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An experimental investigation on low-velocity impact response of nanoclay-reinforced fiber metal laminates

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ABSTRACT: In this experimental study, the effect of nanoclay addition into fiber metal laminates on low-velocity impact response is investigated. The reinforced fiber metal laminates considering 0, 1, 3, and 5 weight percentages of nanoclay were manufactured by hand lay-up technique. The specimens were then subjected to low-velocity impact tests using an instrumented drop-weight test setup at three different energy levels. To gain the range of tolerable impact energies before the fracture occurs, quasi-static tests were performed. Impact behaviors of the fiber metal laminates were compared in terms of force-time and force-displacement responses as well as the final energy absorption of the samples in addition to visual inspection of the damaged area. The results showed that the addition of 1 to 3 wt.% nanoclay into the laminates can improve their impact characteristics. Moreover, a noticeable reduction in physical damage was observed in nano-fiber metal laminates as compared to nano-free ones. On the other hand, it was found that the extra addition of nanoclay into the laminates can decrease their impact characteristics and make them be more brittle specimens than the nano-free samples.

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1- Introduction

Fiber metal laminates (FMLs) consisting of fiber-reinforced composites layers and thin metallic sheets bonded together, inheriting the respective acceptable features of composite and metal materials, have balanced characteristics in terms of specific strength and stiffness as well as impact resistance [1]. Due to these outstanding performances, FMLs have been widely applied in various engineering structures particularly in aerospace, aircraft, and marine industries [2]. Although FMLs were initially proposed to enhance the fatigue properties [3], afterward it was found that the interfaces between composite layers and metal sheets can play a significant role in their low-velocity impact behavior [2, 4]. Generally, composite materials have a relatively high susceptibility to the accidental low-velocity impact that can result in a significant stiffness reduction of the structure and the internal damage may rarely be detected by visual inspections [5]. Hence, investigation of the low-velocity impact behavior of various types of composite structures is of great importance in structural mechanics.

FMLs subjected to low-velocity impact, compared to conventional fiber-reinforced polymers, have the characteristic of visibly showing the effects of impact damage [6]. The improved impact responses of FMLs, in comparison to the monolithic metal, can be attributed to the rate sensitivity of the glass fiber's specific strength [7]. Furthermore, the delamination between layers leads to greater energy absorption by the aluminum sheets resulting in membrane-type behavior in FMLs versus bending deformation of the thick monolithic aluminum sheets [8]. In addition, several types of research have assessed the low-velocity impact response of FMLs upon minimum cracking energy and perforation energy [9, 10].

Traditionally, FMLs were fabricated using aramid and glass fibers, leading to the two most important families of FMLs, commercially known as Arall and Glare respectively, in addition to carbon fibers, known as Carall, which has been described as not widely accepted among FMLs because of their high notch sensitivity. On the other hand, recent achievements in FMLs have emphasized the use of basalt reinforced fibers, as a promising substitute for glass fibers, with comparable mechanical properties and fewer environmental impacts [11, 12]. Furthermore, several studies have implied the better impact response of FMLs with basalt fibers rather than those using glass, aramid, or carbon fibers [13, 14].

In recent years, in order to enhance the mechanical properties of materials, many kinds of research have examined the inclusion of various nano-particles such as nanoclay in the polymer matrix of the composites to take advantage of the nano-particle [15]. The positive effects of nanoclay content on the flexural strength and fracture toughness of glass and carbon fiber reinforced nanocomposites have been investigated [16, 17]. Moreover, it was found from tensile and bending tests on nanocomposites that the addition of

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nanoclay up to 3 wt.% can increase tensile strength and micro-hardness, whereas further clay addition up to 5 wt.% can lead to a reduction in these values [18]. Furthermore, the introduction of nanoclay to the resin of FMLs can make the maximum stress decrease at the interface [19]. Additionally, it was reported that the infusion of nanoclay into the epoxy matrix of the plain weave carbon/epoxy-nanoclay composites under low-velocity impact can increase their stiffness and damage resistance [20]. Investigation of the ballistic behavior of woven glass fibers–epoxy nanocomposites containing the modified nanoclay indicated that the most increase in the energy absorption at the impact velocity of 134 m/s and 169 m/s was observed in 3 wt.% and 10 wt.% of nanoclay, respectively [21]. More recently, the ballistic impact experiments were performed on reinforced FMLs with nanoclay and showed that the addition of nanoclay particles to the structure can significantly increase the ballistic velocity as well as energy absorption [22]. Furthermore, performing the three-point bending test and the high-velocity impact test on FMLs, with different weight percentages of modified/unmodified nanoclay, demonstrated that the maximum effect of adding nanoclay particles on the flexural and impact behavior was obtained by using 3 wt.% of the modified nanoclay [23]. Besides, considering the effect of different percentages of modified nanoclay, the results of the Charpy test showed that nanoclay addition can lead to increasing the absorbed energy values as well as decreasing the interlaminar shear strength of FMLs [24]. From an experimental study on AlMg4.5Mn reinforced nanoclay composites, the natural frequencies of impacted samples were found to be increased in addition of 2.5 wt.% nanoclay [25]. The effect of the addition of nanoclay in the matrix of the syntactic foam was also investigated [26] and it was claimed that the presence of 3 wt.% of nanoclay can enhance the high-velocity impact resistance of a syntactic foam core sandwich panel by about 10%. Despite the various types of research that have been done on high-velocity impact behavior of multi-layer nanopolymer composites [27] and although the effectiveness of the nanocaly addition into composite laminates has been approved by some limited special cases, the low-velocity impact response has not received much attention, as one of the most crucial issues of the FMLs.

