Review Article

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Characterization of spray formed Al-alloys — A Review

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Abstract: A review on the characterization of mechanical, metallurgical, porosity, tribological and corrosion properties of spray deposited Al-alloys are presented in this paper. Al-alloys are potentially used in various applications specifically in bearing materials, aerospace due to low weight to high strength, proper lubrication, excellent wear and corrosion resistance. Al alloys being processed through spray forming technology, which possesses lower processing steps than the other conventional methods like ingot and powder metallurgy. Characterization of Al alloys spray deposits is carried out before and after mechanical processes to know their behaviour. Reviewed the characterization department of Al-alloys before and after spray deposition, effect of mechanical process like cold rolling, extrusion, aging, hot rolling, hot extrusion etc. and porosity on the metallurgical, hardness, tensile strength, elongation, tribological and corrosion properties.

Keywords: Al-alloys; sprayforming; porosity; mechanical processes; microstructure; hardness; strength; wear; corrosion

1 Introduction

Al-alloys are extensively used in the assorted applications like aerospace, electrical, automotive [1, 2], pulleys, bearing materials [3], and electronic industries [4] due to its excellent physical, chemical and thermal properties like low weight, superior wear and corrosion resistance, ease of casting, and lower thermal coefficient values [5, 6]. This pa-

per is mainly focused on the Al, Si and Pb based alloys due to specific usage in bearing material application. To improve the anti-frictional characteristics [8] and wear resistance it is required to incorporate soft phases like Graphite, Sn, Pb etc. to Al-Si [7] alloy, among these it is preferred to add Pb to Al-Si alloys due to lower melting point, ease of availability, soft, self-lubricative, high thermal conductivity [10], excellent frictional properties, low production cost and cost-effectiveness [9]. Due to the large variation in density and melting point of Al-alloys, it is difficult to process through traditional method *i.e.* by ingot conventional method because of the lower chance of success caused due to the slow cooling rate. Pb, Si phase is being separated from the Al matrix [11, 12] due to slow cooling rate. Various processing methods like melt spinning [13], powder metallurgy [14], rheocasting [15], strip casting [16], stir casting [17] and spray forming [18] methods are used to prepare Al alloy and to overcome problems associated with ingot method (*i.e.* to avoid the separation of Si and Pb during molten metal solidification), some of these methods consume higher energy or spawning of coarse microstructure. Among these processing methods spray depositions possesses gives excellent microstructural segregation, accelerated cooling and homogeneous mixing of the alloys [19]. Billets, tubes, circular rods, rings etc. are possible to produce by this method. Porosity is one of the major drawbacks with respect to spray deposition process, which further deteriorates the mechanical, metallurgical, wear and corrosion properties of the alloys. To improve characteristics of the alloys, it is required to apply mechanical processes such as cold rolling [20], hot rolling forging [21], extrusion and hot extrusion [22]. This paper reviews the several characteristics of spray deposited Al- alloys such as (a) shape of the spray deposit (b) porosity behaviour (c) Mechanical process like cold rolling, extrusion, hot extrusion (d) Microstructural behaviour (e) Mechanical performance (f) wear observance and (g) corrosion behaviour.

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2 Shape of the spray deposited Al-alloys

This system, established as a spray impeachment or spray mold process was initially developed by Prof. A.R.E singer and his confreres at the Swansea university wales in late 60 and early 70's. The graduate students from the Swansea have developed the spray deposition method and merchandising by establishing the Osprey Metal Ltd. Laboratory and the route are named as Osprey process. Availability of stainless steels tubes more in Sweden and was initially processed through spray deposition processes by sandvic in Osprey Metals Ltd. This technology was effectively utilized by various countries like Europe, Japan, and the USA to manufacturing various aluminum metal matrix composites. A similar type of deposition was established by Prof. Nick Grant in M.I.T laboratories and it is named as Liquid Dynamic Compaction. The main deviation between the LDC and SD process is that an ultrasonic atomizer used instead of the gas atomizer [23].

Grant *et al.* [24] investigated that spray deposition possesses excellent economical and characterization benefits than the other casting methods like powder metallurgy, strip casting, stir casting methods. spray forming curtails the numerous powder metallurgical operations like sieving, caming, consolidation and powder production in to a single operation. Therefore, spray deposition technique is the best method to prepare the alloy and represented in the Table 1.

See J. B *et al.* [25] investigated the molten metal breakup mechanism as shown in the Figure 1 during the collision occurred between the inert gas and liquid molten metal. conversion of the molten liquid into semi-solid droplets conversion occurred in three stages. in the first stage, turbulence occurred due to nitrogen gas collides the liquid metal with high impact pressure and formed droplets in a bigger size, in the second stage the bigger liquid droplets converted into the fragments and in the third stage, fragmented droplets converted into semi solid droplets and fallen over the rotational substrate.

Figure 1: Molten metal break up mechanism [31].

Table 1: Comparison between ingot, powder metallurgy and spray forming processing

Ingot Process	Powder metallurgy	Spray Forming
Casting	Atomization	Molten metal
Scalping	Screening	
Soaking	Canning	
Rolling	Degassing	
Slab	Consolidation	Pouring
Grinding	Decanning	
Reheating	Billet	
Rolling	Extrusion	
Rolled stock		
Stock	Stock	Stock

Figure 2: Schematic representation of spray deposition process.

Kamalpreet Kaur *et al.* [26] reported about the spray forming process, initially as represented in the Figure 2. Al-Si alloys are cut down into the tiny size particulates thereafter alloys were melted up to the superheated temperature *i.e.* 800°C in the resistance heating furnace. Molten metal passed through the assembled graphite crucible (which is connected to the induction furnace and convergent-divergent nozzle) and nitrogen gas released at a pressure of 10 bar through gas atomizer at the same instance, results molten metal converted into the semi-solid droplets is represented through flow diagram as shown in Figure 3.

K.V. Ojha *et al.* [27] investigated that the shape of the spray deposited Al-alloys depends upon the mainly four factors like (i) distance between the delivery tube and substrate is about 450mm (ii) atomization gaseous should be

Figure 3: Flow diagram of spray forming processing.

Table 2: Optimal processing parameters

Type of gas	Pressure (bar)	Melting Temperature (K)	Type of substrate	Inclination angle (°)	SDD range (cm)	Rotor speed (rpm)
Nitrogen	8-12	800-1100	Copper	15-60	350-550	14-50

maintained 8bar (iii) inclination angle of the rotor is about 0°. (iv) rotor inclination speed was maintained 32rpm. It was observed that the shape of the deposit in the form of the Gaussian or bell curve. Parameters ranges represented in the Table 2.

