Tensile-shear fatigue analysis and comparison of light alloy thin sheet lap-joints obtained by ultrasonic spot welding and ultrasonic spot welding plus adhesive bonding

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Abstract. The present research is part of the HY-LAP (HYbrid LAP-joints) project carried out at the Dept. of Mechanical Engineering of Politecnico di Milano in collaboration with the MUSP laboratory in Piacenza (Italy) and the University of Parma (Italy).

In particular, the present study deals with the experimental characterization of the tensile-shear fatigue behavior of both spot welded lap-joints obtained by ultrasonic metal spot welding and hybrid lap-joints obtained by ultrasonic metal spot welding plus adhesive bonding. All the considered lap-joints were realized joining thin sheets made of AA6022T4 aluminum alloy or AZ31B magnesium alloy. A careful failure analysis is carried out on all the tested specimens and a comparison of the fatigue performance to other spot welding techniques is also presented.

Introduction

The present paper describes part of the results obtained in the frame of the HY-LAP (HYbrid LAP-joints) project carried out in 2008-2010 at the Dept. of Mechanical Engineering of Politecnico di Milano in collaboration with the MUSP laboratory of Piacenza and the University of Parma. The research target of HY-LAP was the study and the general mechanical characterization of lap-joints of thin metal sheets made of light alloys (aluminum and magnesium) obtained by ultrasonic metal spot welding (USMW) and by USMW in combination with structural adhesives. In particular, the characterization of the technological set-up and parameters, of the static and fatigue mechanical behaviors and the metallurgical analysis of the area involved in the joining mechanisms were dealt with.

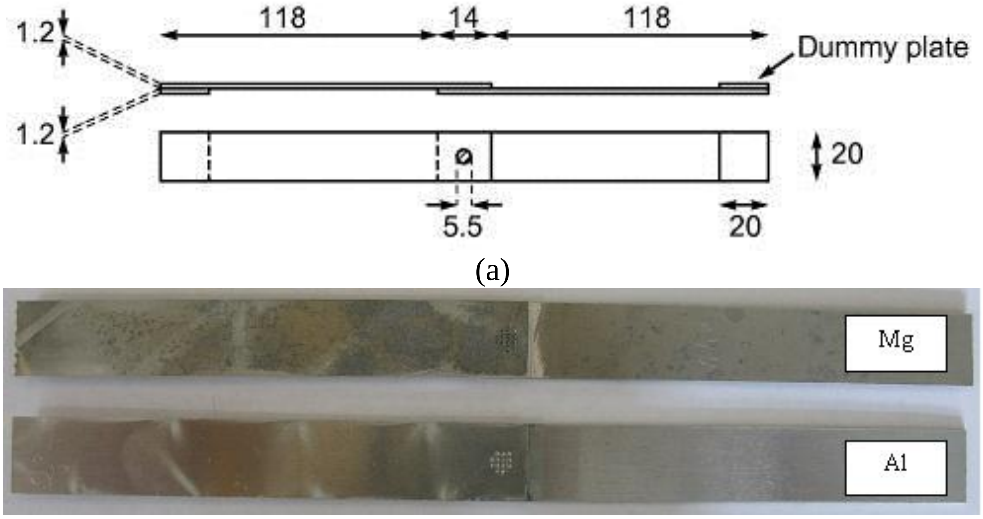
Some attractive aspects can be mentioned regarding the selected joining technologies applied to light alloys, particularly interesting for the automotive and the aerospace industrial fields. USMW is devoted to weld thin metal sheets (down to some hundredths of millimetre) made of similar or dissimilar couples of non-ferrous alloys like copper, aluminum and magnesium. It can count on a low energy consumption [1] and on a joining mechanism based on a solid state plastic deformation [2] which creates a very homogeneous metallic structure between the base materials, free from pores and characterized by refined grains and confined inclusions. Moreover, USMW can join also painted or covered sheet metals. Structural adhesives [3], instead, can join different materials, do not require particular mechanical preliminary operations, produce light joints, have a sealing effect, can electrically and thermally insulate, damp mechanical vibrations and allow process automation. On the other hand, they suffer some drawbacks as the sensibility to temperature and to surface preparation.