In the present study, the effects of nanoclay infusion into FMLs (aluminum 2024-T3-epoxy/basalt fibers) on their low-velocity impact behavior through the use of an instrumented drop-weight test setup at three different energy levels were experimentally investigated. The novelty of the present work lies in identifying the better percentage of nanoclay-reinforcements resulting in the enhancement of the low-velocity impact performance of the aluminum-epoxy/basalt fibers composites.

2- Experimental Details

2- 1- Specimen preparation

The nanoclay-reinforced fiber metal laminates were consolidated using a hand lay-up technique. As the metal part of FMLs, 0.75 mm thick aluminum 2024-T3 sheets were employed. The composite laminates were comprised of four plies of basalt fabric with the areal density of 300 gr/m^2 and EPR1080 epoxy resin (Supplied by Chimex Company, Russia), hardened with 15 phr EA1080 hardener. The modified nanoclay Bentonite B0109 (Supplied by Samchun Chemical Company, Korea) was incorporated at 1, 3, and 5 weight percent of the resin-hardener mixture.

To achieve the desired bonding between aluminum layers and laminates, surfaces of the aluminum sheets, with length and width of 147×147 mm, were first cleaned and degreased by wiping with acetone. Then, aluminum sheets were immersed in alkaline solution (with the following mixture by weight: 6 parts sodium hydroxide to 150 parts distilled water) for 8 minutes at 60 to 65°C, where during the reaction some hydrogen gases were released, as shown by Fig.1(a). After that, the sheets were washed by water with a temperature of 23 to 70°C to be ready for chemical etching. The P-2 Etch solution was formed by 200 ml Sulfuric acid that was gradually added to 800 ml distilled water in addition to 150 gr Ferric sulfate, and afterward, the aluminum sheets were immersed in this solution for 12 minutes at 60°C in the oven. Next, aluminum sheets were brought out of the etch solution, as shown in Fig. 1(b), and were wiped with water at ambient temperature to 50°C for 1 or 2 minutes and desiccated. The prepared sheets could be kept less than 24 hours before adhesion, in an environment whose maximum moisture should be 50% relative humidity. It should be noted that the thickness of the treated aluminum sheets was reduced from 0.75 mm to 0.65 mm due to the chemical processes that occurred on their surface.

In order to prepare the resin-nanoclay mixture, first, the corresponding weight percentage of nanoclay was added to the resin gradually and the solution was mechanically stirred using an electric mixer, as shown by Fig. 1(c). Then, the mixture was sonicated through the use of an ultrasonic homogenizer (BANDELIN SONOPLUS HD 3200 system with 200 W input power and working frequency of 20 kHz). The sonication was carried out for 5 minutes with the energy of 20 kJ and repeated four times to reach the energy of 80 kJ. After the complete dispersion of nanoclays in the resin, as illustrated in Fig. 1(d), the color of the solution tended to darken and then it was cooled to the ambient temperature and the bubbles disappeared over time. Subsequently, the corresponding amount of hardener was added to the solution and the blend was mixed mechanically for 5 minutes and degassed.

The FML specimens were then fabricated by placing the 4 plies of basalt fabrics, with the size of 200 mm×200 mm, between the prepared metal sheets by applying the resin solution (with and without adding nanoclays) by a brush for all layers, as can be seen in Fig. 1(e). A Dacron fabric sheet was used to make the surface of aluminum sheets non-sticky and smooth, as illustrated in Fig. 1(f) and then the laminates were kept under pressure for 24 hours to be consolidated, as shown by Fig. 1(g). Before imposing the mechanical tests, the samples were left a week at room temperature to be completely cured. Individual specimens have an average thickness of 3.22 mm and a fiber volume fraction of roughly 0.53.

