Experimental and Numerical Analysis of Bulletproof Armor made from Polymer Composite Materials

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Abstract

This work focuses on the preparation of polymer matrix composite spcimens by (Hand Lay-Up) method to made bulletproof armor from the unsaturated polyester resin (UP) as a matrix reinforced by kevlar fibers at different volume fractions with and without (3%) of Al_2O_3 powder. The tensile test was performed for these composites specimen which include: (modulus of elasticity, tensile strength and elongation percentage), in addition of ballistic test were studies.

Results of this work show that the values tensile test increase with increase the volume fraction of fibers. And the values of tensile test of composite reinforced by kevlar fibers and addition (3%) of Al_2O_3 powder was less than those composite without addition of Al_2O_3 powder.

The numerical method based on FEM was used to analysis of the bullet proof armor ballistic test of the composite specimens by finding the values of stresses, strains and deformations.

The numerical results that obtained from program (ANSYS 14.5) represents the maximum value of stress happened for the composite specimens when reinforced by eight layers of the kevlar, and vice versa to the deformations and strain also the numerical results shown a good agreement with results that were obtained experimentally.

Results of ballistic test of composite specimens show the volume fraction of fibers have effect on the deformations of front face and back face of these composite specimens. And the values of ballistic test for the composite reinforced by kevlar at eight layers give best values from other each of composite specimens.

Keywords: Kevlar, Alumina, Unsaturated polyester, Tensile, Ballistic.

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التحليل العددي والعملي لدرع مضاد للرصاص مصنوع من مواد متراكبة بوليمرية

الخلاصة:

في هذا البحث تم تحضير مواد متراكبة ذات اساس بوليمري بطريقة الصب اليدوي لعمل درع مضاد للرصاص من راتنج البولي استر غير المشبع كمادة اساس مدعمة بالياف الكفلر عند كسور حجمية مختلفة مع اضافة او عدم اضافة (3%) من دقائق الـ (Al_2O_3). اجريت على هذه العينات المتراكبة اختبار الشد والذي تضمنه (معامل المرونة, مقاومة شد, ونسبة الاستطالة), بالإضافة الى اختبار الاطلاق .

اظهرت نتائج هذا البحث ان قيم اختبار الشد تزداد مع زيادة الكسر الحجمي للالياف. وان قيم اختبار الشد للعينات المتراكبة عند اضافة (3%) من دقائق الـ (Al_2O_3) هي اقل من قيم هذه المواد المتراكبة بدون اضافة دقائق الـ (Al_2O_3) .

استخدمت الطريقة العددية المعتمدة على طريقة العناصر المحددة لتحليل اختبار الاطلاق للدرع المضاد للرصاص للعينات المتراكبة بواسطة ايجاد الاجهادات والانفعالات والتشوهات.

بينت النتائج العددية التي تم الحصول عليها من استخدام برنامج (ANSYS 14.5) ان اقصى قيم للاجهاد تحدث للعينات المتراكبة عندما تقويتها بثمانية طبقات من الياف الكفلر والعكس بالعكس لقيم الانفعال والتشوه, وكذلك بينت النتائج العددية تطابق جيد مع النتائج العملية.

بينت نتائج فحص الاطلاق للعينات المتراكبة بان الكسر الحجمي للالياف تؤثر على تشوهات الوجه الامامي والوجه الخلفي لهذه العينات. وان قيم اختبار الاطلاق للمواد المتراكبة المقواة بالياف الكفلر عند ثمانية طبقات اعطت افضل قيم من كل العينات المتراكبة الاخرى.

الكلمات المرشدة: كفلر، الومينا، البوليستر الغير مشبع، الشد، الاطلاق .

INTRODUCTION

Body armors defined as any defensive coverings worn to protect the body from physical attacks have evolved from readily available materials such as animal skins or natural fibers made from thatch, cotton, and silk often woven in textile forms to metals such as copper, steel, and iron used in plate forms to the technologically complex armors used by today’s armed services and law enforcement [1].

Ballistic vests use layers of very strong fiber to "catch" and deform a bullet. The vest absorbs the energy from the deforming bullet, bringing it to a stop before it can completely penetrate the textile matrix. Some layers may be penetrated but as the bullet deforms, the energy is absorbed by a larger and larger fiber area. While a vest can prevent bullet penetration [2].

Mang studies had investigated the effect of volume fraction, type of fiber and particle on preparation armor bulletproof.

Grujicic et al. (2006) have studied the ability of light-weight all fiber-reinforced polymer-matrix composite armor and hybrid composite-based armor hard-faced with ceramic tiles to withstand the impact of a non-Armor- Piercing (non-AP) and AP projectiles is investigated using a transient non-linear dynamics computational analysis. The results obtained confirm experimental findings that the all-composite armor, while being able to successfully defeat non-AP threats, provides very little protection against AP projectiles. In the case of the hybrid armor, it is found that, at a fixed overall areal density of the armor, there is an optimal ratio of the ceramic-to-composite areal densities which is associated with a maximum ballistic armor performance against AP threats [3].