Rashmi *et al.* [28] investigated that, the thickness uniformity of the spray deposit increases with the increased distance between the delivery tube to a rotational axis of the rotor and inclination angle of the rotor. the required thickness of the deposit obtained at a distance 40cm with an inclination angle about 30 degrees.

H.K.*et al.* [29] investigated, by using the vector calculus concept a spray deposition structure of the rod developed and it was analysed with the help of 3-D mathematical model.

the advancement of the deposit from bottom to top portion interpreted by various parameters like substrate spinning velocity, inclination angle of the rotor and spray deposition distance between rotor and delivery tube. There is no effect on the shape of deposit with respect to higher rotational velocity. Inclination angle was affected the shape of the deposit in the range of 0 to 60°, optimum angle is 30 degrees to obtain the proper shape. The SDD effects the profile of the shape highly. Therefore, the experimental values and values obtained due to mathematical calculation is in agreement.

Markus *et al.* [30] investigated the usage of multiple number of atomizers during spray deposition technique

enlarges the size of the billets, as well as multiple spray layers over deposit beneficial towards incoming mass distribution as well as enthalpy increment. The top layer thermal behaviour was controlled by cooling and grow of the particulate. Any way results obtained by modelling process as well as experimental results in good agreement.

It has been observed that most of the researchers used gas atomizer during the spray deposition experiment but not used centrifugal atomizer, so that there is good scope to conduct spray forming experiment by using it and analysed characterization behaviour of Al-alloys.

3 Microstructural behaviour of sprayed Al-alloys

Wang *et al.* [32] has been investigated the microstructure of Al-20Si-3Cu-1Mg after addition of some amount of Fe and Mn which was prepared by Spray deposition technique. During SEM analysis, it was observed that the alloy is composed of aluminium matrix and silicon phase mostly with a particle shape. A high-volume fraction of needle shaped intermetallic phase has been observed after adding 5% Fe with the alloy. EDS analysis was done to know the composition of Al, Si, Cu, and Mg in the intermetallic particle shape. It was observed that two kinds of intermetallic is formed in the microstructure i.e. δ -Al₄Fe Si₂ and β -Al₅ Fe Si.

Hai gen *et al.* [33] investigated about the fatigue behaviour of Al-Zn-Mg-Cu alloy and mainly the microstructure of the alloy in the process of crack formation and crack growth. XRD, SEM, and Optical microscope were used to study the fatigue fracture of the alloy. Fatigue damage occurs at the fractured Fe-rich inclusion particles or at near the specimen free surfaces. The Fatigue fracture is composed of fatigue crack source zone, fatigue crack propagation zone and fatigue fracture zone. The crack source zone is 25 μm from the free surface of the specimen and it is smaller in size and crack propagation zone takes almost half of the specimen.

Feng *et al.* [34] investigated about the microstructure of spray formed Al-10.8Zn-2.8Mg-1.9Cu by using SEM, TEM and XRD analysis. It was observed that the microstructure of the alloy is composed of Al matrix, Mg (ZnCu)₂ compounds and micro pores. During the extrusion refinement of Mg (ZnCu)₂, micro pores were eliminated from the structure and after solution treatment the Mg (ZnCu)₂ were dissolved in Al matrix and Al₇Cu₂Fe intermetallic particles were found.

Shu *et al.* [35] investigated the microstructural evolution of spray formed Al-11.5Zn-2Mg-1.6Cu alloy during hot extrusion and heat treatment using SEM, TEM, EDS and XRD analysis. It was observed that the microstructure consists of equiaxed and uniform grain with grain size 25 μm . Fine and irregular morphologies are present in top and bottom regions. After hot extrusion large size grain boundaries and intragranular phase disappear instead, η -phase (MgZn₂) and Al₃Zr phase particles precipitate in the matrix.

Pucun *et al.* [36] investigated about the microstructure of a large billet of Al-Zn-Mg-Cu alloy which was prepared by spray deposition technique and further it was processed by hot extrusion, solid solution treatment and aging. It was observed that the microstructure of the alloy consists of dispersed and fine L1-Al₃Zr phases, GP II Zones and η precipitates. Strengthening depends on precipitates hardening and solid solution strengthening.

Cai *et al.* [37] investigated the micro structural evolution of Al-Si-Fe alloy by addition of Mn and Cr using SEM, XRD, TEM and DSC. It was observed that when both was added separately then addition of Cr is more effective than Mn as it decreases the content of harmful rod like β -phase to a great extent. Micro structural evolution obtained by co-addition of both Mn and Cr at a time is more superior to individual addition and co-existence of Mn and Cr plays an important role in optimizing the microstructure.

Hua *et al.* [38] investigated about the microstructure of Spray formed Al-Zn-Mg-Cu alloy with addition of Mn. During Optical Microscopy it was observed that the alloy

has equiaxed grains of size ranging from 5 μm to 25 μm . MgZn₂ with CuAl₂, Al₃Zr and few eutectics were found in as-sprayed alloy and Al₆Mn particles were precipitated at the grain boundaries. DSC results indicate that no thermal effects occurred below 450°C. Both matrix grain and Al₆Mn particles grew monotonously with the increase in annealing temperature.

Wang *et al.* [39] investigated about the micro structural behaviour of Spray formed Zn-30Al alloy with addition of Cu. Microstructures were investigated by using SEM, TEM, XRD. It was observed that when 1% of Cu is added to the alloy then there is no change in the microstructure but when @5 to % of Cu was added then ϵ -Cu Zn₄ compounds were found on the grain boundaries.

Mazze *et al.* [40] investigated the micro structural evolution of Aluminium alloy of 7000 series containing Zn, Mg, and Cu. The chips obtained after machining of the alloy were reprocessed by spray forming and after that hot extrusion and spray forming was done. It was observed that in the microstructures hardening η precipitates were present within the matrix and equilibrium precipitates were present at the grain boundaries, refined grains and low segregation of main element Zn, Mg, Cu. After heat treatment and at the peak aged condition it was observed that the final microstructures consist of GP zones, η metastable and equilibrium phase Al₃Zr dispersoids and the coarse Al₇Cu₂Fe intermetallic were present.

Srivastava *et al.* [41] investigated about the microstructure of Al-Cu-Fe alloy having quasicrystal line phase with and without the addition of Sn which were synthesized by Spray Forming process. It was observed that the alloy prepared without Sn contains quasicrystal line phase with minor λ -Al₁₃Fe₄ phase whereas the alloy which was having Sn contains the i-phase and the crystalline phase of Sn, θ -Al₄Cu, λ -Al₁₃Fe₄ and β -AlFe (Cu) phases.