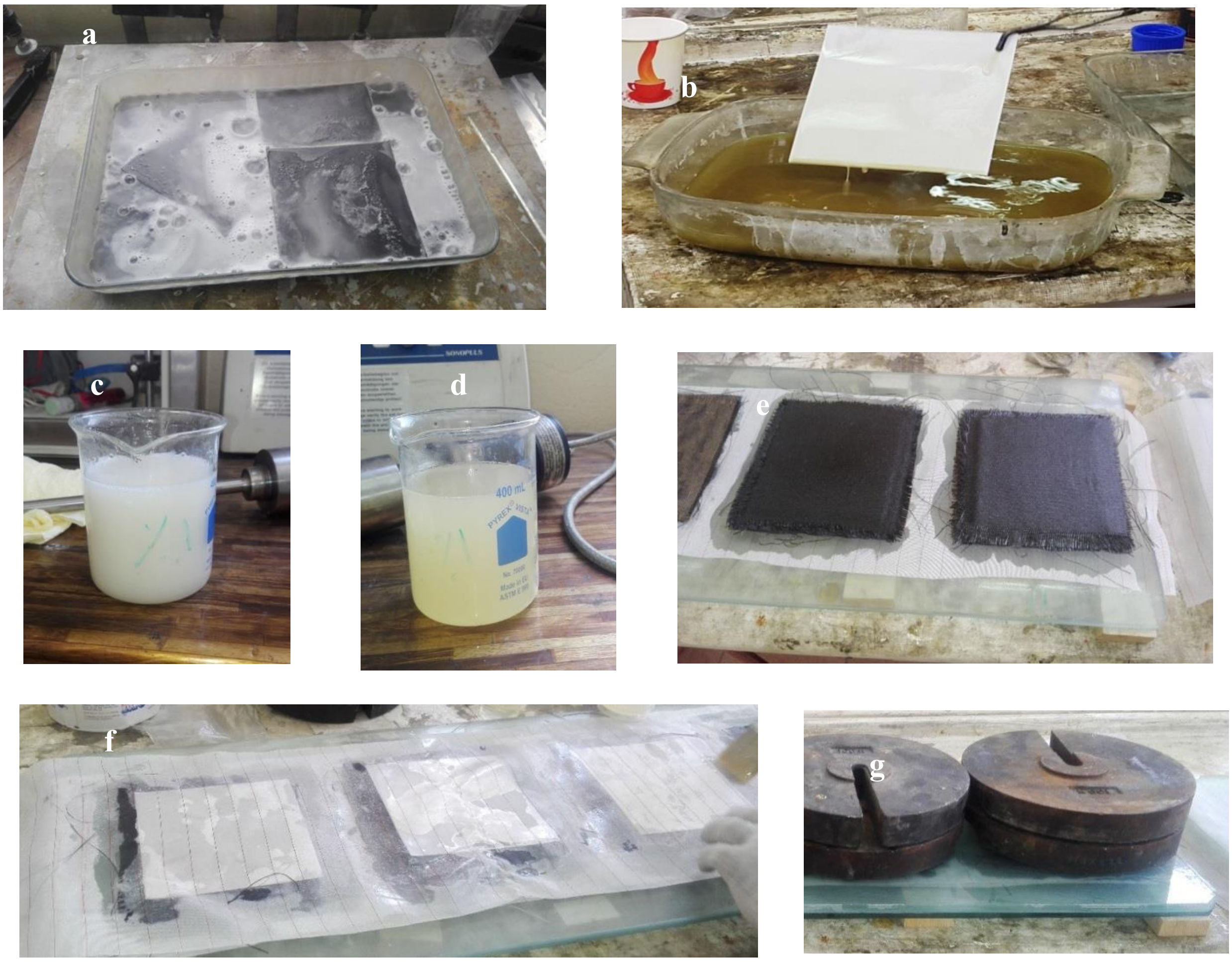


Fig. 1. (a) The aluminum sheets immersed in alkaline solution. (b) The aluminum sheet after the etching process. (c) Resin-nanoclay mixture after mechanical mixing and (d) after ultrasonication. (e) Fabricating the specimens by placing the basalt fabrics between the prepared metal sheets using the hand lay-up technique. (f) Covering them with the Dacron fabric. (g) Applying the pressure for 24 hours.

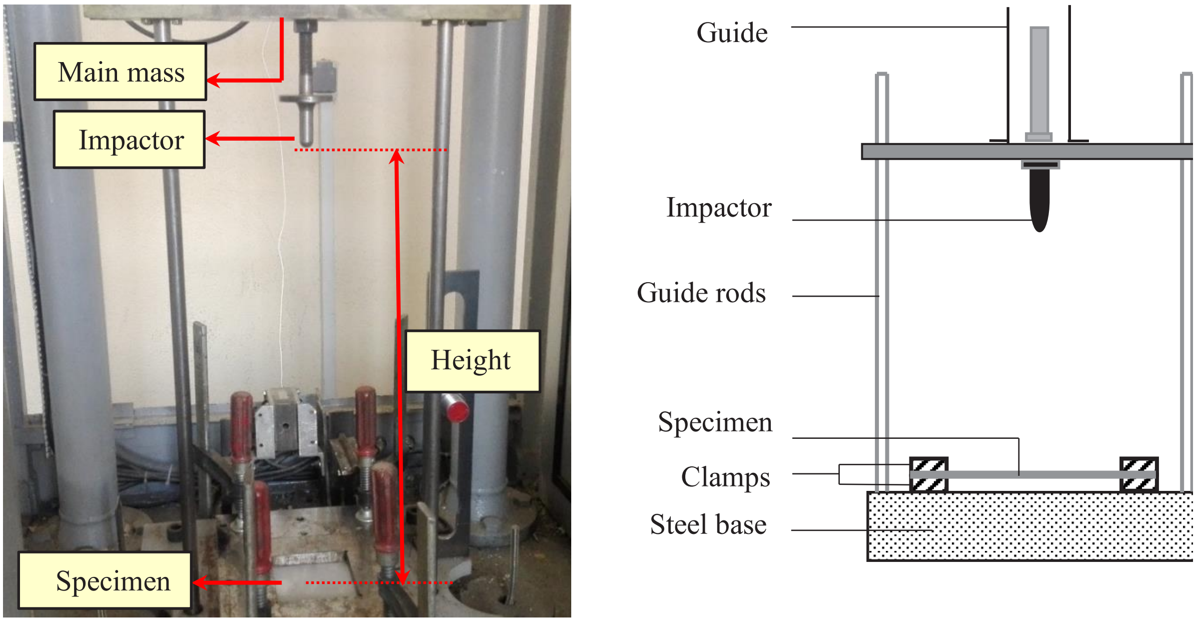
The main objective of the present experimental tests is identifying the better range of nanoclay addition into the FMLs' matrix to make them improve their low-velocity impact resistance.