The technological variability, due to a series of relevant parameters, and a comparison between the static strengths of the USMW and of the hybrid lap-joints are available in [4] and [5], while the modeling of the static strength of tensile-shear lap-joints by means of the cohesive zone model can be found in [6]. It is worth noting that a significant synergic effect of USMW plus bonding on the static strength was observed for hybrid joints with respect to the single applications of USMW or bonding. This suggested to explore and compare the fatigue behaviors, too. The present paper is, then, focused on the experimental tensile-shear fatigue behavior, and the consequent failure analysis, of USMW and of hybrid lap-joints made of AA6022-T4 and AZ31B light alloys. A comparison of the fatigue performance to other spot welding techniques is also presented.

Experimental set-up

It is worth noting that the tensile-shear fatigue behavior of USMW lap-joints made of AA6022-T4 is reported elsewhere [7], so only a summary will be given here focusing, instead, on the fatigue behavior of hybrid joints. Moreover, the fatigue behavior of USMW lap-joints made of AZ31B is not available because not yet studied.

The fatigue behavior of both USMW and hybrid lap-joints was characterized, in this study, adopting the same geometry of specimens obtained by thin sheets made of 6022-T4 aluminum alloy (E=67200 MPa, $R_{p0.2}$=147 MPa, UTS=264 MPa and A%= 27.2%) and thin sheets made of AZ31B magnesium alloy (E=41900 MPa, $R_{p0.2}$=166.5 MPa, UTS=260 MPa and A%= 14%), characterized by dimensions equal to 20x132x1.2 mm^3 (Figure 1) and 14 mm overlapped (the specimens total length is 250 mm). In particular, the thin sheets were spot welded, for both UMSW and hybrid joints, applying the technological USMW parameters shown in Table 1 [5]. The hybrid joints were also bonded, all over the overlapped region, using the Loctite Hysol 9466® [8], a two components epoxy adhesive able to cure at room temperature (taking some days to achieve the maximum resistance) and producing tough, high peel resistance and high shear strength joints; this adhesive is resistant to a wide range of chemicals and solvents and is an excellent electrical insulator.



(a)

(b)

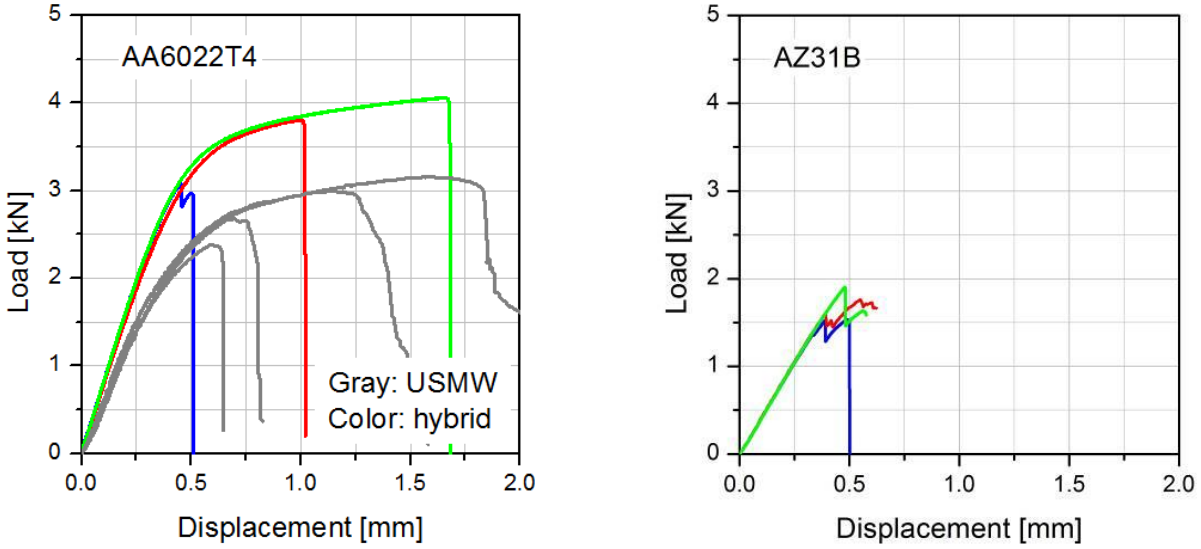
Fig. 1. (a) Specimen geometry; (b) example of specimens made of AA6022-T4 and AZ31B light alloys.

