Fatigue Performance of Friction Stir Weld-Bonded Al-Mg joints

Ricardo Maciel
Institution: LAETA, IDMEC, Instituto Superior Técnico, Universidade de Lisboa
Address: Av. Rovisco Pais, 1049-001, Lisboa, Portugal

Tiago Bento
Institution: LAETA, IDMEC, Instituto Superior Técnico, Universidade de Lisboa
Address: Av. Rovisco Pais, 1049-001 Lisboa, Portugal.

Daniel F.O. Braga
Institution: LAETA, IDMEC, Instituto Superior Técnico, Universidade de Lisboa
Address: Av. Rovisco Pais, 1049-001 Lisboa, Portugal.

Lucas F.M. da Silva
Institution: FEUP - Campus da FEUP
Address: Rua Dr. Roberto Frias, s/n, 4200-465, Porto, Portugal

Pedro M.G.P. Moreira
INEGI, Campus da FEUP
Address: Rua Dr. Roberto Frias, 400 4200-465 Porto, Portugal

Virgínia Infante
Institution: LAETA, IDMEC, Instituto Superior Técnico, Universidade de Lisboa
Address: Av. Rovisco Pais, 1049-001 Lisboa, Portugal

ABSTRACT

The need for weight reduction and leaner manufacturing and assembly processes in aircraft construction has led to the pursuit of alternative joining processes to conventional riveting. One such technology that has been considered for this application is friction stir welding (FSW). Since it is a solid- state joining method, it results in high performing joints in a wide range of materials while avoiding overlap lengths and added weight from fasteners, crack stoppers, doublers, etc. However, the adoption of this technology to the assembly of large fuselage shell components is challenging, due to geometric tolerance management requirements. A hybrid friction stir weld-bonding method combining overlap friction stir welding and adhesive bonding (AB) has been proposed as an alternative, aims to incorporate properties and characteristics of both joining technologies, as well as improving damage tolerance. Fatigue performance of single lap joints of AA6082-T6 Al-Mg alloy was assessed and benchmarked against FSW overlap and hybrid friction stir weld-bonding joints. Significant strength and ductility increase were achieved through the hybridization of the overlap FSW joints. Fatigue strength of the hybrid joints was also higher than FSW overlap joints.

Palavras-chave: Adhesive bonding (AB), FSW.

1 INTRODUCTION

In this work fatigue performance of friction stir weld-bonded single lap joints of AA6082-T6 Al-Mg alloy was assessed and benchmarked against FSW overlap and adhesive bonded joints.

Nomenclature

AB Adhesive bonding
FS Friction stir.
FSW Friction stir welding. SLJ
Single lap joint
PAA Phosphoric Acid Anodization
UTS Ultimate Tensile Strength

In structural design, and particularly in the aerospace industry, there is a constant search for lighter, cheaper structures with at least equal reliability. Beyond economic design drivers (lower manufacturing and operational costs), the reduction of polluting emissions pushes towards lighter structures. Operational costs constitute most of the costs throughout the lifetime of aircrafts, with fuel consumption being the main culprit [1]. Therefore, weight reduction is one of the top priorities in structural design, since it results in cost savings. In addition, there should be a constant effort to lower production and maintenance costs.

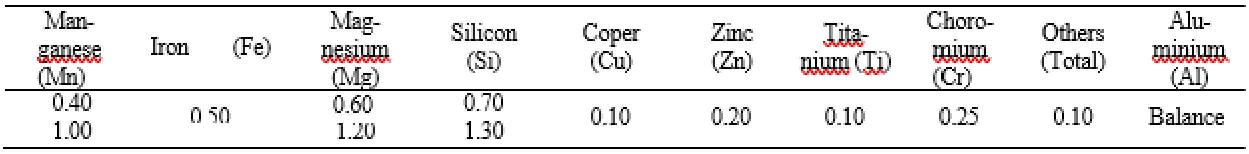
To achieve these goals, innovative manufacturing and assembly processes are required in aircraft manufacturing. However, the aeronautical industry is highly regulated and requires constant certifications and long validation processes of such methods before they can be applied on aircrafts. As a result, the main technology used in joints between structural parts is still riveting. Although the replacement of riveted structural connections by welded and weld-bonded joints presents many challenges, such as avoiding defects that could lead to structural failure, it has potential to provide a major leap in the aerospace world. Within welding technologies, Friction Stir Welding (FSW) has been singled out as one of the most promising technologies for this purpose [2]. Part of the disruptive potential of friction stir welding (FSW) applied to fuselage shell assembly [4, 5], is due to its capacity to weld precipitated hardened alloys (e.g., AA2024 aluminium alloy), creating high performing joints, with lower distortions than conventional fusion welding processes and easier weld quality control. In its most basic form, FSW is performed with a tool composed of shoulder and pin, fractioning and mixing the material to weld. In FSW, the tool is inserted while in rotation into the pieces to be welded and transverses along the weld line. The shoulder is mainly responsible for providing heat from friction onto the sheets or plates to be welded, while the pin’s main job is mixing the materials to be joined. Alternatively, overlap FSW can be combined with adhesive bonding (AB) to increase the effective overlap, decreasing the out-of-plane bending and increasing joint strength. Chowdbury et al. [6] introduced an adhesive layer in magnesium-to-aluminum friction stir (FS) spot welded joints. Both quasi-static and fatigue strength of the joints were increased.

