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The Effect of Acrylic Reinforcement with Different Types of Composite Material on the Impact Energy

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Abstract

The study investigates the improvement of the impact energy of acrylic such as (Elastic modulus (E_c), Impact strength (G_c), and Fracture toughness (K_c)) by reinforcing with a composite material consisting of different shapes of metal mesh at different diameters of the circular longitudinal holes and different volume fraction by adopting the Charpy test in determining the experimental results. The specimens of acrylic prepared by cutting them according to the standard of Charpy test specimens (ASTM D-256) using laser beam type CO_2 by a CNC machine and then drilling them longitudinally with diameters (2, 4, and 6 mm). Increasing the diameter of reinforcement composite material in acrylic at (2 mm, 4 mm, and 6 mm) caused to an increase in the impact energy at ratio (33.3%, 60%, and, 83.3%) respectively for a fiber that has a rectangular shape at (1mm*1mm), while it increased at ratio (44.4%, 50%, and 60%) for rectangular shape with dimensions (2mm*2mm) and increased in a ratio (61.53%, 64.28%, and, 71.42%) for rhombic shape at dimensions (7mm*7mm). The SEM images showed the occurrence of sharp shear in the wire of the metal mesh of fiber without dislocating it from the composite material which indicates the homogeneity of the composite material and the success of achieving the reinforcement to increase the resistance of the impact composite specimens

Keywords: Impact strength, metal mesh, impact toughness, laser.

Nomenclatures

A_0	is impact of pure acrylic material.
A	The specimens prepared from metal mesh type rectangular shape size (1mm*1mm) at diameter (2mm), (4mm) and, (6mm).
B	The specimens prepared from metal mesh type rectangular shape size (2mm*2mm) at diameter (2mm), (4mm) and, (6mm).
C	The specimens prepared from metal mesh type rhombic shape size (7mm*7mm) at diameter (2mm), (4mm) and, (6mm).
W_m	Weight of matrix (polyester) ,(g).
W_c	Weight of composite specimens, (g).
W_f	Weight of fiber (metal mesh) ,(g).
$W_{acr.}$	Weight of acrylic ,(g).
V_f	The volume fraction of fiber , (cm^3).
V_m	The volume fraction of matrix , (cm^3).
$V_{acr.}$	The volume fraction of acrylic , (cm^3).
ρ_f	The density of fiber , (g/cm^3).
ρ_m	The density of matrix , , (g/cm^3).
$\rho_{acr.}$	The density of acrylic , (g/cm^3).
ρ_c	The density of composite, (g/cm^3).
E_c	Elastic modulus of composite (GPa).
E_f	Elastic modulus of fiber (GPa).
E_m	Elastic modulus of matrix (GPa).
E_{acr}	Elastic modulus of acrylic (GPa).
m	Mass of the pendulum (kg)
g	Acceleration factor of gravity (m/s^2)
h	Initial height of pendulum (mm)
h'	maximum height fracturing the impact specimens.
U_c	Impact energy (J).
G_c	Impact strength of material (J/m^2).
A_r	Cross sectional area of specimen (mm^2)
K_c	Fracture toughness (MPa . m$^{1/2}$)

1. Introduction

Within the past decade, researchers have studied the development of composite structures with the increasing industrial and construction applications and attention to improve the mechanical properties of acrylic and reinforce it with composite materials in order to obtain higher specifications. The researchers studied the behavior of acrylic used in the manufacture of dentures as a base material during impact loading using cast notches versus automatic slitting under different temperatures. The two forms of slitting (forming and shaping) were performed equally across all specimens [1]. The researchers studied strengthening the high-impact acrylic resins (Metrocryl HI) and its effect by adding zirconia powder at two different concentrations on transverse strength, impact strength, surface hardness, solubility and water absorption

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[2]. The study presented acrylic as a replacement matrix for thermal hardening compounds for its mechanical superiority and ease formation at low temperature and the possibility of recycling, where Charpy test and, low- speed impact study tests were conducted and compared with conventional compounds manufactured using epoxy resins and polyester with respect to impact resistance[3]. The study investigates the improvement of the mechanical properties of the acrylic layer by creating a crack according to polynomial's function using CO_2-laser and without additives. The cracks were created by the laser at different powers and different speeds [4]. The use of metal and fiber reinforcements produces beneficial results [5–6]. Metal wires can be placed inside polymers, but fibers have been demonstrated to be more effective [5]. Metal and glass fiber exhibits different mechanical properties. Due to their high modulus of elasticity, lack of resilience, and poor adherence to the acrylic resin matrix, metals demonstrated significantly higher interfacial stresses within the resin matrix [7, 8]. Salted fiberglass has the ability to adhere to an acrylic type resin matrix [9]. It also has a low elastic modulus if compared to metals that achieve a more appropriate stress distribution pattern [7]. Fiber reinforcement and resin matrix together have similar mechanical performance without high-stress concentration at the interface reducing chances of failure [8]. The interaction between glass fibers and acrylic resins achieves success when a flexible material (such as a matrix of acrylic resin) is used and strengthened with a material such as glass fiber together [7, 10-11].The study examined the improvement of mechanical properties by strengthening using organic fibers in epoxy resins through tensile and bending tests [12]. He investigated the sheets' microstructure, wear-resistance, and impact stress of polymeric materials manufactured at different composition ratios and their effect on improving their mechanical properties[13].The study examined the behavior of composite materials when exposed to impact at low and high speeds to determine the design is reliable and effective in the field of application as well as the cost[14]. The study examined the possibility of benefiting from the use of synthetic fibers from Bagasse in strengthening polyester at different rates and its effect on improving the elastic modulus and the amount of elongation in it [15].They studied the interlayer bonding on the mechanical behavior of the laminated glass through a mathematical model to predict the mechanical behavior based on the type and thickness of the material and the thickness of the glass plate[16].The current study aims to investigate the improvment the mechanical properties of acrylic such as (Elastic modulus (E_c) , Impact strength (G_c) , and Fracture toughness (K_c)) by reinforcing acrylic impact specimens by inserting composite that material consists of polyester (matrix) reinforced with a different type of metal mesh (fiber) in the cylindrical hole has different diameters.

