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A Review on Plasma Sprayed Al-SiC Composite Coatings

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Abstract

This review is done essentially to study results in the field of synthesis and characterization of SiC reinforced Al-SiC composite coatings using thermal spray process. SiC reinforced composite coatings produced by thermal spray process are being developed for a wide variety of applications, e.g. aerospace, automotive, structural and industrial. It is anticipated that, if properly deposited, Al-ceramic coatings could also provide improved properties like wear resistance and thermal barrier coatings. These results clearly demonstrate that the significant improvement in coating performance can be achieved by utilizing proper thermal spray conditions and SiC % in composite coatings. This paper presents a critical review on SiC reinforced Al-SiC composite coatings using thermal spray by various researchers in past years. The researcher's findings with necessary parameters for achieve good Al-SiC composite coatings are given.

Introduction

Al and its alloys are preferred as structural components due to their high strength to weight ratio. However, they have low wear, erosion and abrasion resistance which limit their use. For, many of the engineering applications where the wear and surface properties are critical than the strength of the component, a wear resistant surface coating on the steel substrates becomes an attractive alternative.

The deposition of Al/SiCp coatings have advantage of the surface properties of the composite, but it shows some problems such as heterogeneity, tendency to agglomeration of particles, porosity formation, low wettability of SiC particles by molten aluminium at low temperatures due to presence of a oxide film at the surface of the aluminum [1-2], and high reactivity between matrix and reinforcement at high temperature that would degrade the reinforcement phase [2-3] or tend to react and dissolve in molten aluminium at high temperatures [4-5]. Employing spraying processes, it is possible to obtain composite coatings with different reinforcements, but the percentage of reinforcements obtained in coating surface are usually limited [6]. Cold gas dynamic spray has been also used to obtain Al/SiCp composite coating with SiC contents varying from 10 to 20 vol.% [6-7], but resulting in cracking of many SiC particles as a result of the high pressure used and also the higher porosity in coating. Plasma spray has been a feasible way for producing coatings of aluminium matrix composites with low porosity and good reinforcement percentage in matrix. Excess SiC has to be added to compensate for the losses. But despite these additions, the volume fraction of SiC that can be obtained in the coating is still limited. This is attributed to the large differences in melting point between the SiC and the aluminum alloy and the poor wettability of SiC by aluminum. The other challenge in applying composite coating by plasma spraying is minimizing the effect of the heat generated by the process on the substrate being coated. However, the major problem for the production of good quality coating is to obtain the wetting of reinforcement (SiC) by the liquid metal, which is very poor [8-10], and is favoured by strong chemical bonding at the interface [8, 11]. The poor wetting is because of presence of an oxide film at the surface of the aluminum [8, 12]. To increase the quality of the coatings, it is usually required to use pre-processing methods like mechanical alloying [13].

This paper presents a critical review on SiC reinforced Al-SiC composite coatings using plasma spray process by various researchers in recent years. The researcher's findings with necessary parameters for achieve good Al-SiC composite coatings are given.

Background of Al-SiC System

Light metals like aluminum, titanium, magnesium are gaining use as structural materials in engineering components. Their low density combined with reasonable tensile strength and ductility has led to their extensive use in the field of aviation and automotive industries. Among these metals, the high strength aluminum alloys, namely the 2xxx series (Cu alloyed), 6xxx series (Mg, Si alloyed), and 7xxx series (Zn alloyed) are gaining popularity because of higher tensile strength than pure Al. One of the limitations of the high strength aluminum alloys is their relatively low elastic modulus compared to other structural alloy systems, e.g. steel and titanium alloys [14].

To overcome this problem, the metal matrix composites (MMC) were first used by the aerospace industry to obtain a higher Young's modulus and strength to weight ratio for the airframe structures [15]. The introduction of a ceramic phase as reinforcement in the form of particulate, whisker or fiber not only improves the strength of the material at room and elevated temperatures but also the wear resistance of the material. Among the various types of reinforcements such as oxides and carbides, the monocarbides of groups IV, V and VI metals like SiC and TiC

exhibit exceptional properties such as high hardness, wear resistance and melting point [16]. However, amongst these SiC having a density (d=3.2 g/cc) close to that of Al (d=2.7g/cc) is the most commonly used reinforcement. The insertion of these carbides in the ductile matrix improves the failure strength by deviating the propagating crack and increasing the crack path [17]. These enhance the elastic modulus and wear resistance of the material. However, the addition of the ceramic phase reduces the ductility of the material depending on the content of the reinforcement. The ceramic does not contribute much to the strength of the MMC in the high temperature range as these particles are usually too coarse (>3μm) to dispersion harden the material [18].