In this study, a hybrid joining method combining FSW overlap and AB, FS weld-bonding, was applied to an aluminium alloy AA6082-T6. This alloy containing magnesium (Mg) and silicon (Si) and is widely used in transportation and construction applications. The FSW and FS weld-bonded parameters used in this study were selected from a combination of trial and error and previous experience in manufacturing FSW lap joints. A base set of FSW process parameters were selected, where only the vertical force was varied. Both quasi-static and constant amplitude cyclic loading was accessed. Adhesive bonded joints were also made and tested for benchmarking purposes.

2 EXPERIMENTAL DETAILS

Single lap joints (SLJs) were made from 2.0 mm thick AA6082 – T6. Plates of 300x150x2 mm were used to produce FSW and FS weld-bonded single lap joints. For adhesive bonded joints, each substrate was 25x150x2 mm. The chemical composition of this alloy, according to the supplier provided material data sheet is presented in Table 1 and relevant mechanical properties are shown in Table 2.

Table 1: Chemical composition of AA6082-T6 (% mass) [8]



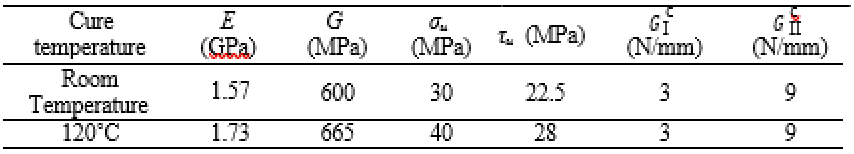
Manganese (Mn)	Iron (Fe)	Magnesium (Mg)	Silicon (Si)	Coper (Cu)	Zinc (Zn)	Titanium (Ti)	Choromium (Cr)	Others (Total)	Aluminium (Al)
0.40 1.00	0.50	0.60 1.20	0.70 1.30	0.10	0.20	0.10	0.25	0.10	Balance

Table 2: Mechanical Properties of AA6082-T6 [8]

Density (kg/m³)	Vickers Hardness	Ultimate Tensile Strength (MPa)	Yield Tensile Strength (MPa)	Elongation at Break (%)
2700	95	290	250	10

The adhesive used in this study was the Araldite 420 A/B, a two-component epoxy adhesive. This adhesive is capable of both room temperature curing and accelerated high temperature curing [9]. This epoxy is a high strength and toughness adhesive, suitable to bond a high variety of materials and its flash point is superior to 300ºC. Table 3 summarizes the mechanical properties of the structural adhesive, as presented in [7]. with curing temperature.

Table 3: Summary of Araldite 420 mechanical properties [10]



Cure temperature	E (GPa)	G (MPa)	σ_u (MPa)	τ_u (MPa)	G_I^c (N/mm)	G_{II}^c (N/mm)
Room Temperature	1.57	600	30	22.5	3	9
120°C	1.73	665	40	28	3	9

In FS weld-bonded joints, the welding procedure is made following adhesive lay-up and joint closing with the adhesive still in an uncured state. The adhesive is subjected to a temperature peak aiding curing but is also left to cure for at least 7 days at room temperature. The adhesive was applied on the bottom plate of the joints with a pistol equipped with a nozzle mixer that combined both epoxy parts. A series of 0.2 mm calibrated metal strips were strategically positioned in-between the shim plates to guarantee a uniform adhesive thickness along the weld line.

