Flexural properties and impact damage behavior of nylon 6/woven basalt fibers composite

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Abstract
Polyamide 6 (PA6) basalt fabric composite laminates were prepared and analyzed in terms of flexural and low velocity impact properties. The BS/PA6 exhibits good flexural performances and a high rigidity in all tests. These data, complemented by morphological inspections and indentation depth measurements, have provided useful information about the involved damage mechanisms.

1. Introduction

Recently, basalt fibre laminates are deeply under the attention of many researchers for potential applications in the civil, naval and automotive fields [1]. The main reason has to be found in the increasing interest in the environment that had promoted the use of natural fibres as reinforcement in polymer matrices [2]. The low cost due to the availability and the simple manufacturing process, very similar to that of glass fibres but without any precursor nor additives, lead to choose basalt fibres to obtain an economic gain and a reduction of the environmental impact [3,4]. Regarding thermosetting matrices, benefits coming from the inclusion of basalt fibers in epoxy, polyester and vinyl ester resins mainly in terms of mechanical and thermal properties [5-8] are well established. However, with the awareness that the sustainability of new products can be encouraged by the recyclability of the involved matrices, recently the focus of the research has been increasingly devoted to thermoplastic systems as polyamides [9-12].
This paper deals with laminated structures including woven basalt fibers and a polyamide 6 matrix. Composite laminates were prepared and analyzed in terms of flexural and low velocity impact properties. These data, complemented by morphological inspections and indentation depth measurements, have provided useful information about the involved damage mechanisms.

2. Experimental

2.1 Materials and composite preparation procedures

The research is focused on composite laminates reinforced with a basalt plain wave type fabric (BS) (weight: 210 g/m^2) from Incotelogy GmbH (Germany).
About the matrix, a Nylon 6 (PA6), Lanxess Durethan B30S-000000 (MFI@260 °C, 5 kg: 102 g/10 min) was considered.

Composite laminates were prepared by a typical film stacking procedure by which stacks of alternated layers of plastic films and woven fibers are subjected to a compression molding step under pre-optimized conditions. Operating in this way, samples constituted by 18 layers, symmetrically stacked with respect to the middle plane, were obtained with a thickness equal to 2.90 ± 0.01 mm (BS/PA6).
Plaques of neat PA6 having the same sizes and prepared under the same conditions were used as the reference.

2.2 Flexural properties of composite laminates

Specimens with dimensions of 100 mm × 12.7 mm. cut from the laminates and the reference plaques, were used for three-point bending tests on a Universal Testing Machine (Instron model 4505). Measurements were performed according to ASTM-D790 at a crosshead speed of testing equal to 2.47 mm/min, using a load cell of 1 kN and a span set at 70 mm, independently of the thickness of the specimen. These latter were tested at room temperature after being equilibrated under standard ASTM condition of 23 °C and 50% relative humidity for 24 h. Results are reported in terms of typical stress-strain curves and flexural parameters averaged on at least 5 determinations for each investigated sample.

2.3 Impact Properties of composite laminates

Impact tests were carried out by a falling weight machine, Ceast Fractovis, at complete penetration (U_p=114J and 100J for PA6 and BS/PA6 system respectively), to obtain and study the whole load displacement curve and, consequently, to derive useful information about the response of the BS/PA6 laminates with respect to the neat PA6. Then, different increasing energy levels corresponding to 25, 50, 75% of the linear increasing stretch of the curve, were chosen to carry out the so called indentation tests, useful to study the damage start and evolution. The rectangular specimens, 100x150 mm, cut by a diamond saw from the original panels, were supported by the clamping device suggested by the ASTM D7137 Standard and were centrally loaded by an instrumented cylindrical impactor with a hemispherical nose, 19.8 mm in diameter. At this regard, a total minimum mass of 3.640 kg was used. This choice, combined with the drop heights, allowed to obtain the selected impact energies, was considered.

