Research Article

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# The influence of powder feed rate on mechanical properties of atmospheric plasma spray (APS) Al-12Si coating

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**Abstract:** In this paper, structural and mechanical properties of APS - atmospheric plasma spray coating Al-12Si are presented. The aim of the research was the optimisation of the flow of powder to produce layers with optimal mechanical and structural properties that will be applied to the worn out parts of airplanes. Three groups of samples were produced, by utilising three powder feed rates: 30 g/min, 45 g/min and 60 g/min. Evaluation of layers' microhardness was done using $HV_{0.3}$ method and the bond strength was determined by testing of tensile strength. Surface morphology of the deposited powder particles was examined on SEM (Scanning Electron Microscope). The microstructure of the coating with the best measured mechanical properties was subsequently examined in etched condition on optical microscope and SEM (in accordance with the standard PN 585005, Pratt & Whitney). Also, fracture morphology of this coating in deposited state was examined using SEM. It was found that powder feed control with atmospheric plasma spraying can produce dense layers of Al-12Si coating with good bond strength.

**Keywords:** Atmospheric plasma spraying (APS), Al-12Si alloy microstructure, Hardness, Bond strength

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## 1 Introduction

The APS - atmospheric plasma spray process is used in many industries to improve the characteristics of components and extend their life span. This technological process is widely used for depositing eutectic and hypereutectic AlSi alloys that have found wide applications in the aerospace industry because of their high strength to weight ratio, excellent corrosion resistance and abrasion resistance, low thermal expansion coefficient and good casting properties, [1–3]. The presence of fine Si particles in the structure of AlSi alloys provides high strength and wear resistance of these alloys. The advantage of APS procedures for depositing AlSi alloys is in very high speed cooling of splats ($10^6$-$10^8$ K/s), which prevents grain growth and maintains the starting structure of the Al-12Si powder during coating deposition. In addition, higher density and improved cohesive strength can be achieved because of the influence of high temperature plasma. This procedure has found wide application in the automotive, petrochemical and other industries. The plasma spray process is one of the most flexible procedures for thermal spray coating and can be configured so that the spray particles have a wide range of temperature and velocity [4]. Fine powder particles are injected into the plasma gas flow and increase velocity due to the transfer of speed and temperature of ions to the powder particles. Under the influence of the substrate (after the spray has reached the surface), the particles are plastically deformed and bind to the substrate to form a coating. The process allows the deposition of a wide range of aluminium alloys and composite coatings [5]. The description of the atmospheric plasma spray process and its application is given in detail in [6–13].

A large number of different coating systems can be obtained by plasma spray coating process. Such systems can have different chemical composition, properties of layers (number, thickness, structure, porosity) and fabrication method [14–16]. Occurrence of cracks, during or after coating fabrication, can significantly decrease the quality of the coating. Having in mind the possible evolution of cracks and similar defects in the material, fracture and failure in different heterogeneous materials are analysed in the literature using a range of experimental, analytical and numerical techniques (examples can be found in [17–20]). More details on the influence of cracks in coatings and on bimaterial interfaces on the structural behaviour is given in [21–24].

Powder Metco 52C-NS is an aluminium alloy with 12wt.% Si. This material is for general purposes and is great for salvaging and repairing parts made of aluminium or magnesium and their alloys. Plasma sprayed coatings of Al-12 Si are mainly used for repairing worn parts of jet engines and restoring the size of parts in the process of overhaul and production of jet engines [25]. One of the main reasons for application of coating Al-12Si is its excellent resistance to abrasion. Clarke and Sarkar confirmed that the wear rate of cast binary AlSi alloys decreased with increasing Si content and was lowest for the eutectic alloy composition for various normal loads [26]. Pramila Bai and Biswas also observed that the addition of 4-24wt.% Si improves wear resistance of AlSi alloys [27]. Aluminium with 12wt.% Si is an eutectic system with a low melting point. Silicon reduces the melting temperature to 577°C while increasing fluidity, specific gravity and the thermal expansion coefficient. It also reduces contracting that is associated with solidification. The silicon present in the material is practically pure, and automatically increases the hardness of the produced coatings and improves wear resistance [28, 29]. Al-12Si powder produces coatings that are harder and denser than coatings produced from pure aluminium powder. For special purposes, other components are sometimes also added to powder Al-12Si, such as polyester and SiC, which reduce the friction coefficient of the coatings [6, 30]. Apart from the application of Al-12Si coating for salvaging expensive parts made of Al and Mg alloys in the aerospace industry, it is also used for repairing castings with excessive holes and cavities. Metco 52C-NS is Al-12Si powder atomized with inert Ar gas. The powder particles are regular spherical forms with density 1.3 g/cm$^3$. Powder particle size range of 45-90 μm with a melting point of 577°C is intended for use in plasma spraying [25]. Coatings Al-12Si have a lower melting temperature than pure Al coatings (660°C), therefore, the Al-12Si powder is more suitable for use on parts made of materials that are sensitive to temperature. Material Al-12Si produces coatings that are harder and slightly thicker than coatings of pure aluminium. The powder can be applied in a thickness > 2.5mm. Microhardness of coating Al-12 Si is in the range of 120-130 $HV_{0.3}$ with micropore content of 4-12 vol.%. The coating bond strength is 5-10 MPa [25]. AlSi powder microstructural characteristics are described in detail by a group of researchers in [31]. In the particles of AlSi powder in $\alpha$-Al solid solution, evenly spaced primary Si particles are present. With gas atomization of liquid molten AlSi alloy, the primary Si particles during solidification are evenly distributed in the base of $\alpha$-Al solid solution powder particles [31].

