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Influence of aluminum casting alloys chemical composition on the interaction with a 304L stainless steel insert

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Abstract

The microstructure and mechanical properties of specimens made out of two different aluminum casting alloys, AlSi7Mg and AlSi9Cu, reinforced with a stainless-steel AISI 304 wire mesh and obtained by gravity casting were investigated. Specimens were observed by optical and scanning electron microscope in both as-cast and solution heat treated conditions with the aim to investigate the effect of matrix chemical compositions on the steel-matrix bonding. No intermetallic phases were observed at the interface in the as-cast conditions. However, a higher fraction of lack-of-filling defects as well as lack-of-bonding areas were detected in the AlSi7Mg alloy. The solution heat treatment induced the precipitation of different thick and brittle intermetallic layers, which compositions depend on aluminum alloy, in the areas where a metallurgical bonding formed during casting. Despite a little improvement of the elongation at fracture induced by silicon particle spheroidization caused by the heat treatment, the brittle fracture at the interface during tensile tests didn't allow the reinforcement to work in both the aluminum matrixes. Finally, basing on the obtained results, improvements are suggested that take into account both the preconditioning of the reinforcement surface and its geometry.

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Keywords: Al/Fe bimetallic castings; interface; intermetallic compounds; microstructure; mechanical properties

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1. Introduction

In view of the huge challenge linked to the climate change, the design for environment is asking for lighter and lighter materials. This could be done by substituting steels with light alloys (Miller et al., 2000) but unfortunately a limit always exists because of their lower stiffness and creep resistance. A breakthrough in this filed is represented by aluminum-steel bimetallic materials produced by different techniques such as stir welding (Springer et al., 2011a), friction welding (Herbst et al., 2017), laser welding (Jia et al., 2015) or the most recent Hybrid Metal Extrusion & Bonding (Berto et al., 2018; Leoni et al., 2020; Leoni et al., 2021). However, the easiest way to produce bi-metallic components is pouring the melted aluminum alloy into a mold containing the steel reinforcement (compound casting). Examples can be found in the production of engine cylinder blocks (Miyamoto et al., 2007), crankcases or pistons (Nunney, 2006; Bennett, 2009). The principal issue to overcome in producing compound castings is the incompatibility between the two metals. In fact, the different thermal expansion coefficients, the low mutual diffusivity and easy-to-form oxide or brittle intermetallic phases at the interface compromise the achievement of a sound metallurgical bounding. The oxide film in the steel insert and liquid aluminum surface reduces the wettability of the steel surfaces to liquid aluminum (Aylward and Findlay, 2002; Papis et al., 2009; Papis et al., 2008); moreover, the brittle and thick intermetallic layers promote interfacial brittle fractures (Springer et al., 2011b; Ferro et al., 2021) that are detrimental for the structural integrity of the component. Different strategies were developed to face those challenging problems. Jiang et al. (2016) used a 0.1 wt% Zn contained thin layer to protect the steel substrate from oxidation before pouring. A second proposed surface treatment consists of steel insert immersion into an ammonium chloride solution at 80 °C followed by aluminizing (780 °C for 200 s). Results showed an increase of the interface shear strength of 40% compared to the untreated specimens (Jiang et al., 2015). The presence of a high concentration of silicon in the aluminum alloy promotes the formation of a thinner layer of $Al_{4.5}FeSi$ that is detrimental because of its platelet morphology causing internal stresses in the insert/alloy interface (Cheng and Wang, 2011; Seifeddine et al., 2008). In particular, it was found that the growth rates of the intermetallic layer decreased when the Si content in the alloy was less than 1.5 wt%. On the opposite, the ternary Fe-Al-Si intermetallic phases appeared and grew quickly as the Si content in the molten metal increased to 2 wt% and 3 wt% (Yin et al., 2013).

The present study is aimed at investigating the influence of aluminum casting alloy composition on the metallurgical and mechanical properties of stainless steel wire mesh–reinforced Al-matrix composite samples obtained by gravity casting. Two common casting alloys are taken into account, AlSi7Mg and AlSi9Cu. The effect of a solution heat treatment (550 °C, 10 h) on the metallurgical bonding at the interface between the matrix and the insert was investigated.

2. Materials and Methods

An AISI 304 square mesh grid with a wire diameter and a pitch of 0.6 mm and 2.3 mm, respectively, was used as insert in the compound casting . The specimens were obtained by gravity casting using two different aluminum alloys, say AlSi7Mg and AlSi9Cu, whose chemical composition are summarized in Table 1.

