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Flame Sprayed Al-12Si Coatings for the Improvement of the Adhesion of Composite Casting Profiles

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In this study, flame sprayed Al-12Si coatings were produced on the surface of inlays (aluminum profiles) of composite castings parts. The aim was to enhance the strength between the joining partners inlay and cast. Due to the high surface roughness and the presence of pores in the coatings, combined with the formation of an intermetallic phase at the interface, the adhesion of flame sprayed inlays could be enhanced by a factor of 2 compared to blank inlays and by a factor of 1.3 when compared to sand-blasted inlays. However, results also show that gaps are present, mostly at the interface between the inlays and the flame sprayed coatings, and these gaps have a negative effect on the joining strength of the composite casting parts. Therefore, optimizing the adhesion of the coating on the Al profiles via an improvement in both the sand-blasting and the flame spraying parameters would be beneficial for further enhancement of the adhesion of composite casting parts.

Keywords aluminum composites, fatigue and fracture, flame spray, influence of properties

1. Introduction

One important advantage of thermal spray processes is the possibility of using lightweight substrates with specially optimized surface properties. For instance, today thermal spray processes are widely used in industry to protect the underlying substrate against a wide range of attacks: wear, corrosion, erosion, high-temperature, electrical current, and so forth (Ref 1-8). By adequately optimizing the spraying parameters, the coating properties can be tailored to meet the application requirements. However, various new fields of application for thermal spray processes, for example in joining of different materials, are gaining widespread recognition (Ref 9).

Flame spraying is one of the oldest, least expensive, and easiest thermal spray process used to produce coatings. In this technique, oxygen and acetylene are used to produce a flame having a temperature of approximately 3000 °C, in which the coating material to be sprayed is injected.

A major disadvantage of the flame spray process is its relatively low particle speed, which accounts for relatively high surface roughness and porosity values in the sprayed coatings compared to other thermal spray processes. However, in the present study, this is considered an advantage since a rough coating surface enables the anchoring of the fluid metal and a highly porous coating can eventually be impregnated by the liquid metal. Thus, it is assumed that both surface roughness, and porosity may contribute to an increase in the adhesion of the components during composite casting.

This article reports preliminary results on aluminum-magnesium (Al-Mg) compound cast joinings, where the solid aluminum part was flame sprayed with Al-12Si to enhance the interface properties of the cast part.

2. Materials and Experimental Procedure

2.1 Aluminum Profile

The aluminum profiles used for these composite casting experiments were made of EN AW 6060 wrought Al alloy. This alloy was chosen because it is one of the most often used alloys for producing profiles in the extrusion industry due to its extraordinary ability to deform plastically and its good machinability and weldability.

As shown in Fig. 1, the Al alloy profiles were rectangular, with dimensions of 25 × 25 × 55 mm, and the wall thickness was 4 mm.

To investigate the effective adhesion enhancement produced by using flame sprayed coatings, a total of three

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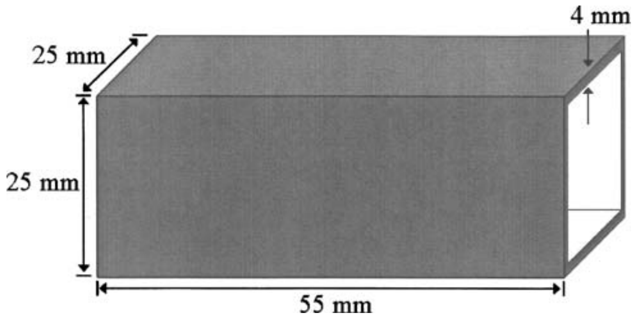

Fig. 1 Geometry of the Al alloy profiles

different Al part surface treatment procedures were compared:

- Blank (no treatment, reference samples)
- Sand-blasted
- Flame sprayed Al-12Si coatings

On the blank samples, no further treatment was performed except for cleaning and degreasing the surface with alcohol before performing the casting experiments. For the sand-blasted samples, the procedure consisted of sand blasting all four surfaces using a standard blasting device with an air pressure of 5 bars and a standoff distance of approximately 15 cm. Following this surface roughening, the parts were cleaned and degreased using alcohol before the casting experiments were performed. The procedure used for the flame sprayed samples is described thoroughly in the following section.