The amount of second phase that can be incorporated into the composite through the conventional routes of casting or powder metallurgy (PM) is limited by the wettability between the Al matrix and the second phase particle. The PM technique is also limited by the sinterability of the system [19]. Hence, the commercially available cast or sintered particulate composites usually have the content of the second phase limited to less than 30 vol% [20].

An additional problem is microstructural optimization of the MMC. For example, one of the main difficulties in producing an Al-based MMC through powder metallurgy is the tendency to agglomerate the reinforcement particles [20]. The primary reason for this phenomenon is the difference in size of the powders of the matrix and the second phase particles [15, 20]. The variation in interparticle distance between the second phase particles is directly proportional to the ratio of the matrix to reinforcement particle size. Development of static charge on the surface of the nonmetallic reinforcements leads to agglomeration of SiC in the Al matrix [15]. Moreover, ceramics have the best wear resistance but they reduce the ductility of and induce residual stresses within the Al component.

Owing to the above mentioned difficulties in obtaining a homogeneous microstructure of a composite, manufacturing a structural component out of MMC is not always economically viable. Hence, for the components where the tribological (wear resistant) properties are more critical than the structural strength, thermal sprayed coatings are preferred. The choice of the coating material for monolithic Al component depends on various factors. MMC coatings are desired as they retain the ductility of the core while providing a wear resistance. The WC/Co (tungsten carbide-cobalt) system, although most widely used MMC coating with high hardness and acceptable oxidation/corrosion resistance behavior, has drawbacks of its own. The high density of WC/Co (d ≈ 13.5 g/cc) does not make them optimal coatings for many of the lightweight aluminum structures (d ≈ 2.7 g/cc). Moreover the cost of using WC/Co coatings is relatively high, approximately US $500/m2 for a 250 μm thick coating with a 65% spraying efficiency [16]. Compared to this, the density of the Al-SiC coating systems have density of 2.7-3.2 g/cc, depending on the SiC content of the Al-SiC coatings and therefore costs 4 to 5 times less for the same volume and spraying efficiency.

Plasma Spray Process

Plasma Spraying is one of the most advanced thermal spraying method. In the process of plasma spraying, a non-transferred arc is used in the torches where the nozzle of the torch serves as the anode. Figure 1 shows a typical plasma torch with an axial powder feed. The nozzle has a diameter slightly smaller than the free burning arc. This constricted arc can have high current e.g. 1000 A at 80 V DC, and temperatures up to 15,000K. Gases passing through the arc are heated, dissociated, ionized and emerge from the nozzle as plasma with velocity greater than 300 m/s. Most devices use nitrogen, argon and helium with some addition of hydrogen which increases the plasma enthalpy and temperature.

This process with its medium to high velocity of spraying and high temperature of the plasma produces coatings with high bond strength. Further, the high spraying efficiency and deposition rate enable it to be used for coating large components.
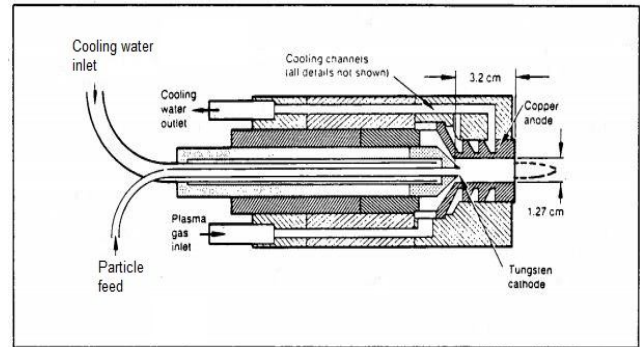

Figure 1: Schematic of an axial powder feed plasma torch.

Heat transfer from plasma jets to the entrained particles depends on the temperature history of the particles moving along their trajectories, on the heat transfer coefficient from the gas and on the gas enthalpy. The gas enthalpy is related to the atomic structure of the molecule. For example, in the case of diatomic molecules additional energy is obtained from the recombination of the dissociated molecules as well as the ions and electrons,