Table 1. Chemical composition (wt%) of the analyzed aluminum casting alloys

	Al	Si	Mg	Fe	Ti	Mn	V	Zn	Cu	Cr
AlSi7Mg	Bal.	7.41	0.347	0.156	0.105	0.032	0.014	0.013	0.012	-
AlSi9Cu	Bal.	8.85	0.446	0.483	0.132	0.301	-	0.664	1.04	0.036

The major difference in composition is the higher amount of Si and Cu in the AlSi9Cu that should induce more fluidity and strength, respectively. However, the greater amount of Fe could influence the intermetallic phases composition at the matrix/insert interface. The steel open die with the reinforcement and the filter positioned inside it is shown in Fig. 1.

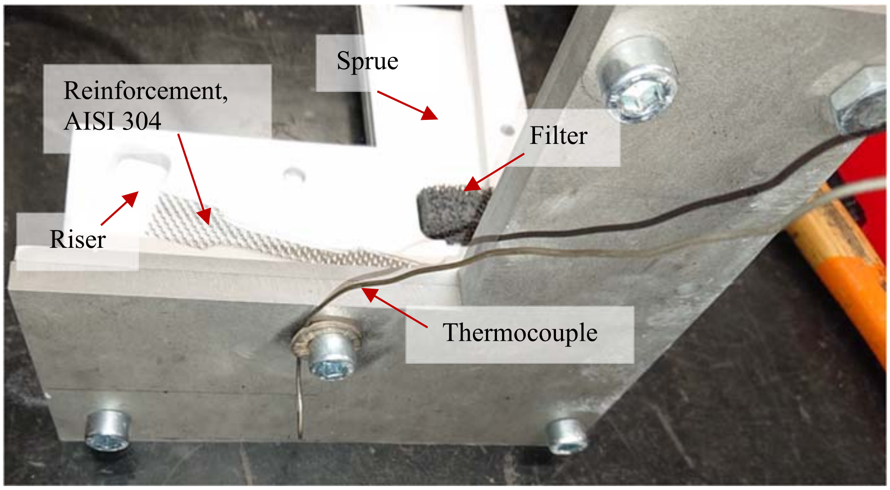

Fig. 1. Steel mold with pouring system used in experiments.

The wire mesh has been degreased using ultrasonic cleaning in acetone and then placed inside the mold cavity (dog bone shaped) with an orientation angle (θ) of 0° relative to the load direction in tensile tests (Fig. 2a). A thermocouple was also placed on mold surface in order to monitor and control the mold preheating temperature (350 ± 5°C) (Fig. 1). 12 samples were casted for each aluminum alloy, of which 6 without the steel insert. The alloys pouring temperature was 730 °C while the maximum mold temperature reached during all castings was 395 ± 3°C. The steel mesh positioning and eventual presence of macro defects in the obtained samples were first investigated by a non-destructive X-Ray radiography testing (RT). The metallurgical investigations were carried out on both transversal and longitudinal sections using the standard metallographic sample preparation (Fig. 2c). Optical (Leica LM2500) and scanning electron microscope (SEM, model Quanta FEG-250 of FEI©) were used for the microstructural characterization with particular attention to the bonding interface and the intersection between the longitudinal and latitudinal wires of the mesh. Image analyses aimed at measuring the volume of lack of filling closed to the wire mesh and the secondary dendrite arms spacing (SDAS) were carried out with the LAS software.

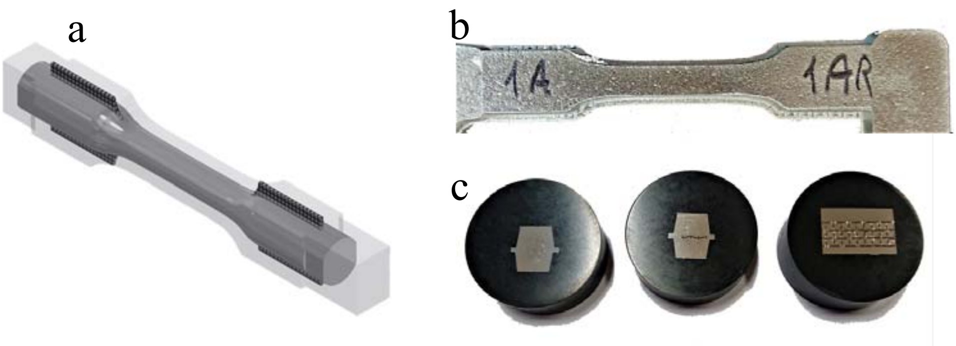

Fig. 2. (a) sample geometry before and after machining; (b) photo of a raw sample; (c) different cross sections analyzed in metallographic investigations.