2. Methodology

Determining the mechanical properties of composite materials depends on determining the volume or weight fraction of the materials included in the composite material (fiber and matrix) and the effect of the properties of each of them on the composite material. Practical tests are the accurate means of measuring the properties of composite material, whether it consists of two or more materials. The calculated volume fraction of the fiber and matrix of the composite material contributes to determining the properties of the final composite material. Mathematical calculations based on experimental results provide real data as well as the effect of changing its ratio on the mechanical properties of the composite material.The resin weight is the difference between the composite specimen and fiber weights[17]:

$$W_m = W_C - W_f \quad (1)$$

And for specimes consist of three composite material the equation will be:

$$W_m = W_c - W_f - W_{acr.} \quad (2)$$

The volume of the fibers (metal mesh) in the composite:

$$V_f = \frac{W_f}{\rho_f} \quad (3)$$

The volume ratioof fiber (metal mesh)to matrix (polyester resin) of the composite material which inserted in the acrylic specimens:

$$\frac{V_f}{V_m} = \left(\frac{W_f}{W_m}\right) * \left(\frac{\rho_f}{\rho_m}\right) \quad (4)$$

While the volume ratio of fiber to the volume of the composite specimens (Vc) consists of three material :

$$\frac{V_f}{V_c} = \frac{V_f \rho_f}{V_f \rho_f + V_m \rho_m + V_{acr.} \rho_{acr.}} \quad (5)$$

Or,

$$\frac{V_f}{V_c} = \frac{1}{1+\left(\frac{W_m\, \rho m + W_{acr.} \rho_{acr.}}{W_f \rho_f}\right)} \quad (6)$$

And, the matrix volume ratio is equal to:

$$\frac{V_m}{V_c} = \frac{1}{1+\left(\frac{W_f \rho_f + W_{acr.} \rho_{acr.}}{W_m * \rho m}\right)} \quad (7)$$

The density of composite material:

$$\rho_c = \rho_f V_f + \rho_m V_m + \rho_{acr.} V_{acr.} \quad (8)$$

The Young modulus (Elastic modulus) of composite material [17,18] :

$$E_c = V_f . E_f + V_m E_m + V_{acr.} E_{acr.} \quad (9)$$

The impact energy in Charpy test, as in the following equation[19]:

$$U_c = m.g.(h-h') \quad (10)$$

The calculation of impact strength can be done by the following equation [20]:

$$G_c = U_c / A_r \quad (11)$$

The fracture toughness,which describes the resistance of material containing a crack to fracture, can be expressed as:-

$$K_c = \sqrt{G_c . E_c} \quad (12)$$

3. Material and Methods

3.1. Materials

The materials tested acrylic layer reinforced with composites which consist of polyester resin as a matrix and a different type of metal mesh as fiber to improve the impact energy absorption of it. The composite material consists of two materials; the first is polyester as a matrix whose specifications [21] are shown in Table 1, the second is a metal mesh of various types as fibers show in Figure 1. The metal mesh specifications [22] are shown in Table 2. The acrylic specimens are prepared by drilling them longitudinally at different diameters to insert the composite material as shown in Figure 2.

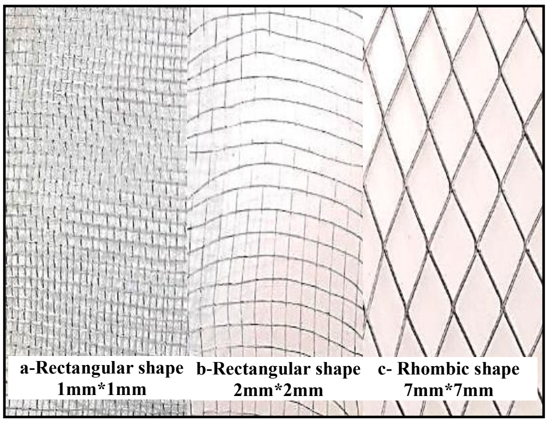


Figure 1. a,b and c Types of metal mesh using for reinforced the impact acrylic specimens.

