IMPACT CHARACTERIZATION AND SIMULATION OF A FML BASED ON A SELF-REINFORCED POLYPROPYLENE

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Abstract

In this work, the low velocity impact behavior in a lightweight fiber metal laminate (FML) system is studied. This FML is based on aluminum 2024 T3 and a self-reinforced polypropylene composite (SRPP). The laminate herein presented was manufactured by compression-molding process. In order to elucidate the strain-rate sensitivity of the composite, quasi-static tensile tests at different velocities in SRPP specimens were undertaken. After that, biaxial bending-impact tests in FML plates were performed with different impact energies to analyze the material's impact behavior. Finally, a preliminary finite element model to simulate the biaxial bending-impact tests by using elastic-plastic models for the materials was developed. Results reveal this FML show a great capability of absorbing energy without taking place interlaminar delamination or debonding between layers. A good agreement between numerical and experimental data was obtained in the loading phase of force-time curves.

1 Introduction

Composite materials are increasingly used in structural applications that require very good mechanical properties with low density. Many of these applications are related to people and goods transportation (aircraft, automotive), where vehicles might be subjected to impacts, being security one of the main requirements. In these cases, it might be required that materials have high impact resistance suffering the least possible damage or, on the other hand, dissipating as much energy as possible by deformation or total failure of the component. In any case, it is essential to understand the impact behavior of composite materials in order to design components in a suitable way depending on the application.

Composite materials based on fiber reinforced thermosetting matrix typically exhibit elastic behavior at break. Although its mechanical strength is generally high, when fail takes place, normally it occurs in a catastrophic way. The dissipation of impact energy occurs due to the breakage of the material, and to obtain a more gradual breakage suitable designs or combination of different types of reinforcement are necessary. In this way, the increasing use of multilayer structures of metal and composite material known by the name of fiber metal laminate (FML) outstands [1] [2] [3]. In these structures, the layers of composite material are responsible for providing stiffness, strength and low density, while metal sheets for providing toughness which prevents failure of the structure from occurring catastrophically.

Among FMLs it should be highlighted those in which the composite material is a self-reinforced thermoplastic. These composite materials present high stiffness, superior to the one of the block material, since they are fibrillar structures; and great toughness, generally higher than many fiber-reinforced thermoset materials due to visco-elasto-plastic nature of fibers and matrix [4]. Moreover, they exhibit other interesting features such as low density, recyclability and possibility of thermoforming [5] [6] [7]. If they are combined with metal sheets to create FMLs, it is obtained much more toughness compared to traditional thermoset matrix FMLs (e. g.; GLARE), what makes them very interesting for certain impact applications. However, proper design of such structures requires a deep understanding of their impact behavior and, specifically, of the one of the self-reinforced thermoplastic composite.

Nowadays, there exists a great amount of works where the analyzed material is a FML based on a thermoplastic matrix composite material. In these ones it is demonstrated its high toughness and, therefore, its good impact behavior. In fact, the configuration of the herein presented material has already been studied denoting the potentiality of this FML for impact applications [8] [9] [10] [11].

In this work, a study of low velocity impact behavior in a FML based on aluminum 2024 T3 and a self-reinforced polypropylene composite (SRPP) is presented. Plates were manufactured by compression-molding process. Firstly, quasi-static tensile tests at different velocities in SRPP specimens were undertaken with the aim of analyzing the strain-rate sensitivity of the material. Secondly, biaxial bending-impact tests in FML plates were performed with different impact energies to know its impact properties. Finally, a preliminary finite element model to simulate the biaxial bending-impact tests by using elastic-plastic models for the materials was developed.