2.2 Flame Spraying

Al-12Si powder was used to produce the flame sprayed coatings. This powder was produced using a gas atomization process, and therefore it featured a spheroidal morphology. Its size distribution was −90 +45 μm.

For the flame sprayed samples, the procedure consisted of sand blasting a 30 mm long section on each of the four profile surfaces, followed by the aforementioned cleaning procedure. The sand blasting of only a 30 mm long section of the profiles was based on the fact that the overlapping length of the casting on the Al profiles in the ceramic form is equal to 30 mm, and therefore there is no need to sand blast the entire profile length. Due to the high affinity of aluminum and its alloys for forming a thin oxide film on their surfaces, no preheating of the samples was performed before the spraying process. In addition, the spraying procedure was initiated as soon as possible (<2 min) after the sand-blasting procedure to minimize the oxidation of the profiles surfaces. The 30 mm long sand-blasted sections of the Al profiles were then sprayed in an *x-y* pattern using a robot. A total of 10 Al profiles were simultaneously flame sprayed; the flame spray parameters used are listed in Table 1.

During the spraying of the profiles, two air compressors were used to cool down the sprayed samples and prevent any surface overheating. After the first side of the Al profiles was sprayed, the spray gun was stopped and the 10 Al samples were manually turned by 90° to expose a new uncoated surface, and the spray procedure was repeated. This was performed until all four sides of the Al profiles were coated. Successfully flame sprayed Al-12Si coatings with a length of 30 mm on Al profiles are shown in Fig. 2.

Table 1 Flame spray parameters used for the production of the Al-12Si coatings

Spray parameter	Value
Oxygen flow rate, L/h	1415
Acetylene flow rate, L/h	880
Powder flow rate, g/min	38
Standoff distance, mm	65
Horizontal speed, m/min	30
Vertical step, mm	8
Number of layers	4
Coating thickness, μm	250-275

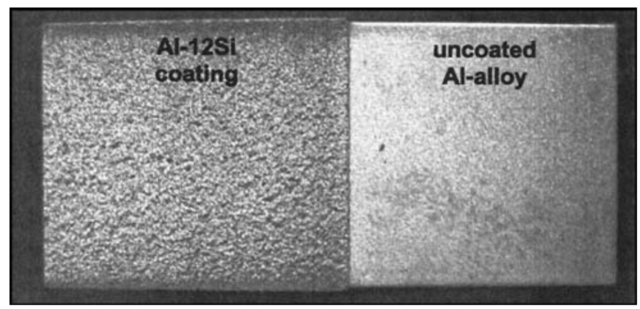

Fig. 2 Flame sprayed Al-12Si coatings on Al profiles with a coating overlapping length of 30 mm

2.3 Composite Casting

The magnesium alloy used for the casting experiments was AZ91-F. The identification label AZ shows that aluminum and zinc are the main alloying elements, and the label F tells us that the alloy did not undergo any further heat treatments following the casting process. This alloy exhibits high strength in the as-cast condition, but at elevated temperatures its strength and creep resistance are rather moderate compared to aluminum alloys.

The casting experiments were performed using a squeeze casting equipment. The casting process is quite similar to the classic die-casting process: a small defined melt quantity is inserted into the casting chamber, and then a hydraulic piston pushes the melt into the cavity with high pressure and speed. The filling of the cavity occurs in a laminar manner. Prior to the casting experiments, the Al alloy profiles with their different surface treatments (blank, sand blasted, or flame sprayed) were installed in a ceramic casting form. To prevent or to minimize Mg infiltration into the ceramic form, which can cause severe adhesion problems and prevents the cast parts from being released from the form, a special procedure was performed, the description of which is beyond the scope of this paper and is not described here (Ref 10).

