REPEATED LOW ENERGY IMPACT BEHAVIOUR OF SELF-REINFORCED POLYPROPYLENE FIBRE METAL LAMINATES

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Abstract
Fibre metal laminates (FMLs) are multi-layered structures where metal and composite thin plies are stacked together to form an hybrid structure. Aluminium and glass fibre epoxy composite FMLs (Glare®) have been commonly used for years in aerospace industry due to their good fatigue and impact specific properties. More recently, self-reinforced thermoplastic composite FMLs (SRFMLs) such as self reinforced polypropylene (Curv®) and aluminium FMLs have demonstrated to exhibit a higher energy absorption capability than Glare®under low energy impact conditions. Contrary to the impact behaviour of SRFMLs which has been widely studied, little work has been reported about their impact fatigue behaviour, when the SRFML is subjected to multiple impacts at the same impact energy. In this study the impact-fatigue behaviour of a polypropylene SRFML has been characterized by drop weight impact tests at impact energies of 20, 15, 13, 10 and 8J. The characteristic peak load, absorbed energy, permanent deflection of laminates and number of impacts to failure have been used to evaluate the impact performance and damage resistance of the material. The main irreversible mechanisms that occur within the material have been the permanent deflection, first and second crack onset and total penetration of the sample.

1. Introduction

Fibre Metal Laminates (FMLs) are hybrid materials where thin metal sheets and fibre-reinforced composites are alternatively layered. These materials can be interesting alternatives for substituting monolithic metal sheets of the same areal density [1]. FMLs combine the superior fatigue and fracture characteristics of the composites with the ductility of the metals. The most widely used and studied FMLs consist on alternating 2024-T3 aluminum and glass fibre reinforced epoxy (Glare®), manufactured by prepreg/autoclave technology. Thus, even if FMLs are promising lightweight materials for aeronautic applications, cost effective out-of-autoclave processes should be developed in order to consider the feasibility of these materials for other transport sectors.

One of these alternatives could be the FMLs based on thermoplastics, which can be stamp formed [2–4] and show higher impact perforation thresholds than the ones based on epoxy resins [5, 9, 10]. Self reinforced polymers, in which both reinforcement and matrix belong to the same polymer family, are emerging as low cost, lightweight and structurally and environmentally superior alternatives to glass fibre and other inorganic reinforcement composites [6–8]. One of the most important safety issues is the impact performance, damage tolerance and durability after impact for structural applications. Carbon

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and glass fibre composites can be damaged under low velocity impact conditions and, consequently, the residual properties of the composites are reduced [5], whereas thermoplastic fibre composites are less sensitive to damage due to their plasticity [9]. Another advantage of the self reinforced polymer is that excellent fibre/matrix adhesion is ensured without any coupling agent.

The aim of this paper is to investigate the effect of low velocity repeated impact on impact fatigue properties of an aluminum and self reinforced polypropylene (SRPP) FML and to understand the impact fatigue lifetime of this material. A systematic low velocity impact testing program based on instrumented drop weight was conducted and the characteristic peak load, absorbed energy, permanent deflection of laminates and number of impacts to failure are used to evaluate the impact performance and damage resistance.

2. Materials and testing

2.1. Materials

The constituent materials of the SRFML are a 0.42 mm thick 2024-T3 aluminium and a 0.63 mm thick SRPP (Curv®). Curv®is a thermoplastic polymer fibre 0/90 woven reinforcement embedded in a same-polymer matrix, supplied by Propex. The mechanical properties of Curv®, provided by the manufacturer, are shown in Table 1.

Table 1. Mechanical properties of Curv®

	0° dir.	90° dir.
Elastic modulus [GPa]	4.2	4.2
Yield stress [MPa]	120	120
Strain to failure [mm/mm]	0.2	0.2
Strain to failure [mm/mm]	0.93	

The constituent layers are stacked in a 2-1 configuration, or $[\mathrm{Al}, \mathrm{PP}]_s$. Composite layers are oriented so that the metals rolling direction and the composite's 0 ° direction are the same. The four layers have been joined by using a 0.06 mm interlayer adhesive (Collano®) consisting on a maleic anhydride modified polypropylene hot melt film. The total nominal thickness of the SRFML is 2.28 mm.