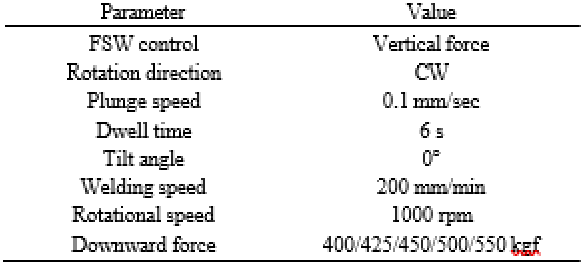
Surfaces to be bonded in FS weld-bonded joints were degreased and sanded followed by chemical treatment with 3M AC-130, which is a sol-gel anodization replacement normally intended for aeronautical repair [11]. It promotes adhesion through the formation of a surface oxide layer. This treatment is faster than conventional phosphoric acid anodization (PAA) and results in similar bonding strength. Besides this, it is easier to perform in relatively large areas, as is the case of FS weld-bonded joints, as it requires less laboratory equipment. The adhesive bonded specimens were degreased and sanded and then chemically treated through PAA.

Maciel et al.in [7] studied both 20 mm and 40 mm overlap hybrid joints with the same parameters and concluded that fracture strength and ductility is considerably higher with a bigger overlap area . The 40 mm overlap chosen is still significantly smaller than current fastened joint designs in aeronautical fuselages, such as the case of longitudinal fuselage joints, which will lead to weight savings [12].

The welds were performed on a dedicated FSW ESAB® (Gothenburg, Sweden) LEGIO 3UL numerical control machine. The machine is capable of welding both in displacement control, as well as load control. The machine integrates a cooling system for the welding tool.

The tool used is composed by a 5 mm diameter cylindrical threaded pin attached to a 16 mm diameter grooved shoulder. The probe length was set to 3 mm to promote an optimal mixture in the stirring zone, Figure 2b. A set of process parameters for both FSW and FSW+AB joints were selected from literature review and past experience. The FSW process parameters listed in the Table 4, with only the plunging force being varied.

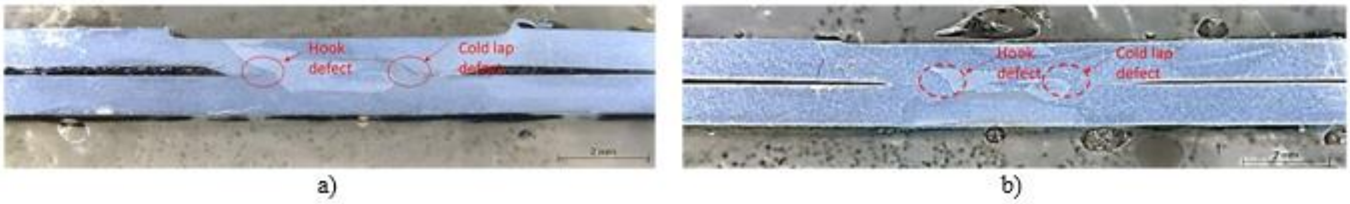
Table 4: Parameters used to perform joints produced.



Parameter	Value
FSW control	Vertical force
Rotation direction	CW
Plunge speed	0.1 mm/sec
Dwell time	6 s
Tilt angle	0°
Welding speed	200 mm/min
Rotational speed	1000 rpm
Downward force	400/425/450/500/550 kgf

Upon manufacturing, FSW and FSW+AB joints were assessed through optical microscopy for possible defects. The resulting macrostructures presented a hook defect at advancing side edge of the weld. This phenomenon is a result of the upward flow of material generated in the advancing side, which at the same is time transported by the tool pin pushing up a zone of un-welded material and curving that section up. This defect was shown to be present in all the manufactured joints in this experiment independently of the applied vertical load. However, the increase in plunging force showed to reduce the size of this defect. Another visible defect is the cold lap defect. This defect appears in the retreating side, and it is a consequence of the initial upward flow under shearing effect of the pin followed by a downward flow in order to fill the space at the bottom of the pin. Figure 1 a) show the defects mentioned above for a vertical load of 400 kgf. Both defects result in thinning of the SLJ joints and degradation of mechanical performance because they result in stress concentration areas. Besides the reduction of the cross-section, the shape and direction of the hook defect acts as a failure initiation location and is the main reason for the lower strength of overlap FSW joints when compared with butt-joints.