2- 2- Mechanical testing

Impact tests were carried out using an instrumented drop-weight machine by applying a steel hemispherical-ended cylindrical impactor with a diameter of 16 mm. The drop-weight test device consists of dropping a dart with a variable mass on a free fall, which guided by two bars to allow just the vertical component of the velocity, as illustrated in Fig. 2.

The effective opening area of the specimens for impact tests was rectangular of 100×100 mm^2 and the samples were fully clamped, as shown by Fig. 3. It is further noted that in practice impact tests are often carried out with the specimen placed on continuous rigid support. This kind of boundary condition suppresses the failure mode core shear failure and makes it determine only the indentation response of the structure.

Low-velocity impacts were applied on the FMLs with energy levels of 14.70 J, 25.42 J, and 27.99 J, corresponding to various weights of the projectile at a drop height of 0.55 m. The variation of impact force with time was recorded by a load cell located inside the impactor rod and the force signal was integrated numerically to compute the velocity and displacement of the impactor. Since during the impact event the impactor is supposed to remain in contact with the sample, the displacement of the projectile was used to present the displacement of the impacted face of the specimen. To reduce the experimental errors, a series of repeated tests were performed and the same outcomes resulted in the reported achievements.



(a) (b)

Fig. 2. (a) Set-up for impact test (b) Schematic of the test set-up

Fig.3. Applying the fully clamped boundary conditions

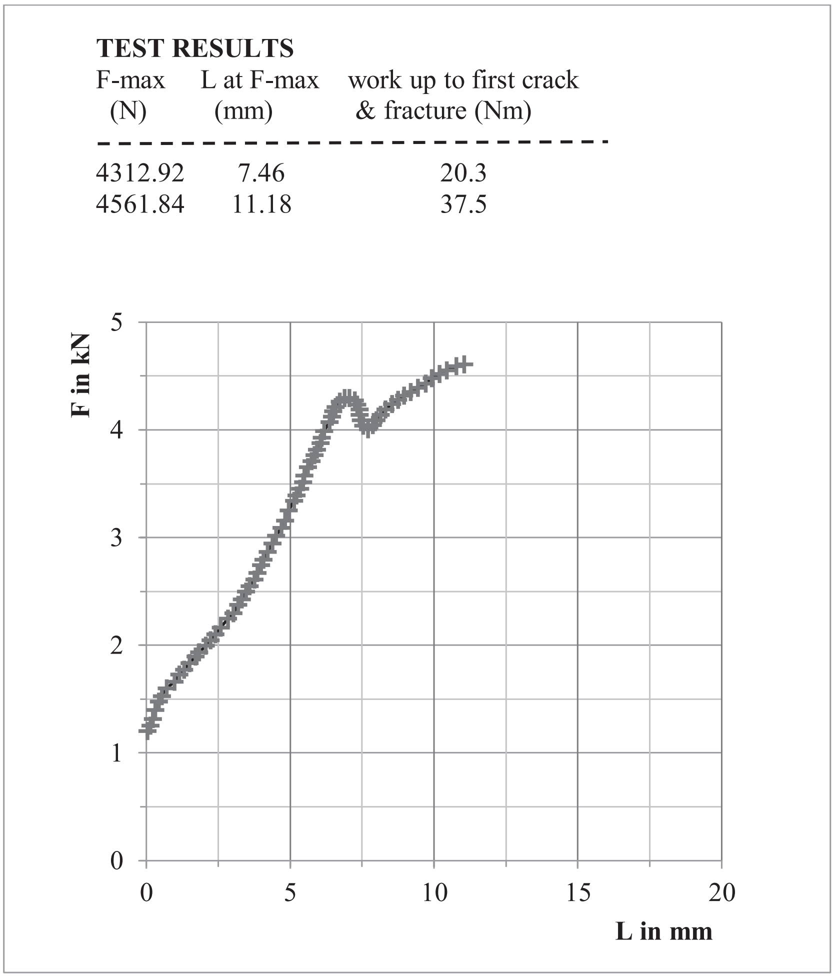
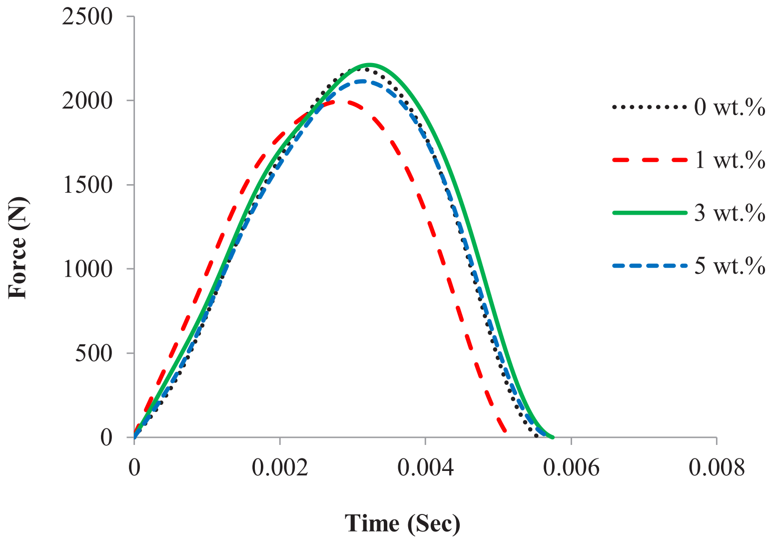


