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Mechanical Behaviour of Magnesium Alloy Based- Fiber Metal Laminates after Fabrication Using Different Metal Surface Treatments

Zheng Liu[1,a*], Enrico Simonetto[1,b], Andrea Ghiotti[1,c], Stefania Bruschi[1,d]

[1]Department of Industrial Engineering, University of Padova, Via Venezia 1, 35131 Padova, Italy

[a]zheng.liu@studenti.unipd.it, [b]enrico.simonetto.1@unipd.it, [c]andrea.ghiotti@unipd.it, [d]stefania.bruschi@unipd.it

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Abstract. This paper presents an experimental investigation of the mechanical response and failure mode of magnesium alloy-based Fibre Metal Laminates (FMLs) having different surface pretreatments under axial compression loading conditions. To improve the interfacial bonding strength between the metal and composite layers, three categories of samples were fabricated by hot pressing using sandblasted, annealed and both sandblasted and annealed AZ31B magnesium alloy sheets. To evaluate the bonding strength along the shear and normal directions, single lap shear tests and T-peel tests were conducted. It was found that the combination of sandblasting and annealing can greatly enhance the shear and normal interfacial bonding strength compared with only sandblasting and annealing, separately. To assess the effect of the interfacial bonding strength on the FML compressive performance, quasi-static buckling tests were performed at varying surface treatments of the magnesium alloy sheets. The analysis of the load-stroke curves and failure modes indicates that delamination can significantly reduce the buckling capability and structural stability, and that the improvement of interfacial bonding strength can dramatically strengthen the FML compressive capability.

Introduction

In the automotive, aerospace and marine industries, there is an increasing requirement for lightweight components to assure lower consumption, but, at the same time, these components must be characterized by high static and dynamic strengths. This has promoted the use of new materials, as the Fiber Metal Laminates (FMLs) that are a kind of hybrid material consisting of thin metal sheets as skins and Fiber-Reinforced Polymer (FRP) as core. Thanks to the combination of the characteristics of metals and composites, FMLs have been applied in a wide range of industrial fields [1,2]. Compared to the traditional thermoset-based FMLs, thermoplastic-based FMLs show significant merits, like recyclability and improved mechanical properties with a lower density.

Aluminum alloy-based FMLs, such as fiber reinforced aluminum laminates (ARALL), carbon fiber referenced aluminum laminates (CARALL), and glass fiber referenced aluminum laminates (GLARE), have been widely applied in manufacturing industrial components, while magnesium alloy-based FMLs have attracted attention more recently thanks to the very high strength-to-density ratio shown by the magnesium alloys [3].

Nevertheless, the interfacial bonding strength plays a key role in assessing the FML performances. Delamination is one of the main failures in FMLs as a result of an insufficient bonding strength when subjected to different loading conditions. It leads to significant reduction of the FMLs structural stiffness, which further lowers the structure capability [4,5]. Especially for thin-walled FMLs structures when facing compressive loading conditions, buckling behavior decides the final structural performance [6]. Therefore, the FML structural stability becomes a crucial factor in designing the component.

Several researches have been conducted to analyze the buckling behaviour of FMLs structures. In [7] the static buckling, impulse buckling, and post-buckling performances of magnesium alloy-based and steel-based 3D FMLs were compared. By replacing steel sheets with magnesium alloy sheets with the same bending stiffness, the static and impact buckling capacities increased by 82% and 31%, respectively. In [8] a novel 3D FML was designed by combining basalt and E-glass fabrics with magnesium and stainless steel sheets: it was found that, via a proper combination of the aforementioned materials, the absolute buckling capacity and the buckling capacity normalized with respect to the materials costs could be optimized. The progressive damage and failure behavior of thin-walled aluminum based FMLs short columns facing in-plane compressive loading were numerically and experimentally analyzed by D. Banat et al. [9].

Although there are various researches available in literature about the FMLs buckling behaviour, most of them focused on the design and optimization of the FML material and structure to enhance the compressive behaviour. In this research, the effect of the interfacial bonding strength on the buckling capability and compressive response was investigated for the first time. The FMLs object of the investigation are made of AZ31B magnesium alloy sheets and glass fiber-reinforced PA6 prepregs. Different surface pretreatments were carried out on the AZ31B sheets in order to evaluate their effect on the shear and normal interfacial bonding strength by conducting single lap shear tests and T-peel tests, and on the buckling behavior by conducting quasi-static buckling tests. In order to do that, the load-stroke curves and failure modes were compared.