SRFML square 250 mm × 250 mm plates have been manufactured by hot pressing. First, composite layers, adhesive films and metal sheets are stacked according to the above configuration; then, the laminate is pressed (30 bar) using a mechanical press with hot plates at 165 °C; this temperature is less than SRPP's melting point but enough to melt the adhesive. Once the adhesive is melted, the hot plates are cooled at a rate of 10 °C/min until the temperature drops below 100 °C to assure that the adhesive is cured. Finally, the laminates are removed from the press and left at room temperature.

2.2. Impact tests

Low velocity impact tests were carried out in a falling weight impact test machine (Fractovis Plus, Ceast), with a 20 mm diameter hemispherical head striker equipped with a 20kN load cell. SRFML samples were 60 mm diameter circular plates, cut by water jet cutting process. Samples were simply supported on an annular ring with an inner diameter of 40 mm and an outer diameter of 60 mm. Contact force history during the test was measured from which the energy absorbed by the sample during the impact was

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determined. Tests were performed with a constant striker mass of 2,045 kg, and impact energies of 20, 15, 13, 10 and 8 J were achieved varying the impact velocity (or the striker release height). Immediately after each impact the striker was caught by a pneumatic clamp to avoid any rebound on the sample. All the tests were performed at room temperature and a minimum number of three samples were tested at the same impact energy level.

The performance evaluation of the SRFML-s repeated impact behaviour involves:

- Number of impacts (n_{imp}) until total penetration of each sample for each impact energy.
- Qualitative analysis of the load-time curves (F-t).
- Peak force of each test (F_{max}), defined as the maximum force recorded by the load cell.
- Energy dissipated in each test (E_{dis}), which is the amount of the impact energy dissipated by the SRFML due to irreversible phenomena such as plastic deformation and damage mechanisms of the constituent materials.
- Permanent deflection (δ), measured on the samples after each impact.

3. Results and discussion

3.1. Single impact behaviour

When subjected to a single impact, the SRFMLs analysed in this study can exhibit four damage stages, depending on the impact energy: i) permanent deformation, ii) first and second cracking, iii) onset of fibre breakage and iv) penetration. A previous study about this material [10] showed that for an impact energy range between 8 J and 20 J, the samples of SRFMLs only suffer a permanent deformation in the first impact, which is reflected by their non-symmetrical shape, without any sudden drop (Fig. 1).

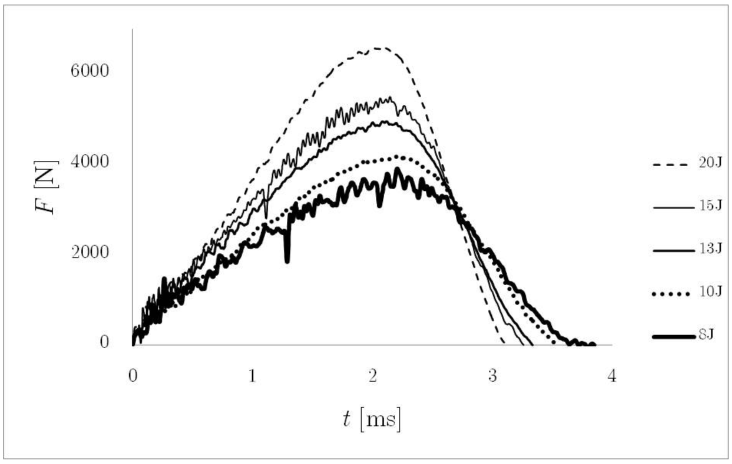

Figure 1. Contact force history for the first impact at different impact energies.

3.2. Repeated impact behaviour

The number of impact events until the total penetration of the samples as a function of the impact energy is shown in figure 2. As expected, when impact energy decreases, the number of impacts that the material

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can support before penetrations increases. It can be seen that for impact energies below 8J the material is capable of supporting 75 impact events but at a slightly higher energy (10 J) this capability is reduced around a 50%, and this reduction sharpens as impact energy increases.