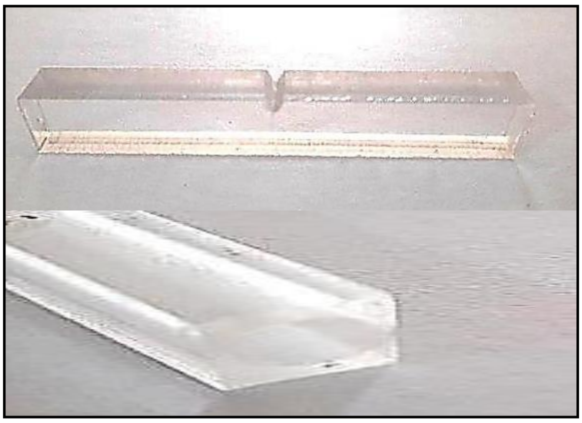


Figure 2. The impact acrylic specimens which prepared to insert the composite material in it

Table 1. Mechanical Properties of Polyester resin.[21]

Value	Properties
1.22	Specific density (at 20 Co)
65 N/mm^2	Tensile stress at break
3.0 %	Elongation at break (50mm gauge length)
3600 N/mm^2	Modulus of elasticity
1268 kg/m^3	Density (p)
70	Rockwell Hardness

Table 2. the properties of metal mesh (fiber) [22].

Mechanical Property Specification

Grade	Tensile strength (MPa)	Yield Strength (MPa)	Elongation %	Hardness Rockwell (HR B)
904L	490	220	35	90

Physical Properties

Grade	Density (kg/m^3)	Elastic Modulus (GPa)	Mean coefficient of thermal expansion			Thermal Conductivity		Specific Heat (J/kg.K)	Electrical resistivity (nΩ.m)
			0-100 Cº	0-315 Cº	0-538 Cº	at 20 Cº (W/m.k)	at 500Cº (W/m.k)		
904L	8000	200	15.0	---	---	13.0	---	0.1846	850

3.1.1. Methods

The study dealt with the variables affecting the reinforcement of the acrylic material represented by changing the cavity diameter of the acrylic impact specimens with diameters (2 mm, 4 mm, 6 mm) by using cylindrical reinforcement on the cavity circumference from a metal mesh having different sizes (1 mm, 2 mm, 7 mm) as in Figure 3, in addition to the ratio of the weight of the materials that make up the composite material on the impact energy.The impact Charpy test is performed for supported acrylic specimens using an impact device of type (XJU-22 Pendulum impact tester) as shown in Figure4-a. The specimens are classified according to their diameter and the type of reinforcing metal mesh (fiber) used in the composite material. The impact tests are prepared by placing the specimen at the base and the notch in the middle and then the pendulum is released to hit the specimen and break it at the notch. The pendulum continues to swing to the maximum height after fracturing the impact specimens that are less than the initial height due to the energy lost in fracturing the specimen which represents the impact energy (U_c). The impact specimens are prepared from an acrylic layer, where the laser beam was used for a machine of the type (CNC- Machine) to cut the impact specimens according to the standard Charpy test specimens (ASTM D-256)[23], which normally measure (55x10x10 mm) as shown in Figure4-b. at impact speed (3.5m/sec). Impact specimens of acrylic were drilled longitudinally with diameters (2, 4, and 6 mm) for casting the composite material in them.

The casting process of composite material in the longitudinal hole is achieved at room temperature and by adding the hardener with a ratio (0.1) to the polyester.

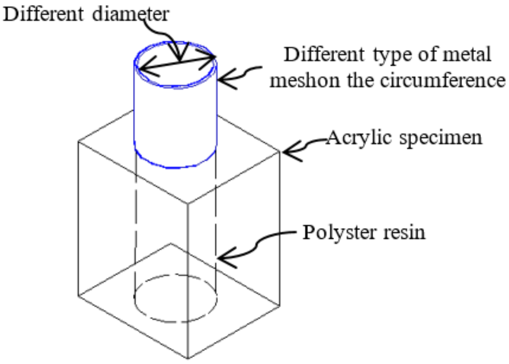


Figure3. The reinforcement method of impact acrylic specimens with metal mesh and polyester resin

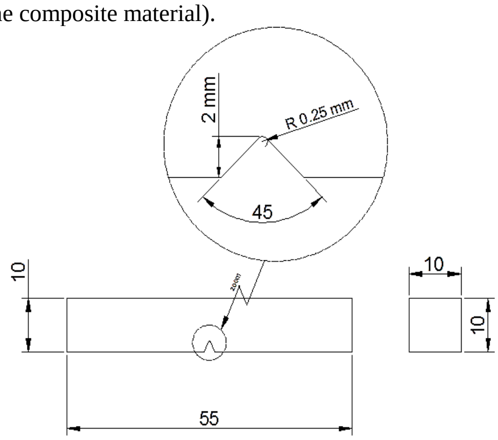
4. Results and Discussion

The purpose of reinforcing acrylic with a composite material in the impact test is to verify the effect of the variable factors on the impact energy and its relationship to the ratio of materials included in the composite material in enhancing the mechanical properties in the impact test such as (volume fraction, type and specifications of the fiber and the matrix so that the method of its arrangement in the composite material).