Fig. 4. Force-displacement graph of quasi-static test

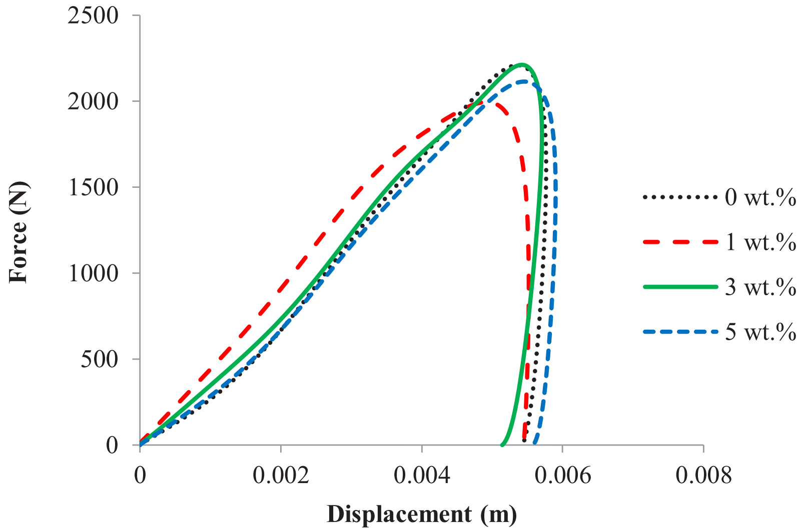
Note that, in order to provide the calibration data, the evaluation of the tolerable maximum impact energy before fracture occurrence was implemented using a Zwick quasi-static test machine. The tests were carried out at a constant rate of displacement on the specimens with clamped supports and employing the same projectile as used in the impact tests to impose the quasi-static load. In the typical quasi-static graph as shown by Fig. 4, calculating the area under the curve resulted in the maximum energy of 20.3 N.m corresponding to the first crack appearance and 37.5 N.m for the occurrence of fracture.

3- Results and Discussion

The results corresponding to low-velocity impact test and impact-induced damage assessments of the specimens are discussed in this section. As previously mentioned, the impact tests were conducted employing a drop weight machine at three different energy levels for four types of FML samples considering various weight percentages of nanoclay (with 0, 1, 3, and 5 wt. %). The contact force history and the force-displacement response of the FMLs corresponding to impact energy of 14.70 J are represented in Fig. 5. As can be seen in Fig. 5(a), there is no significant difference in the force-time trend of FMLs with various contents of nanoclay, especially for 0 wt. %, 3 wt. %, and 5 wt. % whose curves are roughly similar. It might be deduced that among nanoclays and fibers as two reinforcement mechanisms of the samples, fibers dominate the loading capacity of nanocomposites over nanoclays. However, the graph shows that in the case of 3 wt.% nanoclay, the maximum contact force is approximately 1% higher than the case with no nanoclay addition. On the other hand, Fig. 5(b) illustrates that the permanent displacement in the FML with 3 wt.% of nanoclay is lower than the others. In addition, by calculating the area under the force-displacement curves, the impact energy absorption rate for the sample containing 3 wt.% nanoclay is up to 1.5%, 0.6% and 4% higher than the cases of 0, 1, and 5 wt.%, respectively. The less deformation, as well as more absorbed energy, mean that the sample with 3 wt.% nanoclay, in the impact energy level of 14.70 J, has more impact resistance and in comparison to



(a)



(b)

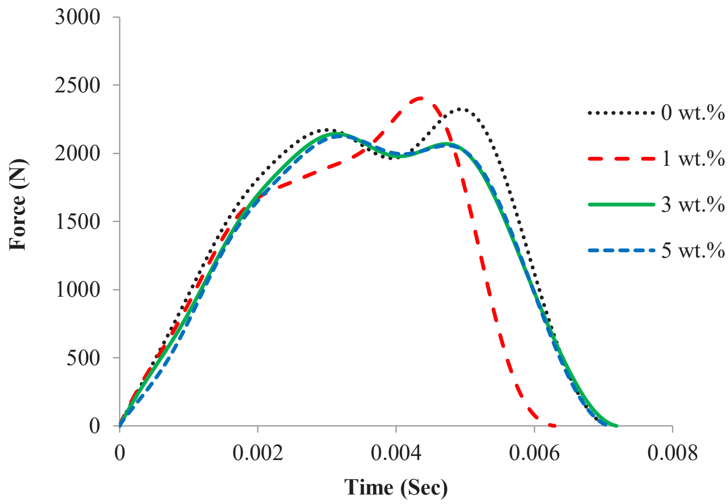
Fig. 5. (a) Force-time history and (b) Force-displacement response of FMLs impacted at energy of 14.70 J

other samples, especially those with 1 and 5 wt.% nanoclay, a relatively smaller portion of the sample has confronted with the damage, as can be observed in Fig. 6 on the non-impacted side. In general, the impact-induced damage in FMLs is categorized as a visible one, including plastic indention and cracking of aluminum as well as internal damage. Hence, the area of damage is easily visible on the non-impacted side due to not penetrating the projectile into the sample and only the occurrence of delamination.