Materials and FML Fabrication

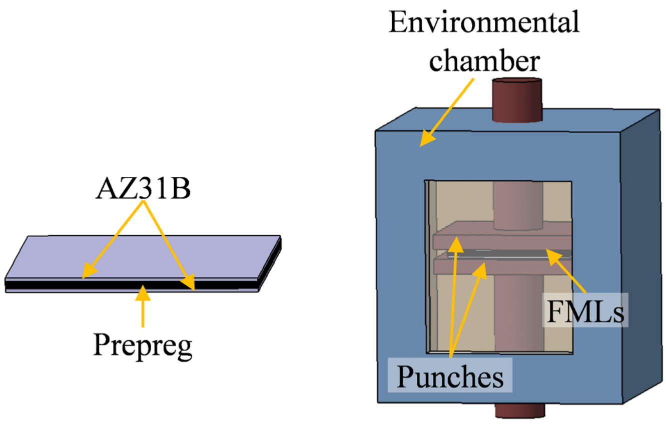
Materials. The investigated FMLs are made of two magnesium sheets as skins of 0.5 mm thickness and one layer of glass fibre-reinforced PA6 prepregs as core of 1 mm thickness. The mechanical properties of the magnesium alloy sheets and prepregs in the as-received condition were evaluated by conducting standard tensile tests (ISO-6892) on an MTS™ 322 (50 kN) hydraulic dynamometer using dog-bone shaped specimens with gauge length of 65 mm and width of 12 mm. Table 1 reports the obtained mechanical properties.

Table 1. Mechanical characteristics of the AZ31B sheets and prepregs.

Material	Elastic modulus [GPa]	Yield strength [MPa]	Tensile strength [MPa]	Strain hardening exponent
AZ31B	45	158±2	248±4	0.19
Prepreg	18	-	270±18	-

Surface Pretreatments of the AZ31B Sheets. To enhance the interfacial bonding strength between the metal and prepregs surfaces, different metal pretreatments were conducted on the AZ31B sheets. Three cases of surface pretreatments were considered in this study, namely sandblasting (S), annealing (A), both sandblasting and annealing (SA). Sandblasting was carried out by using white corundum with a grain size of F120 (Al_2O_3 powder at 99% with a macro-grain size in the range 90–125 µm) at 4 bar pressure for 5 s. Annealing was performed by holding the magnesium alloy sheets at 500°C for 20 minutes in an oven and then cooling them down to room temperature in still air. The SA cases were realized by conducting annealing using sandblasted sheets.

Fabrication of the FMLs Specimens. The pretreated AZ31B sheets and the prepregs were cut by water jetting into the designed dimensions, cleaned with acetone, stacked, and finally bonded via hot pressing. Figure 1 shows the process chain for fabricating the FML specimen. Hot pressing was realized by placing the stacked AZ31B sheets and prepreg within an MTS™ 651 environmental chamber at 250 ± 5°C for 15 minutes to melt the thermoplastic resin of the prepreg, and then applying a 2 ± 0.5 MPa pressure [10] for 5 minutes to make the magnesium sheets and prepreg bonded together through the melt resin. Finally, the stacked specimen was cooled in still air with still the pressure applied in order to ensure a better bonding quality.



(a) Stacking (b) Hot pressing

Fig. 1. Stages of the process chain for fabricating the FMLs: stacking (a), and hot pressing (b).

Experimental Procedures

Single Lap Shear and T-Peel Tests. In-plane and out-of-plane are the main loading conditions of FMLs structures. Therefore, in order to assess the interfacial bonding strength along the shear and normal directions, single lap shear tests and T-peel tests were performed on a 50 kN MTS™ 322 servo hydraulic dynamometer with FML samples having different metal surface pretreatments.

The single-lap shear tests were conducted and the samples manufactured according to the ASTM D1002-10 standard [11] (see Fig. 2 (a)). The bonding area was set equal to 25.4 x 25.4 mm^2 and the tests were carried out at 1 mm/min.

The T-peel tests were conducted and the samples manufactured according to the ASTM D1876-08 standard [12] (see Fig. 2 (b)). The two ends of the specimen were fixed to the testing machine grippers, and the tests were performed by moving the lower gripper at 100 mm/min. All the tests were carried out with a repeatability of 3.