4.1. Effect of Young modulus (E_c):

The experimental results of determining the elastic modulus (Young modulus) of the composite material shown in Figure5 present that the specimens type A used a reinforcement with a metal mesh having the characteristics of (metal mesh type rectangular shape size 1mm*1mm) at different diameters (2mm, 4mm, and 6 mm). The specimens type A achieved the highest increase in impact energy with a percentage of (83.3%), while the specimens type (B and C) get maximum increasing with ratio (60 % and 71.4 %) in comparison with the impact energy of pure acrylic specimens (type A_o) due to increasing the elastic modulus of a composite material of specimens type (A, B and C) with ratio (85.98%, 81.3% and, 82.58%) respectively.

The specimens type (A, B, and C) used a metal mesh with specifications of (rectangular shape size 1mm*1mm, rectangular shape size 2mm*2mm, and rhombic shape size 7mm*7mm) respectively. The increase in the elastic modulus represents an increase in the ability of the composite material to absorb the impact energy because it will require higher stress to pass the area of elasticity which gained that increase through reinforcing it with the composite material causing to raise the stress required for fracture.



a. Standard specimens

b. Charpy impact device

Figure 4. a and b The standard impact specimen (ASTM D-256) and the picture of the Charpy impact test

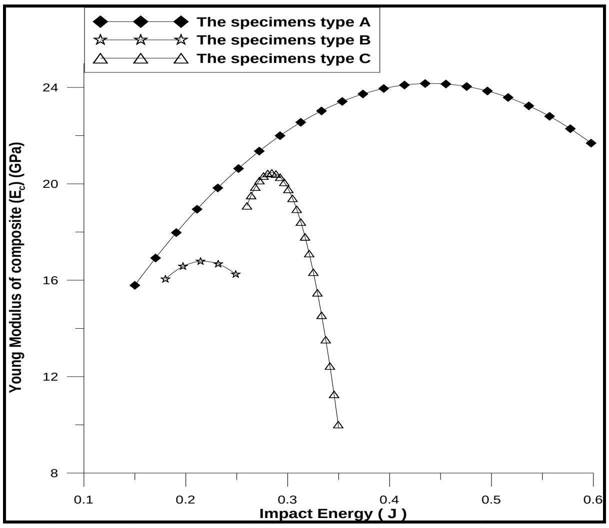


Figure 5. The relationship between the Young modulus and Impact Energy of specimens types (A , B and C)

4.2. Effect of the impact strength (G_c):

The experimental results as shown in Figure 6 reveal that the impact stress has a linear relationship with the impact energy of different types of specimens. The specimens type A showed an increase in impact stress by (83.3%), while the percentage of increase in specimens types (A, and B) was (60% and 71.4%) in comparison to the impact energy of pure acrylic specimens (type A_o). The value of the impact stress is related to impact energy because the cross-sectional area of specimens is constant, which represents the distribution of stress on the cross-section area of specimens during the impact test.

4.3. Effect of the fracture toughness (K_c):

The experimental results shown in Figure7 demonstrate that the strength of the fracture increases for a specific limit in the specimens type (B and C), then the rate of increase gradually begins to decrease as in the specimens of type (B) reinforced with a metal mesh type (rectangular shape size 2mm*2mm), after achieving the maximum increase in the fracture toughness by a ratio (72.65%), while in specimens type (C) reinforced with a metal mesh type (rhombic shape size 7mm*7mm) achieved the highest increase in fracture toughness by (77.69%), then it began to decline. The effective factor on the fracture toughness is the homogeneity of the composite material and the proportion of each of the materials in it. The maximum fracture toughness achieved by specimens type (A) at a ratio(84.71%) reinforced by (rectangular shape size 1mm*1mm).

4.4. Effect of the volume fraction Ratio :

The effect of volume fraction ratio is the effect of the ratio of fiber volume (metal mesh), matrix (polyester), and acrylic to the volume of the composite material on the impact energy as shown in Figure8. The increase of the impact energy at ratio (83.3%) due to increasing the volume fraction ratio of the fiber and the matrix with ratio (80.4%, and 21.87%) respectively, while decreasing the volume fraction of acrylic with ratio (8.42%) of specimens type (A). As to the impact energy of specimens prepared according to type (B) increased at ratio (60%) due to increasing the volume fracture ratio of fiber and matrix at (57% and 79.96%) while decreasing the acrylic volume fraction with ratio (23.6%). Meanwhile, the increase of impact energy at ratio (71.42%) of specimens type (C) as a result of increasing the volume fracture ratio of fiber, matrix at (54% and 44.64%)respectively, while decreasing the acrylic volume fraction at ratio (3.96%).The maximum volume fraction ratio to composite volume achieved by acrylic with ratio (86.72 %, 95.17 % and, 95.837%) than volume ratio of a matrix at (22.51%, 22.05% and, 15.78%) while the volume ratio of fiber at ratio (1.8%, 0.95% and, 1.72%) as shown in Figures9 and 10. of specimens types (A, B and C) respectively.

