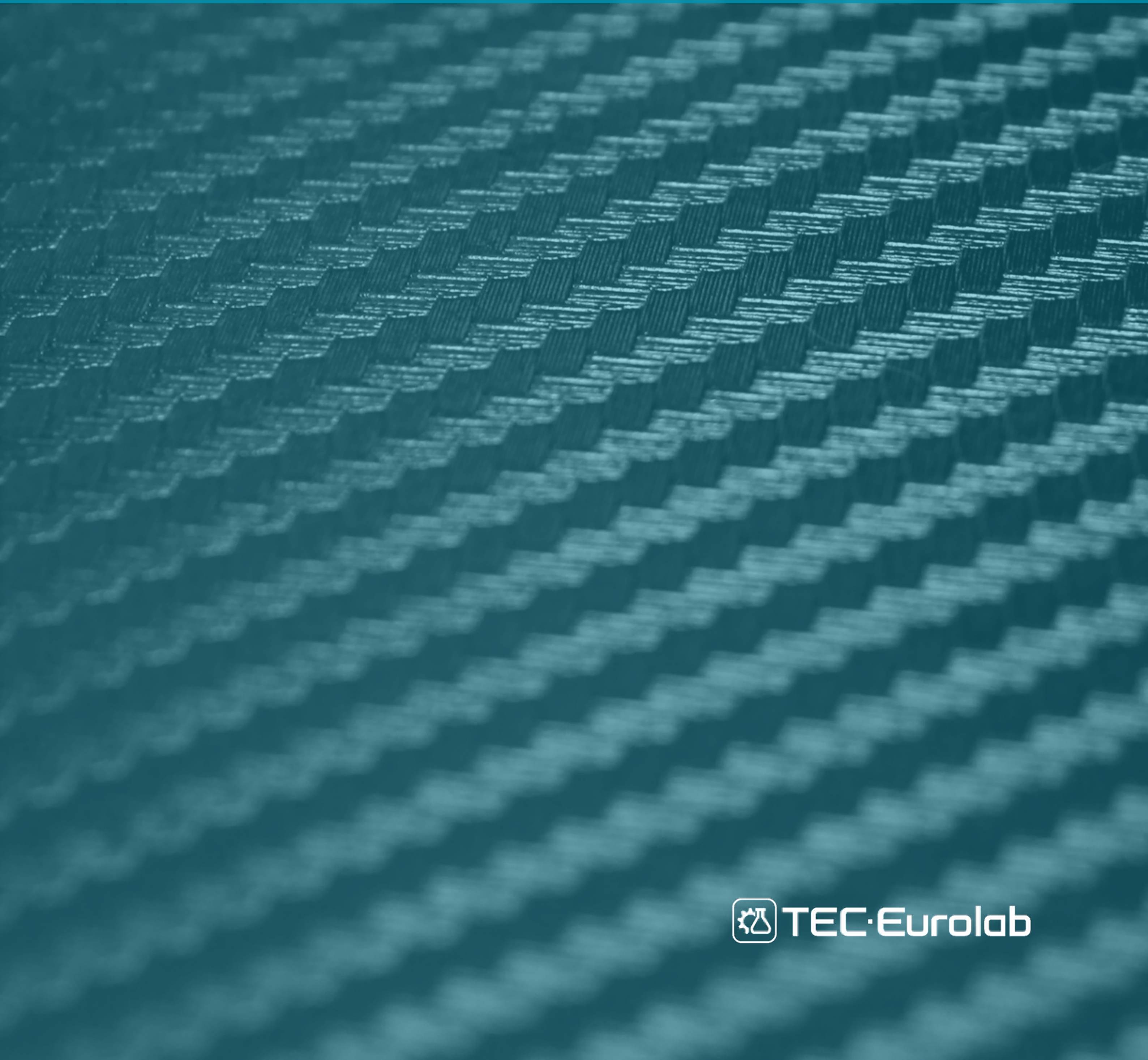
CASE STUDY

STATIC AND FATIGUE ANALYSIS OF BONDED ALUMINIUM – COMPOSITE SINGLE-LAP-JOINTS



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INTRODUCTION

What are the tests that allow to determine the best performance of a composite material designed and manufactured for a specific application? What are the production technologies that give rise to increasingly high-performance components?