In order to choose the proper load levels for fatigue tests, static tensile-shear tests are carried out on four aluminum USMW joints, three aluminum hybrid joints and three magnesium hybrid lap-joints by means of a servo-hydraulic mono-axial INSTRON 8501 facility (maximum nominal load: 50 kN) under displacement-controlled condition. Figure 2 shows a comparison of the obtained tensile strength curves. In absolute terms, the static strength of aluminum hybrid lap-joints seems to be better than that of USMW aluminum joints which seems to be better than that of the magnesium hybrid ones. In particular, the UTS mean value of aluminum hybrid lap-joints resulted to be equal to

3.65 kN (standard deviation equal to 0.51 kN), equal to 2.8 kN (standard deviation equal to 0.34 kN) for USMW aluminum joints, while it resulted to be equal to 1.73 kN (standard deviation equal to 0.19 kN) for magnesium ones.

Table 1. Ultrasonic welding parameters for both USMW and hybrid lap-joints.

	AA6022-T4 lap-joints	AZ31B lap-joints
welding tip	round, diameter = 5.5 mm, knurled	round, diameter = 5.5 mm, knurled
vibration direction	perpendicular to the specimen longitudinal axis	perpendicular to the specimen longitudinal axis
vibration amplitude	40 µm	9 µm
vibration time	1.2 s	1.2 s
clamping force	1170 N	1170 N



(a) (b)

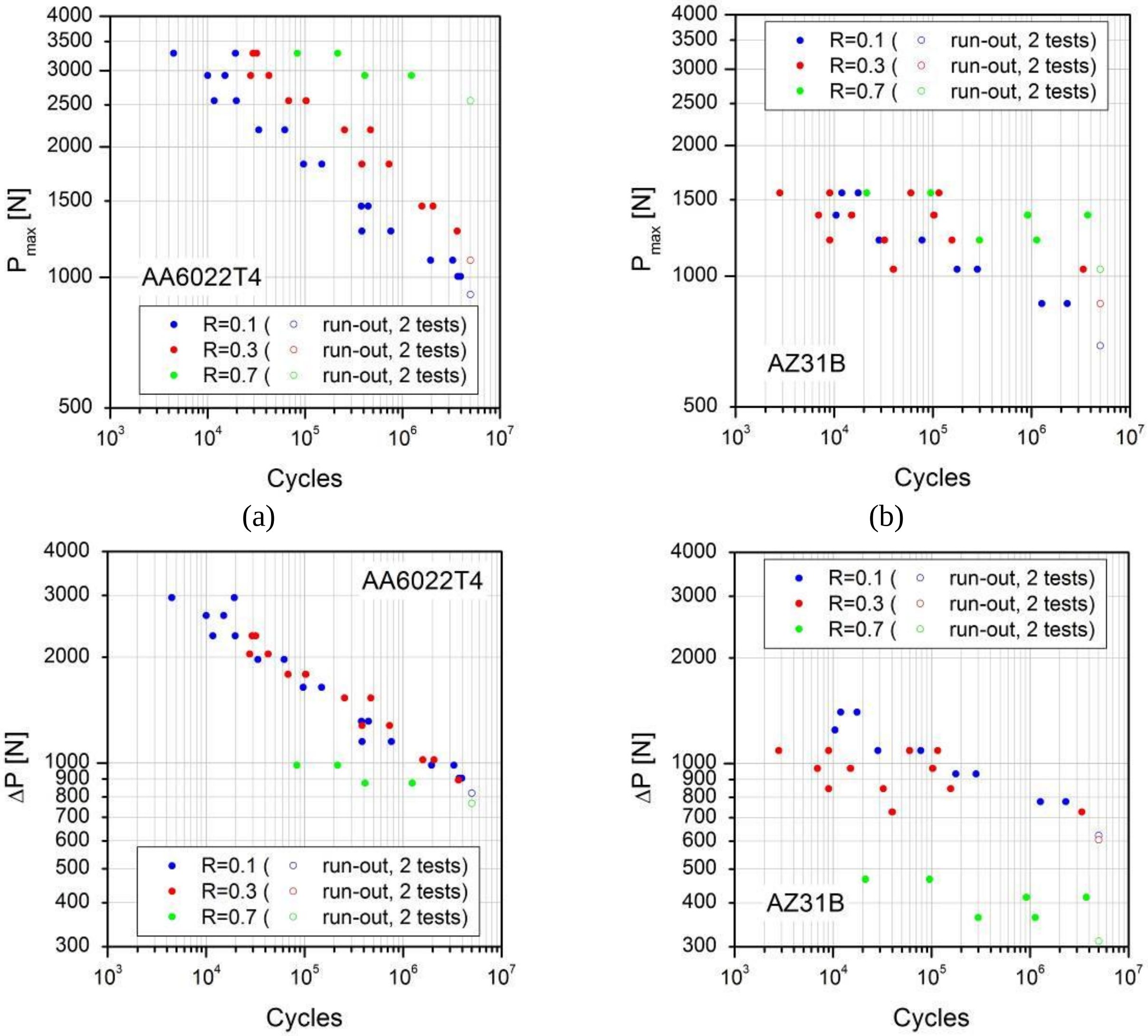
Fig. 2. Tensile strength of considered lap-joints: a) USMW and hybrid AA6022T4; b) hybrid AZ31B.