Figure 3 shows the ceramic form with the glued Al alloy profiles before its installation in the squeeze-casting machine and the composite casting parts after their release from the casting form.

Before performing any tests or characterization, the composite casting parts were cleaned and separated from the overcast material. Thus, for each part, two composite casting test samples were obtained.

2.4 Tensile Testing

In order to quantify the adhesion strength of the composite castings interface, quasi-static tensile tests were performed using a Zwick tensile testing machine. Due to the chosen samples geometry, the tensile tests could be performed without designing and deploying an additional sample holder, but rather by placing the composite casting samples directly in the clamp devices of the tensile testing machine. During tensile testing, the applied force and the displacement of the machine were recorded. The tests were stopped when the Al alloy profiles were pulled out of the Mg castings, and the maximal force was defined as the interface adhesion strength.

2.5 Samples Characterization

The characterization of the interface of the composite casting samples for each surface treatment variation (blank, sand blasted, or flame sprayed) was performed using optical microscopy. The composite casting samples were prepared using standard metallographic procedures to characterize the following features:

- Interface between the Al profile and the Mg cast (blank and sand-blasted samples)
- Interface between the Al profile and the flame sprayed coating (flame sprayed samples) before and after the casting experiments
- Interface between the flame sprayed coating and the Mg-cast (flame sprayed samples) after the casting experiments
- The coating microstructure (flame sprayed samples) before and after the casting experiments.

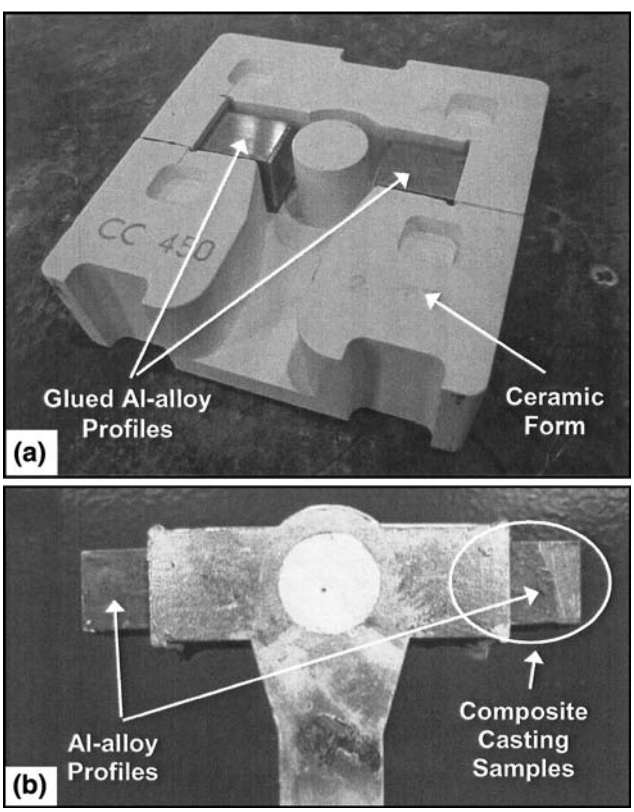

Fig. 3 Ceramic form with the glued Al alloy profiles before its installation in the squeeze casting machine (a) and the composite casting parts after their release from the casting form (b)

3. Results and Discussion

3.1 Profile Surface Characterization Prior to the Casting Experiments

In this section, the surface properties of the different profiles (blank, sand blasted, and flame sprayed) before the casting experiments are presented.

3.1.1 Blank Profile Surface. The topography measurements using a bifocal microscope provided a value of approximately 1 μm (average of three independent measurements) for the average surface roughness.

3.1.2 Sand-Blasted Profile Surface. The topography measurements using the same equipment and procedure as described previously for the blank profiles gave an average surface roughness of 5.7 μm.