$$N_2 \longrightarrow 2N \longrightarrow 2N^+ + 2e^- \qquad (1)$$
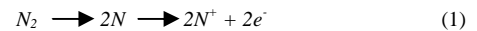
Under identical operating parameters the efficiency of a torch depends on the way powder is fed into the plasma jet. There are broadly two types of powder feeders available for the commercially used plasma torches. Radial Feeder has the powder fed at an angle (usually ninety degrees) to the direction of the plasma jet as shown in Fig. 2. For this type of torch, a careful adjustment of the carrier gas and plasma jet is required to ensure that the bulk of the injected powder stays within the plasma plume and is ultimately deposited. However, even with the best control, a spraying efficiency higher than 40 wt% of the fed powder is rarely obtained for radial fed torches [21]. In the case of an Axial Feeder, powders are injected along the axial direction, i.e. in the direction of travel of the plasma jet.
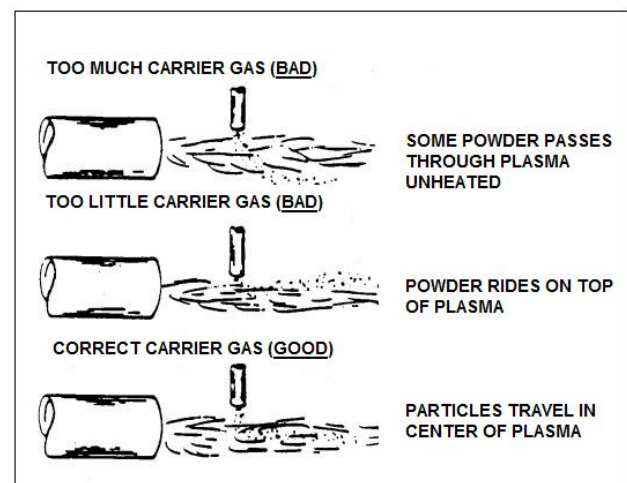

Figure 2: Effect of powder injection velocity in the plasma jet with radial feed [22].

This eliminates the negative effect of radial powder injection on laminar flow of plasma, resulting in lower turbulence in the free expanding plume outside the nozzle. Thus, it allows higher gas and particle velocity. The reduced turbulence allows a higher feed rate and spray rates are 100 to 200% higher than that achievable with

radial feeders. The nearly full entrapment of the powders within the plume allows deposition efficiency as high as 95% and coating costs are reduced by 50 to 60% compared to the radial feeders [21].

Plasma spraying is used to produce coatings for a variety of applications. They are mainly used as protective coatings to improve the wear and corrosion resistance of the material and in some cases to improve the optical, electronic/electrical or thermal properties. Wear and antifretting resistance is imparted to a material by applying a harder and more wear resistant material than the substrate. Corrosion resistance, especially in marine or other corrosive atmosphere is imparted by spraying an inert material, usually a ceramic, on the component.

Thermal barrier coatings are applied on high temperature components like in aircraft engines, where the metallic superalloy components are coated with a high temperature ceramic. This allows a higher operating temperature. Coatings of electrically conductive (e.g. Cu) or insulative materials usually ceramics, are applied on substrates to impart their respective electrical properties. Plasma sprayed coatings are often used to restore dimensions of worn out components and also in medical devices to make them inert. Thus, the use of plasma spraying can be classified in the following three categories [23]: manufacturing (e.g. automobiles), infrastructure repairs (e.g. paper mills and petrochemical industries) and high technology (e.g. aircraft). Depending on the use and properties required the type of materials to be sprayed are selected. The commonly sprayed materials and their uses are summarized in Table 1.

Table 1: Plasma sprayed materials and their uses [23]

Materials	Uses
Metals	
Aluminum	Surface Repair
Stainless Steel	Sliding Wear Resistance
Chromium	Corrosion Resistance
Titanium	
Cermets	Corrosion Resistance
WC-Co	Erosion Resistance
Ti-TiN	Sliding Wear Resistance
Al-SiC/ Al$_2$O$_3$	Spray Forming
Ceramics	
Cr$_2$O$_3$	Corrosion & Erosion Resistance
TiO$_2$	Sliding Wear Resistance
Al$_2$O$_3$	High Temperature Wear
ZrO$_2$	Thermal Barriers

The calculation of the economics of the process of plasma spraying is a complicated procedure and is done by considering the number of years the coating performs, the reduction in maintenance cost it provides, the reduction in scheduled or unscheduled down time, associated loss of production along with the improvement in the quality of the product being processed [24]. Frequently, in the case of thermal spray coatings, the substrate preparation (grit blasting) fixturing and tooling, and/or finishing of a coated component costs more than the actual coating itself. With all the above factors an approximate estimate of the commonly used coatings has been provided by Tucker [24], where the deposition cost of plasma sprayed coatings is found to vary between 0.002 and 0.05 $/($\mu$m cm^2). This value is dependent on the cost of the spraying powder, although, generally it is seen that the powders with higher initial cost has the least total cost when all the other factors are considered.