Fatigue behavior

Fatigue tests were carried out under force-controlled condition by means of the already mentioned INSTRON 8501 facility, at load ratio R equal to 0.1 for USMW aluminum joints and at load ratios R equal to 0.1, 0.3 and 0.7 for hybrid joints, a frequency equal to 50 Hz and assuming “run-out” specimens at $5x10^6$ cycles. In general, a specimen was considered broken when the displacement of the mobile cross member of the testing machine was increased of 0.5 mm with respect to the starting condition given by the maximum load. For all the joint types, the applied maximum load levels P_{max} varied between 90% and 10% of the corresponding mean static ultimate load, as derived in the previous Section.

Considering the hybrid joints, Figure 3 shows the obtained P_{max}-N and ΔP-N curves. In absolute terms, the 6022T4 hybrid joints seem to have a better fatigue performance than the AZ31B ones in terms of both the load entity and the standard deviation. In particular, considering the P_{max}-N curves, 6022T4 results show discernible behaviors at different stress ratios, while AZ31B ones tend to mix up.

Observing the same data in terms of ΔP-N curves, it is instead evident that R=0.1 and R=0.3 finite life results lie on the same line for both materials (even if AZ31B suffers again of the high standard deviation value), while R=0.7 finite life results seem to behave in a completely different way. This suggests that, for high applied mean stresses, a different failure mechanism takes place, in a way very similar to what could be observed by the author for clinching joining [9].
The endurance limits at $5x10^6$ cycles for R=0.1 and R=0.3 are also very similar, in absolute terms, for both the materials and equal to about 22.5% (AA6022T4) and 35% (AZ31B) of the ultimate stress. It is worth noting that this percentage value for AA6022T4 is lower than the typical one for resistance spot welding (i.e. typically 30÷40% in the case of R=0.05÷0.1 [10]), while the percentage value for AZ31B is well aligned with the one for resistance spot welding. Considering R=0.7, for AA6022T4 the percentage is again similar to that of R=0.1 and R=0.3 and equal to 21%, while the one for AZ31B is significantly lower and equal to 18%.



(a) (b)