Figure 1: Macrostructure overall view of hybrid overlap joint with a) vertical load of 400 kgf and b) 450 kgf.



a) b)

In FSW+AB joints, the lower plunging force (400 kgf) also resulted in an inconsistent adhesive thickness, with accumulation of the adhesive at weld edges. This also resulted in higher tool penetration in the workpiece, leading to section reduction and formation of flash. The steering process was more efficient in the case of load 450 kgf as shown in Figure 1 b).

Each joint configuration was tensile tested with three specimens. Quasi-static loading was made at 1 mm/min crosshead speed. Given the joint design, the loaded side of SLJs was the advancing side, as in [10]. Failure occurred under two modes, modes I e II. The average values of maximum load were calculated for all the different configurations to estimate the ultimate tensile strength (UTS). The joint remote section was used to calculate the stress in the joint and consequently the UTS.

In aircraft structures fatigue performance is of paramount importance. So, hybrid specimens, FSW and AB specimens, were subjected to cyclic loading at R = 0.1. The run-out criterion was set at 2 × 106 cycles. Four or five stress levels with three specimens each were used to plot the stress range versus number of cycle's curves. The tests were performed in the INSTRON R 8874 machine shown in Figure 5.

A probabilistic fatigue model based on the Weibull distribution, which allows the correlation of the experimental stress-life data, showed in the Eqn. 1, was used in the fatigue lifetime analysis. ProFatigue software was used to established the probabilistic stress life curves [10, 13].

$$F(\log(N_f);\log(\Delta\sigma)) = p = 1 - \exp\left[-\left(\frac{V-\lambda}{\delta}\right)^{\beta}\right]$$

where,

$$V = (\log(N_f) - B) \times (\log(\Delta\sigma) - C)$$

and

$$V \geq \lambda$$

where Nf is the number of cycles at failure; Δσ is the stress range level; *F*() is the cumulative probability distribution function of Nf for a given Δσ, V the normalized variable, B = log (N0), N0 being a threshold value of lifetime; C = log (Δσ0), Δσ0 being the endurance fatigue limit; and β, δ, and λ are non-dimensional model parameters. β being the Weibull shape parameter, δ the Weibull scale parameter, and λ the Weibull location parameter defining the position of the zero-percentile curve.

3 EXPERIMENTAL RESULTS AND DISCURSIONS

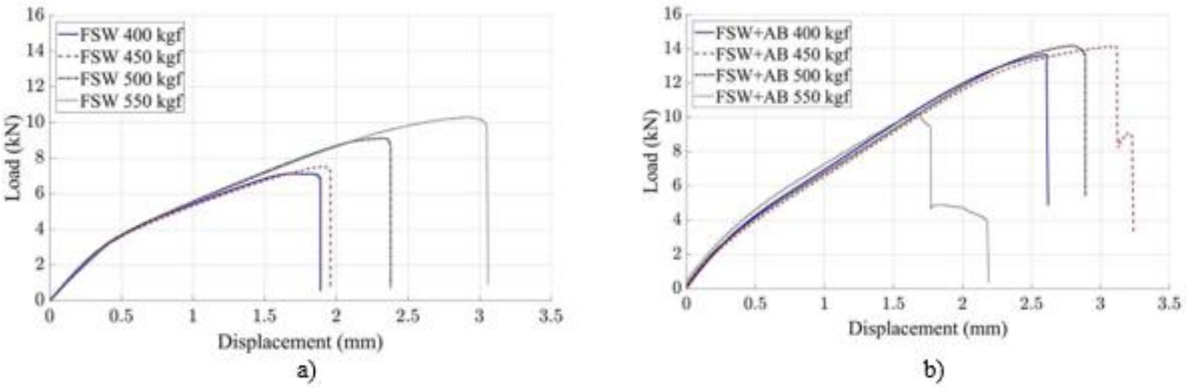
Overlap FSW and hybrid joints subjected to quasi-static tensile loading showed two distinct failure modes, as in [14]. In the first fracture mode, mode I, the fracture originates in the retreating side of the weld, initiated in the cold lap defect, Figure 2 a). This failure mode occurs in FSW joints with 550 kgf and FSW+AB with 500 and 550 kgf where the hook defect is much smaller making it less critical. The second fracture mode, mode II, was present in the majority of the joints and was is in accordance with numerical analysis [9]. In this mode the fracture occurred in the advancing side of the weld, initiated in the hook defect, Figure 2 b).