The obtained castings (Fig. 2b) underwent to machining to reach the target geometry for tensile tests schematized in Figure 2a. Tensile tests were performed using an MTS machine with an elongation rate equal to 4 mm/min. Finally, some samples were treated at 550 °C for 10 h and then water quenched to room temperature in order to investigate the effect of the solution heat treatment on metallurgical and mechanical properties of the reinforced specimens.

3. Results

3.1. Compound castings integrity and metallurgy

X-Ray radiography testing (RT) results are shown in Fig. 3. They easily reveal a greater amount of lack of filling defects at the steel wires intersections in AlSi7Mg matrix-based samples compared to that observed on those made out of AlSi9Cu matrix.

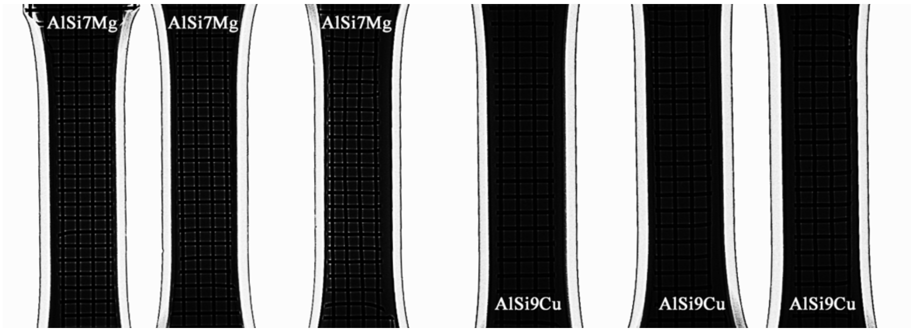

Fig. 3. Results of radiography testing showing the wire mesh position and lack of filling at the wires intersection.

With the aim to investigate the effects of the steel mesh on the cooling rate, more than 15 secondary dendrite arms spacing (SDAS) measurements were carried out on both samples with and without the reinforcement. No significant variation was observed between the two aluminum alloys; however, the steel matrix increased the cooling rate giving an average SDAS value of 22±2 μm, compared to that measured in the steel insert-free samples of 25±2 μm. A porosity estimation was performed by imagine analysis on different cross sections as shown in Fig. 4.

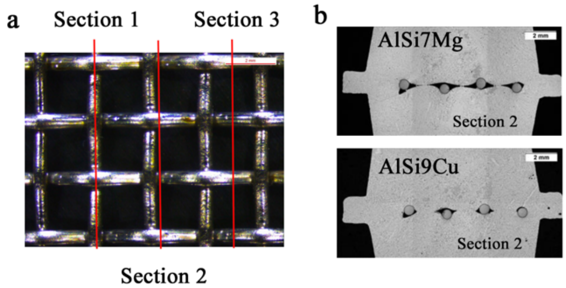

Fig. 4. (a) transversal cross sections and (b) example of macrographs obtained for imagine analysis.

Considering only transversal cross sections (Fig. 4), results showed a mean porosity percentage of 1.22±±0.01% for the reinforced AlSi7Mg alloy against a value of 0.76±0.01% for the compound casting made of AlSi9Cu alloy. This trend confirms the previous RT results and can be considered a direct consequence of the higher fluidity of the aluminum alloy with higher silicon content. Fig. 5 shows details of the microstructure at the interface between the steel insert and the aluminum matrix.