Kausala. M. et al. (2007) have studied that the ballistic resistance capacity of a carbon nanotube. Carbon nanotubes have high strength, light weight and excellent energy absorption capacity and therefore have great potential applications in making antiballistic materials. By examining the ballistic impact and bouncing-back processes on carbon nanotubes, this investigation shows that nanotubes with large radii withstand higher bullet speeds and the ballistic resistance is the highest when the bullet hits the center of the CNT [4].

Theoretical Part

Tensile Test (Stress-Strain)

Tensile test is widely used to provide the designer with information about material strength and maximum elongation and others.

From the tensile curve, the following can be calculated [5]:

1. Tensile strength (MPa).
2. Modulus of elasticity (MPa).
3. Elongation percentage at break (%).

The density of the composite material can be calculated from the following rule:-

$$\rho_c = \mathcal{E}\, V_i\, \rho_i = V_1\, \rho_1 + V_2\, \rho_2 + ---------- V_n\, \rho_n \quad (kg/m^3) \qquad \ldots(1)$$

Where:

ρ_c: the density of the composite material.

ρ_1, ρ_2, ρ_n: the density of each constituent.

V_1, V_2, V_n: the volume fraction of each constituent.

To calculate the volume fraction of each of fiber and matrix basis as follows:-

$$V_f = \nu_f / \nu_c * 100\% \qquad \ldots(2)$$

$$V_m = \nu_m / \nu_c * 100\% \qquad \ldots(3)$$

Where:

V_f, V_m :- Volume fraction of each of the fiber and matrix.

ν_m, ν_m, ν_m :- the volume of each of the composite material and fiber and matrix.

The major Poisson's ratio is given by:

$$\nu_{12} = \nu_f\, V_f + \nu_m V_m \qquad \ldots(4)$$

Where:-

ν_f, ν_m :- Poisson's ratio of fiber and matrix.

Experimental Work

Unsaturated Polyester Resin (UP)

Unsaturated Polyester resin is used as the matrix. It is provided from the Saudi Arabia Company in the form of transparent viscous liquid at room temperature which is a thermally hardened polymer (Thermosets). Table (1) shows the characteristics of unsaturated polyester used in the research .

Kevlar Fibers

The type used in the present work is (kevlar 49) fabric with the mechanical properties show in table (2).

Aluminum Oxide Particles

Aluminum oxide powder (Al_2O_3) is also used as reinforcement in this research. It is a standard powder from the company (RIEDEL – DE HAEN AG) Germany with a particle size of (16 μm) and density of (4.05gm/cm^3).

Ballistic Testing:-

Body (bullet proof) armor ballistic testing is conducted to evaluate the resistance of penetration of body armor test samples. The evaluation of this bulletproof armor happed at constant velocity of the bullets. The armor plate inserts were subjected to ballistic testing in accordance to the standards of the National Institute of Justice (NIJ). Ballistic clay was used as a backing layer in most of the tests to measure performance parameters of the plate post-impact [6 & 7].

The standard states that a chronograph used to record the measurement. The first chronograph start trigger screen will be placed at either 2 m (6.5 ft) or 12 m (40 ft) from the muzzle of the test barrel. The screens will be securely mounted to maintain their required position and spacing (measurement accuracy of ± 1 mm (± 0.04 in)). The testing range was set up according to the standard so that the test equipment is placed as shown in figure (4). In addition, the test barrel was mounted on an appropriate fixture with the barrel horizontal [6,7&8]

The first tests were conducted at the shooting academy, Baghdad. At the shooting academy the officer correction on the samples after (7 m) based on the (NIJ) using the type of gun (9) mm and high speed (80 m/sec) at constant angle (90°) with respect the composite specimen. Figure (5) shows the geometry of ballistic test specimens**.**

Results and Discussion

Tensile Test Results:-

- **Stress – Strain Curve:**

The general trend of stress-strain curves for (UP) reinforced by kevlar fibers with and without (3%) volume fraction of Al_2O_3 powder for particles size of (16 μm) as shown in figures (9&10).

These figures that illustrate the strain increases with the increases in stress in nonlinear relationship at different volume fractions of fibers.

- **Modulus of Elasticity:-**

The variation of the modulus of elasticity with the fibers volume fraction of kevlar fibers with and without of Al_2O_3 are shown in figure (11).

There are many factors affected on the tensile properties of composite materials under study like type of fibers, volume fraction and presence of particles.

It is clear from this figure, that the modulus of elasticity increase with increasing the fiber volume fraction of reinforcing materials in non-liner relationship. This is due to the increase of the number of layers that leads to impede the progress of the failure through the composite material and thus to decrease the strain to failure of the composite material [8].

When addition Al_2O_3 powder in (3%) to composite material the value of the modulus of elasticity is less than this composite without Al_2O_3 powder. The maximum value of the modulus of elasticity obtained for kevlar reinforced composite without Al_2O_3 is (1205 MPa) at (V_f = 43%), but the maximum value of the modulus of elasticity obtained for kevlar reinforced composite with AL_2O_3 is (500 MPa) at (V_f = 43%), the reasons to the nature of the bonding between the matrix and the fillers particles has an important role, i.e. the bad ability of a liquid polyester to spread on the solid particles (bad wettability) may cause decreasing bonding force between the matrix and the fillers material, so the resultant composite will require low stress to break their physical bonding [9].