Figure 2: Different views of mode II failure in a joint.

a) b)

Figure 3 presents representative load displacement curves of FSW a) and FSW+AB b) joints for each downward force used. The increase in downward force, is followed by an increase in joint strength in FSW joints. This result is in accordance with the microscopic and microhardness analysis [7]. The highest strength joint coincided with the lowest size of the hook defect and with higher overall hardness. Along with presenting the highest strength the 550 kgf FSW joint also showed the highest ductility. However, in the case of the hybrid joints, the increment in force is not always followed by an improvement in joint performance. Above 450 kgf of downward force, strength and ductility diminish which may be due to the high force leading to excessive adhesive thinning or possibly the higher temperature may have led to a degradation of the surface to bond and/or the adhesive. The FSW+AB showed higher strength and ductility than FSW joints for all plunging forces used.

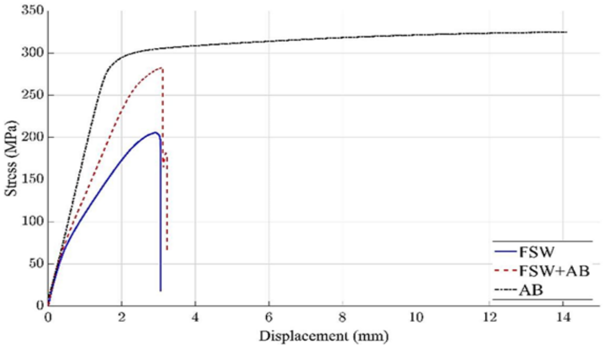
Figure 3: a) Load-displacement comparison of the FSW specimens and b) Load-displacement comparison of the hybrid specimens



a)

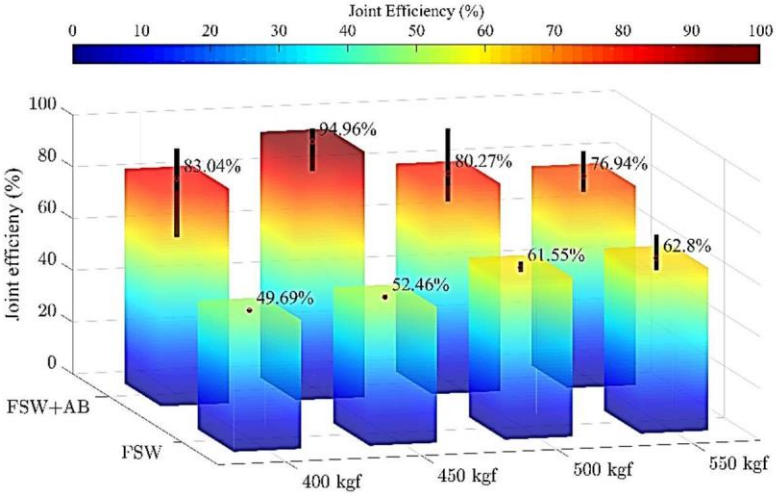
b)

Both the highest strength and ductility was achieved with 450 kgf for the FSW+AB joints which might be considered as an inflection point in joint performance maintaining all the other parameters constant. In Figure 4, the remote stress displacement curve is presented for the highest performing FSW (550 kgf), the highest performing FSW+AB (450 kgf) and adhesive bonded joints. Remote stress was calculated using the remote joint section as in previous works[10, 15].