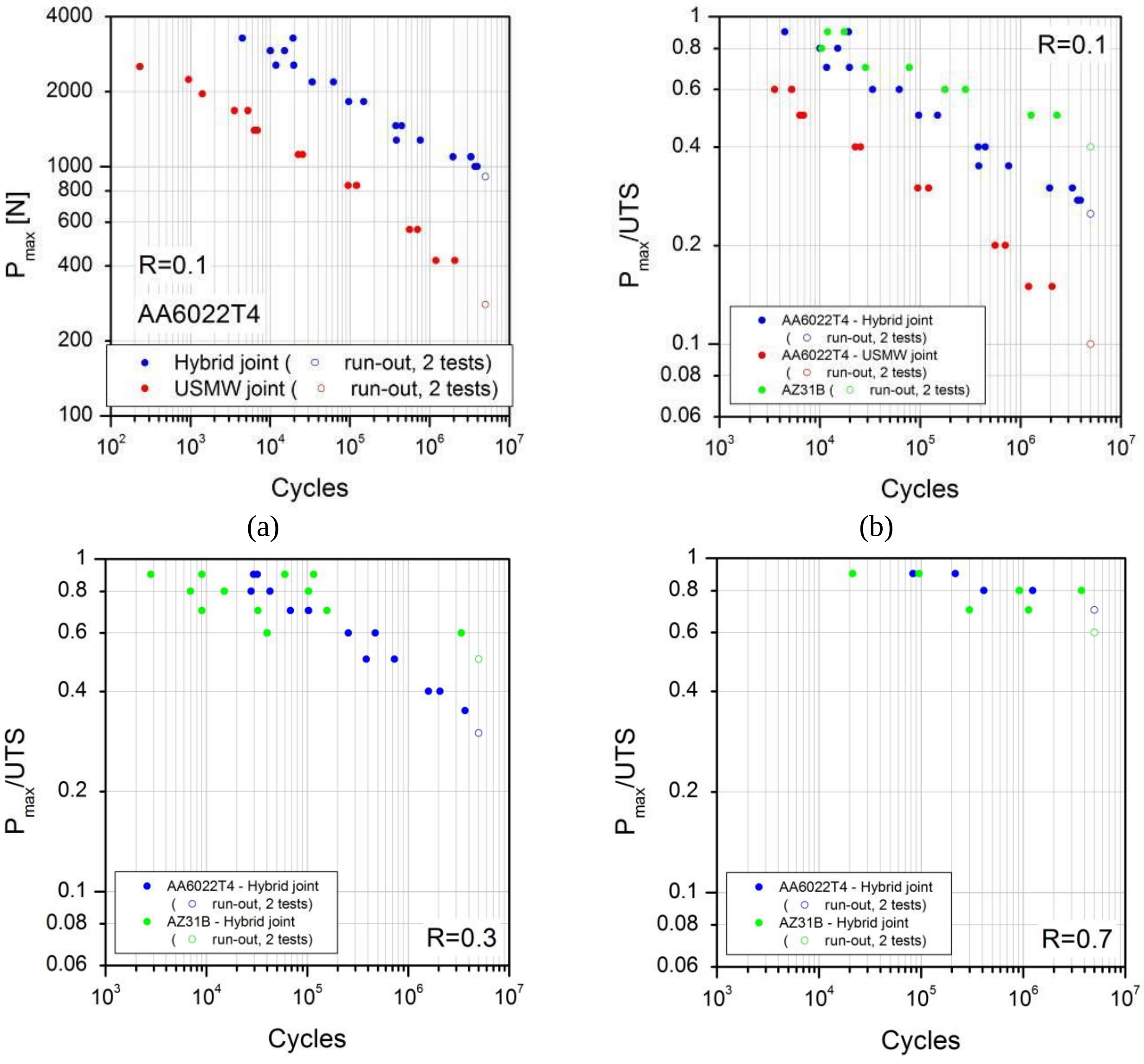
(c) (d)

Fig. 3. Fatigue S-N curves for AA6022T4 (a and c) and AZ31B (b and d) hybrid joints.

Figure 4a shows a comparison of the S-N curves obtained from AA6022T4 USMW and hybrid joints at R=0.1. As it can be seen, the performance of hybrid joints is significantly better than the one of USMW alone and it is also worth noting that, for USMW joints, the endurance limit at $5x10^6$

cycles was found to be about 10% of the ultimate tensile stress, a value significantly lower than the case of resistance spot welding. It is also interesting to note that the trends are definitely parallel: in particular, considering the hybrid joints, the applied maximum load levels can be doubled, with respect to USMW joints, at a given number of cycles.

Figure 4b shows the same comparison, in terms of the applied P_{max} normalized on the UTS, adding the S-N curve obtained from AZ31B hybrid joints at R=0.1. As it can be seen, in relative terms, AZ31B seems to have a better performance with respect to AA6022T4, especially considering low applied load levels. Figures 4c and 4d show the same analysis for the cases of R=0.3 and R=0.7: it is possible to observe that at R=0.3 the performance of magnesium joints is still slightly better than the one of aluminum ones (even if with a lower difference and a part from the huge scatter of magnesium data), while at R=0.7 the performance is comparable for the two materials.