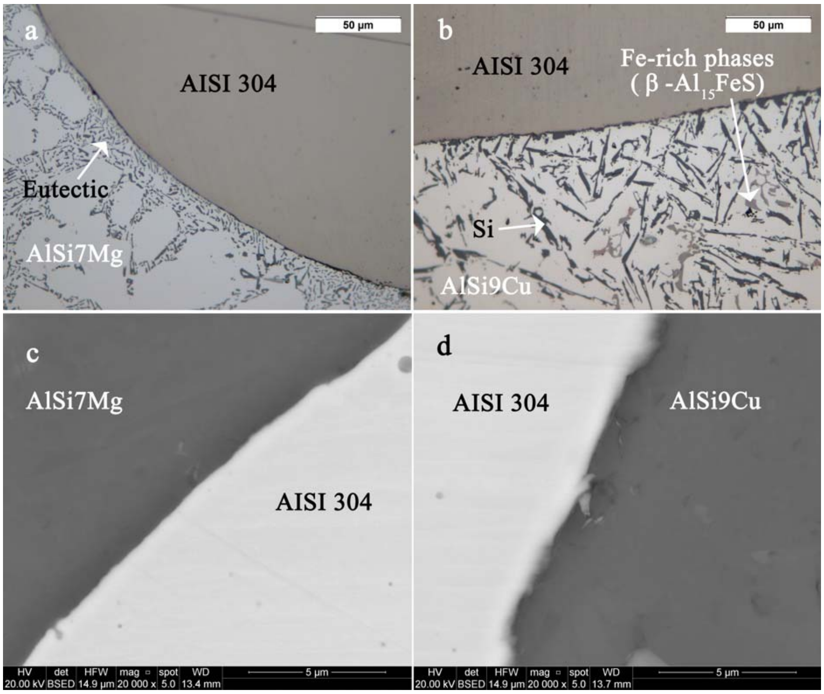

Fig. 5. (a,b) optical and (c,d) SEM micrographs of the interface AISI 304-Aluminum matrix

In both the aluminum alloys the contact with the steel wire mesh is not well defined (Fig. 5(c,d)). In the case of AlSi7Mg alloy, some debonding surfaces seem to appear and the steel wire is completely decorated by the eutectic structure (Fig. 5a). On the other hand, silicon particles seem to nucleate on the steel surface when considering the AlSi9Cu alloy (Fig. 5b). No intermetallic phases were observed at the interface because of the rapid solidification of both aluminum alloys. Finally, Fig. 5b shows typical in-matrix Fe-rich phases of the analyzed aluminum alloy. The Al/steel interface after heat treatment at 550 °C for 10 hours is shown in Fig. 6. The insert/Al-matrix interface was partially decorated with an intermetallic substrate where a metallurgical bonding was previously achieved. The chemical composition of the intermetallic phase changes according to the Al-matrix composition. According to Bakke et al. (2020), the two intermetallic compounds highlighted by the contrast in Fig. 6a, were supposed to be β-$Al_{4.5}FeSi$ (darker grey in SEM micrograph) and/or τ_{10}-$Al_4Fe_{1.7}Si$ (lighter grey in SEM micrograph). On the other hand, when considering the AlSi9Cu alloy, the intermetallic composition seems not to change moving from the interface to the Al-matrix (Fig. 6(b,d)). In this case, however, different cracks were observed in the intermetallic layer that could indicate a more brittle behavior compared to that formed with the AlSi7Mg alloy. It is also observed how the eutectic silicon modified its morphology after the heat treatment from plate-like to almost equiaxed shape.

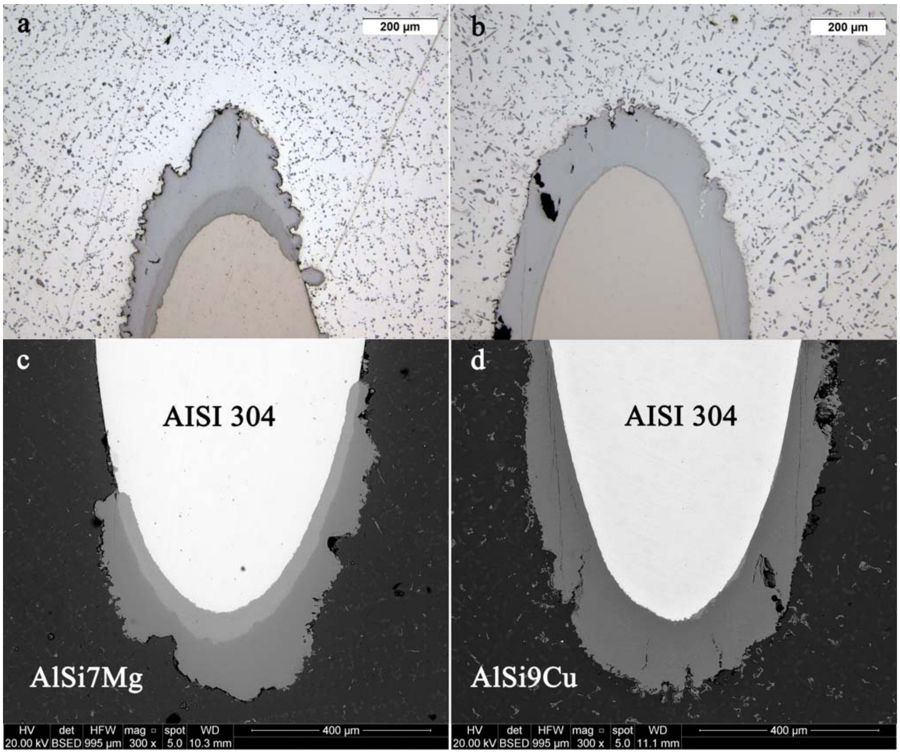

Fig. 6. (a,b) optical and (c,d) SEM micrographs of the interface AISI 304-Aluminum matrix after heat treatment (550 °C, 10h)