Yu *et al.* [42] investigated about the microstructure of large scale Al-Zn-Cu-Mg alloy which was fabricated by Spray deposition technique. It was observed that the high-density nanoparticles were uniformly distributed in the peak aged alloy which results in high strength and large tensile ductility of the alloy. The η phases were fully coherent with the aluminium matrix, with the orientation relationship of (1010) η //{110} μ .

Jia *et al.* [43] investigated the flow behaviour of Al-10.21Zn-2.76Mg-1.45Cu-0.16Zr (wt.) alloy which was prepared by Spray Forming by thermal compression test with temperature and strain rate ranging from 613k to 733k and 0.001/s to 1/s respectively. A micro structural observation shows that the average grain size was below 25 μm due to the high cooling rate. The steady state stress is inversely proportional to deformation temperature. Grain re-

finement and high supersaturated solid solubility was obtained.

Cava *et al.* [44] investigated about the Cu based shape memory alloys which were prepared by Spray forming technique. The microstructure was characterized by Optical and scanning electron microscopy, XRD and DSC. It was observed that equiaxial grains with a martensite structure were present. The grain size varies from 25 μm in the lower region to 160 μm in upper region. The grain size depends on the cooling rate *i.e.* if cooling rate is higher, grain size will be finer. Micro structural characteristics can be adjusted according to its application which enables the alloy to be used in different applications.

Liu *et al.* [45] investigated the microstructure of large scale Al-Zn-Mg-Cu-Zr alloys rods that was fabricated by Spray deposition technique and then it was processed by hot extrusion, solution treatment and T6 treatment. Microstructure observations show that equiaxed grains were formed in the ingots. It shows that high density Nano precipitates were uniformly distributed at the peak aged alloy conditions.

Li *et al.* [46] investigated the effects of Mg and Cu on the microstructure of Al-Zn-Mg-Cu alloy which is fabricated by Spray deposition technique. It shows that η phase is the main phase in all of the alloys, θ phase exist in alloy with high Mg and Cu contents and θ phase exists in alloy with low Mg and high Cu contents. The volume fraction of secondary phase increase by increasing the Mg content which leads to improvement of yield strength.

Li *et al.* [47] investigated about the microstructure of Al-Zn-Mg-Cu-Zr alloys with the addition of scandium which was prepared by Spray deposition method. It shows that both the grain size and coarse secondary phases can be refined by Sc addition due to the formation of a hybrid structure coupled by η -MgZn₂ and Al₃ (Sc, Zr) phases near and at the grain boundaries. TEM results reveal that the presence of primary Al₃(Sc, Zr) particles near and at the grain boundaries play an important role in refining the secondary phase as they can provide nucleation sites for the h-MgZn₂ phase in a divorced eutectic reaction.

Tomar *et al.* [48] investigated the presence of porosity in the disc-shaped Al-Si-Pb alloys by varying Pb composition from 0 to 20%. It has been observed that porosity value increased with the incremented value of the lead percentage, decreased with increased distance from middle to a peripheral portion of the deposit and remains constant with thickness deposition rate. It has observed from optical micrographs of Al-Si-Pb alloys more porosity area belongs to lead and small belongs to Al rich regions.

Yu *et al.* [49] investigated the effect of extrusion on microstructure of spray deposited Al-11.5Si-15Pb and Al-8Si-

10Pb. It has been confirmed that there is no significant change in the microstructure of both preforms before and after extrusion process, Pb particles distributed uniformly along the grain boundaries of the Al matrix, the average Al grain size is about 35 μm . the porosity values decreased after the mechanical process.

4 Mechanical behaviour of the spray deposited Al-alloys

Sharma *et al.* [50] investigated about the fatigue behaviour of Al alloys of 7xxx series which was reinforced with Sic and prepared by Spray Forming. The effect of processing and composition on the properties of alloy was also analysed. The fatigue strength of the alloy was increased to a great strength as compared to conventional high strength aluminium alloys due to low crack growth rates which occurs due to the presence of coherent and semi coherent GP zones and η phase particles of reduced dimensions in the spray formed alloys.

Bask *et al.* [51] investigated about the mechanical properties of Al-Zn-Mg-Cu-Zr-Sc alloy prepared by Spray deposition technique and then processed by hot deformation and heat treatment. It shows that an excellent strength and elongation of alloy is obtained through two step hot deformation process. UTS, YS and elongation was observed as 774 MPa, 734 MPa and 13.7% respectively which is increased by 2.7%, 3.82% and 95% compared with one step deformation.

Zhao *et al.* [52] investigated about the isothermal deformation of Spray formed Al-Zn-Mg-Cu alloy which was done by DEFORMTM process simulation software. The material flow, internal stress and temperature of billet's interior were investigated. It was observed that after heat treatment, the ultimate tensile strength reached to 817 MPa. It was observed that the alloy prepared by spray formed have good deformability and mechanical property. So, it has great potential to be an engineering material as compared to the one prepared by conventional method.

Schreiber *et al.* [53] investigated about the effect of hot extrusion and heat treatment on the mechanical properties of AA7055 which was prepared by Spray forming. The result shows that the strength and ductility of the alloy improves to a great extent due to lowering of porosity and initiation of recrystallization. Hot extrusion and heat treatment both affects the tensile strength of the alloy to a great strength. The combined effect of Spray forming and hot extrusion lead to an alloy with 750 MPa strength, 165 ductility and excellent energy absorption capability.

Godinho *et al.* [54] investigated about the mechanical properties of a spray formed and extruded AA7050 recycled alloy. It will add value to the use of machining chips and can be used in the recycling chain of casting industry without adding value. The material was hot extruded at 420°C and then solution heat treated and age hardened at 3 different condition. The results of tensile tests at room temperature were 623 MPa tensile strength, 563 MPa yield strength and 12% elongation. It was observed that the strength and ductility of the machining chips exceeds the data of AA7050 material.

Zhao *et al.* [55] investigated about the mechanical properties of spray formed Al 7055 which was welded by underwater friction stir welding because the alloy was having Zn as supersaturated solid solution so it requires strict control of heat input during the welding process. The result shows that the tensile strength, hardness and plasticity of underwater welded joint are better than that welded in air. Water environment reduces the residual stress of the joint and reserved compression stress in the weld and it also eliminates the S-line defect. The tensile strength reaches to 495 MPa and the elongation is also higher than the normal joint.

Qu *et al.* [56] investigated about the mechanical properties of spray formed AA 7075 alloy which was processed by heat treatment. After T6 treatment the UTS was 760 MPa due to uniform distribution of the precipitates. After T73 treatment the elongation was increased but it reduces the UTS to 676 MPa due to increase volume fractions of the precipitates. After that RRA was done which increases the UTS to 758 and after that in the final microstructure the UTS increased up to 791 MPa and the elongation also increases to 8.5%.