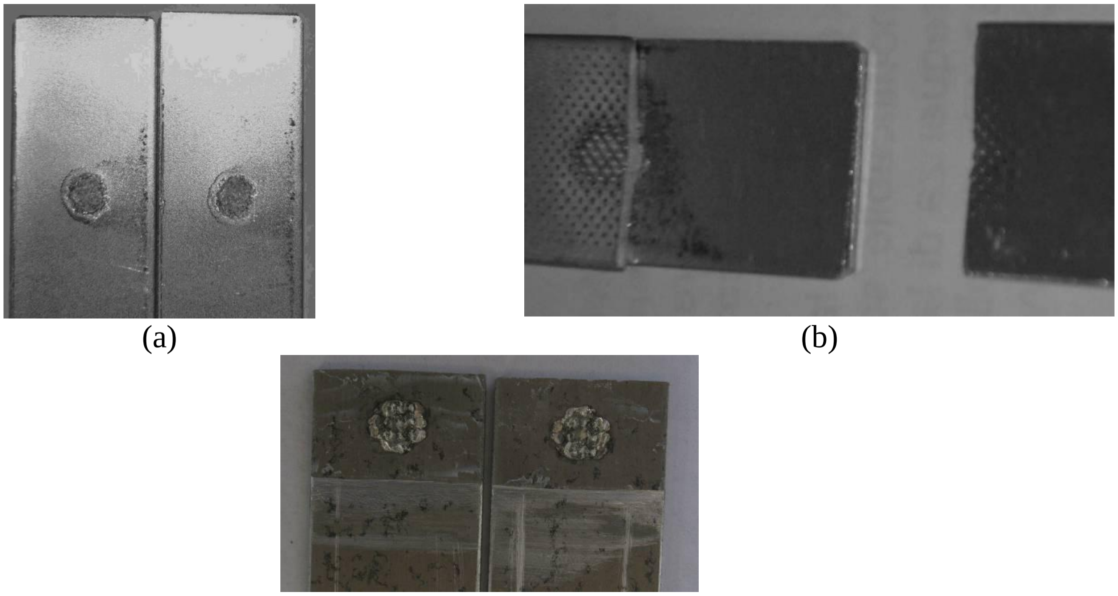
(a) (b)

(c) (d)

Fig. 4. Comparison of S-N curves for USMW and hybrid joints (a); comparison of S-N curves for AA6022T4 and AZ31B hybrid joints in normalized terms at R=0.1 (b); comparison of S-N curves for AA6022T4 and AZ31B hybrid joints in normalized terms at R=0.3 (c); comparison of S-N curves for AA6022T4 and AZ31B hybrid joints in normalized terms at R=0.7 (d).

Fatigue failure modes

In the case of USMW joints, the macroscopic analysis of all the failures allowed to point out two fundamental kinds of damage and consequent failure for both the materials. The first one, systematically observed for high applied loads, consisted in the shearing of the joint (Fig. 5a). It is interesting to add that this is also the typical failure observed in all the static tensile-shear tests. The second kind of failure, systematically observed for low applied loads, consisted in the initiation of a crack along the border of the weld with consequent propagation through the sheet metal (Fig. 5b). Both the failure modes resulted to be very similar to those typically observed in fatigue tensile-shear tests of lap-joints obtained by RSW ([10]-[11]). More details on this analysis can be found in [7]. Considering hybrid joints, very rarely the second failure mode could be observed: in particular, three specimens tested at low applied loads from both materials out of all the carried out tests. This could be explained due to the presence of the adhesive which, evidently and in most of the circumstances, had an influence on the failure mode, allowing the prevailing the shear damage (Fig. 5c shows an example from AZ31B joints) on the sheet one. Dedicated finite element analyses are being carried out in order to support this conclusion.