2 Materials

2.1 Constituent materials

On the one hand, as composite material, a self-reinforced polypropylene (SRPP) supplied by Propex™ (Curv®) was utilized. It is a polypropylene fiber woven (0º/90º) embedded in a polypropylene matrix. Curv® was selected since it combines the versatility and recyclability of a 100 % thermoplastic with the high performance of a fiber reinforced composite, with high stiffness, high tensile strength and outstanding impact resistance at low temperatures. On the other hand, as metal sheet, an aluminum 2024 T3 was used; a one heavily utilized in aircraft applications. This aluminum alloy was selected since it has good machining characteristics and high strength. Finally, as interlaminar adhesive, a polypropylene hot melt was interposed between layers to get the bonding. This material consists in a 60 µm thick polypropylene film. The mechanical properties of the constitutive materials according to their respective data sheets are summarized in the table below (Table 1).

	Density [g/cm³]	Melting point [ºC]	Tensile Modulus [GPa]	Yield Stress [Mpa]	Tensile Strength [MPa]	Strain to failure [%]
Curv®	0.92	175	4.2	-	120	20
Al 2024 T3 (1)	2.7	-	73.1	288	436	16.4
Adhesive (2)	0.92	145	0.5	-	25	600

(1) Engineering values, (2) [11]

Table 1. Mechanical properties of the constitutive materials.

2.2 Manufacturing process

The stacking configuration used in this work is [Al, Curv®]$_S$. The FML was manufactured by the following sequences. Firstly, the SRPP layers, the interlayer adhesive films and the aluminum sheets were stacked as cited above. Secondly, the laminate was pressed by using a screw press with hot plates at the temperature of 165 ºC; less than SRPP's Vicat temperature and bigger than interlayer adhesive's melting point. Thus, by melting the interlayer adhesive, the bonding between composite layers and metal sheets was achieved. With this process, 250 mm × 250 mm FML plates showing very good attachment between layers were manufactured. The nominal thickness of materials and the one of the FML after processing is presented below (Table 2).

Curv®	2024 T3	Adhesive	FML(1)	FML(2)
0.63	0.41	0.06	2.26	2.52
(1) Nominal, (2) After processing				

Table 2. Nominal and after processing thickness.

In this work, FML biaxial bending-impact specimens were water jet cut from plates and two tensile specimens with [Al, 0º/90º]$_S$ and [Al, ±45º]$_S$ stacking configuration were also extracted.

3 Experimental work

3.1 Tensile tests

Tensile tests at different strain-rates in 0º/90º SRPP specimens were undertaken. These tests were conducted with the aim of analyze the strain-rate sensibility of the SRPP in a low velocities range by observing the evolution in the elastic modulus. Moreover, an additional quasi-static tensile test ($2 \cdot 10^{-4}$ s^{-1}) in the aluminum and in the FML was done, as well as in a ±45º SRPP specimen with the objective of obtain the shear modulus of the thermoplastic composite (Figure 1). The SRPP tensile specimens were cut with dimensions 20 x 200 mm, while the aluminum and FML ones according to the ASTM D 638M (Type M - I) (Figure 2).

Tensile tests in the thermoplastic composite were conducted in a universal test machine at the velocities of 1, 5, 10, 50, 100, 200 and 500 mm/min. Strain was measured by using an extensometer with a gage length of 70 mm, what implies strain-rates in a range of approximately $2 \cdot 10^{-4}$ - 0.1 s^{-1}.

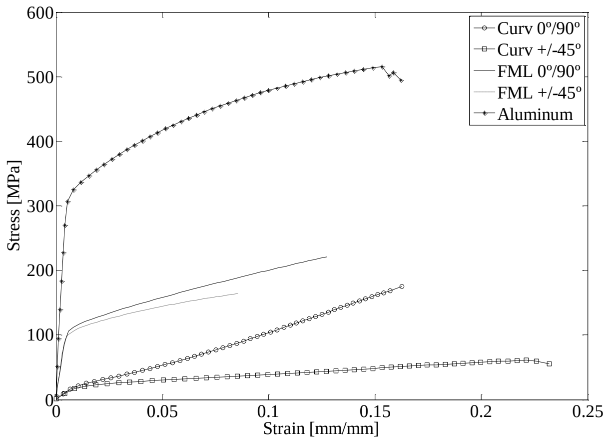

Figure 1. Stress-strain curves of all materials studied.