The use of composite materials in modern design is going through a phase of increasing complexity.
There's a wide range of industrial sectors where composites find their application, from automotive, aerospace, nautical up to the sports sector, and are strongly impacted by the development of new and increasingly performing material combinations, such as the introduction of new production technologies, like additive manufacturing. TEC Eurolab, through his know-how on destructive and non-destructive tests, can **support customers in the design and validation process of materials which need to meet specific needs such as lightness, mechanical strength, impact energy absorption, fatigue strength, chemical resistance and atmospheric aging.**
The aim of TEC Eurolab is to support R&D, design and production departments to increase confindence in selection and use of new materials and technologies. Due to the broad range of services offered, **TEC Eurolab supports companies operating in different sectors that work in the composite materials supply chain, from resin and prepreg producers, to companies dealing with molding, lamination and engineering activities.**

Through this case study we will investigate the behavior of an aluminum-composite system joined by bonding.

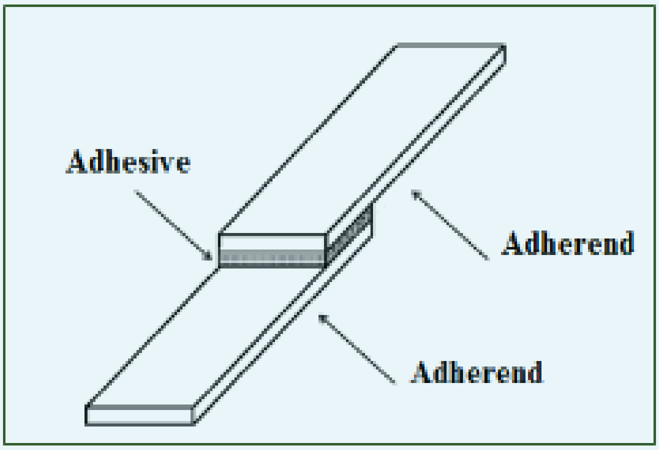

Fig 1 - Schematic of Aluminium 6082-T6 and CFRP specimen used for fatigue characterization

The aim of the testing activity was to **characterize with fatigue tests a bonded joint between 6082-T6 aluminum and a CFRP composite**, using Single-Lap-Point specimens (single overlap configuration). Bonding was performed by means of a 0.3 mm adhesive film consisting of epoxy matrix and glass fiber.
To obtain a good prediction of the failure load of a joint, it could be considered a four key factors model;

1) Knowledge of the failure modes of the joint
2) Knowledge of material behavior
3) Knowledge of the stress/strain state in the joint
4) Correct application of a valid test mode, leading to failure of the joint.

A further complication to the production process of bonded multi-materials joints comes from the **large number of variables that affect the integrity of the joint itself, among them the configuration of the joint, the configuration of the loading modes, the type of adhesive used and the mode of surface preparation of the elements to be connected.**

EXPERIMENTAL ACTIVITIES

The objective of the activity was to **evaluate the mechanical properties and fatigue strength of the above mentioned joints, made according to ASTM D1002.**
More specifically, the testing activity was intended to characterize between specimens made without induced defects, specimens with the addition of a defect between the adhesive layer and the adherent and specimens subjected to thermal aging.
For each of the three types of specimens identified, the following charateristics were derived:

1) Maximum failure stress (τmax = бmin tensile tests), applying a ramp in displacement control with crosshead speed of 2mm/min
2) Wöhler S-N curve, obtained at 5Hz frequency and at R stress ratio equal to 0.1
3) Fatigue limit (τ fatigue limit) obtained with Staircase method
4) Failure mode characterized with visual examination
5) Safety coefficient and maximum б allowable.

The accuracy of a bonding test is highly dependent on the preparation process of the test specimens and the methods with which the individual steps are carried out.

- Dimensioning of the specimens and of the test panels, in particular the maximum allowable overlap length determined by the following relation: $L = Fty \times t / \tau$ where L is the maximum overlap length, Fty is the yield strength of the aluminum, τ is half of the lap shear strengh of the adhesive on the aluminum.
- Surface preparation of the aluminum by sandblasting and subsequent cleaning of the surface with acetone and paper.
- Deposition of the adhesive film on the aluminum surface (during this step half of the test pieces were prepared by introducing a controlled defect in the overlap area)
- Deposition of the individual prepreg plies having the same dimensions as the aluminum test panels
- Autoclaving for 150 minutes at 135 C°.
- Water laser cutting of the test panels
- Application of the tabs and numbering of each sample