Role of powder processing

One important factor in obtaining a good plasma sprayed coating is the quality of the powder which is being used for spraying [25]. The uniformity of SiC in the matrix of the Al-SiC powder determines the spatial distribution of the reinforcement in the coatings. The shape and size of the particles determines the ability of the powder to flow. Compared to the commonly used processes for producing plasma sprayable composite powders- mechanical

blending, fusing and crushing, agglomeration, sintering and mechanical alloying (MA) has a few distinct advantages in producing Al-SiC composite powders [25-26]. Mechanical alloying is a high energy, dry milling technique which can produce composite metal powders with a uniform distribution of the reinforcing second phase particles [26-28]. Since the entire process takes place in the solid state, it can produce alloys that are otherwise impossible to produce by the conventional melting and casting or sintering techniques [25]. Thus, one of the most economical processes to obtain uniformly distributed reinforcements, greater than 30 vol%, is through MA. The reinforcements can be of particulate type or whiskers, and fibers and their sizes may vary from 5 to 100 μm [25-26, 29-30].

Coating Formation

Since coatings are formed by the impact of a stream of particles striking the substrate, the major factors which control the structure of a particular coating are the temperature, velocity and size distribution of the incident particles. The particle size is determined by the feed material but the velocity and temperature distributions depend, in a complex way, on the design and operating conditions of the plasma torch. Direct measurements of particle velocity and temperature distributions in a plasma torch have been related to the coating formation process [31]. Ideally, all of the incident particles which strike the substrate would be completely molten. Unmelted particles bounce off reducing the deposition efficiency and partly melted particles are incorporated within the deposit modifying its microstructure and properties.

When a spherical liquid droplet strikes a flat surface at high velocity, it flattens to a disc but the radially flowing thin sheet of liquid becomes unstable and disintegrates at the edges into small droplets. In the case of plasma spraying the substrate is at a temperature well below the melting point of the droplet and heat transfer to the substrate is rapid so that spreading and breakup of the droplet is interrupted by solidification. The individual particles are therefore equivalent to "splat quenched" material with a cooling rate of around 10^6 K s^{-1}. Classical heat transfer treatment of the cooling of a thin plate suggests that the interface structure is determined by a number of small distributed contact points within an effectively non-conducting film arising from entrapped gas [32]. The microstructure of plasma-sprayed coatings is thus related to the mechanism of formation through two predominant factors, the nature of the interfaces between individual lamellae, and the internal structure within lamellae produced by their rapid solidification.

The main Al-SiC coatings characteristics

### Surface morphology, composition and porosity

It is well-established that surface morphology plays a crucial role in the overall success of a coating-deposition. A number of investigations have been done to achieve best results. Some oxide phases like Al$_2$O$_3$ have been formed during coating deposition [33]. M. Gui et al. [34] have been reported that microstructure observation showed that the Al-SiC have a clear interface and intimate bonding, and no interfacial reaction products such as oxides; have been formed. Also EDS quantitative analysis showed a quite low oxygen level in the coating layer, indicating that oxidation reaction did not occur during plasma spraying.

M. Gui et al. [13] have been reported about porosity formation in their next investigation. They conclude that sprayed composite plates were formed through repeated plasma spray deposition, and consisted of a couple of sprayed layers. A pore in the composites may appear inside layer or be located at the border between two layers. As for the inside layer pore, it was formed due to the deficiency in the flow and filling of liquid Al. The surface of the sprayed layer was relatively rough. Pores would be formed in the layer interface when gaps on the sprayed surface cannot be filled or

compacted during next plasma spray deposition. The high porosity in the composites sprayed from Al-75SiC powders is related to inner-layer solidification and interlayer bonding characteristics. Due to more SiC particles in the sprayed composite of Al-75SiC powder than Al-55SiC powder, the flow and filling of liquid Al becomes difficult, resulting in the increase in the inner-layer porosity. In addition, the composite sprayed from Al-75SiC powder possesses larger stiffness; the filling of the spraying feedstock into the gaps on the sprayed surface becomes difficult, meanwhile the probable compaction of the gaps is also prohibited, which is created from local deformation because the high-speed feedstock clashes. These factors can result in higher interlayer porosity in the sprayed composite of Al-75SiC powder. The porosity in the sprayed composites may be reduced by a post-treatment process, such as hot isostatic pressure (HIP).