3.1.3 Flame Sprayed Profile Surface. Figure 4 shows a cross-section micrograph of the flame sprayed Al-12Si coating on the Al-alloy profile surface before the casting experiments. The coating microstructure is laminar with

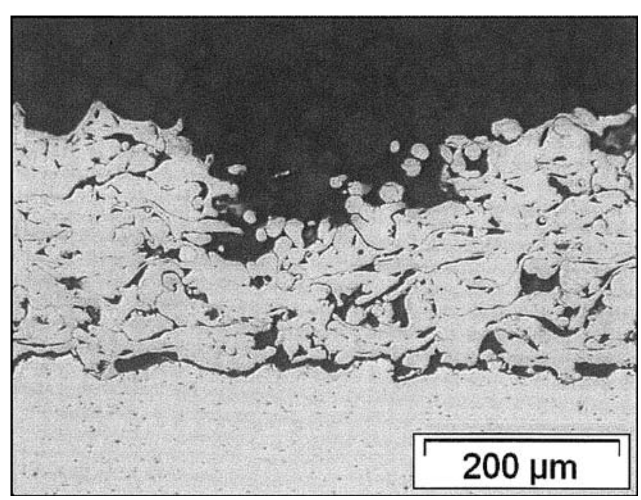

Fig. 4 Cross-section micrograph of the flame sprayed Al-12Si coating on the Al alloy profile surface

unmelted particles (round white particles), pores (black areas), and embedded oxides between Al-12Si splats (tiny lines) and is typical of thermally sprayed coatings. The average coating thickness is approximately 300 μm. The surface of the flame sprayed samples is much rougher than the surface of the sand-blasted profile, and the average of the surface roughness measurements is about 20 μm, which is three to four times higher than the value measured for the sand-blasted surface profile.

3.2 Profile Surface Characterization after the Casting Experiments

In this section, the surface properties of the different profiles (blank, sand blasted, and flame sprayed) after the casting experiments are presented.

3.2.1 Blank Profile Surface. Figure 5 shows a cross section of a composite casting blank profile. The overall interface between the blank profile and the casting is good. For example, it was observed that the corners of the profile are very well bonded to the casting, but as shown in Fig. 5, at larger distances from the corners, a gap at the interface can be observed and its maximum width, which is approximately at the centre of the profile, is equal to about 2 μm.

The gap is believed to have been initiated during the cooling stage of the casting process, due to different cooling rates of the Al and Mg parts, which induces tensile stresses and may result in interface delamination.

Figure 6 shows the diffusion zone present between the blank profile surface and the Mg casting on the inner side, where no gap was present. The top right-hand corner of Fig. 6 is the Mg casting, and the low left-hand corner is the blank profile. It can be easily measured from Fig. 6 that the diffusion zone has a total thickness of approximately 100 μm. The elemental distribution measurement shown in Fig. 7 shows that the concentration of both elements decreases constantly with the distance from their respective sources and that two different phases exist, one of which has an interlocked needle structure. However, no major differences in the phase composition could be identified between the two zones. One of these phases is believed to be $Al_{12}Mg_{17}$ (γ-phase), which is an intermetallic phase and solidifies at a temperature far below Al and Mg and is believed to be also an initiator for the formation of the gap at the interface.

3.2.2 Sand-Blasted Profile Surface. Figure 8 shows micrographs of the cross section of a composite casting sand-blasted profile. A diffusion zone, which is present along the total length of the profile interface, has been identified and no gaps are observed, verifying good adhesion between the sand-blasted profile and the Mg casting. However, pores and oxides are embedded in the diffusion zone.