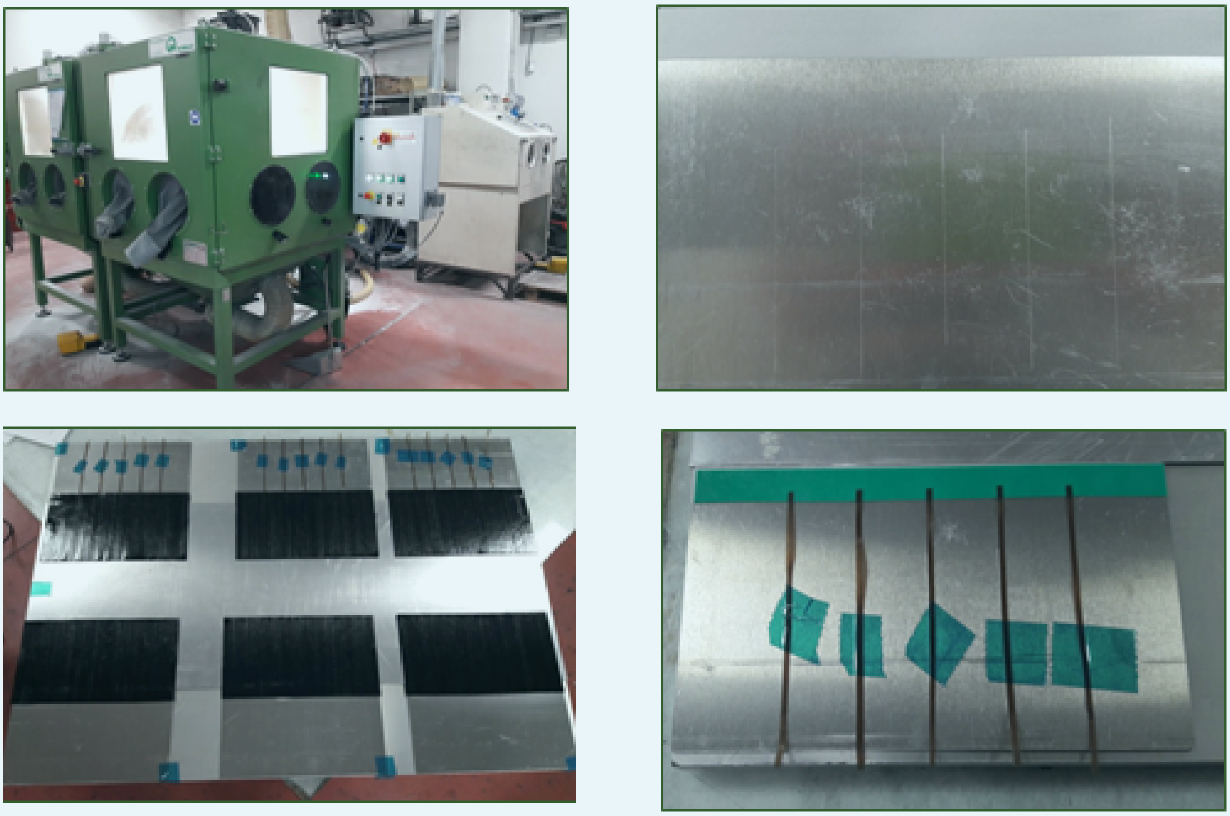

fig. 2 Preparation steps for the lap-shear specimens used in the test campaign

Tensile tests

Once the preparation of the specimens was completed, **the testing activity proceeded with the tensile tests**. Three samples were tested for each different type of specimen (without defect, with defect and without defect subjected to thermal aging) using a universal testing electromechanical machine with a load capacity of 100 kN, applying a ramp in displacement control with crosshead speed of 2mm/min.