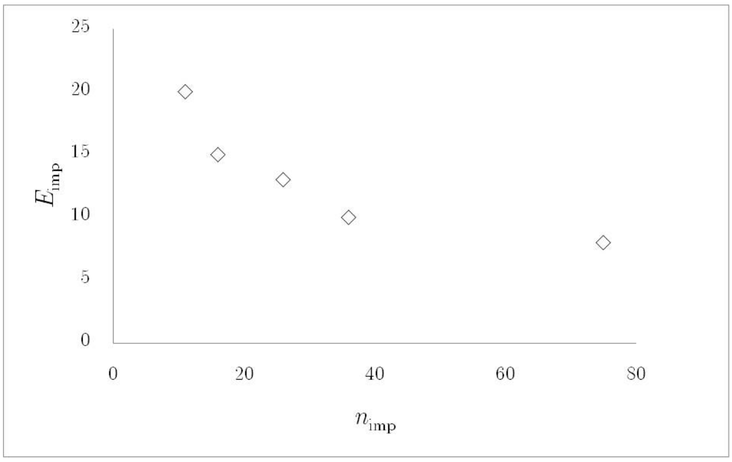

Figure 2. Impact fatigue life curve of SRFML samples.

In figures 3 and 4 the evolution of the force-time curves with the number of repetitions is shown, for an impact energy of 15 J. For the first nine repetitions (Fig. 3) the maximum force increases and contact time reduces, due to the strain hardening of the material. In the 9th repetition the first cracking appears in the non impacted aluminium layer, and it grows until at the repetition 12, a second crack appears in the impacted aluminium layer; between both impact repetitions there are no significant differences among force-time curves. The appearance of the second crack in the impacted side aluminium layer reduces de structural integrity of the sample, and a sudden force drop is produced from around 11000 N to 8000N(Fig. **??**). Due to the presence of the composite, the sample is still capable of supporting some load, and in the subsequent impacts, until at the repetition number 16 the total perforation of the sample is produced. The same tendency has been observed in the force-time curves of all the impact energies analysed.

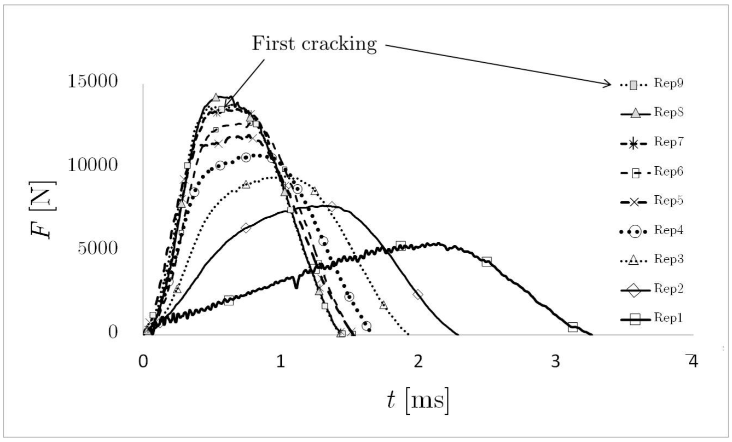

Figure 3. Evolution of the force-time curves for repeated 15 J impacts before aluminium first cracking.

Fig. 5 illustrates the variation of $F_{\max}$ values during the impact fatigue experiments at different energy levels. The changes in $F_{\max}$ values are related to different irreversible mechanisms, that are found in all the impact energies analyzed:

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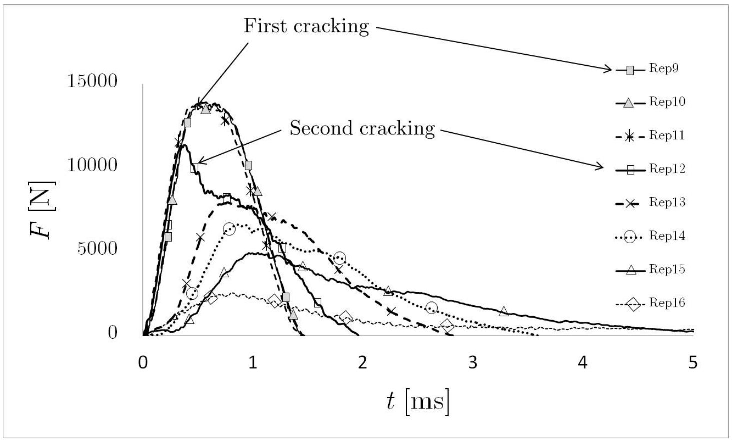

Figure 4. Evolution of the force-time curves for repeated 15 J impacts after aluminium first cracking, involving second cracking and until total penetration of the sample.