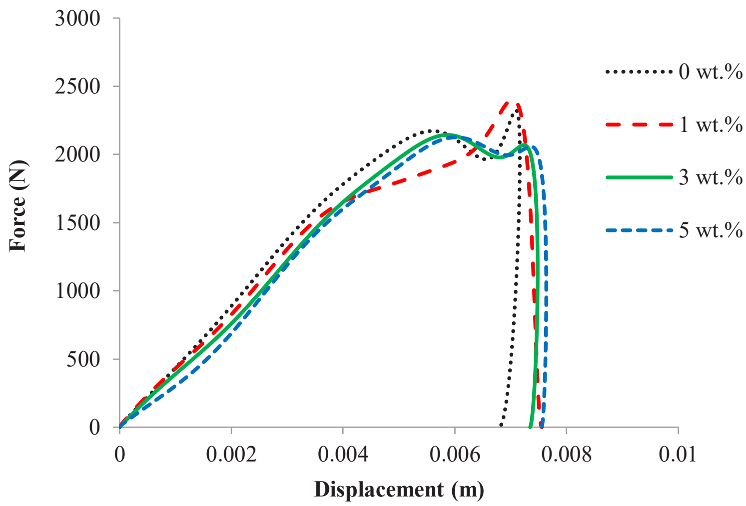
Presented graphically in Figs. 7(a) and 7(b), are the force-time and the force-displacement responses of the specimens stuck with an impact energy of 25.42 J. As can be found from Fig. 7, again there is no significant difference in the impact behavior of the samples with various contents of nanoclay. In light of the area under force-displacement curves, the absorbed energies of the nano-samples containing 1 and 3 wt.% of nanoclay are approximately equal and respectively 1.65% and 1.58% greater than the absorbed energy of the

(a) (b) (c) (d)

Fig. 6. Damage patterns for the FMLs with (a) 0 wt.% (b) 1 wt.% (c) 3 wt.% (d) 5 wt.% of nanoclay struck with energy of 14.70J



(a)



(b)

Fig. 7. (a) Force-time history and (b) Force-displacement response of FMLs impacted at energy of 25.42 J

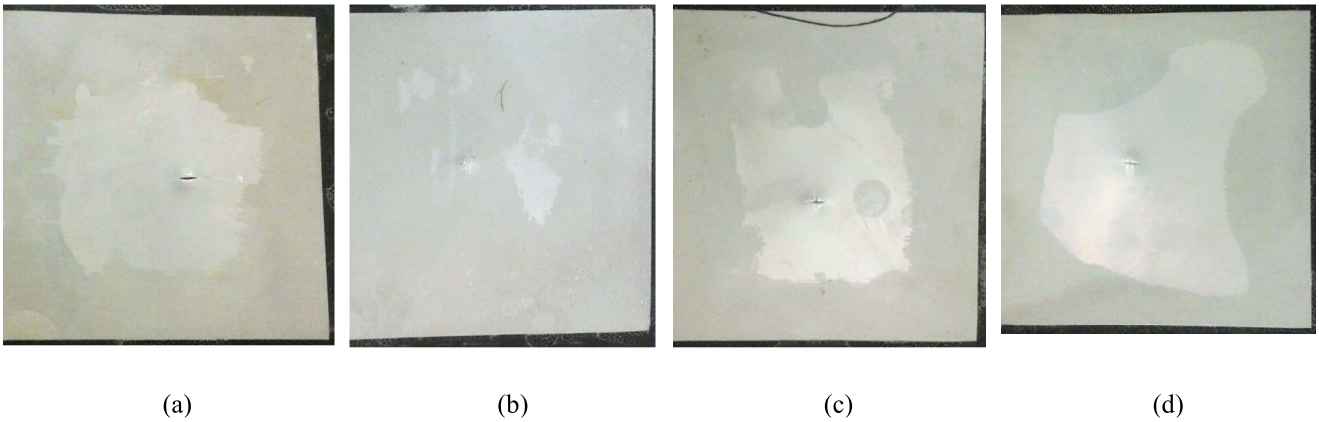


Fig. 8. Damage patterns for the FMLs with (a) 0 wt.% (b) 1 wt.% (c) 3 wt.% (d) 5 wt.% of nanoclay struck with energy of 25.42J

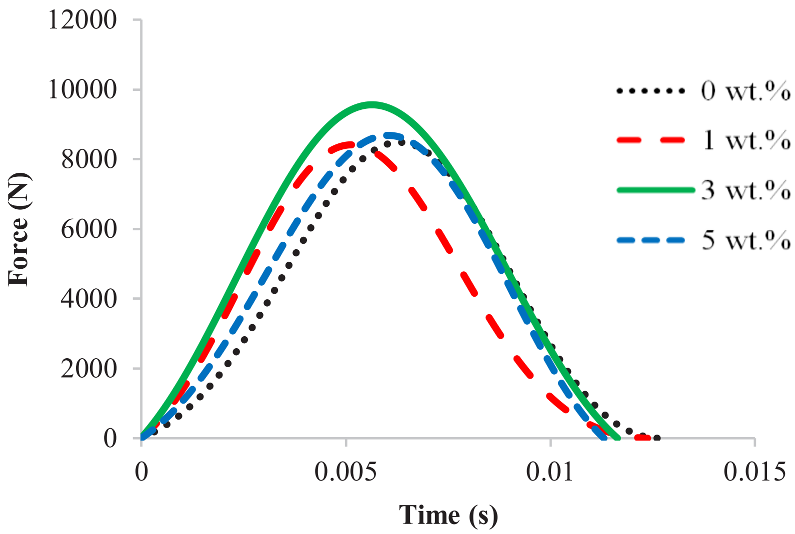
nanoclay-free sample. On the other hand, it can be seen that the maximum contact force in the case of 1 wt.% nanoclay becomes slightly higher and the impact time duration decreases in comparison to other cases. Fig. 8 shows the post-impact damage patterns of the four types of samples at an energy level of 25.42 J. It can be clearly seen that the impact-induced damage area on the sample containing 1 wt.% of nanoclay is smaller than those on other samples.