ID provino		a_0 [mm]	b_0 [mm]	S_0 [mm^2]	Lap Shear [N]	Lap Shear [MPa]
Campioni senza difetto	3	15	25	375	8984	23,9
	8	15	25	375	7367	19,6
	14	15	25	375	9196	24,5
Campioni con difetto	D3	15	25	375	7025	18,7
	D10	15	25	375	7257	19,3
	D15	15	25	375	6922	18,4
Campioni senza difetto invecchiati termicamente	20	15	25	375	8902	23,7
	21	15	25	375	8554	22,8
	24	15	25	375	8374	22,3

Fig. 3 experimental results for tensile tests

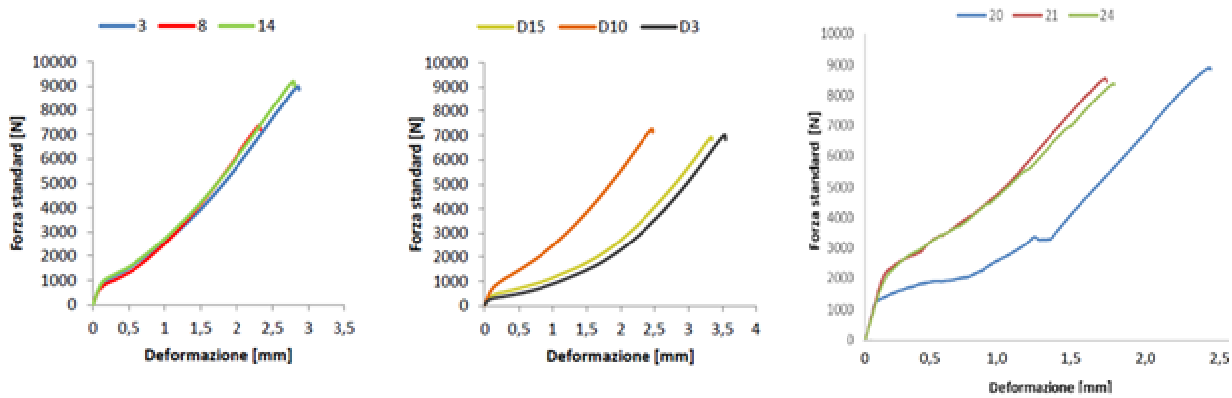

Fig.4 Load-strain graph for the tested sample sets

Fatigue tests

Fatigue tests to obtain Wöhler S-N curves, were performed with an universal testing electromechanical machine with a load capacity of 15 kN. All tests were performed under force control, choosing a sinusoidal waveform with frequency 5 Hz and a stress ratio of 0.1 (R= σmin/ σmax).

The Wöhler S-N curve is obtained by decreasing load cycles starting from a maximum load corresponding to 60% of the average lap shear value, until the fatigue limit is reached, i.e. the б max value for which there is no failure of the bonded joint. Generally, S-N curves have a horizontal asymptote that tends to a stress value called fatigue limit. This value represents the limit of б below which, even for an ideally infinite number of cycles, the material will not break due to fatigue.

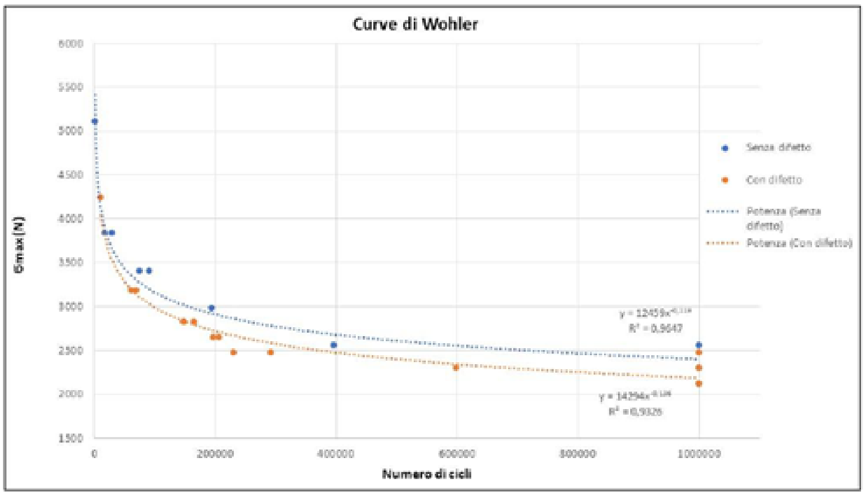

Fig.5 Wöhler S-N curves for charaterized specimens

Limite di fatica provini standard	Limite di fatica provini con difetto	Limite di fatica provini post invecchiamento termico
2300 N (27% del carico di rottura)	2119 N (30% del carico di rottura) (2148 N con Metodo Staircase)	2153 N (25% del carico di rottura)

Fig.6 Comparison of fatigue limit values obtained for the three different types of specimens

Visual examination

Following the tensile and fatigue tests, the surface of the adhesives in the overlap area of the bonding was investigated by **visual examination, to evaluate the types of failure.**

Visual examination shows that the predominant failure mode is adhesive type, both on the aluminum and composite, in different percentages for each sample. In particular, the percentage of adhesive failure on the laminate is higher in most of the specimens, both for defected and defect-free condition.