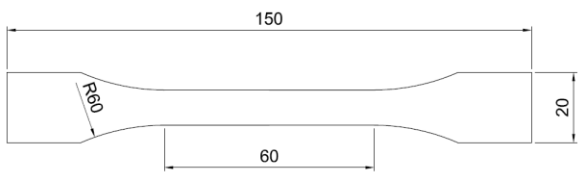

Figure 2. Geometry of the tensile specimen according to ASTM D 638M (Type M – I).

3.2 Biaxial bending-impact tests

Biaxial bending-impact tests with different impact energies in circular FML impact specimens by using a falling weight test machine were carried out. Tests were conducted with the aim of analyzing impact behavior of the FML. The machine, a Fractovis-Plus of Ceast, was equipped with a 20 kN load cell attached to the striker which measured contact force history. The hemispherical head of the striker was 20 mm diameter. Striker mass was 2.045-5.045 kg, depending on the test, and the energy was varied in the 1-50 J range by increasing falling height. Specimens were 60 mm diameter and in tests were supported on an annular ring with an inner and outer diameter of 40 and 60 mm respectively (Figure 3). Finally, before testing, they were gripped by a clamping device consisting in other annular ring like the one used as supporting. After testing, specimens were cut in half to view them with a macroscope and to identify a possible delamination.

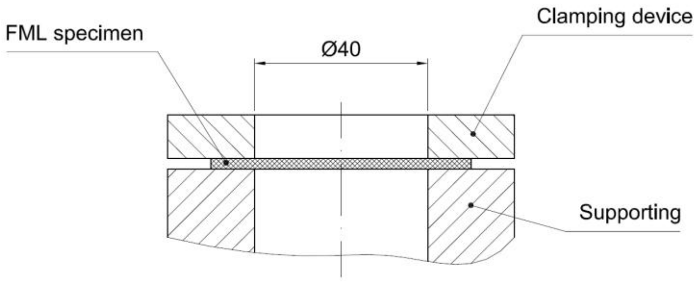

Figure 3. Scheme of the clamping device of the falling weight test machine.

4 Experimental results

4.1 Tensile tests results

Figure 4 shows the stress-strain curves obtained in tensile tests at low velocities in 0º/90º SRPP specimens. A moderate dependence on strain-rate of the mechanical behavior of the material was found in the range of velocities analyzed. While the elastic modulus remains approximately constant, the slope in the plastic region varies significantly by increasing the velocity. However, according to a previous work [5] based on instrumented tensile-impact tests, the strain-rate sensitivity at higher velocities is also accused in elastic modulus as figure 5 indicates.

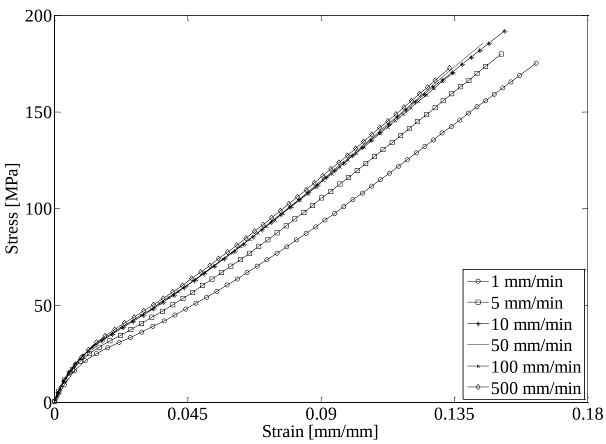

Figure 4. Evolution of peak force and contact time respect to impact energy.