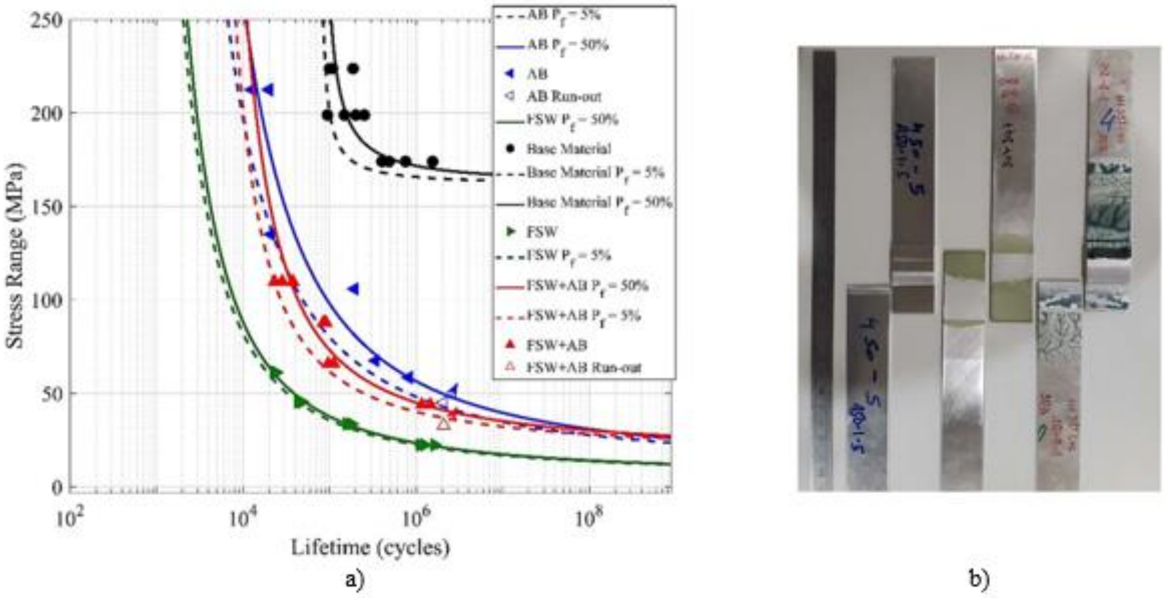
Joint efficiency was calculated by dividing the maximum strength of each joint by the base material UTS. Figure 5 presents the joint strength for each joint including the dispersion in the results. It is observable that the hybridization process results in an improvement between 20-30 % in most cases. The dispersion was shown to be higher in FSW+AB joints which may be related to variations in surface treatment, as the joint strength is very sensitive to the bonding strength.

Figure 4: Joint efficiency with dispersion for all configurations tested.



To assess the fatigue strength of FSW+AB joints, hybrid and FSW joints made with 450 kgf downward force together with adhesive bonded joints were submitted to cyclic loading. with the applied load ration was R = 0.1. In Figure 6 a), the experimental data for these joints in the S-N field along with the 50% and 5% probability of failure curves are plotted. As in the quasi-static loading, the addition of an adhesive interlayer to the FSW overlap welds resulted in an improved performance. As in quasi-static this difference in performance may be explained by the effect of the hook defect in the FSW joints, which acts as a crack like defect loaded in primarily in mode I. In FSW+AB the entire overlap is bonded and as such the edges of the weld become less critical. In addition to eliminating the mentioned effect in the FSW-only joints, the adhesive interlayer by itself has very good fatigue performance due to its high ductility and continuous layer with no stress concentrations.

Figure 5: a) p-S-N curves of the three joint types: Adhesive bonding, hybrid and FSW, b) failure modes



In the fatigue test the observed failure modes (see Figure 6 b) were like those presented in the quasi-static tensile test with specimens breaking through the advancing side for both the FSW and hybrid joints. This failure mode was consistent in all load levels. Given the optical microscopy analysis, this failure mode was expected, as the hook defect is a crack like defect perpendicular to the loading direction, making it even more critical in cyclically loading.

4 CONCLUSIONS

Friction stir weld-bonding was studied regarding quasi-static and fatigue performance. This hybrid joining process was benchmarked against more established joining methods, namely FSW and adhesive bonding.

Regarding the quasi-static tests, the FSW joints were proven to have lower strength and ductility when compared with the hybrid joints. In the FSW, the strength and ductility increased continuously with the increase in downward force from 400 to 550 kgf. However, in the hybrid ones, this increase in performance was only verified from the 400 up until the 450 kgf diminishing for higher levels of plunging force. There was a significant correlation between FSW joints cross-section macrostructure and the performance in quasi-static and fatigue testing. In FSW, the higher strength and ductility was correlated with the smaller size of the hook defect. In FSW+AB the joints performance is dictated by the adhesive strength and the quality of the surface treatment. The highest joint efficiency achieved was 94.96%.

FSW and FSW+AB joints made with 450kgf were then subjected to cyclic loading at constant amplitude at R = 0.1, in order to plot the Wöhler curves. Similar trends as in quasi-static loading were observed while cyclic loading, with the adhesive bonded joints having the highest fatigue strength, followed by the hybrid and the lowest performing being the overlap FSW joints.

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