3.2. Tensile tests

Fig. 7 shows the results of the tensile tests (the most representative curve for each case). The two aluminum alloys showed a different behavior. In the first case, referring to the AlSi7Mg aluminum matrix (Fig. 7a), the steel wire mesh reduced the mechanical properties of the samples, in terms of both ultimate tensile strength (UTS) and elongation at failure (A%). This is attributed to the great number of lack-of-filling zones that promoted a premature debonding between the matrix and the reinforcement and a reduction of the cross-section area compared to the specimens without the insert. The improvements obtained with the heat treatment are attributed to the silicon morphology modification. In particular, the enhanced ductility of the matrix resulted in a reduced crack initiation sensitivity and thus an improvement of the mechanical properties of the compound casting in the heat-treated condition compared to those of the compound casting in the as-cast conditions.

In the second case (Fig. 7b), the heat treatment reduced the UTS but improved the elongation at fracture in all the tested conditions. The steel wire mesh reduced the mechanical properties of the as-cast specimens but slightly improved those of the heat-treated compound castings when compared to the heat-treated alloy without the insert. It is supposed that this behavior is due to the reduced number of lack-of-filling zones, compared to that found in the previous aluminum matrix, and a consequent metallurgical bonding improvement promoted by the heat treatment.

In all samples, the steel wire mesh didn’t fail at the end of each test.

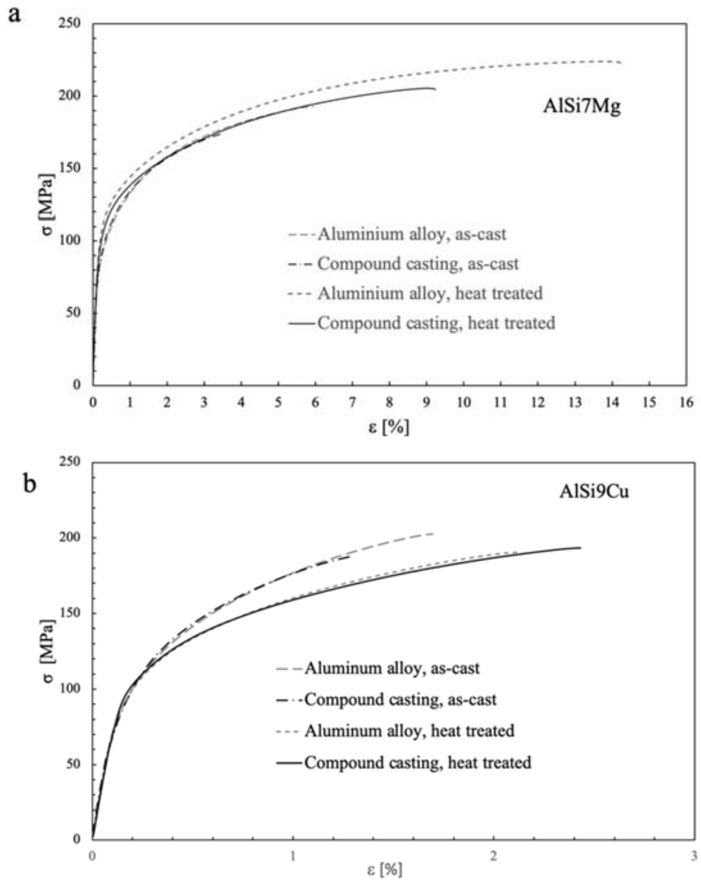

Fig. 7. Tensile tests with and without both the steel reinforcement and heat treatment; a) AlSi7Mg, b) AlSi9Cu