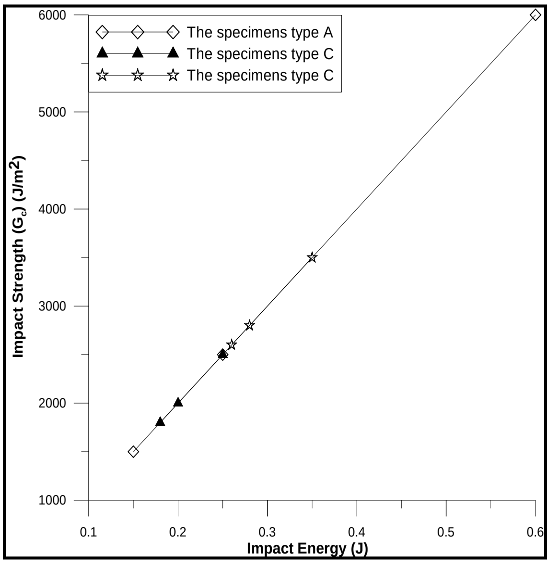


Figure 6. The relationship between the impact strength and impact Energy of specimens types (A , B and C)

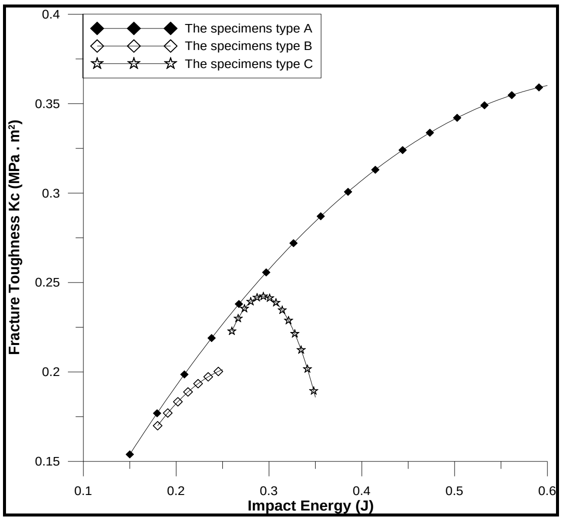


Figure7. The relationship between the fracture toughness and impact energy of specimens types (A , B and C)

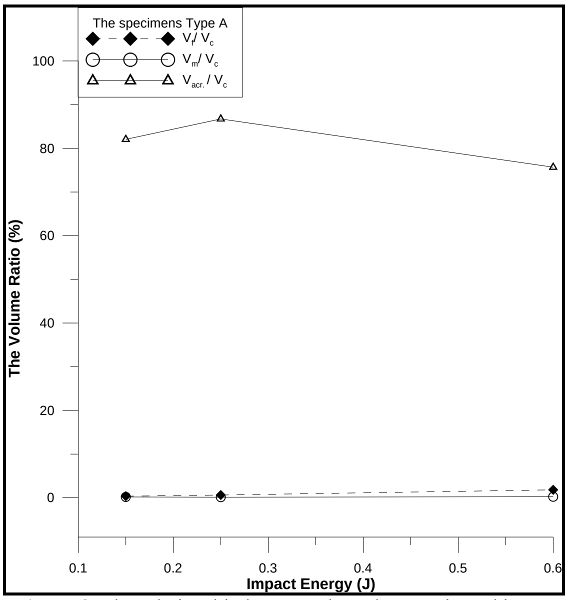


Figure 8. The relationship between the volume ratio and impact Energy of specimens types (A)

4.5. Effect of the weight ratio:

Determining the mechanical properties of the composite material depends on the weights of those materials that make up the composite material and the ratio of each to the weight of the final composite material. The experimental results showed an increase of power energy at ratio (83.3%) due to an increase in the weight ratio of each of the fibers and the matrix of (78.7% and 15.29%) respectively, while the percentage of acrylic decreased at (17.65%) for the specimens of type A, as shown in Figure(11). The decrease of the weight ratio of acrylic due to the increase in the diameter of the longitudinal cavity of the specimens tangentially causes a decrease in its weight with an increase in the weight ratio of the two other materials of fiber and matrix. The percentage of increased weight ratio of the fibers and the matrix was at (55.18% and, 79.11%) respectively in the specimens type B, while the weight ratio of the acrylic decreased by (28.85%) that caused to increase impact energy at (60%). The weight ratio of the fibers and the matrix increased at ratio (51.63% and 41.7%) respectively, while the weight ratio decreased at ratio (9.4%) of specimens type C causing to increase impact energy at (71.42%) as shown in Figures 12 and 13.

The experimental tests run on composite specimens of types (a, b, c) and prepared at different diameters and enhanced with different types of fibers and different fractional volumes. It was found that the fracture plane in most of the specimens was at the same fracture plane at V-notch in the Charpy test during the impact test as shown in Figure14 due to the homogeneity of the composite material in the cavity of the acrylic specimens.The fracture zone of the impact specimens is important in clarifying the behavior of the composite spacimens during the impact test which shows the behavior of the composite material without dislocations of the fiber material (metal mesh) reinforcing the composite material from its place througth impact test.