Coating Al-12Si has a dense lamellar structure with distinct inter-boundaries. The microstructure of the Al-12 Si coating in deposited state consists of two phases: $\alpha$-Al solid solution and $\alpha$ - Al + Si eutectic. Along the boundaries of $\alpha$-Al solid solution by dendritic solidification, fine eutectic grains of $\alpha$-Al + Si are uniformly formed.

In the microstructure, primary Si particles are also present, which are homogeneously distributed throughout the $\alpha$-Al + Si eutectic [32]. Due to the high cooling rate, fine Si particles are formed because of the lack of time for growth. The Si particles settle from the AlSi alloy with a very high degree of nucleation, which is attributed to rapid solidification of $10^3$-$10^5$ K/s in the deposition process [33].

The main objective of this study was to examine layers of Al-12Si coating deposited with three different powder feed rates: 30 g/min, 45 g/min and 60 g/min. This coating is intended for application to worn aviation parts made of Al alloys and exposed to a combination of corrosion and wear. Mechanical properties of the coating layers are analysed, and subsequent metallographic analysis is done on the coating with the best determined mechanical properties.

## 2 Materials and experimental details

Powder labelled Metco 52C-NS of the Sulzer Metco Company was used for the experiment, [25]. Alloyed aluminium powder with 12 wt.% Si was produced by atomization of liquid molten alloy Al-12Si with inert gas argon. The produced powder particles are spherical, which enables smooth flow of powder into the plasma stream. The range of grain sizes of the powder particles used in the experiment was 45-90 μm. Figure 1 shows the SEM - scanning electron micrographs of the morphology of Al-12Si powder particles.

For deposition of Al-12Si powder, the following equipment was used: atmospheric plasma spray system (APS) from the firm Plasmadyne and a plasma gun SG -100, which consisted of a cathode type K 1083-129, anode type A 2084-145 and a gas injector type GI 2083 -113. As an arc gas, Ar was used in combination with He and power of 40 KW. The Al-12 Si powder feed rate (g/min) was the main

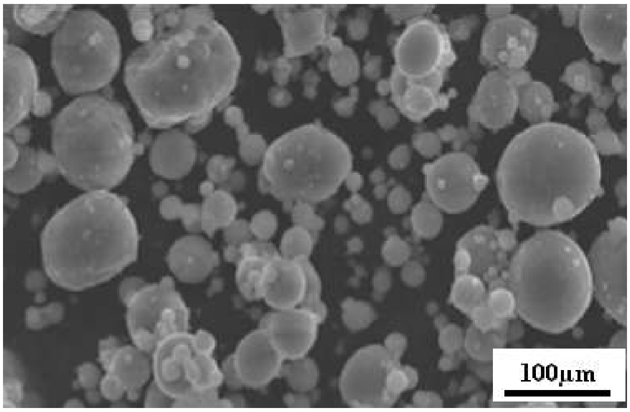


**Figure 1:** (SEM) Scanning electron micrograph of Al-12Si powder particles

varied parameter for powder depositing. The experiment involved three powder feed rates: 30 g/min, 45 g/min and 60 g/min. Powder feed rate is one of the most important parameters that affect the quality of the coating, which is directly related to cohesion strength, microhardness and adhesion of coating. With high powder feed rates, the particles do not have enough time to completely melt, leading to an increase in the share of partially molten particles and pores in the coating layers. Partially molten powder particles, together with pores, reduce the cohesive and adhesive strength of the coating. With a lower powder feed rate, the particles are completely melted and uniformly plastically deformed due to the interaction with the substrate; also, they bind with the substrate with a smaller share of pores. Detailed values of plasma spray parameters are shown in Table 1.