4. Discussion

Compound castings were produced by using two different aluminum alloys, i.e. AlSi7Mg and AlSi9Cu, in order to investigate the effects of the chemical composition on their metallurgical and mechanical properties. In both cases, lack-of-filling defects at the intersections of the steel wires were found detrimental for the mechanical properties. In fact, they act as stress concentration points promoting an easy debonding of the steel wire mesh from the matrix, and avoiding, *de facto*, the reinforcement to work. However, due to its greater Si content and therefore higher fluidity, AlSi9Cu was found more suitable in producing compound castings because of the reduced number of induced lack-of-filling defects. This advantage was in particular observed in the heat-treated specimens since the greater metallurgical bonding area associated to the improved ductility of the matrix allow to retard the steel wire mesh detachment. Some uncertainties derive from the heat treatment parameters. As a matter of fact, temperature and time should be calibrate in order to obtain the best combination of aluminum matrix ductility and a reduced thickness of the brittle intermetallic phase. In this work, the intermetallic thickness was about 200 μm and, as expected, brittle fractures occurred during the steel wire mesh detachment as shown in Fig. 8.

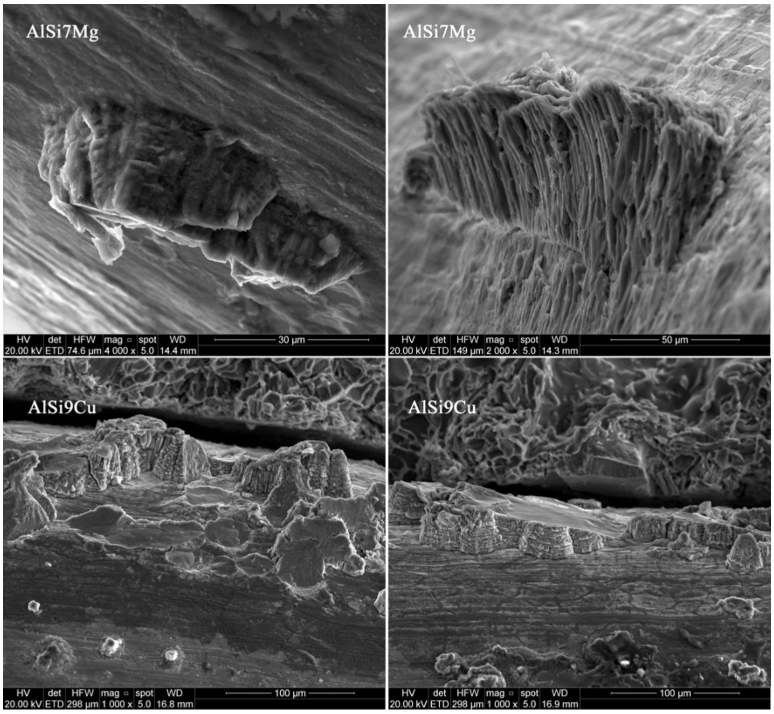

Fig. 8. Fragments of intermetallic in the steel wire

The observed cracks in the intermetallic layer after heat treatment (Fig. 6) are attributed to the build-up of thermal stress at the interface during quenching due to the different thermal expansion coefficients of aluminum, steel and interfacial intermetallic phases. Keeping this in mind, the following improvements are suggested for further investigations:

(i) process parameters, such as pouring and mold temperatures, should be optimized in order to eliminate voids due to lack of filling;

(ii) heat treatment parameters should be optimized with the aim to avoid brittle fractures in the intermetallic layer and obtain the best combination aluminum matrix ductility/reduced intermetallic layer thickness;

(iii) steel surface preconditioning should be promoted: according to literature (Yin et al., 2013), a Cu coating will result more effective, compared to Zn, against the intermetallic layer formation;

(iv) insert geometry improvements working on roughness and shape of the mesh, difficult-to-fill zones, stiffness of the insert that should be very closed to that of the matrix, should be taken in deep consideration; such results can be achieved by exploiting the new advances in additive manufacturing processes (Ferro et al., 2020).

5. Conclusions

The influence of aluminum casting alloys chemical composition on the interaction with a 304L stainless steel insert was studied. Reinforced samples were obtained by gravity casting using two different aluminum alloys, i.e. AlSi7Mg and AlSi9Cu. Some samples were heated at 550 °C for 10h followed by water quenching. Results were obtained and compared in terms of metallurgical microstructure, with particular reference to the in steel/matrix interface and static mechanical properties. Finally, improvements were suggested for future tests. The main difference in using the two aluminum alloys consisted in the Si content. The alloy with higher silicon content allows to obtain samples with a lower number of lack-of-filling defects, considered the main reason of the reduced mechanical properties of the obtained compound castings. In combination with the improved matrix ductility induced by the heat treatment, it was possible to retard the steel wire mesh brittle detachment and to obtain a little improvement of the mechanical properties compared to those of the matrix alone.

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