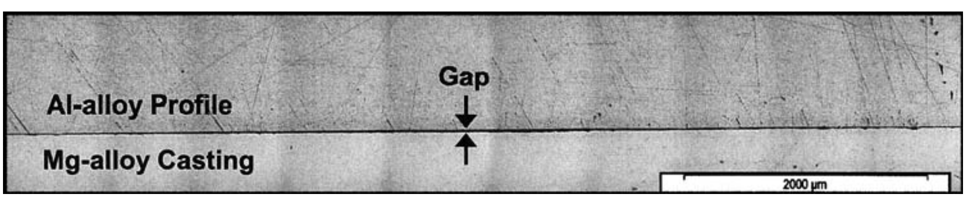

Fig. 5 Cross-section micrographs of a composite casting blank profile

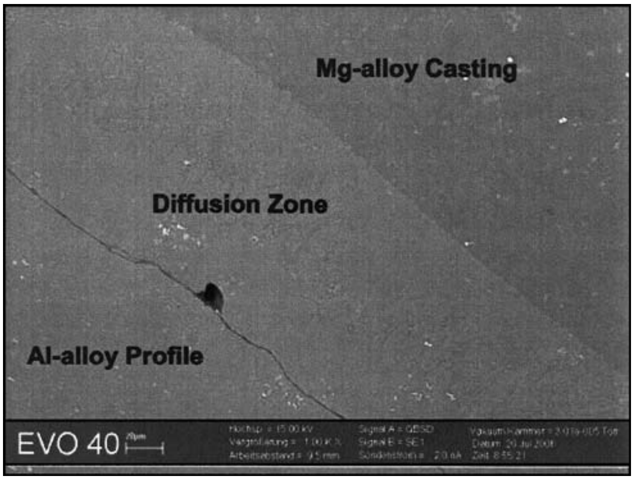

Fig. 6 Micrograph of the intermetallic phase zone of the blank profile interface, where no gap was present

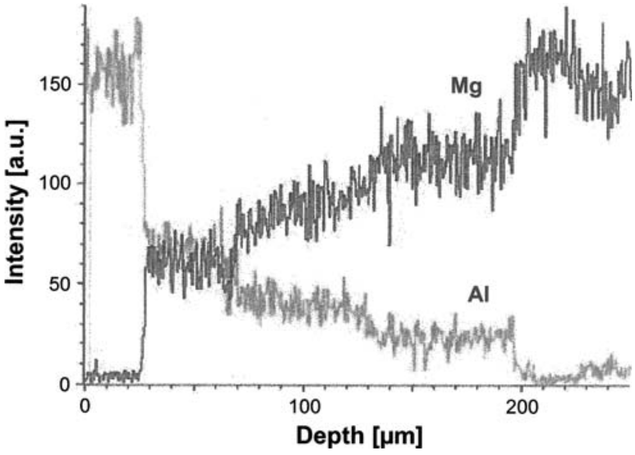

Fig. 7 EDX analysis of the blank profile interface

Figure 9 shows micrographs of the interface between the sand-blasted profile and the Mg casting. The top right-hand corner of Fig. 9 is the Al profile and the low left-hand corner is the Mg casting. It is again clearly visible that a diffusion zone exists. It can be easily measured from Fig. 9 that the diffusion zone has a total thickness of approximately 100 μm. Elemental distribution measurements have shown that the concentration of both elements decreases constantly with the distance from their respective sources. Extended EDX measurements (not shown in this paper) have shown that the upper part of the diffusion zone consists of a homogeneous mixture of Al and Mg, while the lower part consists of large Al phases embedded in the Mg matrix. As described previously, one of these phases is believed to be $Al_{12}Mg_{17}$ (γ-phase), which is an intermetallic phase and solidifies at a temperature far below Al and Mg and is also believed to be an initiator for the formation of the gap at the interface.

3.2.3 Flame Sprayed Profile Surface. Figure 10 shows a micrograph of the cross sections of the interface between the flame sprayed Al profile surface and the Mg casting. It can be seen that the corners show very good adhesion to the casting, but in the middle of the profile, a gap has formed between the coating and the casting (depending on the chosen parts geometry). At several locations, it can be observed that the Mg casting has impregnated the flame sprayed Al-12Si coating for a few micrometers. More detailed observations on magnified micrographs (not shown in this paper) have shown that the adhesion zone could be divided in four different zones: Al profile, flame sprayed coating, diffusion zone, and Mg casting.