The achieved results were reported through load-displacement and energy-time curves and also discussed in terms of the so-called ductility index (DI). This parameter is defined as the absorbed energy up to the maximum peak force, reflecting elastically controlled dissipative mechanisms, divided by the propagation energy absorbed after it, due to plastic controlled ones. The ductility index, representing the ability of investigated materials to react in ductile way during the penetration stage, were evaluated and reported in the same table.
The ductility index (DI) is calculated using the following equation:

$$DI = \frac{U_{tot} - U_{peak}}{U_{tot}} \quad (1)$$

where U_{tot} represents the total area under the load deflection curve and U_{peak} is evaluated as the area under the curve up to the point in which the maximum force is reached.
After the impact tests, the specimens were observed by visual inspection to investigate the internal damage, whereas a confocal microscope, Leica DCM3D, was used to measure the indentation depth.

3. Results and discussion

3.1 Mechanical Properties

Fig. 1 compares the stress-strain curves of the examined composite system BS/PA6 and the matrix used PA6. A non linear trend of the first section of these curves is always shown, with the point of deviation from linearity usually attributed to the failure initiation due to the development of cracks on the tension side. Moreover, the BS/PA6 composite reflecting the greater toughness of the matrix, shows high values of the strength at break. In particular, the inclusion of the basalt fabric, thanks to the presumable good interfacial adhesion, leads to a significant increase in the flexural parameters (modulus, strength) of the hosting matrix of an order of magnitude.

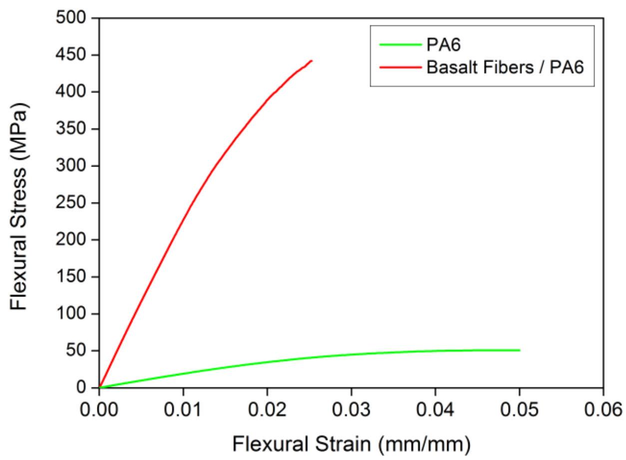

Figure 1: Flexural stress-strain curves of PA6 and BS/PA6

Average values of the flexural parameters are summarized in Table 1.

Table 1. Flexural parameters of investigated composite laminate

System	***Flexural strain (mm/mm)***	***Flexural modulus (MPa)***	***Flexural strenght (MPa)***
BS/PA6	0.0241 ± 0.0013	23510 ± 444	419.2 ± 23.4
PA6	0.05*	2006 ± 132	51.1 ± 2.3

*The test was interrupted at 5% of strain, as required by the reference Standard normative.

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3.2 Impact Properties

The load-displacement curve represents an important starting point to study the impact behavior of composite laminates. From the curves it is possible to obtain useful information about the response of the material under loading.

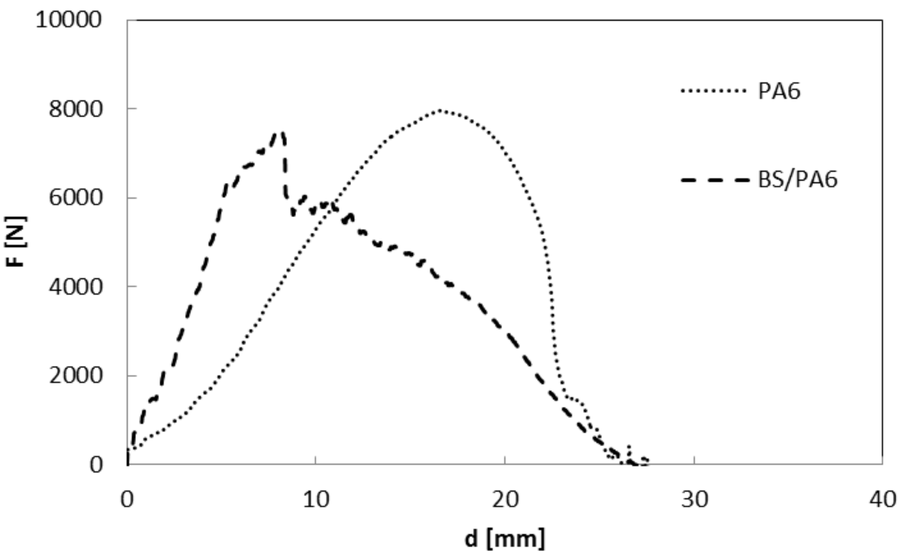


Figure 2. Load curves at penetration: polyamide 6 (PA6) and polyamide 6 basalt composite (BS/PA6).

