Tensile-Shear Fatigue Behavior of Aluminum and Magnesium Lap-Joints obtained by Ultrasonic Welding and 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 of Piacenza and the University of Parma. In particular, the present study deals with the fatigue behavior of hybrid lap-joints (obtained by USMW plus adhesive bonding) made of light alloys thin sheets. Fatigue tests were carried out at different stress ratios (0.1, 0.3 and 0.7) finding that a different failure mechanism takes place with higher applied mean stresses. The S-N results then allowed to appreciate the better performance of the hybrid joints with respect to the application of USMW alone, while the direct comparison of the fatigue behaviors of AA6022T4 and AZ31B alloys allowed to draw some interesting conclusions.

Keywords: tensile-shear; lap-joint; aluminum alloy; magnesium alloy; ultrasonic metal welding; adhesive bonding; fatigue

1. Introduction

The present paper describes part of the results obtained in the frame 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 of Piacenza and the University of Parma. The research target of HY-LAP was the study and characterization of hybrid lap-joints obtained from thin metal sheets made of...
light alloys (aluminium and magnesium) by the application of UltraSonic Metal spot Welding (USMW) in combination with structural adhesives. This characterization involved 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 hybrid joining mechanism.

Some attractive aspects can be mentioned regarding the concurring technologies selected for the hybrid welding:
- 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, aluminium 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; USMW can join also painted or covered sheet metals; recently, this technology has been deeply studied by the authors ([3]-[4]);
- structural adhesives [5] 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 combination of the mentioned characteristics seems to be promising for joining light alloys, particularly interesting for the automotive and the aerospace industrial fields.

Other publications, regarding the results obtained during HY-LAP, include the technological performance variability [6] and the modeling of the static strength of tensile-shear lap-joints by means of the cohesive zone model [7]. The present paper is, instead, focused on the experimental tensile-shear fatigue behavior, and the consequent failure analysis, of hybrid lap-joints made of AA6022-T4 and AZ31B light alloys.

2. Experimental set-up

The fatigue behavior of hybrid lap-joints is characterized, in this study, adopting specimens obtained by spot welding and adhesive bonding 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, these thin sheets were spot welded applying the technological USMW parameters shown in Table 1 [6] and 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.

![Specimen geometry](image1.png)

**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 three aluminum and three magnesium lap-joints, produced applying the same parameters shown in Table 1, 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 lap-joints seems to be significantly better than that of magnesium ones. In particular, the UTS mean value of aluminum lap-joints resulted to be equal to 3.65 kN (standard deviation equal to 0.51 kN), 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.

| Parameter               | AA6022-T4 hybrid lap-joints | AZ31B hybrid 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                 |

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

3. Fatigue behaviour

Fatigue tests were carried out under force-controlled condition by means of the already mentioned INSTRON 8501 facility, at load ratios R equal to 0.1, 0.3 and 0.7, 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. The applied maximum load levels P_max varied between 90% and 10% of the mean static ultimate load, described in the previous Section, for both materials.

Figure 3 shows the obtained P_max-N and ΔP-N curves. In absolute terms, the 6022T4 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 P_max-N curves, 6022T4 results, as expected, 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 authors for clinching joining [9].

The endurance limits at 5x10^6 cycles for R=0.1 and R=0.3 are also very similar for both the materials and equal to about 22.5% (AA6022T4) and 35% (AZ31B) of the obtained ultimate stress. It is worth noting that this percentage value for AA6022T4 is lower than the typical one for resistance spot welding (i.e. 30÷40% in the case of R=0.05÷0.1 [10]-[11]), but higher than the one of USMW alone (i.e. about 10% in the case of R=0.1 [4]), 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%.

Figure 4a shows a comparison of the S-N curves obtained from AA6022T4 at R=0.1 joined by USMW alone [4] and by USMW plus adhesive. It is worth remarking that the technological parameters for the USMW welding were the same for the two joining approaches. As it can be seen, the performance of hybrid joints is significantly better than the one of USMW alone. It is also interesting to note that the trends are definitely parallel: in particular, the applied maximum load levels can be doubled 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 (for which no USMW alone curve was
determined). As it can be seen, in these terms, AZ31B seems to have a better performance with respect to AA6022T4, especially considering low applied load levels. This conclusion could be drawn also considering data at R=0.3, while at R=0.7 the two materials gave very similar results.

![Comparison of S-N curves for USMW alone and USMW plus adhesive (a); comparison of S-N curves for AA6022T4 and AZ31B in normalized terms (b).](image)

Fig. 4. Comparison of S-N curves for USMW alone and USMW plus adhesive (a); comparison of S-N curves for AA6022T4 and AZ31B in normalized terms (b).

### 4. Fatigue failure modes

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 consists in the joint shearing (Fig. 5a shows an example for AZ31B). 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 is consists in the initiation of a crack along the border of the weld with consequent propagation through the sheet metal (Fig. 5b shows again an example for AZ31B). Both the failure modes resulted to be very similar to those typically observed in tensile-shear tests of lap-joints obtained by RSW ([10], [12]) or USMW [4] on steel and aluminum thin sheets. Actually, the second failure mode should be prevented by the presence of the adhesive which, evidently, in some circumstances fails before the spot weld, allowing the instaurations of the typical fatigue damage phenomena observed in spot welding alone. A deeper analysis is being carried out in order to better characterize and describe these failure modes.

![Fatigue failure modes in the case of AZ31B.](image)

Fig. 5. Fatigue failure modes in the case of AZ31B.
5. Concluding remarks

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

- in absolute terms, the 6022T4 joints seem to have a better fatigue performance than the AZ31B ones in terms of both the load entity and the standard deviation;
- for high applied mean stresses ($R=0.7$), a different failure mechanism takes place in 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;
- two fundamental kinds of damage and consequent failure could be observed for both the materials.

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