In later investigation M. Gui et al. [35] have been reported that the silicon phase was found in the sprayed composites (Fig. 3) and proposed the possible reactions as

$$3SiC + 4Al \longrightarrow Al_4C_3 + 3Si \qquad (2)$$
$$SiC \longrightarrow Si + C \qquad (3)$$
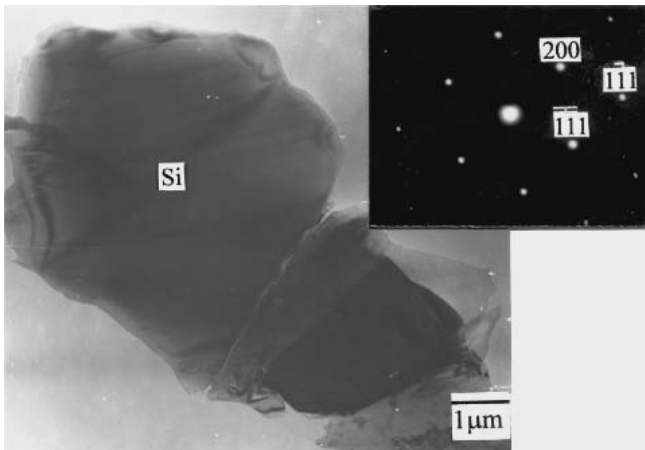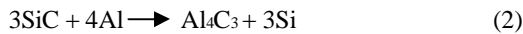
Figure 3: TEM image of the silicon phase and selected area diffraction pattern at a zone axis of [011] in the composite sprayed using Al-75SiC powder with high-input electrical power of 500 A and 70 V [35]

Eqn. 2 often occurs at the Al/SiC interface in the Al/SiC composites system, with reaction products Al4C3 and silicon. In Eqn. 3, SiC decomposes to solid carbon and liquid silicon. But in sprayed composites, no Al4C3 could be detected by XRD and TEM. Therefore, silicon should have originated from the decomposition of SiC. A significant characteristic of SiC is that it can withstand temperature to its decomposition point. The temperature of SiC decomposition depends on the crystalline grain structure and purity, so different values can be found. Temperatures of 3076 and 4175 °C, the temperature at which solid SiC decomposes, have been reported in different studies [36-37].

Liquid silicon, as one of the decomposed products, would solidify into the silicon phase or take part in the reaction with other elements in the feedstock to form compounds after the impact with the substrate. On the other hand, a carbon particle derived from the decomposition of SiC is in a much different situation. Due to the poor wettability of carbon and aluminum, plus the light mass, the small carbon particle is very difficult to deposit on composites. So, most carbon may be lost with the flame flow or may become a gas by a reaction in a plasma atmosphere (such as the reaction with hydrogen and oxygen). However, the carbon particle may still have been deposited, although the amount would be very limited so that it would barely be detected by XRD.

M. Gui et al. [2] have been reported that the thermal expansion coefficients of the sprayed layers in the transition zone are not sharply changed to those of the normal sprayed layers. Therefore,

the difference of the thermal expansion coefficients between the sprayed material and substrate in their border can be minimized. As a result, the residual stress caused by mismatch of the thermal expansion coefficients of the materials is reduced effectively, and the bond strength of the sprayed layer and the substrate is improved significantly. This effect is similar to that in plasma-sprayed gradient materials [38-39].

J. Rams et al. [40] has been reported that porosity in the Coatings with a sol–gel silica coated SiC reinforcement (Fig. 4) (up to 30 vol.%) about 1.0 vol.%. This can be explained because sol–gel silica coatings increase the wettability of the SiCp by molten aluminium [41-43] giving rise to a more continuous coating.
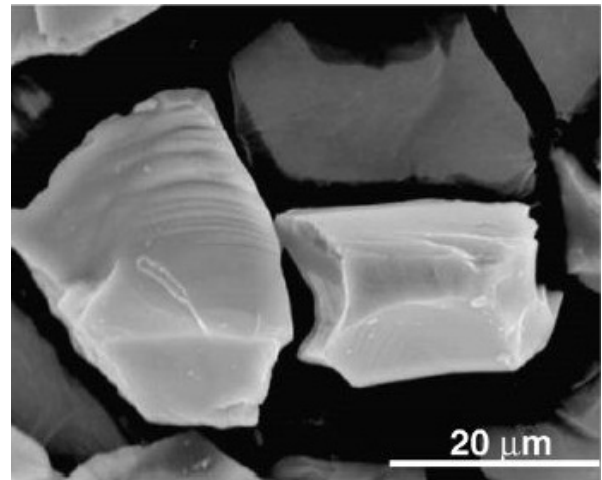
Figure 4: SEM images sol–gel coated SiC. [40]

The work done by N.N. Rammo [44] and his co-workers on Box–Wilson design that fixes the optimum spraying parameters of Al/SiC wt.% composition, substrate temperature and spraying distance. By employing the Box–Wilson design, N.N. Rammo et al. were able to achieve optimum spray conditions of the three coded variables at the expense of minimal real experimental trials, which otherwise would have consumed materials and time and end up to unacceptable number of trials to achieve optimization. Different optimum coded variables were found for hardness and adhesion that can be applied either to achieve high hardness or high adhesion strength depending on where the coat is used.