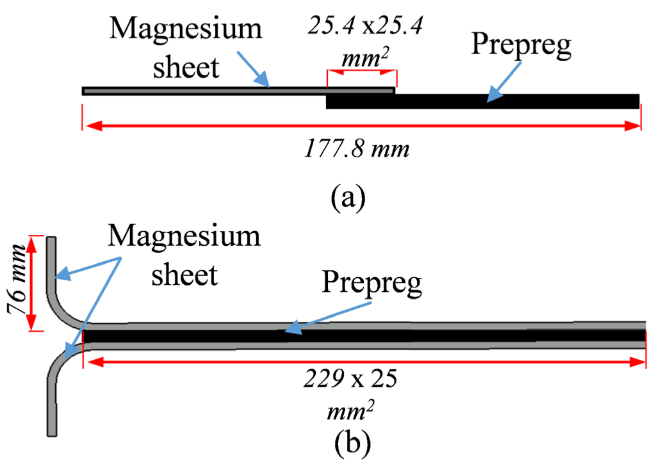


Fig. 2. Geometry of the specimen for the single lap shear tests (a) and T-peel tests (b).

Quasi-Static Buckling Tests. The compressive and buckling behavior of the FMLs samples was evaluated by performing quasi-static buckling tests on the MTS™ 322 dynamometer, with a repeatability of 3 for each condition. Figure 3 shows the experimental set-up and the specimen used for the quasi-static buckling tests. The two fixed areas of the specimen were clamped using a pressure of 5 MPa, which was proved to be enough to avoid sliding between the machine grippers and the specimen. The specimen was then compressed by moving the lower gripper upwards at 1 mm/min.

Dino-Lite digital microscope camera system was used to monitor inline the deformation of the working area.

For being a reference for the other cases, also the unbonded case was designed as it allows observing the FML compressive behavior without bonding. This case was realized by just stacking the annealed magnesium alloy sheets and prepregs of the FMLs without bonding them.

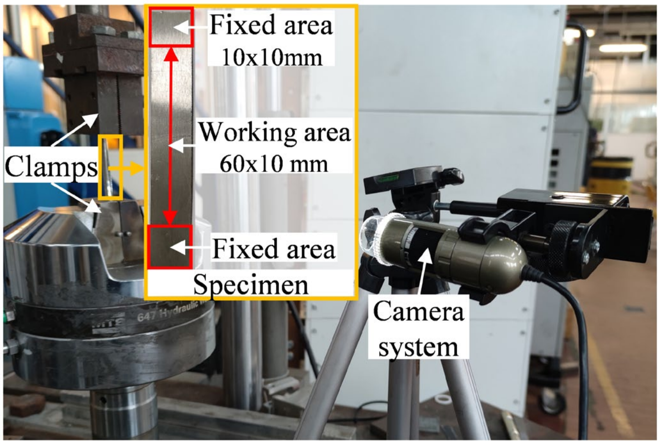


Fig. 3. Experimental set-up and geometry of the specimen for the buckling tests.

Results

The Effect of the Metal Surface Pretreatments on the Shear and Normal Bonding Strengths. The load-stroke curves obtained from single lap shear and T-peel tests are shown in Fig. 4 and Fig. 5. It can be seen that in both the tests, the peak forces relative to the FMLs with the magnesium alloy sheets in the SA condition are the highest, meaning that the sandblasting and annealing metal surface treatments provided the strongest interfacial bonding strength along both the normal and shear directions; on the contrary, the FML specimens with the magnesium alloy sheets in the S condition showed the lowest shear and normal interfacial bonding strengths. As example, in the single lap shear tests, the peak force in the case of the SA condition reached 7.39 ± 0.05 kN, over 2 times higher than the same in the case of the S condition (3.05± 0.05kN). Whereas, the stroke at rupture in the case of the SA condition was 57% and 161% higher than that in the case of the A and S conditions, respectively. Similar conclusions can be drawn from the T-peel tests: the peak load in the case of the SA condition was the highest (53± 2N), 61% and 211% higher than the one in the case of the A and S conditions, respectively. In all the T-peel tests, after reaching the peak point, the force dropped gradually to a stable level. The force at the stable level in the A condition is 76% lower than that in the SA case, while it is 240% higher than the force in the S case.