**Table 1:** Plasma spray parameters

| Deposition parameters | Values |
|---|---|
| Plasma current, I (A) | 800 |
| Plasma Voltage, U (V) | 32 |
| Primary plasma gas flow rate Ar (l/min) | 47 |
| Secondary plasma gas flow rate He (l/min) | 12 |
| Carrier gas flow rate (l/min) | 6 |
| Powder feed rate (g/min) | 30/45/60 |
| Stand-off distance (mm) | 80 |

Before depositing the powder, the surfaces of the substrates are made coarse using corundum $Al_2O_3$ with particle size of 0.7 - 1.5 mm. The coatings were deposited with a thickness up to 0.35 mm.

Investigation of mechanical and structural properties of coatings was performed according to Pratt & Whitney standard [34]. The bases on which the Al-12Si coatings were deposited for micro hardness testing and evaluation of microstructure in deposited condition were made of aluminium alloy AMS4117 (AlMg1 EN5005) measuring 70 × 20 × 1.5mm. The bases for testing the bond strength were also made of aluminium alloy AMS4117 (AlMg1 EN5005) size ⌀25 × 50mm [34]. Microhardness testing of Al-12Si coating layers was done using $HV_{0.3}$ method and the bond strength was determined by testing tensile properties. Microhardness measurement was done in the direction along the lamellae. Five readings of the values were performed, in the middle and at the ends of the samples, which were averaged. Bond strength testing was done at room temperature with a strain rate of 1 cm/min. For each group of samples, three specimens were examined. The morphology of Al-12Si powder particles was examined by scanning electron microscopy (SEM). Microstructure of the best Al-12Si layers (best measured mechanical properties) in deposited state was tested using the (OM) optical microscope. The coating with the best features was examined in etched condition using the (OM) optical microscope and the scanning electron microscope (SEM). Coating etching was done using Keller's reagent (5 ml $HNO_3$, 3 ml of hydrochloric acid, 2 ml HF and 190 ml $H_2O$). The morphology of fracture of the best layers of Al-12Si coating in deposited state was examined with a SEM.

## 3 Results and discussion

The microhardness and bond strength values of deposited Al-12Si coatings, depending on powder feed rate, are shown in Figures 2 and 3. The microhardness values of the layers were directly related to the powder feed rates. The microhardness values and bond strength of the de-