- **Tensile Strength:-**

The variation of tensile strength of specimens composite with varying fiber volume fraction of kevlar fibers reinforced composite material is presented in figure (12).

It is clear from this figure, that the tensile strength increase with increasing the fiber volume fraction of kevlar fibers, it is noted that the tensile strength is increased from (95 MPa) at (V_f=5%) to reach (237 MPa) at (V_f=43%) of kevlar fibers. The increase in tensile strength occurs because increasing in volume fraction of fibers will need more energy to create the crack initiation and crack propagate to end with failure, and it makes the composite to need more forces to failure, and that means increasing in strength for composite materials [8].

when addition Al_2O_3 powder in (3%) to composite material the value of the tensile strength is less than tis composite without Al_2O_3 powder, the reasons to when the matrix material content the particles lead to difficulty of penetration between the fiber, that have been observed in practice which reduced the convergence between the both surface of the matrix and fiber as well as surface of particles with each other, which make the process of wetting surface of the fiber and particles is not complete process, which leads to the weakening of bonding between matrix and strengthen materials, and reduces the efficiency of the transfer of load on the material overlapped by the particles and fiber material therefore will be broken the composite material at less stress [10].

- **Elongation Percentage at Break**

The results of elongation percentage at break for kevlar fibers reinforcing unsaturated material are shown in figures (13).

It is shown that the elongation percentage at break of the composite specimens increases with increasing of fibers volume fraction of kevlar fibers. this is because the presence of fiber imparts the stiffening effect within the matrix and thus imposes a mechanical restraint on the composite**.**

Numerical results of ballistic test:-

This section includes the results of analysis by ANSYS program (finite element) for ballistic test that includes bullet model, meshing, applied the bondary condition with different material properties to abtain the stress, strain and deformation of ballistic test. Table (3) shows the materials properties of the composite specimens.

Equivalent Von Mises stress results:

Figure (14) show the contour plots for equivalent (von-mises) stress distribution for (UP) reinforced by kevlar fibers with or without Al_2O_3 powder, which display the overall distribution of the equivalent Von Mises stress throughout the material, as well as to determine the approximate location and value of the maximum equivalent Von Mises stress.

There are many factors affected on the ballistic test of composite materials under study like type of fibers, volume fraction and number of layers. The figures illustrates that the equivalent (von-mises) stress increases with increasing volume fraction and number of layers of fibers. The values equivalent (von-mises) stress of kevlar reinforced composite material more than the values stress of kevlar reinforced composite material with (3%) of Al_2O_3 powder, that due to the change in the properties of materials in additional to the matrix material content the particles lead to difficulty of penetration between the fibers, that have been observed in practice which reduced the convergence between the both surface of the matrix and fiber as well as surface of particles with each other. Which leads to the weakening of bonding between matrix and strengthen materials, and reduces the efficiency of the transfer of load on the material overlapped by the particles and fiber material therefore will be broken the composite material at less stress.

Equivalent elastic strain results:

Figure (15) show the contour plots for equivalent elastic strain for (UP) reinforced by kevlar fibers with and without Al_2O_3 powder, which display the overall distribution of the equivalent elastic strain throughout the material, as well as to determine the approximate location and value of the maximum equivalent elastic strain.

It can be illustrates from This figure that the strain decreases with increasing volume fraction and number of layers of fibers. This is due to the increase of the number of layers that leads to impede the progress of the failure through the composite material and thus to decrease the strain to failure and deformation of the composite material but increase stress of composite material.

Total deformation results:

Figure (16) show the contours of the total deformation for (UP) reinforced by kevlar fibers with or without Al_2O_3 powder.

This figure display the overall distribution of the total deformation throughout the material, as well as to determine the location and value of the maximum deformation, the total deformation decreases with increasing volume fraction and number of layers of fibers.

Ballistic Test Results:

The experimental work of the ballistic test show that the effect of the volume fraction on the deformation of front face and back face of deform after ballistic test where the specimen of less volume fraction represent high deformation especially around the point of contact of bullet of front face of specimen and high deformation of back face and vice versa [11] .

The values of deformation for the composite reinforced by kevlar at eight layers best from each other composite specimens at different volume fraction. Figure (16) shows the geometry of front face after ballistic test specimens, figure (17) shows the back face deformation after ballistic test specimens.

Conclusion

1. The mechanical properties (modulus of elasticity, ultimate tensile strength, elongation percentages at break) increase with the increase in the volume fraction of kevlar fibers. The values of this mechanical properties were (1205 MPa, 237 MPa, 22%) respectively at (V_f= 43%) of kevlar fiber.
2. (UP) reinforced by kevlar fibers when content (3%) alumina powder have mechanical properties less than this composite material without alumina powder.
3. ANSYS numerical solutions suggested in this study give a good agreement with the mechanical properties. The values of the equivalent (von-mises) stress increase with the increase the volume fraction and number of layers of kevlar fibers and the values of the equivalent elastic strain and total deformation decrease with the increase the volume fraction and number of layers of kevlar fibers. The maximum values of the equivalent (von-mises) stress was (127.85 MPa) at (Vf= 43%) of kevlar fibers and the minimum values of the equivalent elastic strain and total deformation was (0.22004 % and $4.9464*10^{-3}$ m) respectively at (Vf = 43%) of kevlar fibers.
4. The ballistic test shows the less deformation with increase the volume fraction of reinforcement.