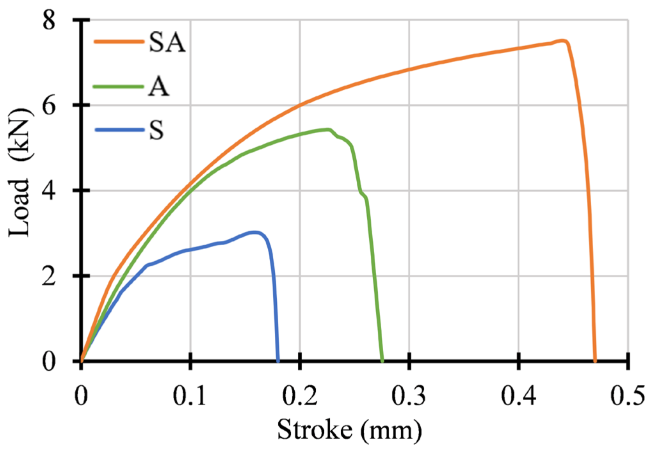


Fig. 4. Experimental results of the single lap shear tests.

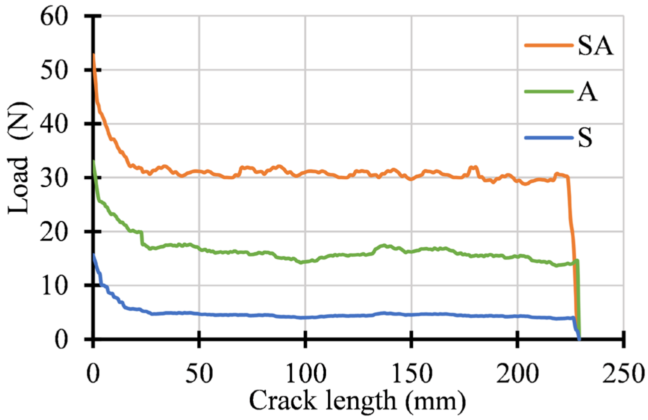


Fig. 5. Experimental results of the T-peel tests.

The Effect of the Interfacial Bonding Strength on the Compressive Performance. Figure 6 reports the results of the buckling tests for the unbonded case. In the pre-buckling period, namely from the initial point (point 1) to the buckling capability point (point 2), the force increases rapidly to the critical buckling limit, after which it enters the post-buckling period and reduces gradually until a sudden force drop is evident at point 3. The latter is indicative of the prepreg rupture as shown at point 3 in Fig. 6 (b) that basically results in the FML structural destruction, thus almost resetting its structural loading capability. Due to the bending stiffness difference between the magnesium alloy sheets and the prepreg, the gap between them in the translation area (between the middle area and fixed end as shown at point 3 in Fig. 6 (b)) increases as the stroke increases gradually from point 2 to point 3, which causes this area to become a potential one for delamination.

Figure 7 presents the buckling test results for the bonded FML with annealed magnesium alloy sheets. As expected, the load values are much higher than the ones of the unbonded case, but also the evolution of the load as a function of the stroke shows some dissimilarities. In the pre-buckling period and first segment of the post-buckling period (before point 3 (Fig.7)), the force shows a similar tendency to the one of the unbonded case. Since the interfacial bonding strength supplied by the annealing pretreatment is sufficient to assure the structural integrity, it results in higher force at equal stroke, and higher buckling capability compared to the corresponding unbonded case. The occurrence of delamination at point 3 (Fig.7) makes loose the FML structural stability, which is shown by the sudden drop of the force. Afterwards, the force remains at a stable level until point 4 (Fig.7) where the prepreg rupture occurs, which causes another force drop and subsequent lower force level. As the force level in half-delaminated status after point 3 (Fig.7) is still higher than the one in unbonded case, this demonstrates the positive effect of the interfacial bonding on the structural capability.