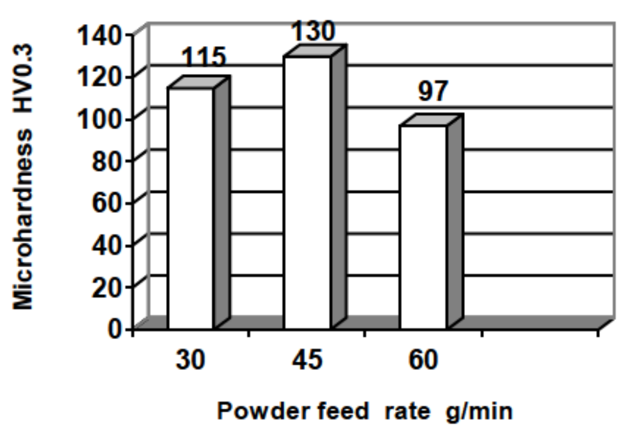


**Figure 2:** Microhardness of Al-12Si layers

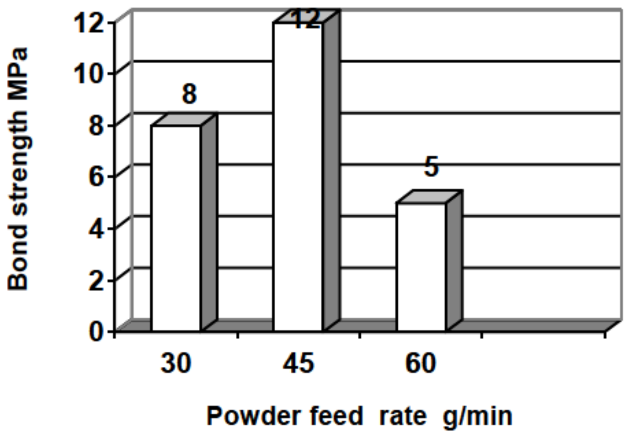


Figure 3: Al-12Si layers' bond strength

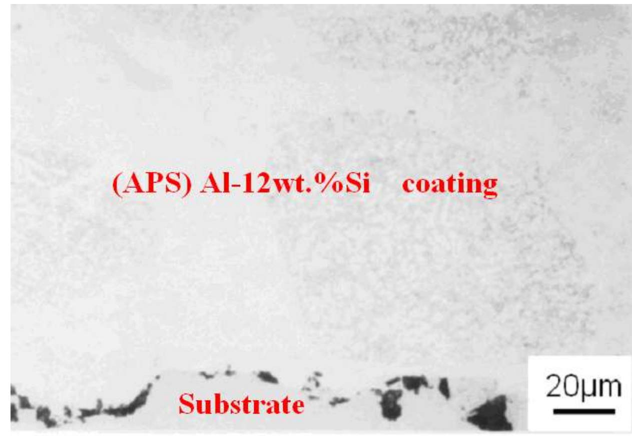


Figure 4: (OM) Al-12Si coating microstructure deposited with powder feed rate 45 g/min

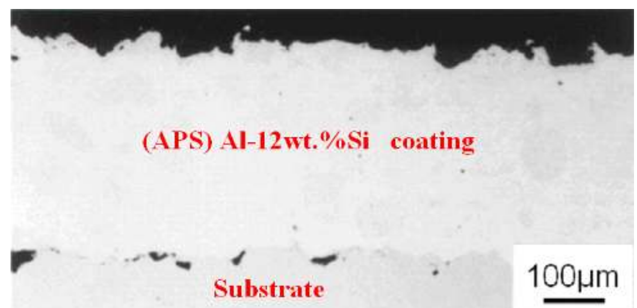


Figure 5: (OM) Al-12Si coating microstructure deposited with powder feed rate 45 g/min

posited Al-12Si layers were significantly influenced by the powder feed rates. Only layers deposited with the powder feed rate of 45 g/min had microhardness values in the specified range (120 - 130$HV_{0.3}$) [25] - this was the highest microhardness value (130$HV_{0.3}$) among the examined specimens. These layers have an adequate microstructure with dense packing of splats on one another, and with a low level of pores, as confirmed by metallographic examination. The lowest microhardness value of 97$HV_{0.3}$ is obtained for the layers with the highest amount of pores which were deposited with the highest powder feed rate of 60 g/min. The microhardness of these coatings is much lower than the value set by the manufacturer of the powder [25]. Higher powder feed rate caused less efficient melting of the powder particles and less efficient packing on one another with higher content of inter-lamellar pores.

Bond tensile strength was directly related to the powder feed rate of Al-12 Si. The highest value of bond strength of 12MPa is obtained for the layers that had the highest microhardness value. Those are layers deposited at a powder feed rate of 45 g/min. The lowest value of bond strength of 5 MPa is obtained for the layers deposited with the highest powder feed rate of 60 g/min, which also had the lowest microhardness value. Measuring of the bond tensile strength showed that, for all three powder feed rates, obtained bond strength values were within or above the range of 5-10 MPa as set by the powder manufacturer [25]. The failure mechanism for all of the deposited coatings was adhesion at the interface between the substrate and the Al-12 Si coating.

Figures 4 and 5 show (OM) micrographs of Al-12Si layers deposited with a powder feed rate of 45 g/min, which had the best measured mechanical properties.

Qualitative analysis of Al-12Si coating showed that the layers were deposited on the substrate continuously without interruption and without the presence of micro-cracks at the interface. At the interface between the coating and the substrate, remnants of corundum are visible, from coarsening which did not significantly affect adhesion. The layers are dense and homogeneous with a very small amount of pores, below 1%. In the layers, there are no unmolten particles or precipitates. Through the deposited layers, there are no observed microcracks. Micrograph in Figure 4 shows a two-phase structure which is not clear in polished condition and that is why etching was done.

The (OM) micrograph in Figure 6 shows the microstructure of Al-12 Si coating in etched condition. The coating structure is lamellar, well connected to the substrate. In the microstructure of the coating, two phases can be observed, one of which is light coloured and the other is dark coloured [32]. The dark coloured phase is $\alpha$-Al solid solution, in which there is evenly formed eutectic $\alpha$ - Al + Si phase of a light white colour [32]. For a better view of phase distribution in the microstructure, Figure 7 shows a SEM micrograph of an etched coating deposited with a powder feed rate of 45 g/min.