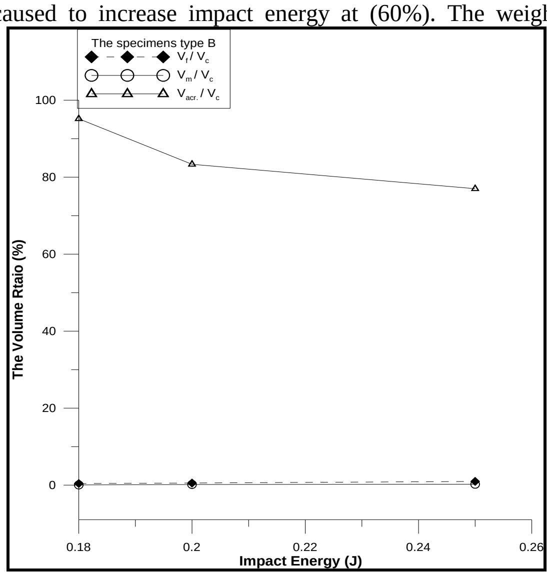


Figure 9. The relationship between the volume ratio and impact Energy of specimens types (B)

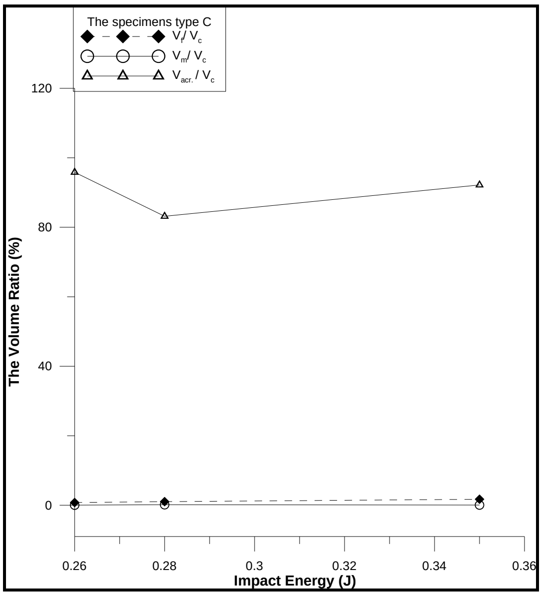


Figure 10. The relationship between the volume ratio and impact Energy of specimens types (C)

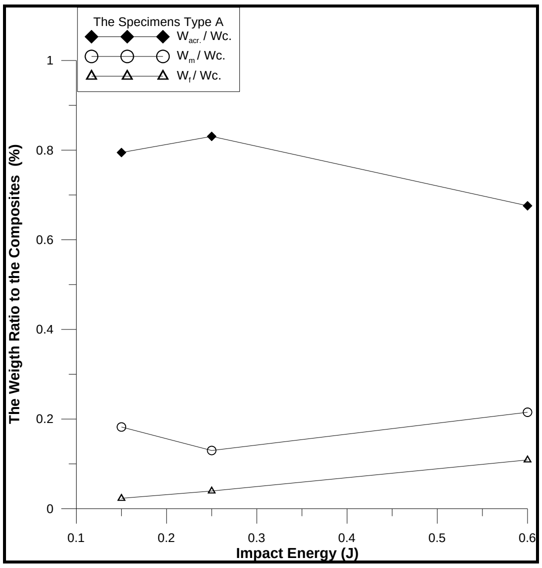


Figure11. The relationship between the weight ratio and impact Energy of specimens types (A)

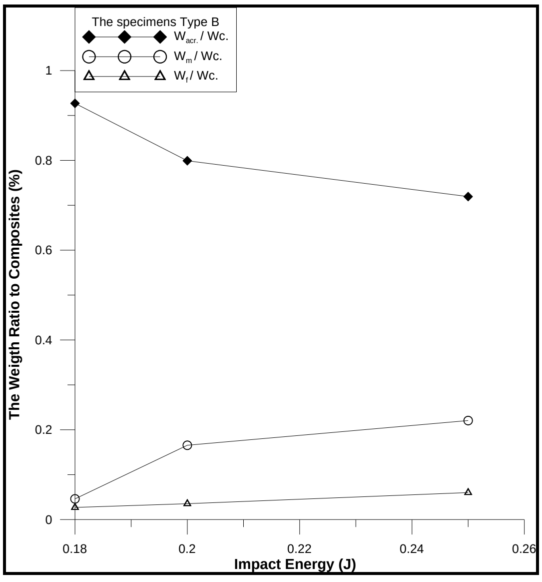


Figure12. The relationship between the eight ratio and impact Energy of specimens types (B)