Table (1): Characteristics of unsaturated polyester used in the research .

Density (gm/cm^3)	Young Modulus(GPa)	Tensile strength (MPa)	Percent elongation (EL%)	Poisson's Ratio
1.04-1.46	2.06-4.41	41.4-89.7	<2.6	0.33

Table (2): Specification of the used kevlar fibers .

Density(gm/cm3)	Young Modulus (GPa)	Tensile Strength (MPa)	Poisson's Ratio
1.44	139	3750	0.36

Table (3): Mechanical properties of the composites specimens of this work.

NO.	Matrix+ Reinforcement	E(MPa)	Poisson′s Ratio	Density (gm/cm^3)
1.	Up + Kevlar	571	0.3315	1.26425
2.	Up + Kevlar	700	0.3369	1.29755
3.	Up + Kevlar	900	0.3399	1.31605
4.	Up + Kevlar	1205	0.3429	1.3345
5.	Up + Kevlar+AL_2O_3	300	0.3279	1.346
6.	Up + Kevlar+AL_2O_3	400	0.3333	1.3793
7.	Up + Kevlar+AL_2O_3	450	0.3363	1.3978
8.	Up + Kevlar+AL_2O_3	500	0.3393	1.4163

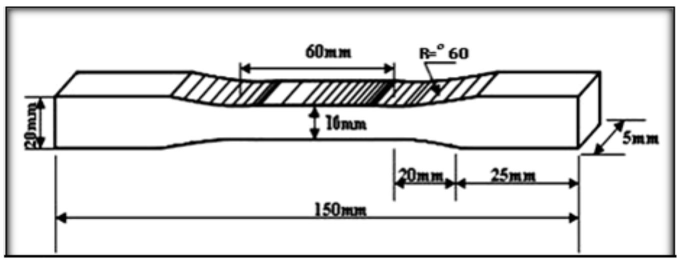
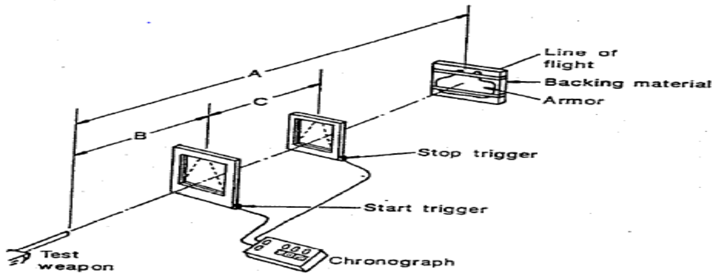


Figure (1): Tensile test standard specimen [9].

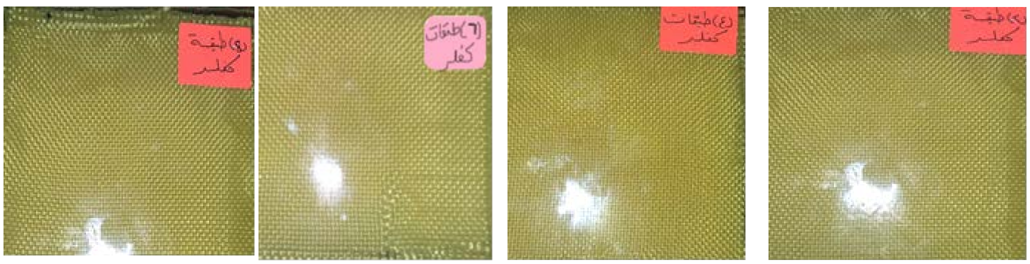
Figure (2): Experimental specimens test.

(a) before test **(b) after test**

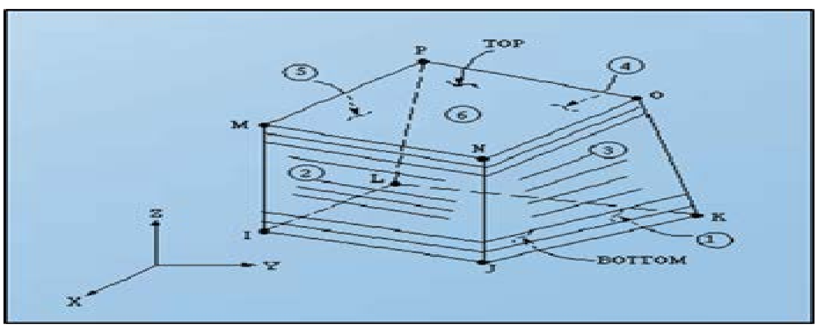
Figure (3): Specimens for tensile test.