- First, for a low number of impact repetitions, F_{max} increases due to the strain hardening of the material, that occurs both in the aluminum and the SRPP[8].
- Then, the peak force stabilizes around a maximum value. This is related to the onset of the first crack, that in all the cases occurs in the non-impacted aluminum layer. For subsequent impact repetitions, while the size of the first crack increases slightly, the peak force is maintained at this maximum value.
- After the onset of the second crack which occurs in the impacted aluminum layer for all the cases, the peak force decreases sharply, which indicates that the material looses an important part of its structural integrity. Beyond this point both cracks grow faster in the aluminum layers, and it is mainly the SRPP which withstands the subsequent impact loads. The edge of the crack in the impacted side aluminium shears the polypropylene fibres [10] as the number of impact repetitions approximates to the total perforation threshold.

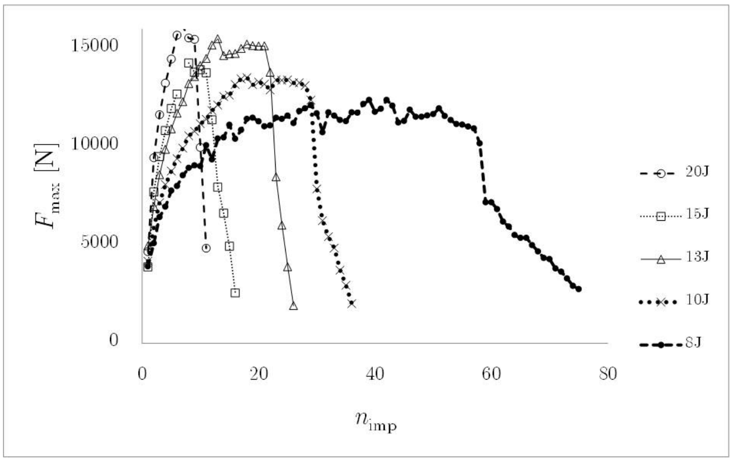

Figure 5. Evolution of the peak force with the number of impacts, for different impact energies.

The evolution of the dissipated energy with the number of impacts is shown in figure 6. All the curves show a similar evolution with the number of impacts: In the first impact repetitions a high amount of

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energy is absorbed, and as the number of impacts increases, the energy absorption decreases gradually which is related to the strain hardening of the material. This tendency is maintained until the first cracking occurs in the non impacted side aluminium layer, but no evidence of this phenomenon is detected in the dissipated energy values. After that, the dissipated energy continues to decrease very slightly, until the second crack onset is reached; in this case, there is a sudden increase of the dissipated energy (of around a 20%) in all the cases. Finally, beyond this point, the dissipated energy increases in all the cases except for an impact energy of 10J.

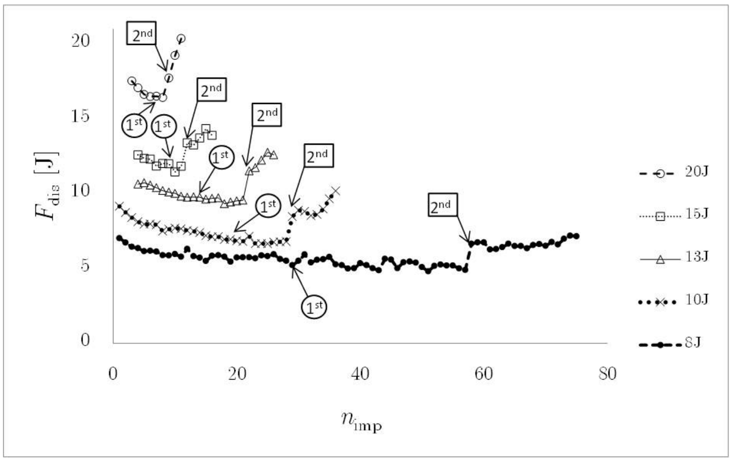

Figure 6. Evolution of the dissipated energy with the number of impacts, for different impact energies.