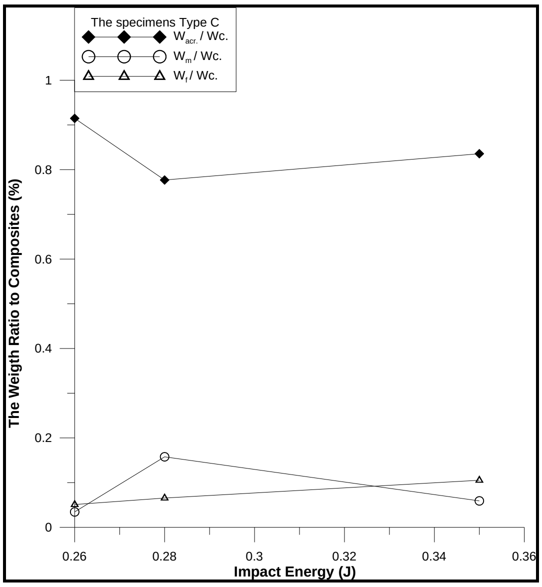


Figure13. The relationship between the weight ratio and impact Energy of specimens types (C)

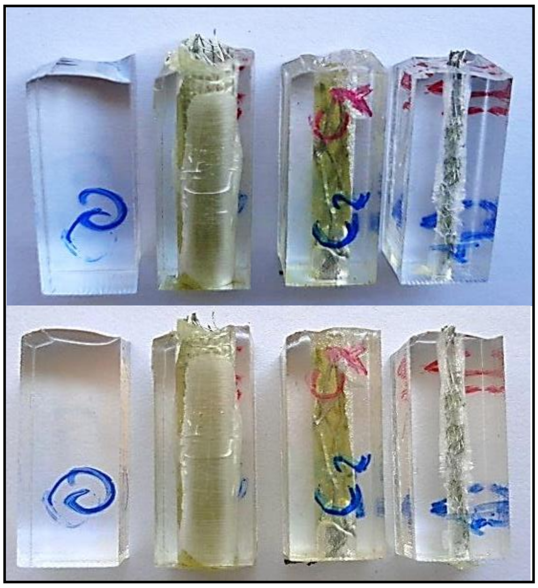


Figure 14. The fracture impact composite specimens type (A, B and C)

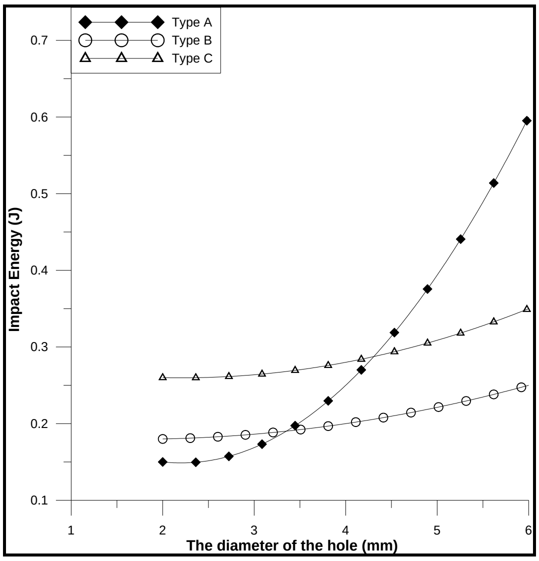


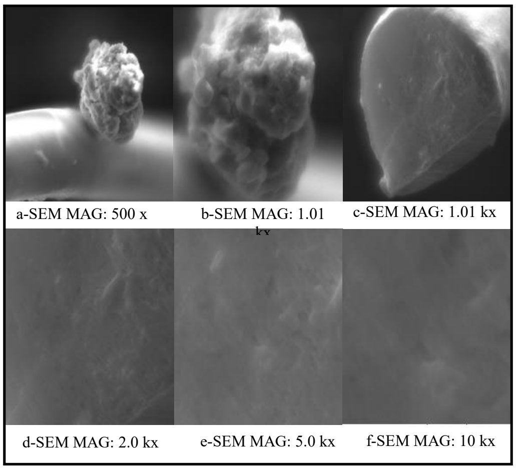
Figure 15. The effect of the hole diameter of composite which inserted in acrylic on the impact energy

4.6. Effct of diameter of composite material :

The effect of weight ratio is the effect of the ratio of fiber weight (metal mesh), matrix (polyester), and acrylic to the total weight of the composite material on the impact energy. The experimental results showed the effect of the diameter of the composite material reinforcing the acrylic specimens at diameters (2 mm, 4 mm and, 6 mm), which increased the impact energy by (33.3%, 60% and, 83.3%) respectively in the specimens type (A) so that, it increased with ratio (44.4%, 50% and, 60%) and (61.53%, 64.28% and, 71.42%) for specimens type (B and C) as shown in Figures.15 a and b. The largest increase in impact energy was at the diameter (6) mm in the specimens of type (A) due to the cohesion of the composite material consisting of fibers (metal mesh) of small size (1 mm * 1 mm) due to the increase in the number of metal wires in fracture plane which increases the resistance to the movement of dislocations in the composite material during fracture in an impact test.

The increase in impact energy is due to the increase in the percentage of the reinforced composite material that has higher mechanical and physical properties than acrylic. The diameter at (6 mm) achieved the maximum increase in type A specimens by (83.3%), while the percentage increase was (60% and 71.4%) in specimens type (B and C) compared to specimens type (A_o) at the same diameter.