Fig. 9 illustrates the comparison between the contact force versus the impact duration as well as the contact force as a function of displacement of samples with the four different contents of nanoclay impacted at an energy of 27.99 J. Considering the higher peak load of about 10% and the less permanent displacement of approximately 7% associated with the sample containing 3 wt.% nanoclay than other samples, in Figs. 8(a) and 8(b) respectively, more impact resistance is expected in the case of 3 wt. %. Nevertheless, as presented in Fig. 10, less damage area has occurred in the reinforced FML with 1 wt. % nanoclay. Although there is no noticeable difference between the calculated absorbed energies of the nano-samples at this level of impact energy, the energy absorption of the 3wt.% nanoclay sample has the highest value and it is almost 1.4% and 0.2% greater than the cases of 0 and 1wt.% of nanoclay respectively, and in comparison, there is a 2.1% reduction in the absorbed energy of the 5 wt.% nanoclay sample which might come from the agglomeration of the nanoclays and as a result the presence of stress concentration points.

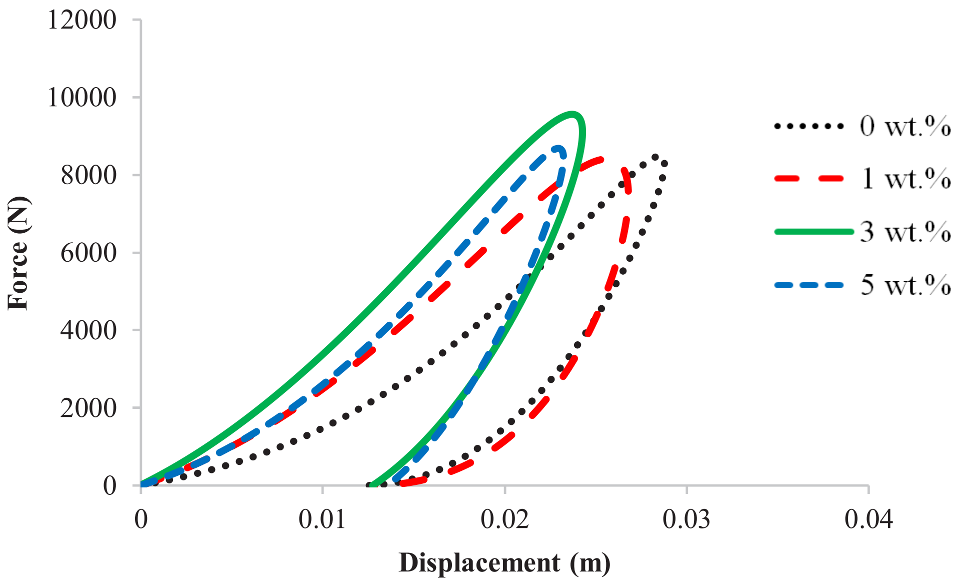
A comparison of obtained absorbed energies between FMLs with various nanoclay content impacted at three different energy levels is depicted in Fig. 11. It can be indicated that the samples with respectively 3 wt.% and 1 wt.% of nanoclay addition have better resistance against low-velocity impact as compared to other samples. Therefore, nanoclay addition in the range of 1 to 3 wt.% can improve FMLs' some impact performances. However, further addition of nanoclay into the FMLs can decrease the impact characteristics of them and just leads to a more rigid specimen.

4- Conclusions

In the current study, the low-velocity impact behavior of the nanoclay-reinforced FMLs, considering different weight percentages of nanoclay, stuck by the steel hemispherical impactor with various impact energy levels was examined. The FML samples with 0, 1, 3, and 5 wt.% nanoclays were produced using a hand lay-up technique and before performing drop-weight tests on the specimens, the quasi-static test was carried out to evaluate the tolerable maximum impact energy up to fracture. Afterward, the impact characteristics of specimens in terms of contact force histories as well as force-displacement responses were presented and the final absorbed energies were calculated to provide more quantitative information. Moreover, the assessment of the damaged area in impacted structures by visual inspection was investigated. It was revealed that the impact energy absorption rate of the samples containing 3 wt.% nanoclay was 0.6% to 4% more than the other cases at an impact energy of 14.70 J leading to a more impact resistant FML. Furthermore, considering the impact energy of 25.42 J, the absorbed energy of the nano-FMLs with 1 and 3 wt.% of nanoclay was approximately 1.6% greater than the nanoclay-free samples and the impact-induced damaged area on the specimen containing 1 wt.% of nanoclay was smaller than the other cases. Moreover, an increase of around 10 % and a reduction of approximately 7 % for respectively peak load and permanent displacement were found in the FMLs with 3 wt.% nanoclay at the impact energy of 27.99 J. Therefore, the experimental evidence at the three impact energy levels indicated that reinforcing FMLs with nanoclay at the range of 1 wt.% to 3 wt.% leads to enhancing impact resistance as well as decreasing the impact-induced damage of the samples. However, adding more nanoclay just results in a more brittle FML.