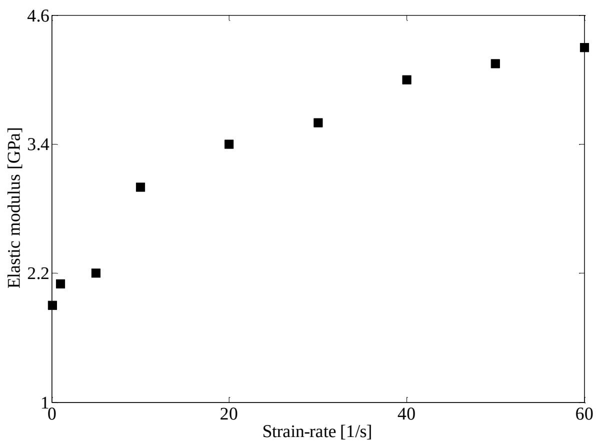

Figure 5. Absorbing energy versus impact energy.

Results herein presented are supported by the ones of McKown and Cantwell [7] in their study about the strain-rate effect in a self-reinforced polypropylene composite. They concluded that the material behavior showed strain-rate dependence; their results indicated that elastic modulus was not bigger than 4 GPa up to a strain-rate of approximately 0.1 s^{-1}. From there on, the value of the elastic modulus increases notably up to the maximum strain-rate (10 s^{-1}) they analyzed. Small differences between their work and the herein exposed can be accused to the fact that they utilized a laminate with some SRPP layers bonded with an interlaminar hot melt adhesive, while in this work a single layer of thermoplastic composite was used in tests.

4.2 Biaxial bending-impact tests results

Figure 6 shows the force-time curves obtained in biaxial bending-impact tests. The evolution of peak force and contact time during test with impact energy is summarized in figure 7.

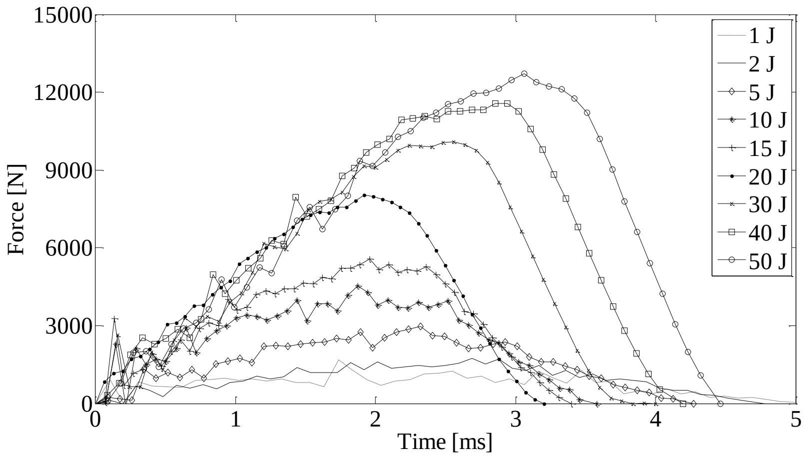

Figure 6. Force-time curves at different impact energies.

On the one hand, peak force naturally increases with impact energy until the case of 50 J. On the other hand, contact time shows a more complex evolution; it decreases at the beginning, in the lowest impact energies, and then starts to increase with a clear new trend from 20 J on; since the quantity of kinematic energy is bigger, the impact is more severe and does not allow the striker to lose easily the contact with plate during test.

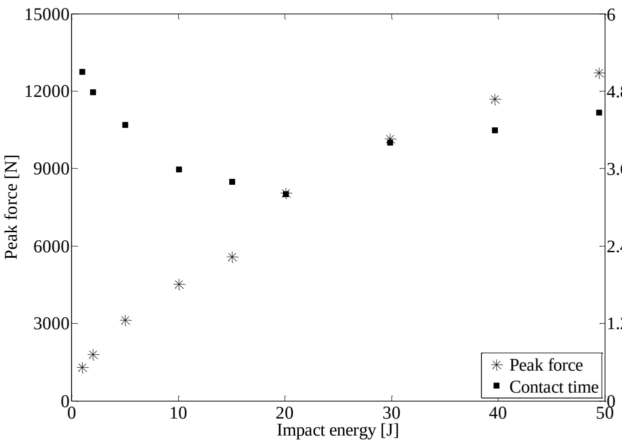

Figure 7. Evolution of peak force and contact time respect to impact energy.