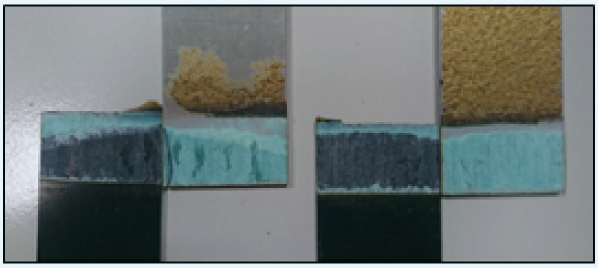

Fig.7 Fracture area macroscopic examination

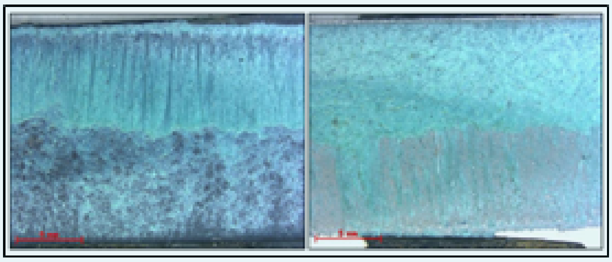

Fig.8 Fracture surface of defect-free specimens

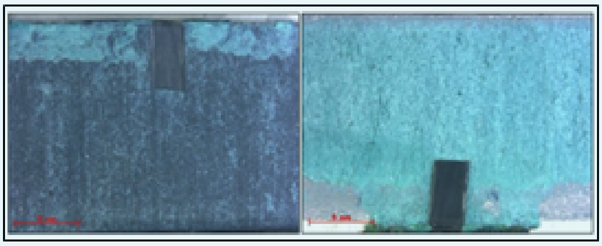

Fig.9 Fracture surface of specimens with defects

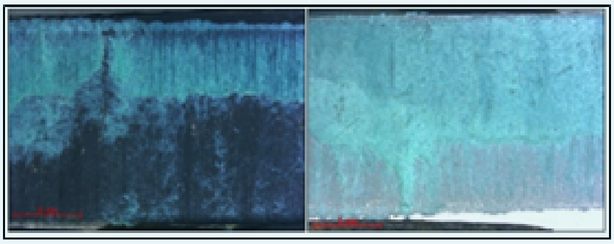

Fig.10 Fracture surface of aged specimens

ID PROVINO	TIPO DI FRATTURA	ID PROVINO	TIPO DI FRATTURA
1	Adesiva: 65% (C), 35% (A)	D2	Adesiva: 90% (C), 10% (A)
2	Adesiva: 75% (C), 25% (A)	D5	Adesiva: 80% (C), 20% (A)
4	Adesiva: 75% (C), 25% (A)	D6	Adesiva: 90% (C), 10% (A)
5	Adesiva: 70% (C), 30% (A)	D7	Adesiva: 85% (C), 15% (A)
6	Adesiva: 55% (C), 45% (A)	D8	Adesiva: 85% (C), 15% (A)
7	Adesiva: 70% (C), 30% (A)	D9	Adesiva: 90% (C), 10% (A)
13	Adesiva: 60% (C), 40% (A)	D11	Adesiva: 85% (C), 15% (A)
15	Adesiva: 75% (C), 25% (A)	D13	Adesiva: 75% (C), 25% (A)
3	Adesiva: 70% (C), 30% (A)	D3	Adesiva: 90% (C), 10% (A)
8	Adesiva: 60% (C), 40% (A)	D10	Adesiva: 85% (C), 15% (A)
14	Adesiva: 75% (C), 25% (A)	D15	Adesiva: 75% (C), 25% (A)

Fig.11 The table below shows the percentage of surface area that experienced adhesive failure on the composite (C) and aluminum (A) side.