Figure 11 shows longitudinal micrographs of this interface. The coating thickness was measured to be

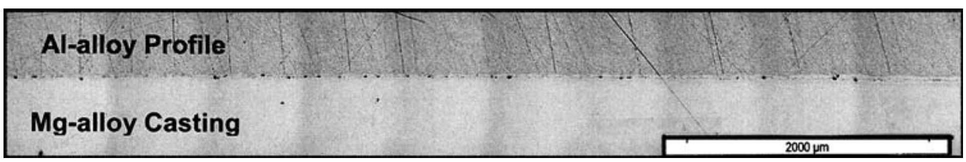

Fig. 8 Cross-section micrographs of a composite casting sand-blasted profile interface

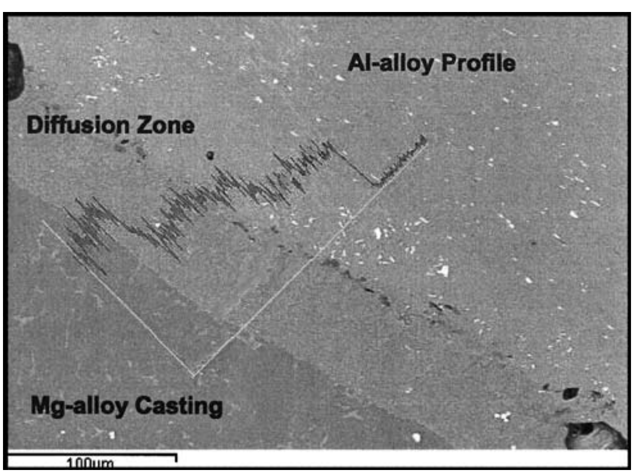

Fig. 9 Micrograph of the diffusion zone and EDX analysis of the sand-blasted profile interface

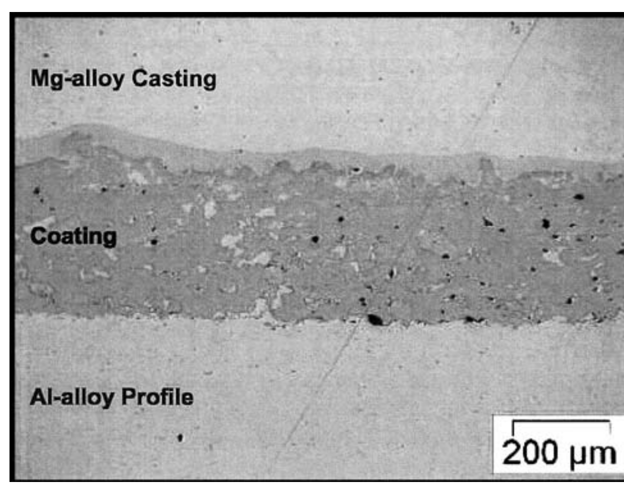

Fig. 11 Micrographs of a cross section of a composite casting flame sprayed profile interface

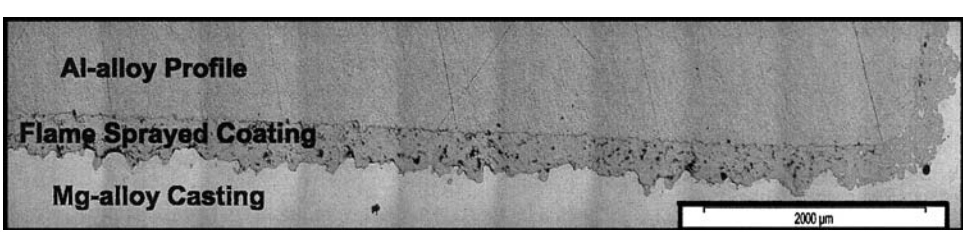

Fig. 10 Cross-section micrographs of a composite casting flame sprayed profile interface