Figure(4): Test range configuration as stated by the NIJ Standard)[3].



Figure(5): shows the geometry of ballistic test specimens.



Figure(6): Layered SOLID 46 element.

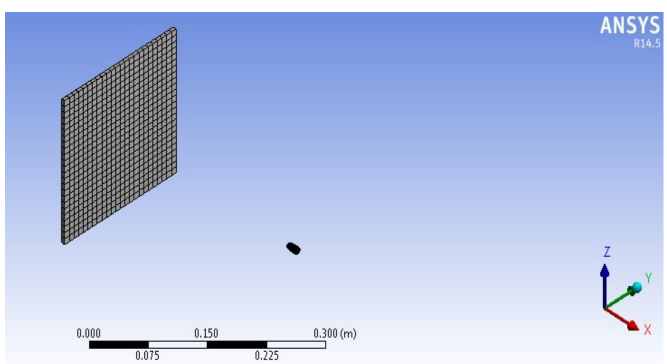


Figure (7): The mesh of the bullet proof armor composite .

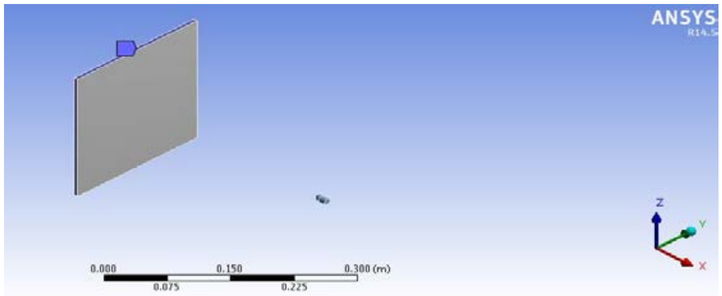


Figure (8): The applied load (displacement) on the bullet proof armor composite

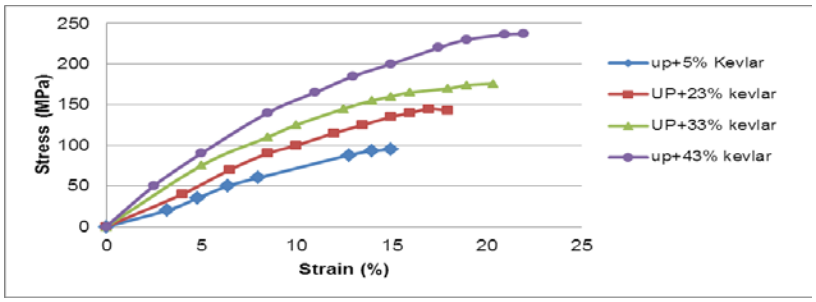


Figure (9): Stress – strain curve of UP resin reinforced with kevlar fibers

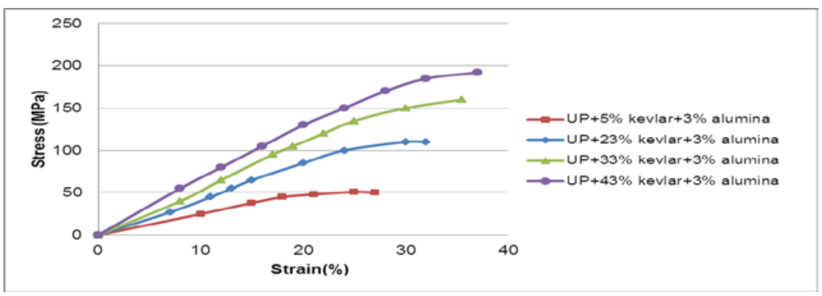


Figure (10): Stress – strain curve of UP resin reinforced with kevlar fibers with (3%) of AL_2O_3 powder.

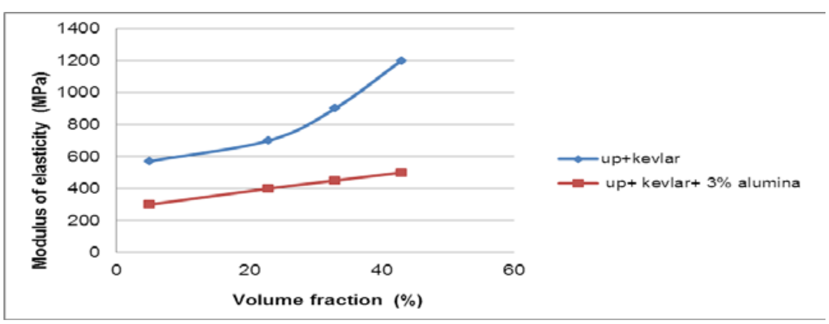


Figure (11): The relationship between the modulus of elasticity and volume fraction for UP resin reinforced with kevlar fibers at different volume with and without of (3%) of AL_2O_3 powder .