(a)



(b)

Fig. 9. (a) Force-time history and (b) Force-displacement response of FMLs impacted at energy of 27.99 J

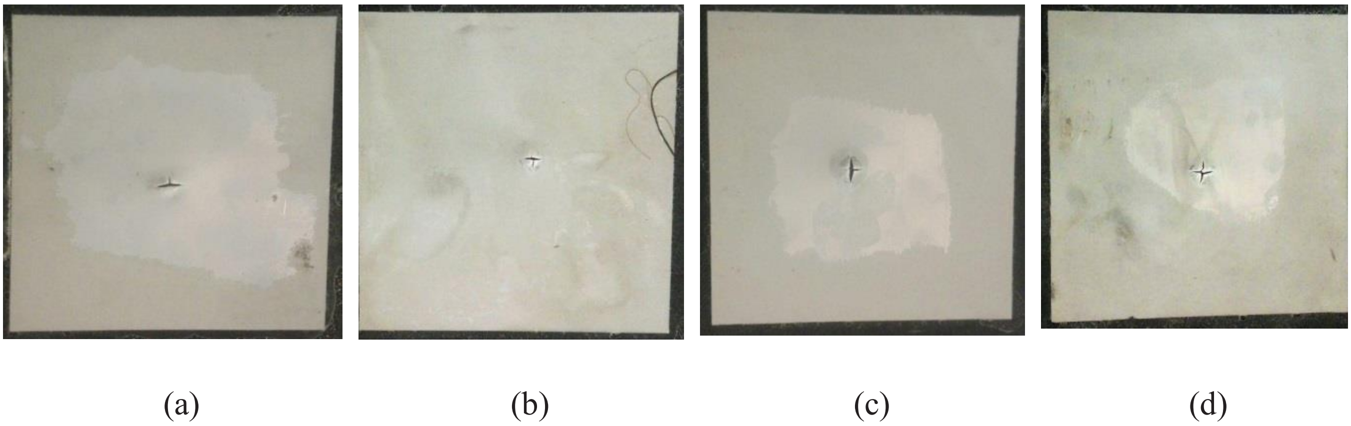


Fig. 10. Damage patterns for the FMLs with (a) 0 wt.% (b) 1 wt.% (c) 3 wt.% (d) 5 wt.% of nanoclay struck with energy of 27.99 J

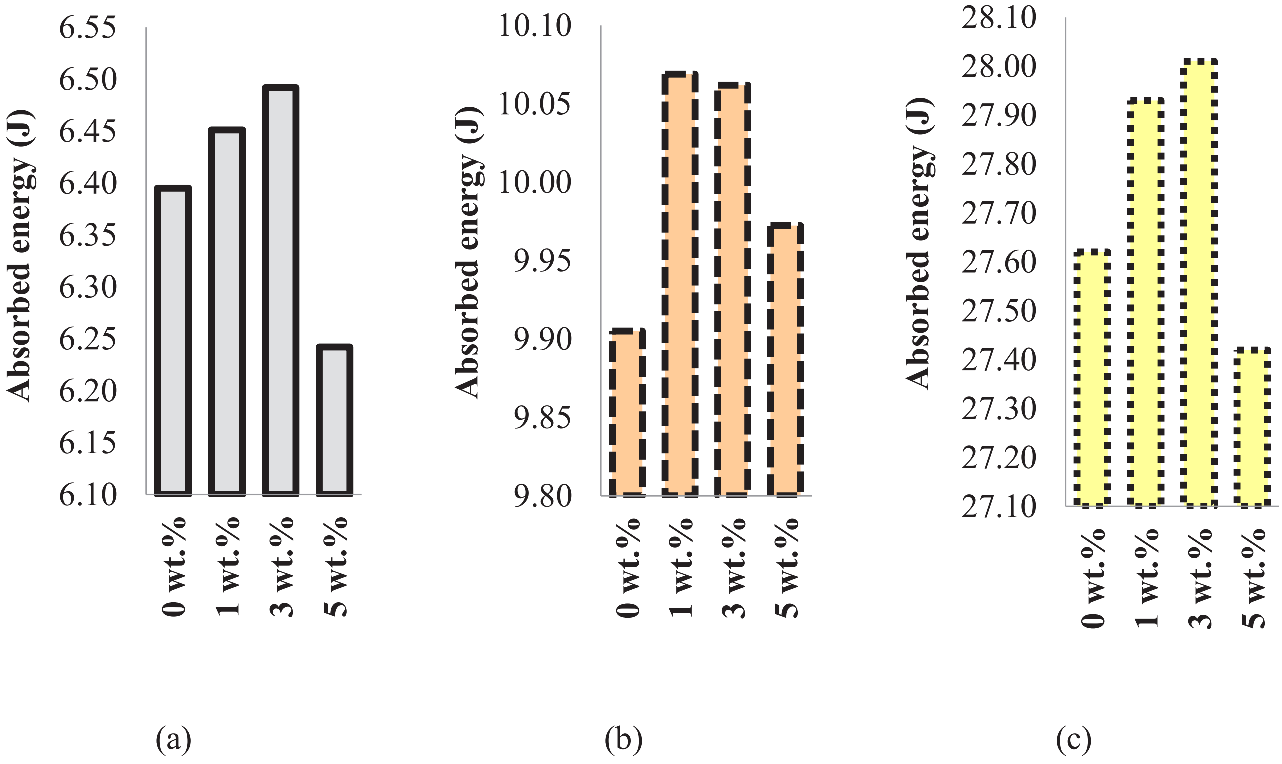


Fig . 11. Comparison between the final absorbed energies considering various weight percentage of nanoclay, for impact energy levels of (a) 14.70, (b) 25.42 and (c) 27.99 J

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