Wang *et al.* [57] investigated about the strengthening mechanism of spray forming Al-Zn-Mg-Cu alloy by underwater friction stir welding. It was observed that the joint is defect free with tensile strength of 406.06 MPa and elongation also improved by 1.96%. It increases the strength by 30% as compared to traditional joint and also the hard-etched zone gets eliminated. It improves the mechanical properties of the weld to a great extent as compared to the traditional welding.

Tomar *et al.* [58] investigated about the mechanical properties of Spray formed Al-Si-Pb alloys. It was found that the ultimate tensile strength, proof stress and elongation to fracture decrease linearly and exponentially with increase in the lead content and porosity of the deposit respectively. The strength and elongation of the alloy decreases with the increase in Pb content but increases with the increase in distance from the centre to periphery of the deposit. The UTS and proof stress are higher at higher sil-

icon content and they have a linear relationship with the hardness of the deposit.

Tomar *et al.* [59] investigated about the porosity in disc shape spray formed Al-Si-Pb alloy preform. It was observed that the porosity decreases with distance from centre to periphery for all compositions of lead. It increases with increase in the lead content because of the difference in solidification shrinkage of aluminium and lead. The lead solidifies after the solidification of aluminium rich phase as the solidification shrinkage of lead is higher than that of aluminium. It remains constant with thickness of the deposit. The effect of lead content decreases with the distance from centre to periphery of the deposit.

Yibin *et al.* [60] investigated about the distribution and evolution of porous defects in spray formed 7XXX aluminium alloy. Morphology characteristics of pores and their formation along with the influence of HIP treatment and homogenizing treatment on porous defects were investigated. The porous defects are interstices, interlinked pores and gas pores. The main defects in centre of the alloy are interstices and gas pores. The morphology of gas pores remains nearly spherical on the inside walls and other porous defects shows irregular geographies. The pores in the middle were smaller in size as compare to that on the topside and the edges of the alloy.

Müller *et al.* [61] investigated about the effect of reactive elements on porosity in Spray formed Copper alloy billets. In spray formed performs, it is difficult to avoid porosity because of entrapping of atomizing gas during the process. It has been seen that the reactive element has additional effect on the porosity as it reacts with the atomizing gas. A large number of CuSn-, CuAlFe- and CuMnNi- alloy has been prepared with and without adding Titanium and after that density was calculated by buoyancy balance, and data from these billets were used for calculating the porosity. It was observed that the addition of Titanium can reduce the porosity by a factor of 3.

Candan [62] investigated the effect of alloying additions on the porosity of SiC_p performs which is infiltrated by aluminium. Effect of alloying additions (Pb, Mg, Cu and Si) on amount of porosity of infiltrated preforms was investigated. It was observed that the porosity increases on the addition of Pb, while addition of Cu and Si did not affect the porosity to a great extent. The porosity was almost eliminated by addition of Mg to pure aluminium due to increased wetting behaviour of the alloy.

5 Wear behaviour of spray deposited al-alloys

Mittal *et al.* [63] investigated the wear observance of spray deposited Al-Si-Pb alloys by varying the loads, it has been observed that with the increased load the wear rate increased, whereas Pb composition increased the wear rate decreased and also lower wear rate in case of %12Si than the %6Si alloy. With increased spray deposition distance from the centre to peripheral regions the wear decreased. The coefficient of frictional values decreased up to a load 40N thereafter it is constant and also lower for higher Pb composition

J. An *et al.* [64] investigated the enhancement of wear characteristics of the stir cast Al-Si-Pb alloys by the mechanical process like hot extrusion. it has been observed that the wear rate was tremendously decreased after the hot extrusion process due to two reasons *i.e.* (i) decrement in the porosity levels (ii) increment in lead composition. The Pb composition lies in the range of 20-25 percentage, wear resistance improved significantly due to the presence of lubrication over the surface of the deposit.

Wang *et al.* [65] investigated the wear behaviour of the Al-%20Si alloys produced by casting and spray deposition techniques by varying the loads like 9N, 18N, 27N and 37N. in this context for all varying loads, it was confirmed that spray deposited Al-Si alloys possessed excellent wear resistance properties than the cast deposited alloys. wear rate is lower in case of spray deposit due to oxidative layer formation mechanism over the surface, whereas in case of casted alloys delamination mechanism formed and non-homogeneous mixing of the alloy also one reason.

Gui *et al.* [66] investigated the significance of porosity on wear properties of the sprayed and forge deposited Al-6Cu-Mn/SiCp composite. it has been discussed the porosity effect and wear mechanism presented in various wear zones. For both deposited (Al-6Cu-Mn) *i.e.* sprayed and forged, wear test was conducted at the load range 5-400N and reinforced with the 13-percentage composite SiCp. up to 100N load they spray-deposited and forged alloys were possessed same wear rate in all wear zones (Transition, mild and severe). The load has increased the alloy transitioned from mild to severe zone and is controlled by the adhesion mechanism, whereas mild zone controlled by the oxidation, delamination, and subsurface-cracking assisted adhesion wear. For lower loads of spray deposited alloys, there is no transition occurred to the pores presented below the surface of the alloys, hence there no cracking takes place, so that wear resistance is more in this case. Whereas the applied load greater than 100N, the pores

were broken in the form of cracks and wear resistance rate decreased.

J. An *et al.* [67] reported the Pb influence on the wear characteristics of the stir cast Al-Si-Pb alloys. Wear behaviour deposit evaluated at room temperature, 100°C, 200°C. Initially, Pb is not endorsed with Al-Si alloy at RT, which results in poor wear resistance. The deposit is hot extruded at the temperature 100°C and deployed Pb composition 20%, which results in a coefficient of friction low and wear resistance is improved substantially due to the formation of tribo-oxide layer over the surface of the deposit. If the temperature is beyond 200°C, there is no tribo-oxidation layer observed.

Chaudhary *et al.* [68] investigated the observance of the wear characteristics of the spray formed and stir cast Al-2Mg-11TiO₂ composites. It has been observed that the wear rate is less in case of the spray deposited alloy than the base and stir cast one due to the incorporation of the TiO₂ to Al-2Mg alloy.

G.B *et al.* [18] investigated the wear behaviour of spray formed Al-Si-Pb alloys, it was observed that the wear rate is lower in case of the Al-Si alloy containing 20%Pb than the base Al-Si due to uninterrupted smearing over the surface of the deposit.