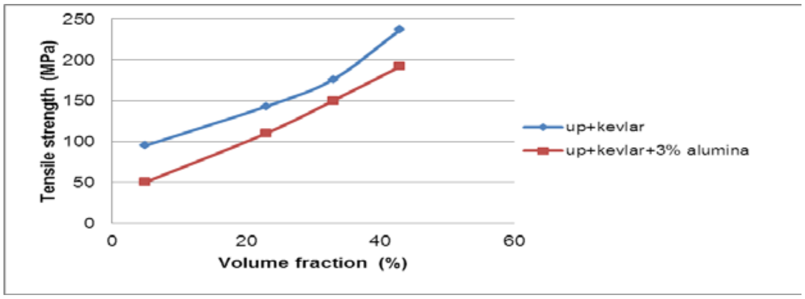


Figure (12): The relationship between the tensile strength and volume fraction for kevlar reinforced composite materials at different volume fraction with and without (3%) of AL_2O_3 powder.

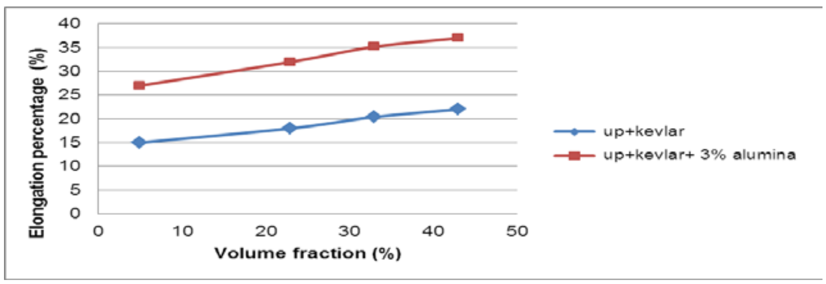
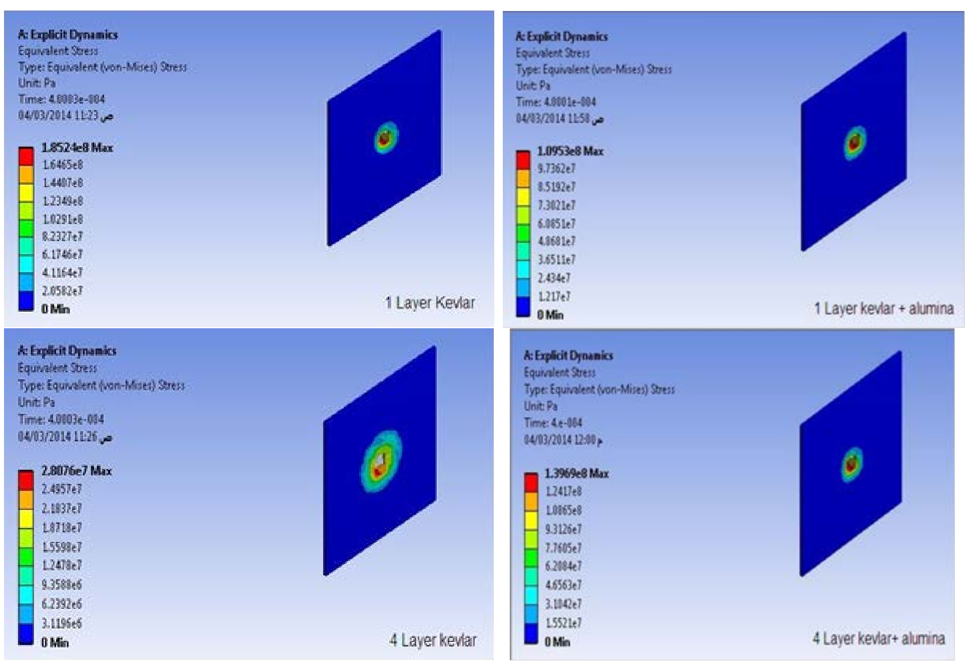


Figure (13): The relationship between the elongation percentage and volume fraction for kevlar reinforced composite materials at different volume fraction with and without (3%) of AL_2O_3 powder.