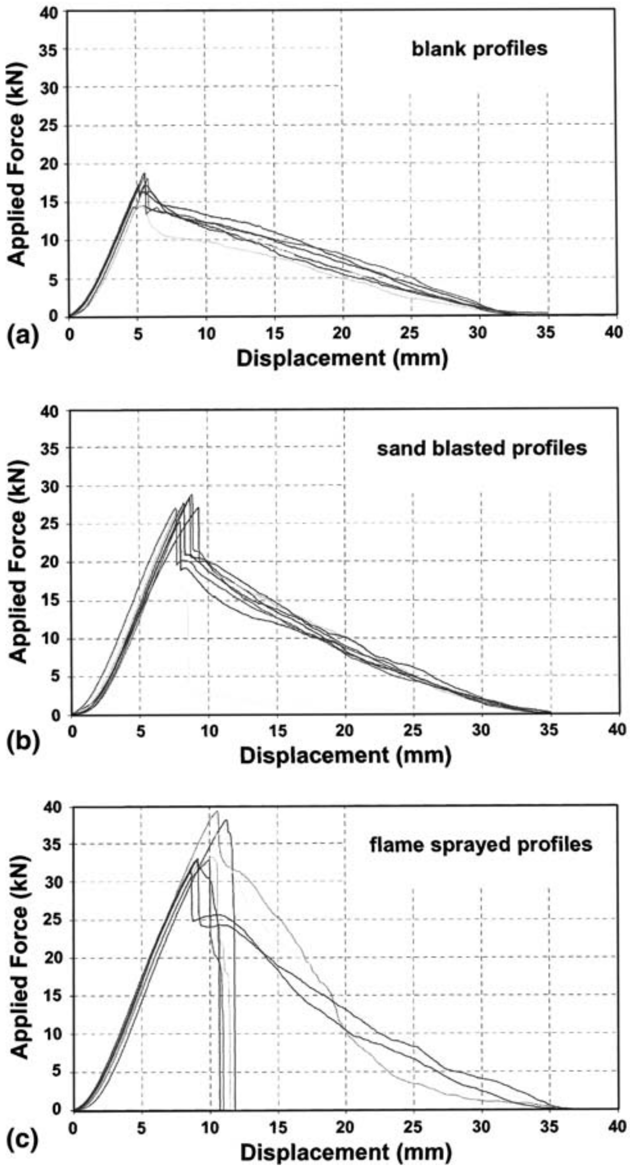

Fig. 12 Graphs showing the applied force as a function of the displacement for profiles having a blank (a), sand-blasted (b), or flame sprayed surface (c)

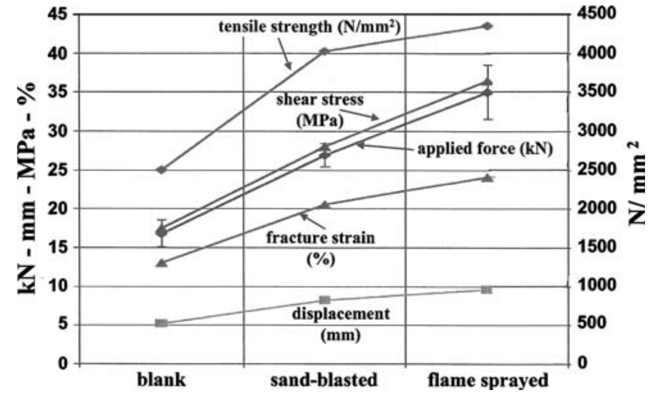

Fig. 13 Graph showing the average values of the applied force (kN), displacement (mm), shear stress (MPa), fracture strain (%) (all four on the left axis), and the average value of the tensile strength (N/mm^2) (on the right axis)

approximately 300 μm and possesses good adhesion throughout its interface with the Al profile and with the Mg casting. In addition, a distinct diffusion zone with a thickness of approximately 40 to 50 μm and a partial impregnation of the Mg casting into the flame sprayed coating can be observed. As reported earlier, the flame sprayed coating is partially impregnated from the Mg casting, and this could be observed on the EDX analysis by isolated Mg peaks in the coating.