Zhenhua *et al.* [69] investigated the effect of silicon content and thermo mechanical analysis of the dry sliding wear characterization of the spray-deposited Al-Si/SiCp composites. it has been observed that by varying the Si content 9, 15 and 20 percent the wear resistance increased due to the Si phase acted as a load bedding element to the spray deposit, higher Si composition controls the eradication of the abrasive wear and protects the surface of the deposit. spray deposits have undergone thermo mechanical heat treatment process at temperatures 510, 470, aged up to 5hrs and water quenched. it was observed thermo mechanical treated spray deposits shown less wear rate.

Rudrakshi *et al.* [70] investigated the wear behaviour of the liquid immiscibility alloys Al- than the Al-Pb alloys due to the Pb provided continuous lubrication over the surface of the deposit. Pb and Cu-Pb, it was observed that the Cu-Pb deposit possessed superior wear resistance rate.

Rudrakshi *et al.* [19] investigated the wear analysis of the spray deposited Al-3.5Cu-10Si-20Pb under different environmental conditions like air and vacuum. it was observed that wear rate is more in presence of the air due to the formation of the oxide layers over the surface which results in the formation of flakes. if the wear test conducted in the vacuum, there is no chance to the formation of oxide layers and obtained surface is ultrafine. therefore, wear resistance rate is good in presence of vacuum than air.

M. Elmadagli *et al.* [71] investigated the wear resistance of cast, sand cast and spray deposited Al-Si alloys by varying the Si composition (9%, 18% and 25%), it has been observed that as the load increased >150N the wear transition resumed from mild to severe and it is directly proportional to load impedance $W=C(L)$. there is no significant change in all deposits even the load varies with the transition. Wear rate is improved in case of spray forming process than the other casting techniques.

B.V.R *et al.* [72] reported the wear behaviour of the spray formed Al-Pb alloys at fixed Pb composition is about 20%, it was observed that wear rate increased with load, mild wear observed in the load range of 20-40N and transition wear observed in the range of 20-25N. therefore load to obtain wear resistance it is required to test at lower loads.

Kumar *et al.* [73] investigated the wear performance of the cold forged and spray deposited Al-Si alloys under dry conditions. it has been observed that more the forged thickness reduction in spray deposited samples, lower the wear rate. for 75% the wear rate is lower because of the lower porosity and fine surface obtained.

Goudar *et al.* [74] investigated the effect of copper and iron on the wear behaviour of Al-28Si alloy and for that Al-28Si-5Cu-4Fe was prepared by Spray forming technique. It was observed that the wear resistance of Spray formed quaternary alloy was higher than that of as cast alloy. The wear resistance of Al-28Si alloy increases after the addition of Cu and Fe. The wear resistance of Spray formed and hot-pressed Al-28Si-5Cu-4Fe is highest and coefficient of friction is minimum as compared to the as Spray formed and cast alloys.

K.V. Ojha *et al.* [75] investigated about the wear properties of Spray formed hypoeutectic Al-Si alloys. The disc shape spray form castings were made of Al-6.91Si and Al-10.1Si alloys and their wearing properties were studied. Wear rate of both the alloy at constant sliding speed 0.75 m/s and constant load 3 kg have been studied. It was observed that the wear rate of alloy having 10.1% Si is lower than that of 6.91% Si alloy because of the silicon which is a hard substance and when percentage of Si increase hardness increases and wear rate decreases. It was observed that the wear resistance of both the alloys depends upon the shape and size of second phase particle.

Mittal *et al.* [76] investigated the wear behaviour of disc shape Spray formed Al-Si-Pb alloys using a pin on disk type wear testing machine. Wear rate behaviour of the alloy was observed in three stages, in the second stage the rate of increase in wear rate was lowest and highest in the third stage. It was observed that if the lead content is increased then the wear rate will decrease as it was lower for alloy having 12% Si as compared to that having 6% Si in

Al-Si-Pb alloys. Wear rate also decreased with the increase in distance from centre to periphery of the deposit.

Choudhury *et al.* [77] studied about the wear behaviour of spray formed and stir cast Al-2Mg-11TiO₂ composites and compared along with the base alloy which is also tested under the same sliding condition. It was observed that the wear properties improved with addition of TiO₂ particles. Wear rate of spray formed composite is lower than the base alloy and stir cast composite. It was seen that as the load is increased severe wear occurs much faster in alloy as compared to composites. The spray formed composites shows a mixed mode of oxidative-abrasive wear mechanism. The coefficient of friction of the composite and stir cast composites is lower than the base alloy and decreases with increase in load.

Wang *et al.* [78] studied about the sliding behaviour of a hypereutectic Al-Si alloy prepared by spray deposition and compared it with one prepared by conventional casting methods. Four loads were taken *i.e.* – 8.9, 17.8, 26.7 and 35.6N. It was observed that the spray formed alloy shows an improved wear resistance in comparison to the conventional casting alloy. The dominant wear mechanism was also different of spray formed alloy as compared to the cast alloy Oxidative mechanism was the dominant mechanism for spray formed alloy and delamination mechanism for cast alloy.

Mittal *et al.* [79] studied about the dry sliding behaviour of spray cast Al-6Si alloy in both as-Sprayed and different cold rolled reductions. The Spray casted preform have equiaxed grain morphology containing some irregular pores. These pores were almost eliminated by the cold rolling. Wear rate increases with the increase in applied load for all thickness reduction. Wear rate is highest for 40% thickness reduction due to increase in the crack porosity. Wear rate decreases up to 20%, increases from 20% to 40% and beyond 40% reduction crack annihilates due to which wear rate again decreases.

Gouthama *et al.* [80] investigated the wear characteristics of alloys based on Al-Pb and Cu-Pb which was prepared by spray forming technique. It was observed that the wear rate of Cu-20Pb alloy was higher than that of Al-4Cu-20Pb alloy at low load and sliding velocity but when the load and sliding velocity is high, the wear rate of Cu-20Pb alloy was observed to be low as compared to Al-4Cu-20Pb alloy. A continuous film of Pb was observed during the examination of worn out surfaces of the test pin extracted from severe wear condition in case of Cu-Pb alloy whereas in case of Al-4Cu-20Pb alloy a discontinuous film was observed.

Rudrakshi *et al.* [81] studied about the spray formed Al-Si-Pb alloys and also about its wear characteristics. It

was observed that the wear rate and coefficient of friction of Al-Si-Pb alloy were lower than that of Al-Si alloy at different applied load. The wear rate of spray formed alloys was observed to increase with an increase in applied load. A continuous film of lead was smeared over the surface of alloy containing lead whereas irregular shape debris particles are observed in the alloy that is free from lead.