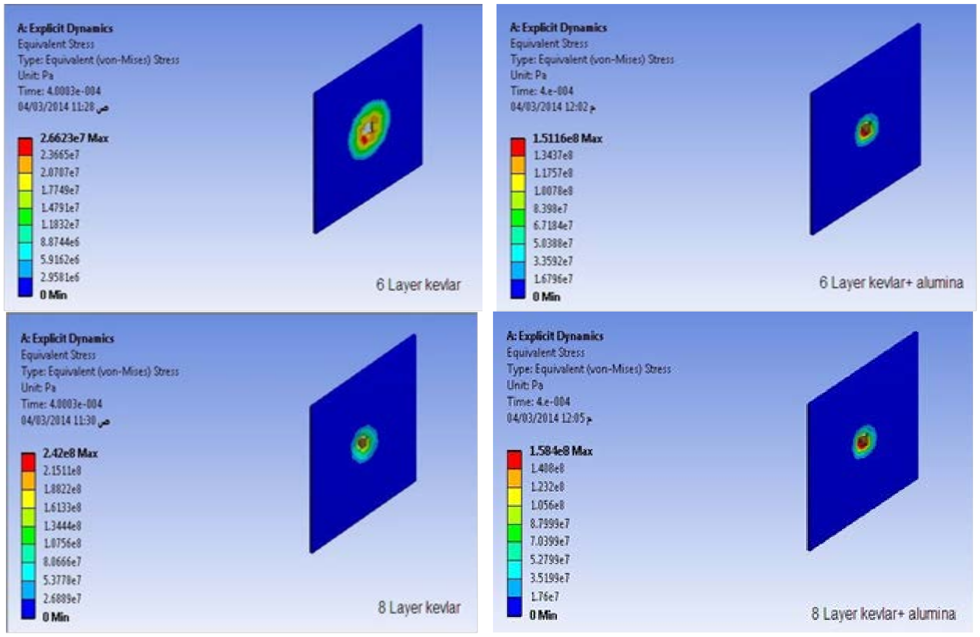
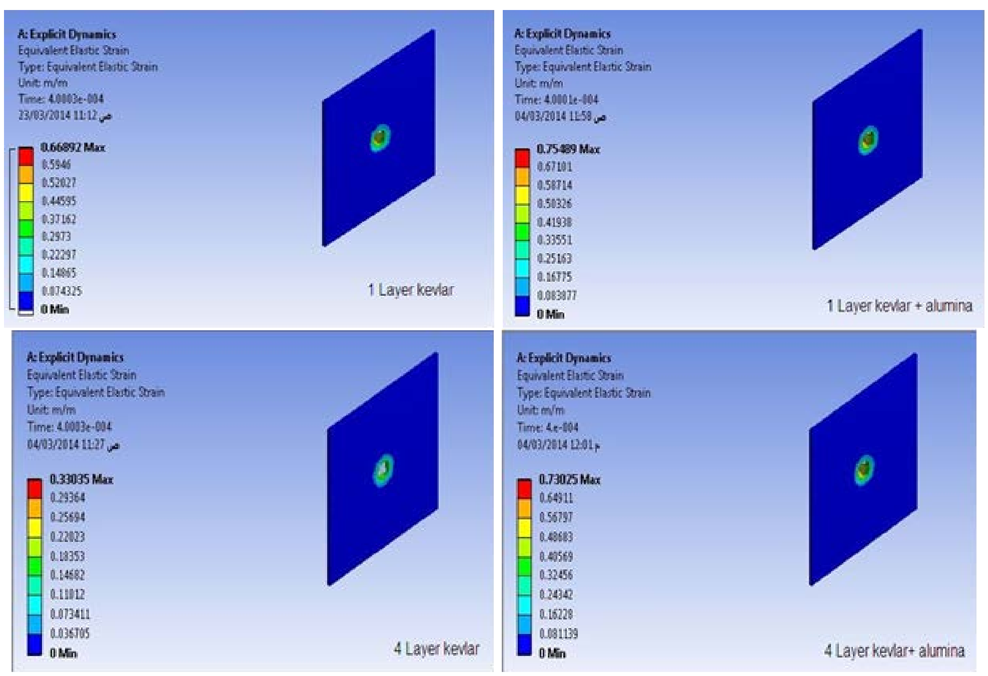


Figure (14) : Contours of equivalent Von Mises stress distribution of composite &hybrid materials (1,4,6 and 8 layers) with and without alumina powder .