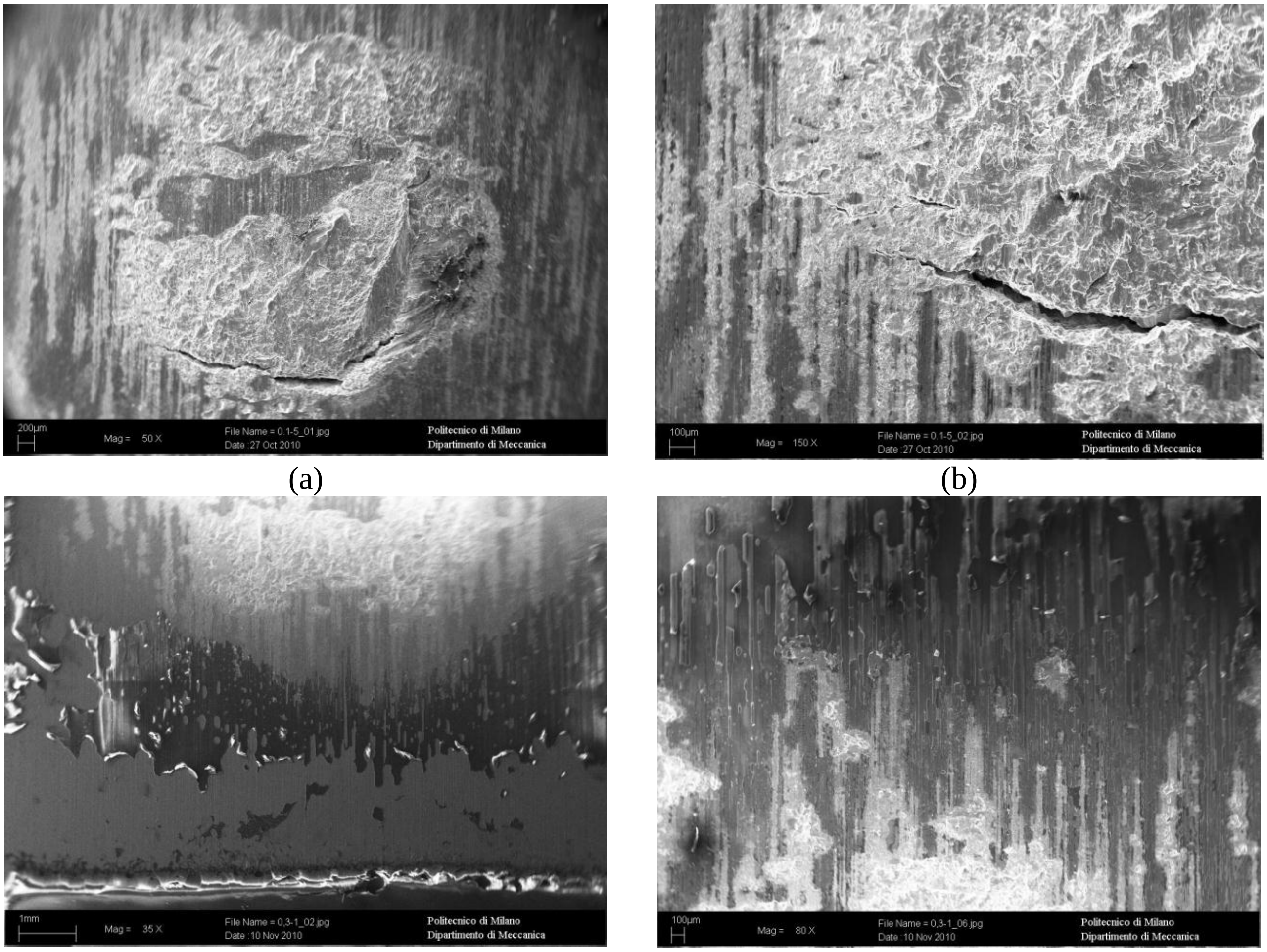

(a) (b)

(c)

Fig. 5. Macroscopic fatigue failure modes: a) and b) USMW aluminum joints; c) hybrid magnesium joints.