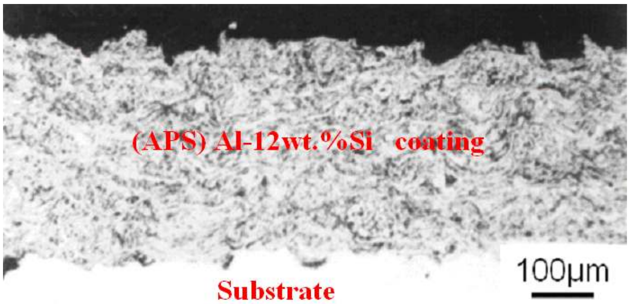


**Figure 6:** (OM) Etched Al-12Si coating microstructure deposited with powder feed rate of 45 g/min

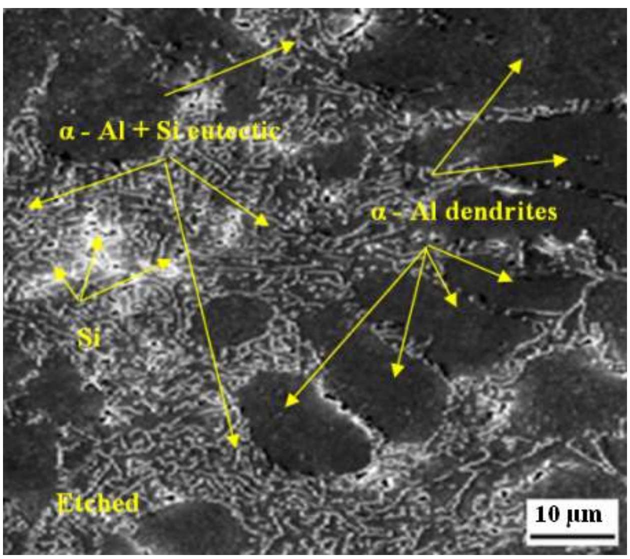


**Figure 7:** (SEM) Etched microstructure of the Al-12Si coating: α-Al dendrites, α-Al + Si

The SEM micrograph shows that the Al-12Si coating has a dense and homogeneous microstructure. The coating base is made of α-Al solid solution, which contains α - Al + Si eutectic grains [32]. By dendritic solidification of α-Al solid solution, at the α-Al grains boundaries, fine eutectic α - Al + Si grains are uniformly formed. In the microstructure of the eutectic α - Al + Si, fine primary, light white colour Si particles are present. The Si particles are clearly visible in the eutectic α - Al + Si, and are distributed homogeneously throughout the eutectic [32]. Due to the high cooling rate, Si particles are fine; they do not have enough time to grow. From the molten liquid of melted Al-12Si alloy particles, Si particles are deposited with a very high degree of nucleation, which is attributed to rapid solidification of $10^3$-$10^5$ K/s in the deposition process [33]. By etching of coating, the Al dissolved from the α-Al solid solution and the α-Al + Si eutectic, while the Si remained elevated above the solid solution. This is the reason why Si crystals in the eutectic are light white coloured and the dendrites in the α-Al solid solution are black.

Figure 8 shows a SEM micrograph of fracture of Al-12Si coating layers deposited at a powder feed rate of 45 g/min.