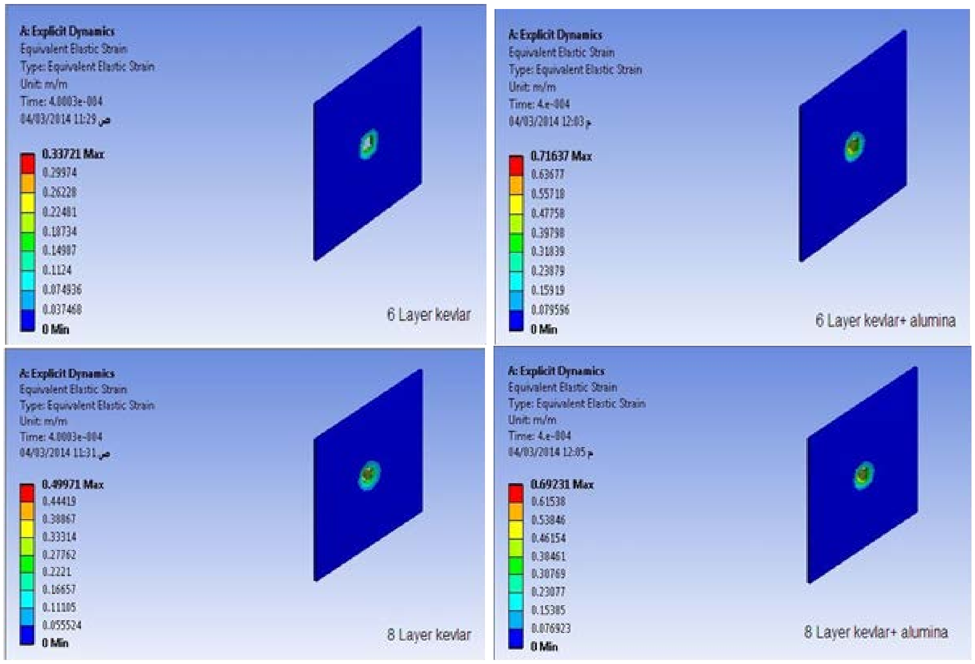
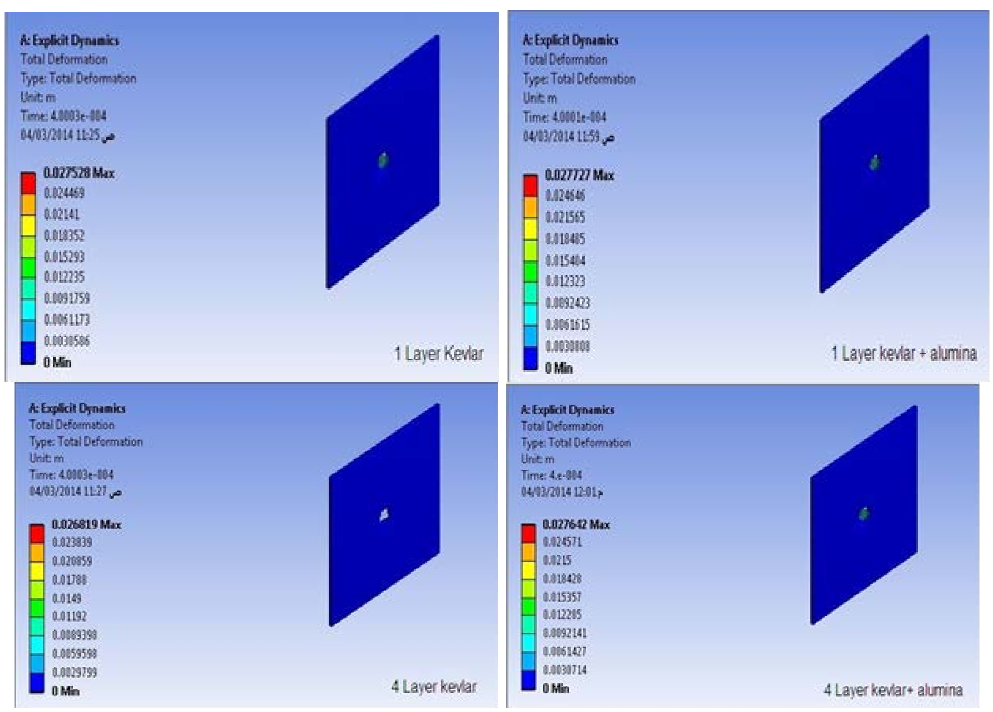


Figure (15): Contours of equivalent elastic strain distribution of composite & hybrid materials (1,4,6 and 8 layers) with and without alumina powder .



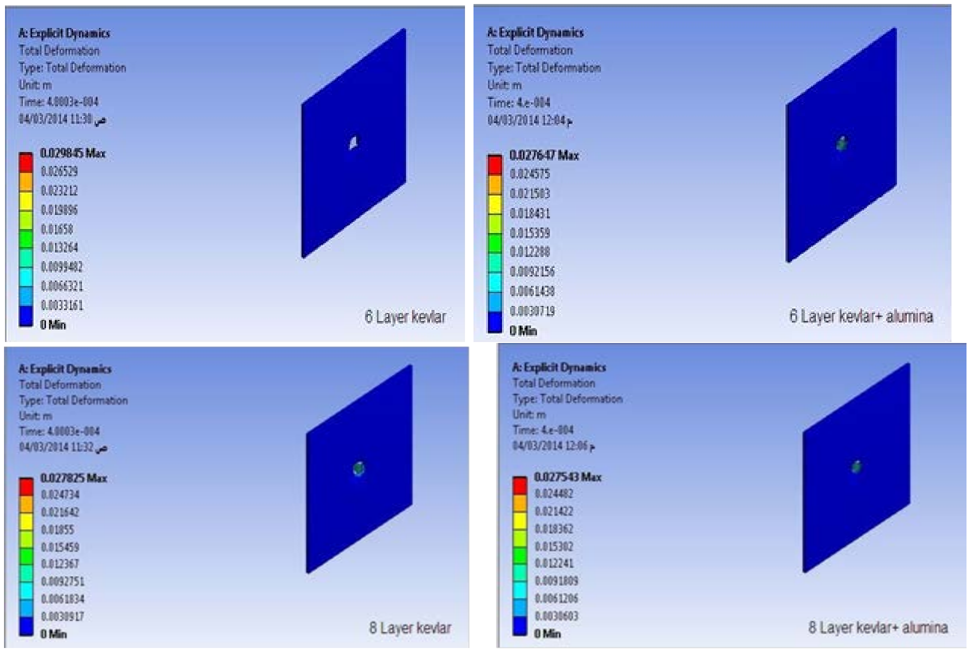


Figure (16) : Contours of total deformation of composite & hybrid materials (1,4,6 and8 layers) with and without alumina powder .

Figure (17): shows the geometry of front face deformation after ballistic test .

Figure (18): Shows the geometry of back face deformation after ballistic test.

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