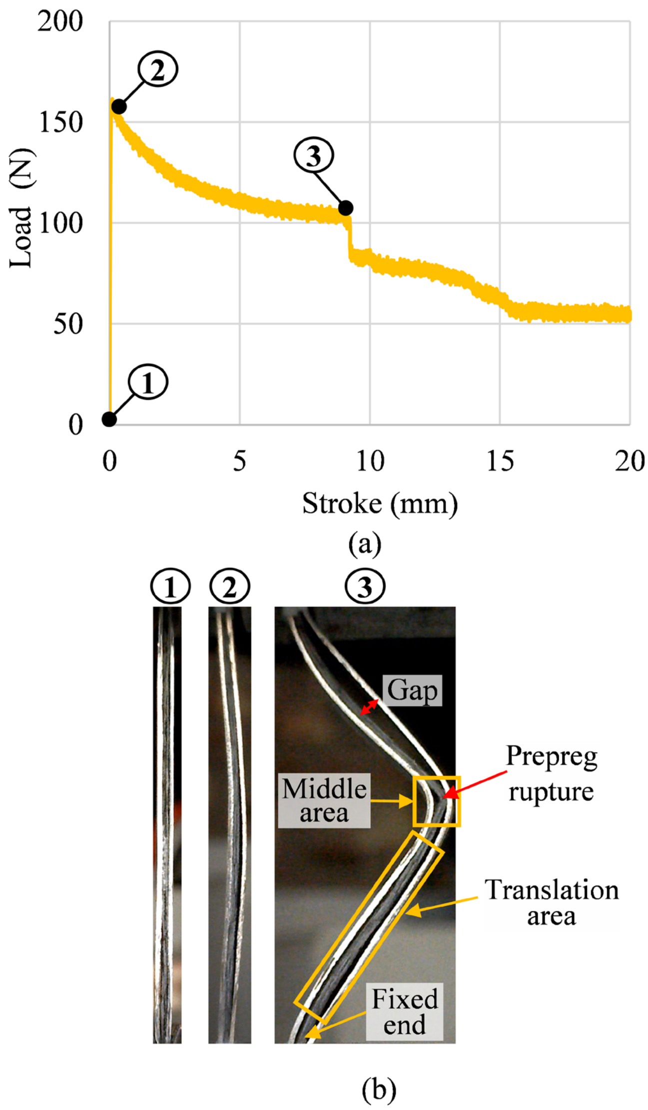


Fig. 6. Experimental results of the buckling tests for the unbonded FMLs: load-stroke curve (a) and image of each point (b).

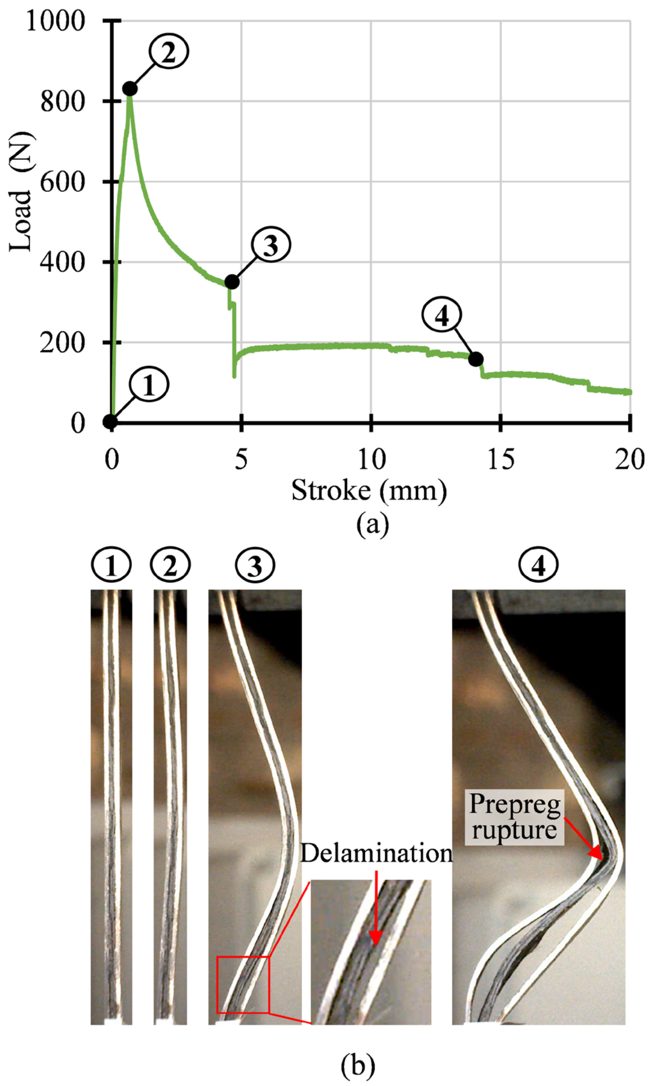


Fig. 7. Experimental results of the buckling tests for the bonded FML with annealed AZ31B sheets: load-stroke curve (a) and image of each point (b).