S. Tailor et al. [27-30] have been reported that MA has drastic effect on SiC distribution in Al matrix and its influence on Al-SiC composite coatings. S. Tailor and co-authors worked on SiC reinforced AlSi, 2014Al and 6061Al alloys. The porosity as 1-2% has been achieved successfully with uniform SiC distribution in the MA processed powder coatings. Further they have also proposed a mathematical model "Tailor-Chandra Model"[45] on energy transport during plasma spray process.

Adhesive properties

K. Ghosh et al.[33] found in their investigations that the adhesion strength of the coating was highest when Al substrates were used. Nickel showed the next highest average peel strength for a given composition of the powder, while stainless steel (SS) showed the lowest adhesion strength. Sexsmith et al. [46-49] obtained a correlation between the yield stress of the substrate and the peel strength obtained for a given coating material. A low yield stress allows an easier accommodation of the residual stress built up at the interface during spraying and thereby improving adhesion strength. Thus, the low yield stress of Ni, compared to that of steel is one probable reason for the high peel strength.

The variation in peel strength with SiC content and size was most noticeable with Al and Ni substrates. The peel strength

decreased with increase in SiC content and increased with the increase in SiC particle sizes for all the different substrates used in this investigation. This can be correlated to the changes in inter-particle distance, with increasing concentration and decreasing size of the SiC reinforcements. The decrease in the inter-particle distance reduces the area fraction of metal in contact with the substrate at the interface. Since metallic coatings have higher adhesion strength [47-49], the decrease in metal content at the interface reduces the peel strength of the composite. Moreover, since the Al in the MMC only melts during spraying, there is only mechanical bonding between the SiC particles and the substrates.

J. Rams et al. [40] have been reported that the incorporation of sol−gel silica coated SiC particles reduces the coefficient of thermal expansion of the composite coating and enhances its adhesion to the substrates more than when uncoated SiC particles were used. The CTEs measured on coatings made with sol−gel SiCp are about a 10% lower than those fabricated with SiCp. This indicates that stronger bonds that favour the load transfer between matrix and reinforcement were produced.

S. Tailor et al. [25, 29-30] have been reported the adhesion properties of AlSi-SiC, 2024Al and 6061Al-SiC and found exceptionally high adhesion strength. It was attributed as in general, cleaning and grit blasting is important for surface preparation. This provides a more chemically (diffusion) and physically active surface needed for good adhesion. The increased surface area leads to good bonding while the rough surface profile promotes mechanical keying. But in the present work MA feedstock powder was used which itself also is highly active due to increased surface area (flaky shape) and presence of high dislocation density in it. Also the plasma spraying coating was done at high current of 500 A leading to a high thermal energy input. Also there is possibility of formation of aluminium oxide and interaction with nickel present in the substrate. Both these reactions are exothermic reactions resulting in additional thermal energy input. All these factors lead to increased degree of diffusion resulting in high adhesion bonding. Micro-alloying between MA powder and substrate at the interface, during the spraying, may be the possible cause for this exceptionally high adhesion strength.

Wear properties

The use of coatings is one of the most effective strategies to protect materials against corrosion and to increase the wear resistance of materials. This allows developing components with optimized surface behaviours using cheaper or more processable materials, like mild carbon steel. Different coating alternatives of carbon steel can be seen in the literature: stainless steel [50], Mo, Cr–Ni y Cr–Mn [51], organic coatings [52-53], ceramic coatings [54-56],WC–Co [57], diamond reinforced composite coatings [58] and Al–MMC [59–63], among others. Aluminium matrix composites reinforced with ceramic particles have received considerable attention due to the combination of their tribological properties without sacrificing the corrosion resistance of aluminium alloys [64-65]. These composites are currently being developed for various applications, such as, pistons and cylinder liners in automotive engines [66].

SiC, B_4C, Al_2O_3 and TiC in the shape of particles are excellent reinforcement materials for Al–MMC, due to their high hardness and chemical and thermal stabilities, although carbides, in particular SiCp (SiC particles), tend to react and dissolve in molten aluminium at high temperatures [5, 67].