In Fig. 2, a comparison between the load curves at penetration of polyamide 6 (PA6) and polyamide 6 basalt composite (BS/PA6) is reported. Although the composite system shows an impact rigidity higher than the neat matrix, as evaluated by the initial slope of the curves, some parameters such as the penetration energy (U_p) and maximum contact force (F_{max}) seems to be slightly reduced in presence of the basalt woven fibers as indicated in table 2.
About the shape of the load-deflection curve relative to the BS/PA6 laminated sample, a significant slope change, usually ascribed to incipient delamination phenomena, is observed at about 6.4 kN while at about 7.5 kN a complete rupture of the reinforcement occurs. Subsequently, the load initially shows a sudden drop up to about 5.8 kN and then appears to be largely sustained by the intrinsic ductility of the matrix and the presumable good interfacial adhesion between the polar polyamide 6 and the reinforcing fibers. In fact, as also witnessed by the evaluation of the ductility index (DI) (see Table 2), the reinforcing basalt fibers induce a remarkable increase of this parameter with respect to the reference matrix.

Table 2: Impact at penetration properties

	U_p [J]	F_{max} [N]	U_{peak}[J]	U_{tot} - U_{peak}	DI
PA6	114	7965.18	69.54	44.56	0.39
BS/PA6	100.92	7543.89	34.51	66.41	0.66

In Fig. 3, the load curves obtained on polyamide 6 / basalt fabric composite laminates at increasing energy levels were overlapped. The picture clearly demonstrates that, under the applied test conditions, closed type curves are obtained: the samples are not penetrated/perforated by the impactor that rebounds and the area enclosed in the loop of the loading/unloading curve is the energy absorbed by the laminate to create damage or to bend, depending on the thickness.
As expected, the maximum impact load, F_{max}, increases as the impact energy, U, increases. Also the absorbed energy, U_a, increases at the increasing of the impact energy, U, meaning that the increasing energies lead to increasing internal damage (figure 4 and 5)