Zhenhua *et al.* [82] investigated the effect of silicon content on the wear behaviour of spray deposited Al-Si/Sic composites by using a ring-on-ring test at room temperature under dry conditions. In this experiment five composites were prepared having different composition, density and hardness. It was observed that due to the increase of silicon content the wear rate of the composite decreases as the hardness increases. The wear resistance of the composite has been improved to a great extent as compared to as-sprayed composite after thermo mechanical treatment.

6 Corrosion behaviour of spray formed al-alloys

K. Raju *et al.* [83] investigated the corrosion behaviour of the spray formed Al-Si alloys by varying the Si composition. It has been observed that with increased Si composition from the 12 to 20 percent the corrosion rate decreased tremendously due to the homogeneous distribution of the Si composition in the Al matrix. Due to the presence of the porosity in spray deposited alloys the cavities developed over the surface of the deposit and analysed with corrosion tests, it revealed the type of corrosion presented is Pitting corrosion in that alloy. It was also observed that the corrosion rate is more in case of chilled cast alloys than the spray-deposited alloys.

Santos *et al.* [84] conducted corrosion test to the spray deposited hypereutectic Al-Si-Cu alloys in various solutions like acidic, basic and alkaline mediums by using electrochemical spectrography (EPS). It was confirmed that corrosion rate is more in case of the alkaline solution than the other mediums due to the captivation and precipitation of tiny particles from the alloy leads to the development of the cracks. In the other mediums like acidic due to the intended localized attack, the significance of corrosion rate is almost nil. In neutral medium also, the metal passivated in smaller areas but nullified with the decremented impedance value, therefore, the rate of corrosion value almost null.

K.L Moore *et al.* [85] conducted the polarization tests to reveal the pitting corrosion behaviour of the newly spray formed OX24(Al-Li-Mg-Zr) and OX27(Al-Cu-Mg-

Li-Zr-Ag) and compared with the spray deposited Aluminium alloys AA5083 and AA7034. It has been observed that OX27 showed poor corrosion resistance than the OX24 due to the polarization potential differences. OX24 and AA5083 showed almost same corrosion resistance. Therefore, among four deposits AA7034 showed very poor corrosion resistance due to the higher potential differences in their metals.

Su R *et al.* [86] Investigated the recession and aging effects on the stress corrosion cracking, exfoliation, and intergranular corrosion cracking spray deposited Al-7075 alloy. It has been observed corrosion resistance is more in case of the IGC as the RRA times increased at a constant temperature of 200 degrees due to enlarged precipitation zones. Whereas in EXCO (exfoliation corrosion) and SCC (stress corrosion cracking) cases with the incremental value of RRA the corrosion resistance decreased due to the presence of concentrated precipitated free zones.

S.M *et al.* [87] conducted the corrosion test for spray deposited Al-Si-Cu alloys in Ethanol automobile fuel environment and compared it with grey cast iron deposit. It has been observed that Al-Si-Cu alloys possess high corrosion resistance than the grey cast iron due to the presence of higher silicon content. If the percentage of Silicon content more in spray deposited alloy then it leads to lower corrosion resistance.

Uozato *et al.* [88] investigated the corrosion behaviour of the ferrous powder sprayed over the aluminium billets in sulphuric acid water solutions. Ferrous powder available in two combinations like Fe-C-Ni-Cr-Cu-V-B and Fe-C-Si-Cr-Sn. Corrosion test results showed more Ni composition more resistance to corrosion. Therefore nickel based ferrous powder having more corrosion resistance than the Fe-C-Si-Cr-Sn.

7 Conclusions

The following consequences were made from the present investigated review paper

Reasonable Bell or Gaussian shape of the spray deposited Al-alloys obtained at optimal processed parameters like, pressure range 8-10bar, optimal spray deposition distance (SDD) is about 350-430mm, inclination angle of the substrate 15-30 degrees, delivery tube diameter in the range of 4-5mm. It has been proved that the shape of the rod theoretically calculated by using 3-d mathematical modelling and experimentally verified processing parameters in the good agreement. The thickness of the spray deposit directly proportional to the SDD, rotational angle

of the copper substrate. Billets size enlarged, enthalpy and incoming flow rates increased due to multiple atomizers. It is conformed from the Literature review centrifugal atomizer not used to make spray deposits and not analysed the characterization part.

It is conformed from the optical microscopy, before spray deposition there is homogeneous distribution of alloying metals in the Al matrix and grains also coarse in size and with the range of 40-50 μm , after spray deposition alloying elements distributed in metal matrix homogeneously and grains are fine in size of the range 10-15 μm . After spray deposition the main problem is porosity and it is controlled through mechanical process.

It is confirmed that mechanically processed spray deposited alloy possessed the better hardness values, fatigue curves, controlled porosity than the base spray deposition process (without mechanical processes). It is also conformed ingot, stir casting, powder metallurgy routes possessed poor mechanical properties than spray deposited one.

Al-Si-Pb alloys processed through various routes like conventional route, stir casting and spray forming and compared wear rate. It is confirmed that the wear is lower in case of spray deposited and mechanically processed alloy than the other methods. In case of spray deposited alloys It is conformed that increased load effects the wear rate of the seriously, Mechanical processes like hot extrusion, cold rolling process tremendously increased the wear resistance rate than the base alloy, In Al-Si-Pb possesses reasonable wear resistance properties than Al-Si alloys before and after mechanical process.

It is confirmed that dominant mechanism in case of spray deposits is oxidative, where as in casting it is delamination.

It is confirmed the rate of corrosion is more in case of casted deposits than the spray ones. Rapid solidification rate decreased the corrosion resistance rate due to the presence of porosity inside the deposit and improved by the addition of the more Si percentage to Al and is optimal range is 12-20 percentage. In case of spray deposited Al-alloys corrosion resistance rate mainly depends upon the composition, potential difference between the metals, type of medium (acidic, basic, alkaline, ethanol, NaCl, etc.), width of the precipitate free zones, grain boundary and matrix precipitate rate.