The contribution of each impact event to the permanent deflection of the laminates is shown in figure 7. It can be seen that, whatever the impact energy, the highest permanent deflection is induced at the first impact event, and then, as the number of impacts is higher, the permanent deflection induced in each impact becomes smaller. This tendency is maintained for all the impact energies, until the second cracking occurs in the impacted side aluminum layer. beyond this point, the relative permanent deflection induced in each impact increases. This behavior is in total agreement with the dissipated energy evolution with the number of impacts, as higher permanent deflections requires a higher energy dissipation.

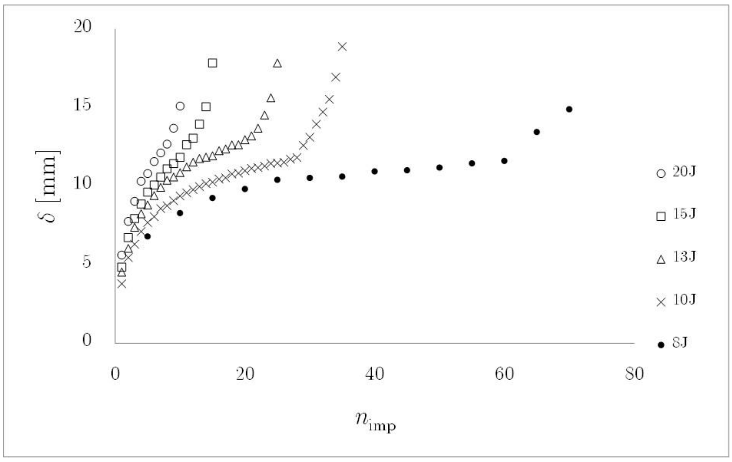

Figure 7. Evolution of the permanent deflection with the number of impacts, for different impact energies.

In figure 8 samples tested at 20, 15, 10 an 8 J are shown. It can be seen that for the highest impact

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energies (20J and 15J), the rupture occurs due to one main crack and some ramifications that appear in the last impacts near total penetration. For the lowest impact energy levels, only a single crack is produced.

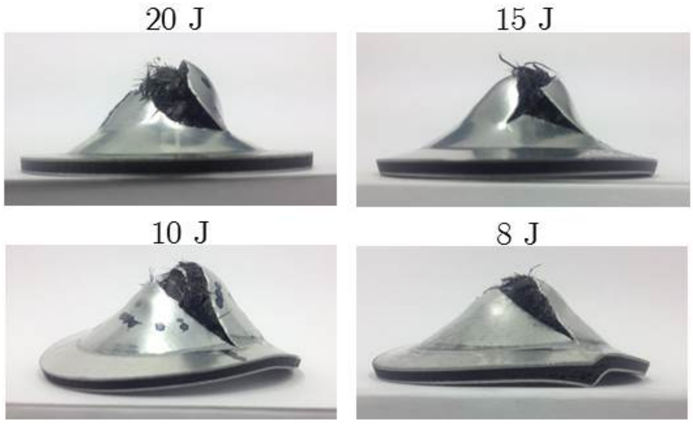

Figure 8. Impact fatigue life curve of SRFML samples.

4. Conclusions

The repeated impact behaviour of an FML composed of aluminum and self-reinforced polypropylene layers has been characterized, in an impact energy range of 8-20J. Based on this work, the following conclusions can be drawn:

- For all the impact energy levels the material shows a similar behaviour, involving permanent deformation, first cracking in the non impacted side aluminum, second cracking in the impacted side aluminum and finally, total penetration.
- The permanent deformation is the dominant damage mechanism for all the impact energies. Once the second crack onset is reached, the structural integrity of the material is reduced drastically and the material looses its capacity for withstanding subsequent impacts.
- In the impact energy range analyzed, the energy dissipating capacity of the material reduces as the number of impacts increase. This tendency changes when the second crack onset is reached, from where the failure mechanisms change in the structure, and more energy is dissipated until the total penetration of the sample is produced.
- The number of impacts that the material can withstand before total penetration is more or less inversely proportional to the impact energy for the range 10-20J. At 8 J the number of impacts that the material can support is around a 50% higher that for 10 J.

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