As reported in the tensile test section, the flame sprayed coating has a strong tendency to adhere to the Mg casting; that is, the fracture mainly occurs between the Al alloy profile and the flame sprayed coating.

3.3 Tensile Tests

Figure 12 illustrates the results of the tensile tests as graphs of the applied force as a function of the displacement of the tensile machine crosshead for the profiles with a surface which was either blank, sand blasted, or flame sprayed. For almost all the samples, the displacement of the crosshead was equal or higher than the overlapping length of the casting. For the samples for which this displacement was smaller, the Mg casting broke away from the profile quite rapidly. Apart from these samples, independently of the experiments and of the side from which the sample was taken, the tensile results are quite reproducible, as can be seen in Fig. 12. For all the composite casting samples, by comparing the average maximum applied force, it can be observed that the blank profile surfaces have the lowest applicable force (15-18 kN), followed by the sand-blasted profiles (25-28 kN) and that the flame sprayed profiles surfaces possess the highest applicable force (30-40 kN) (comparison of Fig. 12a, b, and c). Therefore, the applied force seems to be proportional to the average surface roughness of the profile surfaces; that is, the roughest surface (flame sprayed profiles) may withstand the highest applied force.

In addition, the presence of a diffusion zone in the interface between sand-blasted profile surfaces and Mg casting may explain the increase in the applicable force compared to the blank profile. This diffusion zone enables the formation of a better adhesion between the Mg casting and the profile. For the flame sprayed samples, the benefit of such a diffusion zone is also present, but partial impregnation of the Al-12Si coating by the Mg casting is also assumed to be responsible for the further increase of the applied force when comparing these samples to the sand-blasted profile surfaces.

From Fig. 13, it can be easily observed that the applied force, displacement, shear stress, fracture strain, and tensile strength increase steadily when the profile surface is changed from a blank to a sand-blasted and finally to a flame sprayed surface. In fact, the applied force withstood by the composite casting samples is 60% higher when comparing the sand-blasted to the blank profile surface, and this applied force is 30% higher when comparing the flame sprayed profile to the sand-blasted samples. As discussed previously, this is believed to be due to the higher average surface roughness of the flame sprayed profiles but also to the presence of a diffusion zone combined with a partial impregnation of the Al-12Si coating by the Mg casting.

4. Conclusions

The use of a flame sprayed Al-12Si coating to enhance the adhesion strength between an Al-alloy profile (solid) and a Mg alloy (as cast) in composite casting samples shows impressive and successful results. Due to the fact that the flame sprayed coating surface has a higher surface roughness combined with the presence of a diffusion zone and a partial coating impregnation by the Mg casting, the latter being due to the intrinsic porous nature of typical flame sprayed coatings, the interface properties are significantly enhanced. In fact, the adhesion of flame sprayed composite castings increases by a factor of 2 compared to blank castings and by a factor of 1.3 when compared to sand-blasted castings.

However, delaminations are always present in the composite castings, and this is believed to be caused by high cooling rates and different temperature distributions along the profile surface and also to the chosen geometry. This could be eliminated by optimizing the cooling rate during the casting process and by optimizing the composite casting samples geometry by finite element programs (Ref 11, 12). However, the presence of such a gap indicates that part of the overlapping length does not participate in the overall adhesion strength of the sample.

The microscopic investigations as well as the tensile test results show that the adhesion between the flame sprayed coating and the Mg casting is much better than the adhesion between the coating and the Al profile. Therefore, an optimization of the adhesion of the flame sprayed coating to the profile would help to increase the strength of such composite casting samples. This could be achieved by optimizing the sand-blasting parameters and improving the flame spray parameters.

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