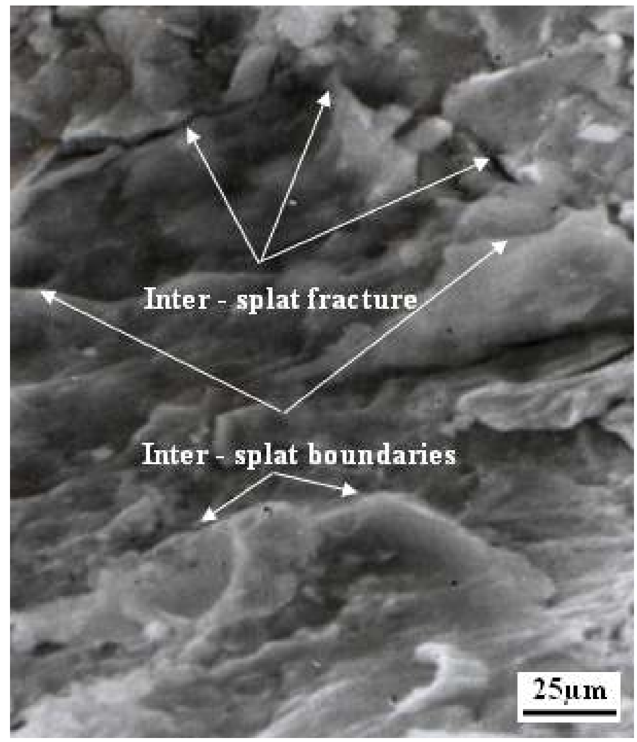


**Figure 8:** (SEM) fracture morphologies of Al-12Si coatings deposited with powder feed rate of 45 g/min

Fracture surface of Al-12 Si coating shows a compact structure with layered deposited splats. Inter-splat boundaries are visible in places where deformation occurred during fracture. On the micrograph, two fracture phenomena are seen, that is, between the deposited splats and within the deposited splats.

During the fracture, the crack usually runs between the deposited splat boundaries, where the connection is weaker, rather than through the Al-Si grain boundaries in each deposited splat. For fractures within the deposited splats, because of the nature of fracture, the crack is always positioned along the boundaries of the eutectic Al-Si grains with dendrites of the α-Al solid solution. This mechanism requires much higher strain than in the case of fracture between deposited splats. Thus, Figure 8 shows the better mode of Al-12Si coating fracture, which took place between deposited splats during fracture.

The highest values of microhardness and bond strength were found in the layers deposited with the powder feed rate of 45 g/min; these layers did not have coarse pores, unmelted particles or semi-molten particles in the microstructure, as shown by subsequent metallographic examination. Good inter-lamellar bonding of the lamellae in the deposit increases the value of microhardness and fracture toughness, which is in agreement with the mechanical testing of coatings. Since the presence of pores, unmelted particles and oxides is directly related to the values of the microhardness of coatings and bond strength, the measured values of the coating deposited with the powder feed rate of 45 g/min indicate that their share is the lowest in this coating. Lower and higher powder feed rates caused less efficient melting of the powder particles and less efficient packing on one another, which results in worse mechanical properties.

For the lowest feed rate, the particles are melted very rapidly; their surface evaporates, hence the particles are unable to form a good connection with the substrate. The edges of the disks are breaking, and fractured ends remain in the coating as precipitates, which decrease the mechanical properties of the coating. For the highest powder feed rate, the particles are not completely melted, and they are deformed in the shape of a half-disk, which leads to a high content of micro-pores, which also diminishes mechanical properties.

## 4 Conclusions

In this study, Al-12Si coatings were deposited using atmospheric plasma spraying, with a powder feed rate of 30, 45 and 60 g/min. Analysis of the mechanical properties and microstructure of the coatings in deposited state lead to the following conclusions.

Microhardness and joint strength of Al-12Si coatings were dependent on the powder feed rate of the deposition process. Layers with the best mechanical properties were obtained with a powder feed rate of 45 g/min. In accordance with the standard PN 585005, Pratt & Whitney, these layers were subjected to metallographic examination. It is determined that they are homogeneous and dense with a pore share below 1%, which gave them the highest values of microhardness and joint strength.

The structure of the Al-12Si coating layers is lamellar, consisting of $\alpha$-Al solid solution which includes $\alpha$ - Al + Si eutectic grains. Along the $\alpha$-Al grain boundaries, fine $\alpha$-Al + Si eutectic grains are evenly formed. In the microstructure of $\alpha$ - Al + Si, eutectic fine primary Si particles are present. In the etched microstructure of Al-12 Si coating, $\alpha$-Al solid solution is black and the Si crystals in the eutectic are light white coloured.

Fracture surface of Al-12Si coating shows a compact structure with layered deposited splats. The crack usually runs between the boundaries of deposited splats, where the connection is weaker than through the boundaries of Al-Si grains in each deposited splat. In fractures within the deposited splats, the fracture runs along the boundaries of the Al-Si eutectic grains with $\alpha$-Al solid solution dendrites. Fracture mode was favourable during fracture of Al-12Si coating - it took place between the deposited splats.

Obtained results showed that Al-12 Si powder feed rate during the deposition process affects the mechanical properties and microstructure of the coating layers. Coatings tests confirmed that the best layers are those deposited at the powder feed rate of 45 g/min.

Using Al-12Si coating, deposited at a powder feed rate of 45 g/min in repair of Al alloy aviation parts which were exposed to a combination of corrosion and wear significantly improves the work efficiency and reliability of parts in operation and significantly reduces repair costs.

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