The fracture surfaces of all the tested specimens were also observed at the scan electron microscope (SEM). Regarding USMW joints, the analysis is reported in [7], while some interesting examples coming from the hybrid joints are described in the following. Figures 6a and 6b show the case of an aluminum hybrid joint tested at R=0.1 applying a low load level (50% of the UTS). As it can be seen and contrarily to USMW joints, the ultrasonic spot is not homogeneous: this resulted to be true for all the hybrid joints, suggesting an influence of the adhesive (which is spread on the whole surface of the jointed part before applying the ultrasonic spot welding) on the welding performance. It remains that, also in this condition, the hybrid joints showed better static and fatigue behaviors than USMW alone (Fig. 4a). Another important observation is the presence of a big crack and some smaller ones around it (Fig. 6b) in the position where the typical sheet fracture initiated in USMW joints. Most of the specimens showed the presence of such kind of cracks, but then failed for shearing. As already stated above, this is thought to be due, again, to the lowering influence of the adhesive on the driving force acting on the crack.

Figures 6c and 6d show two regions around the spot weld of an aluminum hybrid joint tested at R=0.3 applying a high load level (90% of the UTS). Starting from the spot border and moving radially (Fig.6c), it was possible to observe firstly a material damage in terms of tearing due to the separation of the material with the break of the adhesive. Then, in an almost continuous way, the adhesive remained glued to the surface (Fig. 6d). This behavior has to be yet understood.



(a) (b)

(c) (d)

Fig. 6. a) and b) Fracture surface of a specimen tested at R=0.1 applying a low load level; c) and d) regions around the spot weld of a specimen tested at R=0.3 applying a high load level.

Comparison to other spot joining techniques

Fatigue performance of aluminum USMW and hybrid joints is compared (Fig. 7) to the performance of other joining techniques available in the literature. In particular, relevant data for single spot joints made of Al-Mg-Si (i.e. 6xxx alloys like the one considered in the present research) subjected to fatigue tensile-shear loading at R = 0.1 and obtained by resistance spot welding [10] and self-pierce riveting [12] can be found. As it can be seen, the fatigue behaviour of USMW seems to be worse than the other considered joining techniques, while the hybrid joints show a behavior comparable to the resistance spot welding, without having the well-known drawbacks of this technology. This suggests that the hybrid joints realized by USMW and adhesive bonding can be considered a good alternative to USMW alone. Moreover, the application of USMW can be a good way to fix parts to be joined while the adhesive cures, allowing to work on pieces without the need to wait for its polymerization.

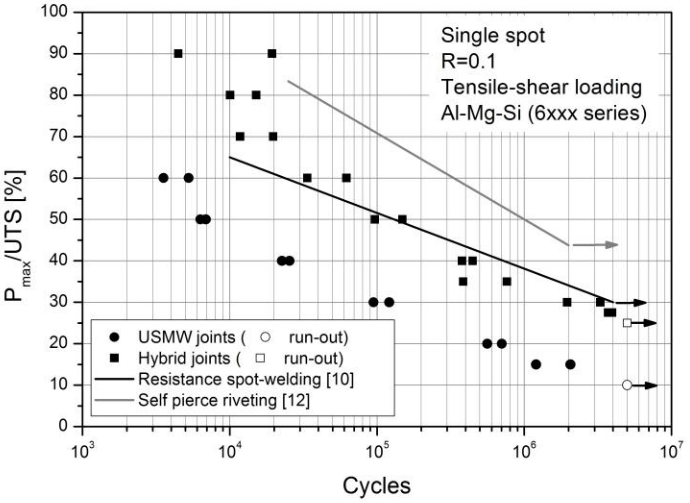


Fig. 7. Fatigue behaviour at R=0.1 of different spot joining technologies applied to AA6xxx.

Concluding remarks

The fatigue behavior of hybrid lap-joints (obtained by USMW plus adhesive bonding) made of AA6022T4 and AZ31B thin sheets was studied and compared to USMW alone. The results can be so summarized:

- in absolute terms, AA6022T4 joints seem to have a better fatigue performance than AZ31B ones in terms of both load entity and standard deviation;
- for high applied mean stresses (R=0.7), a different failure mechanism seems to take place with respect to R=0.1 and R=0.3;
- the performance of hybrid joints is significantly better than the one of USMW alone, while, in relative terms, AZ31B seems to have a better performance with respect to AA6022T4;
- contrarily to traditional spot welding, it seems that the presence of the adhesive allows just one failure mode (shear failure) for hybrid lap-joints.

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