Dsc analysis

As a last point of the characterization activity, DSC analysis was performed to **verify the chemical and physical state of the epoxy matrix present in the laminate and in the adhesive.**

From the thermograms, particularly in the first heating, it was noted the presence of an exothermic peak associated with a residual reaction of post-crosslinking of the resin, both of the adhesive and of the laminate. In the second heating, the maximum achievable transition temperatures (following post-cure) were observed.

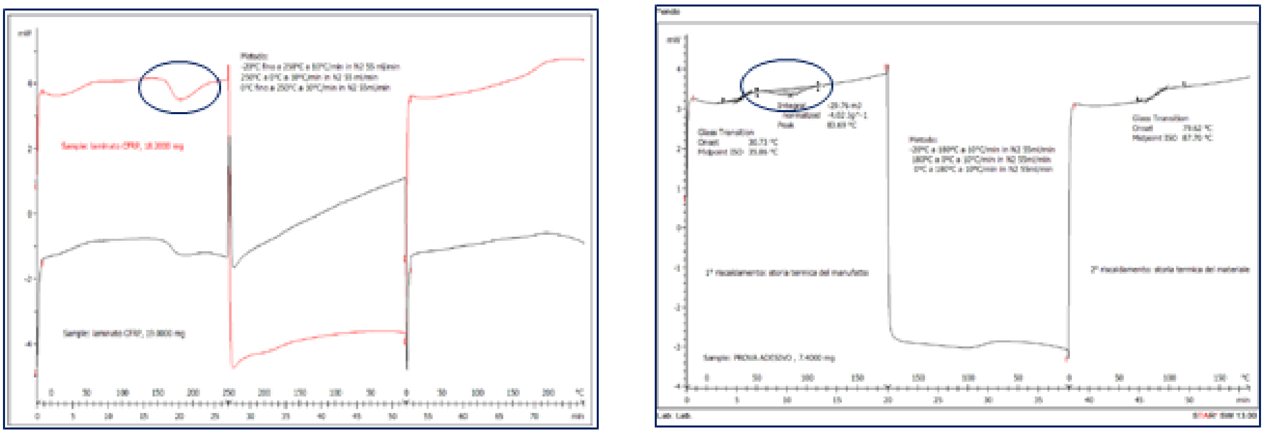

Fig.12 DSC Analysis: first heating (left) and second heating (right)

FINDINGS AND CONCLUSIONS

Analyzing the results gathered from the mechanical tests, it was observed that the **presence of the defect and thermal aging did not direclty affect the fatigue behavior; on the contrary the defect presence led to a 10% load drop during tensile test.**

The visual examination allowed to establish that the preponderant type of failure, for every tested sample, is the adhesive type, both on the CFRP laminate and on the aluminum.

In particular, **adhesive type failure area was found to be preponderant on the CFRP laminate side in all three types of specimens.**

From the data obtained with static and dynamic tests, it was possible to derive the admissible tension values, starting from the braking stress or the yield stress, dividing by an appropriate safety coefficient. (see calculations in appendix).

Appendice

Di seguito vengono mostrati i calcoli:

$\tau_{max} = 19.6\ MPa$ (Valore di lap shear minimo delle 3 prove di trazione per provini senza difetto);

$\tau_{max}^{dif} = 18.4\ MPa$ (Valore di lap shear minimo delle 3 prove di trazione per provini con difetto);

$\tau_{fat} = 6.1\ MPa$ (Tensione corrispondente al limite di fatica per campioni senza difetto);

$\tau_{fat}^{dif} = 5.7\ MPa$ (Tensione corrispondente al limite di fatica per campioni con difetto);

$C_1 = \frac{\tau_{max}}{\tau_{max}^{dif}} = 1.1$ MPa (coefficiente che tiene conto della presenza di un possibile difetto e che va a diminuire la resistenza meccanica statica del provino);

$C_2 = \frac{\tau_{max}}{\tau_{fat}} = 3.2$ MPa (coefficiente che tiene conto della sollecitazione a fatica a cui è sottoposto il provino senza difetto);

$C_3 = \frac{\tau_{max}}{\tau_{fat}^{dif}} = 3.5$ MPa (coefficiente che tiene conto della sollecitazione a fatica a cui è sottoposto il provino con difetto);

$$C_{tot} = C_1 * C_2 * C_3 = 12.3 \text{ MPa}$$

Infine,

$$\tau_{amm} = \frac{\tau_{max}}{C_{tot}} = 1.59 \text{ MPa}$$

con $\tau_{progetto} < \tau_{amm}$.

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