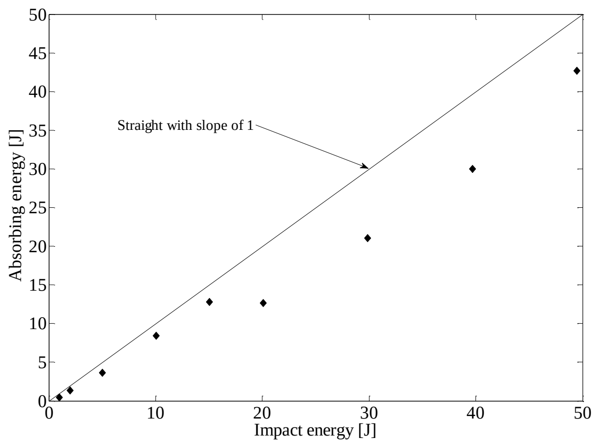

Figure 8. Absorbing energy versus impact energy.

Figure 8 indicates the absorbing energy in each impact denoting the good impact performance of this FML. The penetration of the striker in the plate was not achieved in the impact energies range analyzed being 50 J the maximum allowed with the impact machine. A great amount of impact energy was always dissipated by plastic strain and, as it will be shown later, no delamination or debonding took place. Figure 9 presents some images of impacted plates where the important role of the plastic strain can be appreciated. Moreover, crack initiation in aluminum sheets was not identified.

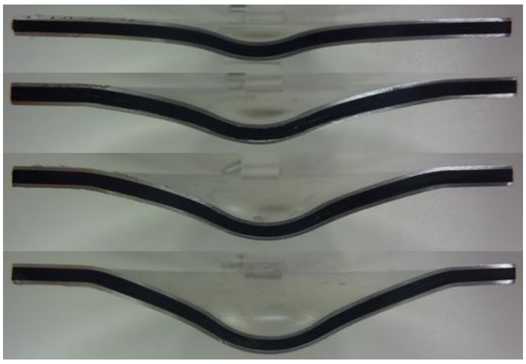

Figure 9. Biaxial bending-impact specimens cut in a half. Energies of 5, 10, 30 and 50 J (descendent).

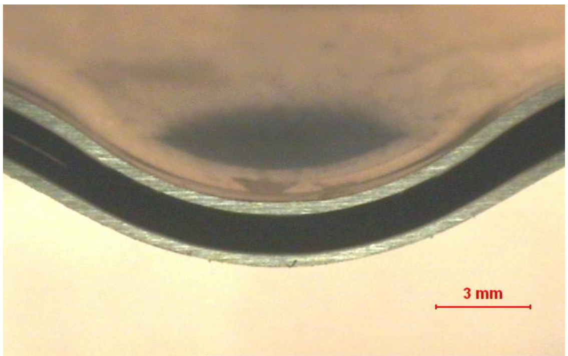

Figure 10. Detail of the 50 J specimen impacted.

In order to elucidate the interlaminar behavior, plates were cut in a half and visualized with the macro-scope after being correctly polished. As commented before, no interlaminar delamination or debonding between layers occurred; figure 10 shows a detail of the impacted region of the 50 J specimen without the presence of the phenomena previously described. Results suggest that the manufacturing process with the hot melt adhesive utilized was very good for these FML systems. As failure mode, an increasingly thinning in the metal sheets around the impact region was identified, as well as an important permanent deformation.