The experimental results of the buckling tests for all the cases are shown in Fig. 8. The lines 1 and 2 represent the instants of the occurrence of delamination for the magnesium alloy sheets in the S and A conditions, while the points 3, 4 and 5 indicate the occurrence of the prepregs rupture for the S, A and SA cases, respectively. In case of magnesium alloy sheets in the S condition, before the sample reaches the buckling capability point of this structure, delamination occurred and resulted in the lowest peak force compared to cases with the magnesium alloy sheets in the A and SA conditions. In the post-buckling period, the propagation of delamination can be observed through the sudden drop of the force in line 1. The load after line 1 is almost the same as the one in the unbonded case meaning that the structure was fully delaminated, which can also be further confirmed from the failure photo of the sandblasted sample after buckling tests shown in Fig. 9 (a). The higher interfacial bonding strength in the A case compared to the S case contributes to the later delamination onset (line 2), indicating a higher compressive structure capability. The FML with magnesium alloy sheets in the SA condition does not present any delamination that makes the structure hold the compressive capability until the prepreg rupture occurs at point 5. It is worth underlining that the prepreg rupture in the latter case also results in the fracture of the magnesium sheets in the middle area, which, in turn, is responsible of the fact that the force after point 5 is lower than the one in the other cases. As a consequence of the half-delamination status of the FML with the magnesium alloy in the A condition as shown in Fig. 9 (b), its load curve lies in between the SA and unbonded cases after line

2. Therefore, the higher the interfacial bonding strength the more benefit the structure has in terms of compressive capability.

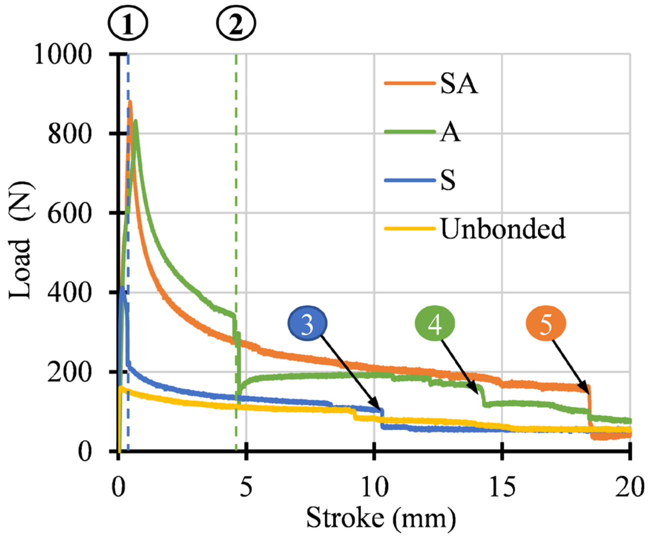
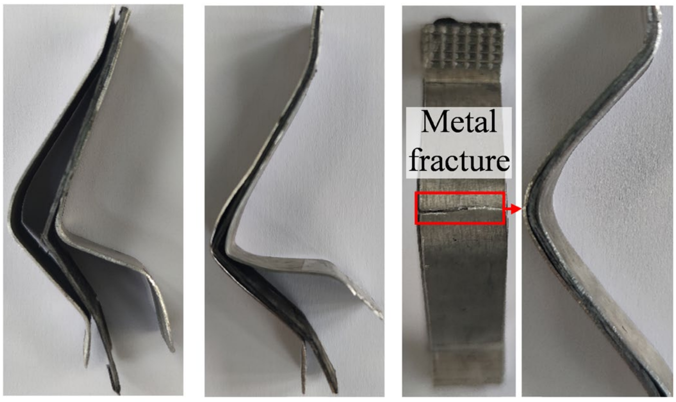


Fig. 8. Comparison between the experimental results of the buckling tests.



(a) (b) (c)

Fig. 9. FML failure after buckling tests in case of magnesium alloy sheets in the: (a) S, (b) A, and (c) SA conditions.

Conclusions

In this study, a comprehensive series of experiments were conducted to gain a better understanding of the effect of metal surface treatments on the interfacial bonding strength, and their further effect on the buckling responses of magnesium alloy-based FMLs. The main findings of the present research work can be summarized as follows:

Different metal surface treatments showed to have a positive effect on the interlaminar bonding strength along both the normal and shear directions. The combination of mechanical and thermal treatments carried out on the magnesium alloy sheets improved the bonding strength more than when only sandblasting or only annealing surface treatments were carried out.

The buckling capability and structure performance of the FMLs subjected to compressive loading conditions were proved to be highly affected by the interfacial bonding strength. At increasing bonding strength, the FMLs structure stability and buckling capability were also improved.

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