The deposition of Al/SiCp coatings take advantage of the surface properties of this composite, but it shows some problems such as heterogeneity, tendency to agglomeration of particles, porosity formation, low wettability of SiC particles by molten aluminium at low temperatures [68-69], and high reactivity between matrix and reinforcement at high temperature that would degrade the reinforcement phase [2-3]. To increase the quality of the coatings it is usually required to use pre-processing methods

like mechanical alloying [13] or post-processing ones like laser treatments [70]. Although the properties achieved are interesting, their main disadvantage is their high cost.

Most spraying processes allow obtaining differently reinforced composites, but the reinforcement rates obtained are usually below 20 vol.% [71]. Cold gas dynamic spray has been also reported to obtain Al/SiCp composite coating with SiC contents varying from 10 to 20 vol.% [71-72], but many SiCp cracked as a result of the high pressure used. Plasma spray and high velocity oxy-fuel (HVOF) processing are also feasible ways for producing coatings of aluminium matrix composites [69-70, 72], but these coatings were porous and required post-processing methods.

Hwang and Chung [73] suggested three possible mechanisms for the SiC to break loose from the surface: brittle fracture, pull out from the matrix, or subsurface ductile fracture in the Al alloy matrix and the SiC particles are carried away when the latter detaches. The load of 35 N was not high enough to cause brittle fracture of the SiC particles. Besides, the Al 6061 alloys show a good interface strength which makes them one of the most popular matrix alloys for particle reinforced Al composites [33]. Therefore, it is not likely that the SiC pulls out. The investigation of the abraded surfaces [33] under SEM (Fig. 5) indicates the subsurface fracture to be the dominant mechanism, which has been confirmed by K. Muller et al.[74]. Thus, with an increase in SiC particle size, the propagation of the subsurface fracture is limited, and this improves the wear resistance. Similarly, the increase in the volume fraction of the reinforcements results in increased deviation of the subsurface crack and improved wear resistance. The lower wear resistance is attributed as due to the reduced matrix content resulting in pullouts.

E. CELIK et al. [75] have been reported that addition of SiC with Al is very useful as Piston Alloys for Diesel Engine Motors. Compared to AlSi coatings, the beneficial effects of SiC particles in AlSi coatings were clearly shown in terms of wear properties.
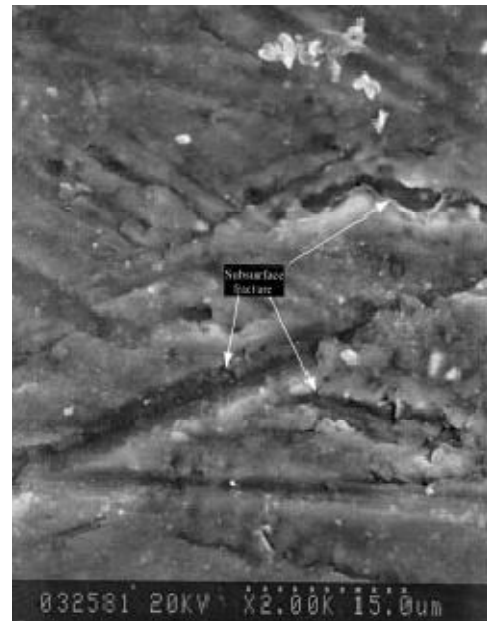
Figure 5: Abraded surface of Al-50SiC15 coating showing plastic deformation of the Al matrix. [33]

K. Ghosh et al. [33] have concluded in their investigations that Al-50 vol.%SiC coatings can improve the surface wear resistance of structural Al components without producing any significant change in the ductility of the component. The wear resistance of the coating was comparable to or better than the commercially available cast Al-20Al₂O₃ composites, thereby providing an alternative to the costly manufacture of structural MMC

components. Alternatively, the composites can also be used as a material for surface repair of worn structural MMC.

P. Rodrigo et al. [5] reported that the wear behaviour of these coatings has been tested using the pin-on-disk technique and the reinforced coatings provided 85% more wear resistance than uncoated ZE41 and 400% more than pure Al coatings. Friction coefficients were similar in all the tests; they increased slightly with the incorporation of the pure aluminium coating and reduced with the incorporation of SiCp into the coatings. This evolution can be due to the higher adhesion between alumina, used as counterbody, with aluminium than with Mg alloy. This was also favoured by the higher plastic deformation of the aluminium coating as a result of its lower hardness. The presence of SiCp reduced the adhesion between the ball and the coatings and also reduced the deformation of the coatings. The wear rate strongly changed with the use of coatings. The pure aluminium one suffered the highest wear rate which was 160% higher than that of the ZE41 substrate used. In spite of it, the pure aluminium coatings are frequently used to provide corrosion protection in industrial applications. The addition of SiCp to the coating reduced the wear rates by a strong amount, obtaining values that were 77% lower than those of the aluminium coating and 39% lower than those of the ZE41 substrate used. These values were similar for the as-sprayed coating with the lowest reinforcement rate used and for the two compacted coatings tested. The highest reinforced coating in its as-sprayed state showed wear rate similar to that of the ZE41 Mg alloy.