References

- [1] Anand, S., Srivatsan, T.S., Wu, Y. and Lavernia, E.J., *Journal of Materials Science*, 32 (11) (1997) 2835-2848.
- [2] Zhou, J., Duszczek, J. and Korevaar, B.M., *Journal of materials science*, 26(11) (1991) 3041-3050.
- [3] Pathak, J.P., Tiwari, S.N. and Malhotra, S.L., *Wear*, 112(3-4) (1986) 341-353.
- [4] Tomar, A., Mittal, R. and Singh, D., *International Journal of Minerals, Metallurgy, and Materials*, 21(12) (2014) 1222-1227.
- [5] Estrada, J.L. and Duszczek, J., *Journal of materials science*, 25(2) (1990) 1381-1391.
- [6] Wang, R.Y., Lu, W.H. and Hogan, L.M., *Journal of Crystal Growth*, 207 (1-2) (1999) 43-54.
- [7] Feyzullahoglu, E. and Şakiroğlu, N., *Materials & Design* (1980-2015), 31(5) (2010) 2532-2539.
- [8] Anil, M., Srivastava, V.C., Ghosh, M.K. and Ojha, S.N., *Wear*, 268 (11-12) (2010) 1250-1256.
- [9] An, J., Liu, Y.B., Lu, Y., Zhang, Q.Y. and Dong, C., *Wear*, 256 (3-4) (2004) 374-385.
- [10] Mittal, R., Tomar, A. and Singh, D., *Adv. Mat. Lett.*, 3(1) (2012) 55-63.
- [11] Akhlaghi, F. and Pelaseyyed, S.A., *Materials Science and Engineering: A*, 385 (1-2) (2004) 258-266.
- [12] An, J., Liu, Y.B. and Lu, Y., *Materials Science and Engineering: A*, 373 (1-2) (2004) 294-302.
- [13] Suh, Y.C. and Lee, Z.H., *Scripta metallurgica et materialia*, 33 (8) (1995) 1231-1237.
- [14] An, J., Dong, C. and Zhang, Q.Y., *Tribology international*, 36(1) (2003) 25-34.
- [15] Fang, X. and Fan, Z., *Scripta materialia*, 54(5) (2006) 789-793.
- [16] Zhao, J.Z., Drees, S. and Ratke, L., *Materials Science and Engineering: A*, 282(1-2) (2000) 262-269.
- [17] Mohan, S., Agarwala, V. and Ray, S., *Wear*, 140(1) (1990) 83-92.
- [18] Rudrakshi, G.B., Srivastava, V.C., Pathak, J.P. and Ojha, S.N., *Materials Science and Engineering: A*, 383(1) (2004) 30-38.
- [19] Kotadia, H.R., Das, A., Doernberg, E. and Schmid-Fetzer, R., *Materials Chemistry and Physics*, 131(1-2) (2011) 241-249.
- [20] Rizzi, P., Habib, A., Castellero, A. and Battezzati, L., *Journal of Alloys and Compounds*, 509 (2011) 275-278.
- [21] Mittal, R. and Singh, D., *Transactions of the Indian Institute of Metals*, 67(4) (2014) 551-557.
- [22] An, J., Dong, C. and Zhang, Q.Y., *Tribology international*, 36(1) (2003) 25-34.
- [23] Carter Jr, W.T., Benz, M.G., Basu, A.K., Zabala, R.J., Knudsen, B.A., Jones, R.F., Lippard, H.E. and Kennedy, R.L., *JOM-e*, 51(4) (1999) 7.
- [24] Grant, P.S., *Progress in Materials science*, 39(4-5) (1995) 497-545.
- [25] See, J.B. and Johnston, G.H., *Powder Technology*, 21(1) (1978) 119-133.
- [26] Kaur, K. and Pandey, O.P., *Journal of Alloys and Compounds*, 503(2) (2010) 410-415.
- [27] Raghukiran, N. and Kumar, R., *Materials Science and Engineering: A*, 657 (2016) 123-135.
- [28] Mittal, R., Tomar, A. and Singh, D., *Adv. Mat. Lett.*, 3(1) (2012) 55-63.
- [29] Seok, H.K., Lee, J.C., Lee, H.I., Lee, H.C., Oh, K.H. and Ra, H.Y., *Metallurgical and Materials Transactions A*, 31(5) (2000) 1479-