The surface of the fracture zone in the impact specimens as shown in Figures.16-a and b by using a Scanning Electron Microscope (SEM). The pictures show the adhesion of the polyester material grains to the fiber (metal mesh) in impact specimens type (A) in the fracture zone after the fracture occurred in the impact test. The continuity of the adhesion of polyester particles on the metal wire after the specimens fracture in the impact test, enhances the homogeneity of composite material which consists of the polyester and fiber, causing to improve the mechanical properties of the reinforced acrylic specimens by increase the resistence of impact energy. So that, Figure16-c shows the end of the wires of fiber in the composite material after the impact test. The shear region confirms the successful reinforcement of the composite material inserted in the acrylic specimens and the uniformity of their structure during the impact test. The regions in Figures (16- d, e and f) refer to crack growth path during the impact test process in the wire of fiber which reinforced the composite material due to the resistance of metal mesh. The fracture surface of impact specimens showed that the wire of fiber was sheared at the same share stress plane of the matrix as a result of homogeneity of the composite material which was inserted in impact specimens.



Figures 16. a, b, c, d, e and f The SEM pictures of fracture surface of composite impact specimens type (A) at different diameter holes (2mm, 4mm, and 6 mm)

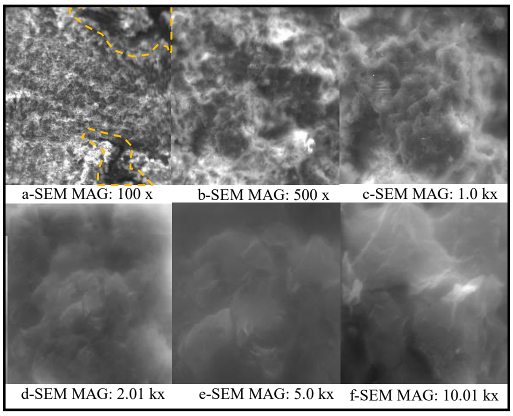
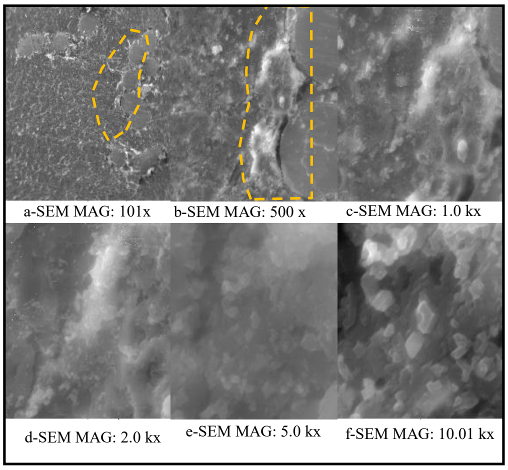


Figure 18. The SEM pictures of fracture surface of composite impact specimens type (C)at different diameter holes (2mm, 4mm, and 6 mm)

The SEM picture of the fracture zone of specimens type B at different diameter holes (2mm, 4mm, and 6 mm), shown in Figures 17-a, b, c, d, e and, f show the effect of the concentration of stresses in the regions surrounding the fiber (metal mesh) of the fiber material caused by the impact process of the composite material specimens. The concentration of the stress effect in the matrix surrounding the fiber matrix indicates the occurrence of a high concentration of stresses in the area surrounding the fiber due to the fiber's resistance to impact stress without dislocation the metal wires of the fiber from its place in the composite material. The (SEM) pictures also show that the fiber was sheared sharply at the same plane stress of acrylic plane fracture indicating the effectiveness of the fiber's resistance to shear stress caused by the impact energy of the composite specimens, thus improving their resistance against failure.

The scanning electron microscope (SEM), shown in Figure 18. demonstrates fracture region for impact specimens type C at different diameter holes (2mm, 4mm, and 6 mm) and the growth of the crack in the matrix (polyester) in the composite material caused by the effect of high impact energy on the one hand and the effect of high fiber resistance that explains the presence of more than one crack on the surface of a matrix



Figures 17. a ,b, c, d, e and f The SEM pictures of fracture surface of composite impact specimens type (B) at different diameter holes (2mm, 4mm, and 6 mm)

(polyester) in the composite specimen. The regularity behavior of the composite material which is inserted in acrylic specimens as one material in resisting the stresses generated by the impact energy without dislocation the fiber enhances its homogeneity in resisting fracture.

5. Conclusions

The current study has the following conclusions:

- The maximum increasing in impact energy at a ratio of (83.3%)was achieved with specimens reinforcement with metal mesh and rectangular shape of size dimensions (1 mm * 1 mm) at a diameter (6 mm).
- The increase of the diameter of reinforcement composite material in acrylic at (2 mm, 4 mm, and 6 mm) increased the impact energy at ratio (33.3%, 60%, and 83.3%) respectively in the specimens type (A) while it increased at ratio (44.4%, 50%, and 60%) for specimens type (B) and (61.53%, 64.28%, and 71.42%) for specimens type (C).
- The SEM images showed the occurrence of sharp shear in the wire of the metal mesh without dislocating it from the composite material which indicates the homogeneity of the composite material and the success of achieving enhanced impact resistance of the composite specimens.

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