However, the presence of voids and independent splats in the coating may have favoured the initiation and propagation of cracks [76]. The plastification of the coating seems to be the responsible of the high wear values measured. Transference of material from the coating to the pin was also observed, indicating also the presence of adhesive wear mechanisms.

B. Torres et al. [77] studied the wear behaviour of Al-SiC coatings. Most requirements of the ASTM standard G133 [78] were followed for wear characterization. Elastic modulus and hardness values were evaluated following the Oliver–Pharr procedure [79] by averaging eight different indentation tests on each sample. Before the tests, the Berkovich diamond indenter was calibrated on a standard fused silica specimen. The wear resistance of the aluminium coatings was greatly enhanced by the incorporation of the SiCp reinforcement getting wear resistances that were up to 54% higher for 10N load. For high loads, i.e. 30 N, the wear resistance was more than 10 times higher. The wear resistance of the post-sprayed treated coatings was between 77% and 140% higher than that of as-sprayed composite coatings for all loads studied because of their higher mechanical properties.

However there are several examples of Al/SiC coatings deposited on magnesium substrates by various spraying technologies [80-83]. From the mechanical point of view, these coatings usually show higher hardness and wear resistance than unreinforced Al coatings or uncoated magnesium substrates. However, the presence of SiC reinforcement can decrease the corrosion resistance of the coating and facilitate the formation of brittle aluminium carbides during heat treatments [80].

S. Tailor et al. [25, 27, 29-30] have been studied wear properties of AlSi-SiC, 2024Al and 6061Al-SiC. The composite coatings display a significant improvement in wear resistance (>100%) by the addition of SiC particles in the matrix. The worn surfaces of the specimen and the debris generated were found to contain Al_2O_3 and Fe_2O_3. This shows a typical characteristic of oxidative wear. Therefore, the oxidation wear is a dominant wear mechanism in those composite coatings. This is not consistent with the observations on some other aluminum alloys [84-85] and aluminum based MMCs [86-87]. It has been reported that iron oxides have a low coefficient of friction [88], and therefore, lubricate the worn surface and reduce the wear rate.

On the other hand, some platelets in the debris and many dimples [which were formed of thin sheets (i.e., platelets)], were formed in the debris. The platelets in the debris must have been created due to subsurface crack formation and propagation in the specimen. Surfaces which are loaded repeatedly, even if they display some plastic deformation in the initial stages of their history, can generate patterns of subsurface protective stresses which are sufficiently strong to enable the applied loads to be carried entirely elastically in the longer term after many applications of the load cycle—they are said to shake-down [89]. Despite the alleviation of stress levels that this generates, surfaces that have shaken down can still wear subsequently by processes of surface fatigue or allied phenomena. Subsurface cracks may be nucleated at microstructural defects or inclusions in the material, giving rise to characteristic pitting fatigue generating wear or debris particles which are more or less equiaxed. Where the friction or traction forces are sufficient to deform the surface layer, material may be lost, in the form of thin flakes or platelets. In such delamination wear subsurface plastic shear is associated with the formation and propagation of cracks nucleating from pre-existing voids or inclusions present in the material structure [90-91]. The thickness of the wear sheet is controlled by the location of these subsurface cracks, and is typically of the order of a few microns. Therefore, the wear process of the composite coatings is consistent with delamination as well as of oxidative wear.

Conclusions

The 0, 10, 20, 30, 50 and 75wt% SiC-reinforced AlSi composite coatings were deposited on the various types of substrates through the atmospheric plasma spray system. The pre powder processing like mechanical alloying (MA) has drastic effect on powder properties as well as on coating properties. MA helps to achieve good mechanical properties via uniform distribution of SiC in the Al matrix. Coatings with a sol–gel silica coated SiC reinforcement increase the wettability of the SiC by molten aluminium giving rise to a more continuous coating. It has been found that the coating properties are also strongly depends on used plasma spray parameter during coating deposition. The minimum porosity of 1% has been achieved. The microhardness values of the coatings increased with increasing SiC content. Also, the wear results revealed that SiC particles increased the resistance against wear. The hardness values and the wear behaviour of the coatings strongly depend on porosity, oxidized, un-melted and semi-melted particles.

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