015, Turkson et al., 2016], and ~ 40% - 50% of frictional losses occur in automobile engines from cylinder liners and piston ring. Due to the varying parameters such as sliding distance, sliding speed, applied load, and type of counter surface, the lubrication states in an engine keep changing and affect the tribological properties [Ali et al., 2015]. The above parameters also depend on the type of lubricant utilized [Durga et al., 1998]. Lubrication acts as a protective film between asperities of the counter surface resulting in less friction and wear [Puhan et al., 2019]. Some researchers have studied the effect of lubricants on the tribology of PEEK with steel counter surface and reported a reduction in friction and softening effect on wear track due to the presence of a lubricant.

The tribological properties of composites are influenced by various other parameters such as surface morphology, loading condition, medium of working, operating velocity and sliding distance, and so on. In automobile parts where tribological properties are key requirements, the excessive applied load, velocity, and sliding distance leads to high wear and results in failures of components [Gautam et al., 2015]. It is essential to accurately predict the wear parameters to stop catastrophic loss along with economic loss. Also, analysis of optimum parameters can lead to effective utilization of MMCs for specific needs. Research findings suggest various mathematical modeling techniques to analyze the optimum parameters. Statistical modelling techniques help in reducing the iterative procedure by optimizing the parameters with lesser experiments [Genel, 2003]. Many researchers have used different statistical modelling techniques such as Design Expert (DOE), Taguchi, factorial design, Artificial Neural network (ANN), etc for tribological parameters optimization for MMCs [Ponugoti et al., 2018, Palanivel et al., 2013, Rajsekaran et al., 2003].

Studying the effect of these variables, there is an enormous scope of implementing statistical techniques for analysis, prediction, and optimization for maximum benefit. The design of experiments provides a statistical and systematic approach to optimize the process parameters using interpretation and analysis. Response surface methodology (RSM) is a multivariate technique and has been widely utilized to optimize the variable parameters for the best performance of materials and it is based on the fit of a polynomial equation to statistical data [Chang et al., 2015, Lin et al., 2002].

Artificial Neural Network (ANN) provides a substitute for the polynomial regression technique as a modelling tool. Research in computing technique has allowed the application of ANN as non-linear modelling for response surfaces and optimization. Many researchers have used ANN to predict the wear behavior of composites in the tribological analysis [Harsha et al., 2007, Jian et al., 2008]. ANN modelling to predict the wear behavior indicates that a well-trained network is expected to be very accommodating and significant [Velten et al., 2000]. One of the main advantages of this technique is that there is no need to make a prior assumption about concerned material behavior. Ponugoti et al., (2018) have utilized RSM and multi-objective optimization to study the wear properties of Al-based hybrid composite and optimized the parameters that affect wear characteristics. Another researcher used RSM to study the wear properties of Al-TiC composite and concluded that sliding speed and particle reinforcements were the main factor to influence wear properties in the Analysis of variance (ANOVA) [Reddy et al., 2019]. Surya et al., (2021) used Box-Behnken-based RSM analysis and reported that wear characteristics of Al-SiC composite were most influenced by sliding speed and reinforcement amount while the load had the lowest effect. Also, they reported the adhesion mode of mechanism at lower reinforcement of SiC while abrasion and delamination as the content of SiC increases. Gangwar et al., (2020) have used ANN and Taguchi to predict the wear properties of Zn-Al based composite and reported wear response was most affected by reinforcement content.

From the literature, this can be inferred that Zn-Al reinforced with suitable *insitu* formed nanoparticulate reinforcements may overcome the above-stated problems, however, it has not been explored. And further statistical modelling can help in reducing time and resource consumption by reducing repetitive experiments by optimizing relevant parameters. The literature survey clearly indicates this area has not been explored much for the present material system and possesses opportunities and advantages.

In view of the above, for the present study, Zn-Al (73:27) alloy has been chosen as matrix material and ZrB_2 as reinforcement to prepare *insitu* composite by DMR technique, and the effect of vol.% ZrB_2 particles on microstructure, mechanical and tribological properties has been analyzed.

1.6 OBJECTIVE OF THE PRESENT WORK

The main objective of the current project is to develop ZA/ZrB_2 *insitu* composites with improved mechanical and tribological properties for tribological applications.

The following steps are followed to achieve the goal:

- Fabrication of ZA/ZrB_2 *insitu* composites with different vol.% of ZrB_2 using DMR casting route.
- Study of microstructural behaviour of ZA alloy and composites to critically examine the ZrB_2 reinforcement particle morphology, size, size distribution and interfacial characteristics between ZA matrix and ZrB_2 particles.
- Study the influence of ZrB_2 particle reinforcement on mechanical properties of ZA/ZrB_2 composites at atmospheric conditions.
- Study the influence of different parameters such as sliding distance, applied load and vol.% of ZrB_2 on tribological properties of ZA/ZrB_2 composites in dry sliding condition and lubricating sliding condition.

- Study of worn surface and wear debris under different tool such as SEM, EDS, AFM, surface profilometer to understand the various wear mechanism involved during the wear process.
- Comparison of tribological properties of ZA/ZrB_2 composites in dry and lubricating sliding conditions to widen the scope of applications of present material.
- Development of statistical modelling technique to optimize/predict the wear parameter for both dry sliding and lubricating sliding condition to further reduce the number of experiments and resources for similar material system.