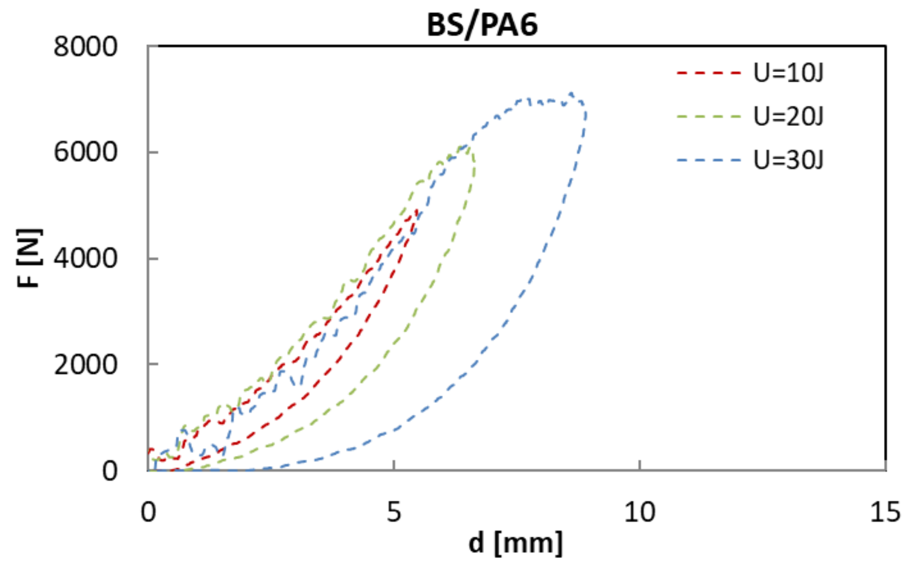


Figure 3. Load curves at indentation: BS/PA6; U=[10,20,30]J

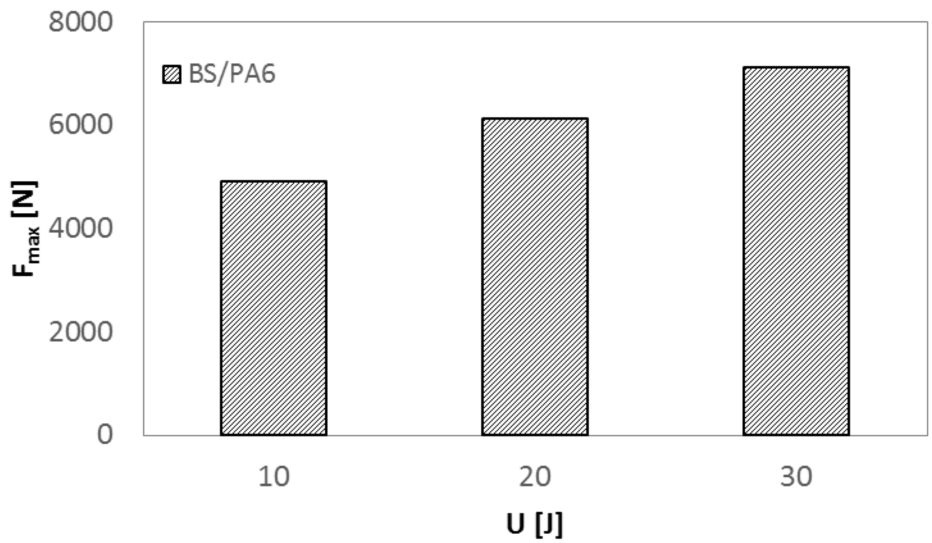


Figure 4. Maximum load, F_{max}, versus impact energy, U.

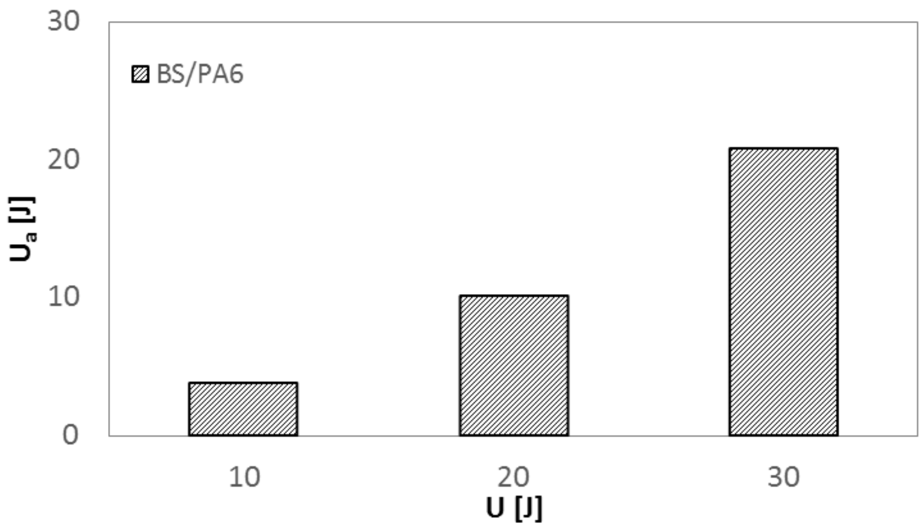


Figure 5. Maximum absorbed energy, U_a, versus impact energy, U.

This consideration is confirmed by the progression of the indentation depth, I, representing the footprint impress by the impactor on the impacted side of the specimen, as the impact energy, U, increases (see figure 6).