5 Simulation

5.1 Model

Abaqus/Explicit was utilized to develop numerical simulations of the biaxial impact-flexion tests. A 3D model that included the support, the clamping device, the striker and the FML plate was used. The support and the clamping device were modeled as discrete rigid shells, the striker as analytical rigid and the FML plate as deformable solid that only took into account the thermoplastic composite layers and the metal sheets. For both materials an elasto-plastic material model was considered by taking the $2 \cdot 10^{-4}$ s^{-1} tensile tests as input data; specifically, an isotropic one for the aluminum and an orthotropic one for the SRPP.

The part of the model that corresponded to the FML plate was partitioned in different cells to assign the different material layers, and reduced integration eight-node quadrilateral finite elements to mesh the FML plate were used.

This model was a preliminary one and did contemplate neither visco-elasto-plasticity of materials nor damage criteria.

5.2 Numerical-experimental correlation

The test corresponding to 20 J was taken to be correlated with the numerical model (figure 11). A good agreement between numerical and experimental data was obtained in the loading phase of force-time curves.

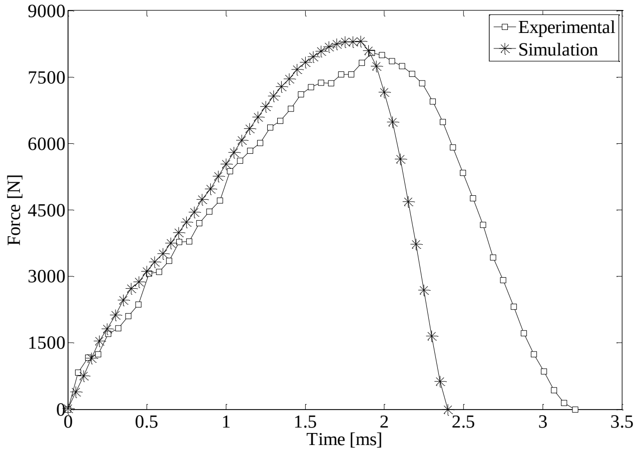

Figure 11. Force-time curves of experimental test and simulation.

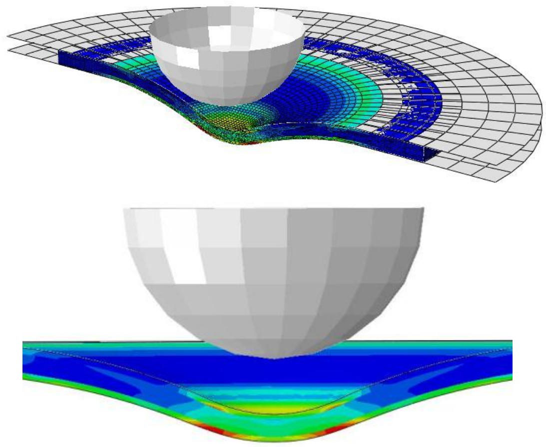

Figure 12. 3D model cut in half with a detail of impact region.

6 Conclusions

A study of low velocity impact behavior in a FML based on aluminum 2024 T3 and a self-reinforced polypropylene composite (SRPP) was carried out. Firstly, quasi-static tensile tests in SRPP specimens at different velocities were performed and contrasted with results obtained in a previous work based on instrumented tensile-impact tests. From data could be concluded that the SRPP presented strain-rate dependence; reflected exclusively in plasticity at strain-rates lower than 0.1 s^{-1}, however, from there on accused in elasticity as in plasticity. Secondly, biaxial bending-impact tests in FML plates were conducted to analyze the material's impact behavior. Results indicate that the laminate is capable of absorbing large amounts of impact energy by plastic strain without causing delamination in the thermoplastic composite or debonding between layers. Finally, a numerical-experimental correlation of a 20 J biaxial bending-impact test was done; a good agreement was obtained in the loading phase of force-time curves. Generating knowledge about the impact behavior of this class of FMLs is very interesting for structural applications in transportation sector. Moreover, knowing the strain-rate effect on mechanical properties of constituent materials is valuable data to simulate the FML system, what can greatly help in design work.

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