- 1488.
- [30] Markus, S., Cui, C. and Fritsching, U., *Materials Science and Engineering: A*, 383(1) (2004) 166-174.
 - [31] See, J.B. and Johnston, G.H., *Powder Technology*, 21(1) (1978) 119-133.
 - [32] Wang, F., Zhang, J., Xiong, B. and Zhang, Y., *Materials characterization*, 60(5) (2009) 384-388.
 - [33] Jian, H.G., Jiang, F., Kang, W.E.N., Jiang, L., Huang, H.F. and Wei, L.L., *Transactions of Nonferrous Metals Society of China*, 19(5) (2009) 1031-1036.
 - [34] Wang, F., Xiong, B., Liu, H. and He, X., *Journal of Alloys and Compounds*, 477(1-2) (2009) 616-621.
 - [35] Shu, G., Ning, Z.L., Cao, F.Y. and Sun, J.F., *Transactions of Nonferrous Metals Society of China*, 19(2009)343-348.
 - [36] Bai, P., Hou, X., Zhang, X., Zhao, C. and Xing, Y., *Materials Science and Engineering: A*, 508(1-2) (2009) 23-27.
 - [37] Cai, Y., Liang, R., Hou, L. and Zhang, J., *Materials Science and Engineering: A*, 528(12) (2011) 4248-4254.
 - [38] Cai, Y.H., Liang, R.G., Su, Z.P. and Zhang, J.S., *Transactions of Nonferrous Metals Society of China*, 21(1) (2011) 9-14.
 - [39] Wang, F., Xiong, B., Zhang, Y., Liu, H., Li, Z., Li, X. and Qu, C., *Materials Science and Engineering: A*, 532 (2012) 100-105.
 - [40] Mazzer, E.M., Afonso, C.R.M., Galano, M., Kiminami, C.S. and Bolfarini, C., *Journal of Alloys and Compounds*, 579 (2013) 169-173.
 - [41] Srivastava, V.C., Huttunen-Saarivirta, E., Cui, C., Uhlenwinkel, V., Schulz, A. and Mukhopadhyay, N.K., *Journal of Alloys and Compounds*, 597 (2014) 258-268.
 - [42] Yu, H., Wang, M., Jia, Y., Xiao, Z., Chen, C., Lei, Q., Li, Z., Chen, W., Zhang, H., Wang, Y. and Cai, C., *Journal of alloys and compounds*, 601 (2014) 120-125.
 - [43] Jia, Y., Cao, F., Guo, S., Ma, P., Liu, J. and Sun, J., *Materials & Design*, 53 (2014) 79-85.
 - [44] Cava, R.D., Bolfarini, C., Kiminami, C.S., Mazzer, E.M., Botta Filho, W.J., Gargarella, P. and Eckert, J., *Journal of Alloys and Compounds*, 615 (2014) 602-606.
 - [45] Liu, B., Lei, Q., Xie, L., Wang, M. and Li, Z., *Materials & Design*, 96 (2016) 217-223.
 - [46] Li, H., Cao, F., Guo, S., Jia, Y., Zhang, D., Liu, Z., Wang, P., Scudino, S. and Sun, J., 2017. *Journal of Alloys and Compounds*, 719 (2016) 89-96.
 - [47] Li, H., Cao, F., Guo, S., Ning, Z., Liu, Z., Jia, Y., Scudino, S., Gemming, T. and Sun, J., *Journal of Alloys and Compounds*, 691 (2017) 482-488.
 - [48] Tomar, A. and Singh, D., *J. Powder Metall. Min*, 1(2) (2012) 1-4.
 - [49] Yu, F., Dwarakadasa, D.S. and Ranganathan, S., *Journal of Materials Processing Technology*, 137 (1-3) (2003) 164-167.
 - [50] Sharma, M.M., Ziemian, C.W. and Eden, T.J., *Materials & Design*, 32(8-9) (2011) 4304-4309.
 - [51] Basak, A.K., Celis, J.P., Vardavoulas, M. and Matteazzi, P., *Surface and Coatings Technology*, 206 (16) (2012) 3508-3516.
 - [52] Zhao, W., Cao, F., Gu, X., Ning, Z., Han, Y. and Sun, J., *Mechanics of Materials*, 56 (2013) 95-105.
 - [53] Schreiber, J.M., Omcikus, Z.R., Eden, T.J., Sharma, M.M., Champagne, V. and Patankar, S.N., *Journal of Alloys and Compounds*, 617 (2014) 135-139.
 - [54] Godinho, H.A., Beletati, A.L., Giordano, E.J. and Bolfarini, C., *Journal of Alloys and Compounds*, 586 (2014) 139-142.
 - [55] Zhao, Y., Wang, Q., Chen, H. and Yan, K., *Materials & Design* (1980-2015), 56 (2014) 725-730.
 - [56] Qu, Y.D., Su, R.M. and You, J.H., *Materials Today Communications*, 4 (2015) 109-115.
 - [57] Wang, Q., Zhao, Z., Zhao, Y., Yan, K., Liu, C. and Zhang, H., *Materials & Design*, 102 (2016) 91-99.
 - [58] Tomar, A., Mittal, R. and Singh, D., *International Journal of Minerals, Metallurgy, and Materials*, 21(12) (2014) 1222-1227.
 - [59] Tomar, A. and Singh, D., *J. Powder Metall. Min*, 1(2) (2012) 1-4.
 - [60] Yibin, Y., Yongan, Z., Baiqing, X., Feng, W., Hongwei, L., Zhihui, L. and Xiwu, L., *Rare Metal Materials and Engineering*, 43(12) (2014) 2974-2979.
 - [61] Müller, H.R., Ohla, K., Zauter, R. and Ebner, M., *Materials Science and Engineering: A*, 383(1) (2004) 78-86.
 - [62] Özcan, D., Bicen, H. and Aydar, C.M., *Procedia Social and Behavioral Sciences*, 15 (2011) 1.
 - [63] Mittal, R., Tomar, A. and Singh, D., *Journal of materials engineering and performance*, 23(3) (2014) 975-981.
 - [64] An, J., Dong, C. and Zhang, Q.Y., *Tribology international*, 36(1) (2003) 25-34.
 - [65] Wang, F., Ma, Y., Zhang, Z., Cui, X. and Jin, Y., *Wear*, 256(3-4) (2004) 342-345.
 - [66] Gui, M., Kang, S.B. and Lee, J.M., *Materials Science and Engineering: A*, 293(1-2) (2000) 146-156.
 - [67] An, J., Liu, Y.B. and Lu, Y., *Materials Science and Engineering: A*, 373(1-2) (2004) 294-302.
 - [68] Choudhury, S.K., Singh, A.K., Siva Ramakrishnan, C.S. and Panigrahi, S.C., *Wear*, 258(5-6) (2005) 759-767.
 - [69] Chen, Z., Teng, J., Chen, G., Fu, D. and Yan, H., *Wear*, 262(3-4) (2007) 362-368.
 - [70] Rudrakshi, G.B., Srivastava, V.C., Pathak, J.P. and Ojha, S.N., *Materials Science and Engineering: A*, 383(1) (2004) 30-38.
 - [71] Elmadagli, M., Perry, T. and Alpas, A.T., *Wear*, 262(1-2) (2007) 79-92.
 - [72] Reddy, B.V.R. and Kummitha, O.R., *Materials Today: Proceedings*, 4(2) (2017) 267-276.
 - [73] Kumar, S., Singh, R. and Singh, D., *Materials Today: Proceedings*, 5(2) (2018) 3486-3496.
 - [74] Goudar, D.M., Raju, K., Srivastava, V.C. and Rudrakshi, G.B., *Materials & Design*, 51 (2013) 383-390.
 - [75] Ojha, K.V., Tomar, A., Singh, D. and Kaushal, G.C., *Materials Science and Engineering: A*, 487(1-2)(2008)591-596.
 - [76] Mittal, R., Tomar, A. and Singh, D., *Journal of materials engineering and performance*, 23(3) (2014) 975-981.
 - [77] Chaudhury, S.K., Singh, A.K., Sivaramakrishnan, C.S. and Panigrahi, S.C., *Wear*, 258(5-6) (2005) 759-767.
 - [78] Wang, F., Ma, Y., Zhang, Z., Cui, X. and Jin, Y., *Wear*, 256(3-4) (2004) 342-345.
 - [79] Mittal, R. and Singh, D., *Transactions of the Indian Institute of Metals*, 67(4) (2014) 551-557.
 - [80] Rudrakshi, G.B. and Ojha, S.N., *Journal of Materials Processing Technology*, 189(1-3) (2007) 224-230.
 - [81] Rudrakshi, G.B., Srivastava, V.C., Pathak, J.P. and Ojha, S.N., *Materials Science and Engineering: A*, 383(1) (2004) 30-38.
 - [82] Chen, Z., Teng, J., Chen, G., Fu, D. and Yan, H., *Wear*, 262(3-4) (2007) 362-368.
 - [83] Dalke, A., Buchwalder, A., Zenker, R. and Spies, H.J., *Tribology Letters*, 67(1) (2019) 6.
 - [84] Santos, H.O., Kuniishi, C.T., Rossi, J.L. and Costa, I., *In Materials Science Forum*, 530 (2006) 126-131.
 - [85] Moore, K.L., Sykes, J.M., Hogg, S.C. and Grant, P.S., *Corrosion Science*, 50(11) (2008) 3221-3226.

- [86] Su, R., Su, J., Qu, Y., You, J. and Li, R., *Journal of Materials Research*, 32(13) (2017) 2621-2627.
- [87] Traldi, S.M., Costa, I. and Rossi, J.L., *Key Engineering Materials*, 189 (2001) 352-357.
- [88] Uozato, S., Nakata, K. and Ushio, M., *Surface and Coatings Technology*, 169 (2003) 691-694.