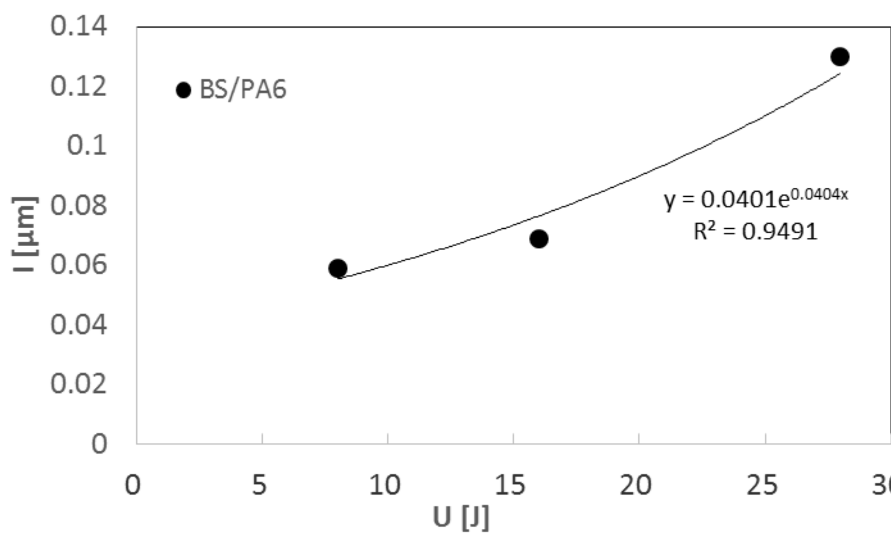
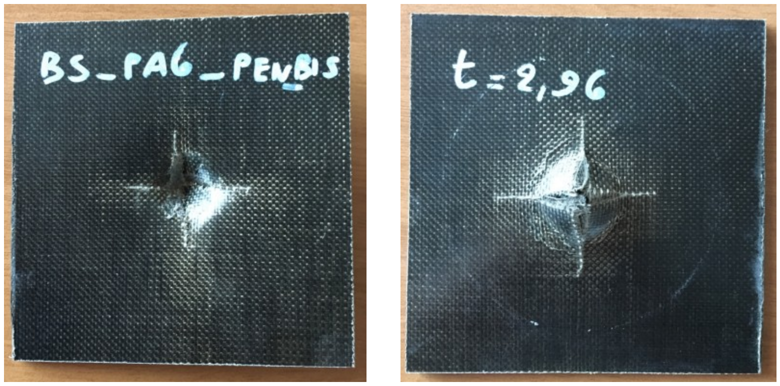


Figure 6. Indentation depth, I, versus impact energy, U, for the investigated BS/PA6 sample.

3.3 Damage

Visual inspections of both front and back sides of impacted samples, reported in Fig. 7, confirmed the absence of delamination propagation in all the investigated cases with localized compression load effects.
In general, it is possible to assume that impacts induce the formation and propagation of cracks within the matrix which did not result in delamination effects, and always give rise to comparable damaged areas. It is worth to note that these findings are in contrast with what is generally reported in the literature [14,15] where from the first damage represented by cracks in the matrix, delamination starts and propagates larger than the area covered by the material/impactor contact point. The delamination represents the most

important reason of the residual strength decay and the fact that, in this case, a very limited internal damage was found could mean higher residual properties. Anyway, this is a crucial point worth to investigate on in a future work.



Front side Back side

Figure 7. Photographic images of front and back side of BS/PA6 impacted at penetration

4. Conclusions

The flexural and low velocity impact behavior of polyamide 6 based laminates reinforced by a commercial basalt fabric have been studied and compared to samples of the neat matrix prepared under the same conditions. Experimental tests highlighted that the composite system, thanks to the good fiber-matrix compatibly, exhibits high flexural parameters (modulus, strength).
As far as the impact behavior is concerned, the maximum impact load, Fmax, and the absorbed energy, Ua, increase as the impact energy, U, increases as a sign of a growing internal damage. These results were also confirmed by the progression of the indentation depth, I, with the impact energy, U, and by visual inspections of damaged areas. The studied composite system does not seem to undergo any delamination. However this consideration is still under investigation through ultrasound non-destructive evaluations of the damaged area, A, that could be useful to understand the involved mechanisms of damage initiation and propagation.

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