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Improving the Properties of Acrylic by Creating Crack Using Laser Beam

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Abstract. The study investigates the improvement of the mechanical properties of the acrylic layer by creating a crack according to polynomial's function by using the CO₂- laser and without additives. The cracks were created by the laser at different powers and different speeds. The shape of the cracks was created according to six degree polynomial's function by using CNC-laser machine. The study focused on the effects of creating an edge on both sides of the crack generated from the laser heat helping to change the microstructure on it to resist the failure crack growth. The study adopts a laser beam path according to equation $g(x)$ to show the effect of the shape of the laser beam on improving the properties of the acrylic specimens. The experimental results have shown the effect of laser beam speed and laser beam power on the stress-strain. The experimental results shown increasing in the stress with average rate (12.25%) due to increasing laser beam power at (40, 50 and 60). The experimental results of specimens type (O and A4) shown improving in the stress at average rate (12.87%) and comparing the experimental results of specimens type (O, A5 and A6) has revealed an increasing in the tensile stress with average rate (14.088%).

1. Introduction

Today's laser applications are widely used in industrial and technological fields such as welding and laser cutting in polymeric materials and other materials. Extensive is use of acrylic material and transparent materials in windows for structures, ships and submarines used in marine exploration and marine life studies as well as geological nature and seabed erosion. Acrylic has also been applied in many tourist buildings with the advancement of technology in the manufacture and improvement of properties of acrylic material.

Konstantin Hofmann et. al. [1] They studied the effect of alloying strategies on the thermal energy input and the metal structure resulting from modified tool surfaces. The cooling behavior of the mixing lines was also of the length of the input unit of different interest; the microstructure was analyzed with respect to the fine hardness as well as the carbide formation. E. Abouda et. al. [2] He studied the mechanical component that operates under high pressure conditions and high temperature conditions and needs enhanced mechanical and cognitive properties using the laser beam. Frank L. Palmieri et.al.[3] The investigation into the laser ablation process was developed to carefully remove the target depth of the resin, approximately (0.1 to 20) μm , of the composite surface of the carbon fiber reinforced epoxy while simultaneously changing the surface chemistry and achieving micro-roughness. Yusuf Z. Akpınar



et.al.[4] The study of the effect of the different angles of the laser beam on the strength of the cement cut Y-TZP-resin (SBS) was evaluated. The forty-plate ceramic Y-TZP is randomly selected to be four groups ($n = 10$). The application ensures the laser pulse of the femtosecond amplifier on the Y-TZP surface at angles (90° , 75° , 60° , 45°). Md. Saidin Wahab et. al. [5] It made progress in research on the advantage of laser cutting in carbon fiber and reinforced plastics (CFRP) and composite materials used in the space structures. CFRP is a high performance material and is one of the most important materials in the aviation industry. Rajib Kumar Mandal et.al [6] Adopted laser beam welding study (LBW) which has become increasingly used in manufacturing and manufacturing which is due to its distinctive characteristics. LBW offers high energy density around its concentration, making it well suited for welding a certain class of materials that are difficult to weld. M. M. Noor et. al. [7] their study developed a model to predict the roughness of the surface by cutting the laser beam (LBC) into acrylic layers. The using of the Box-Behnken design was depend on the surface response method to predict the effect of laser cutting marks, including the ability, cutting speed and tip distance to surface roughness during operation.

The aim of this study is to improve the mechanical properties of acrylic by creating laser beam crack without additions. The study adopts new investigation field depending on improving the mechanical properties by creating a crack laser beam that effects on micro-structure of acrylic specimens when determining the concentration of stresses in the test specimens and by using a crack created by laser beam to redistribute the concentration of stress and increase the stress required for failure.

2. Theoretical analysis

Tensile strength is described as a function of the increase in gage length. Where, the relationship between tensile strength versus tensile elongation will be of little value if not compared as ratio of the dimensions of the specimen. Engineering Stress, or nominal stress, (σ), is defined as [4]:

$$\sigma = \frac{F}{A} \quad (1)$$

Where,

F: is the tensile force

A: is the initial cross-sectional area of the gage section.

Engineering strain, or nominal strain, (e), is defined as

$$e = \frac{DL}{L} \quad (2)$$

Where,

L: is referring to the initial gage length,

DL: is referring to the change in gage length ($L_f - L_o$).

Where (L_f) is represented the final length and (L_o) is the initial length.

When force elongation data is translated into stress and geometrical stress, the stress and strain curve are similar in shape to the longitudinal force curve. The ability to deal with stress versus strain rather than force versus elongation is that the stress and strain curve is almost independent of the dimensions of the test specimen. Failure is due to fracture results in the separation of the body into two or more parts. This process is accompanied by the formation of new surfaces. For example, with the formation of fracture surfaces, the associated dynamics can not be described in a simple manner. Conclusions are possible and based on experimental results. They show two basic patterns to form fracture surfaces. For a fracture controlled by normal stress, the fracture surface coincides with the cross section to the maximum extent of the main stress, which should be the concentration of tension as shown in Figure 1.a. When the fracture surface is formed by cross sections where the specific shear stress (e.g. τ_{max} , τ_{oct} (octahedral shear stress, etc.) reaches a critical value, this is called shear fracture predominates as shown in Figure 2.b. Depending on the state of stress and physical behavior, both types also occur in different mixed forms.[5].

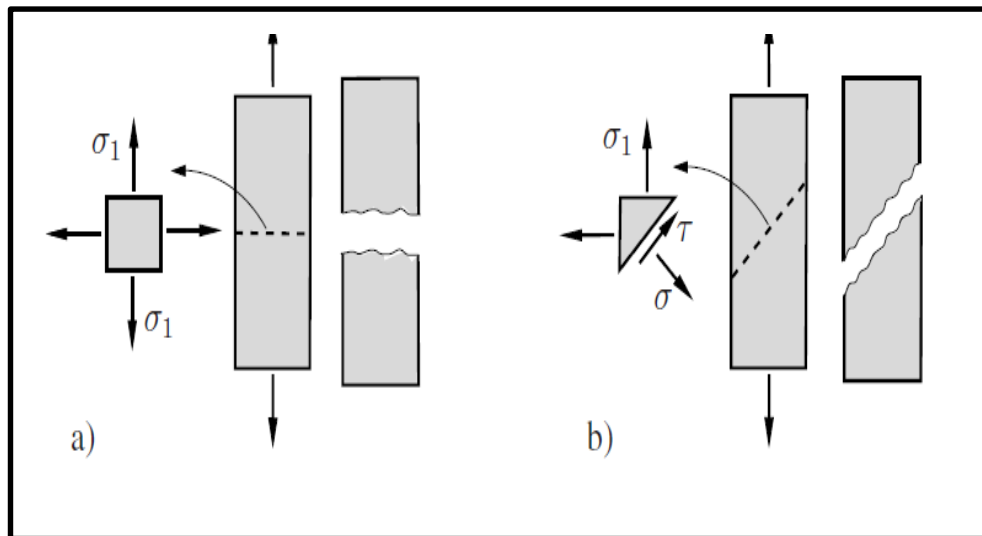


Figure 1. a, b. show the fracture surface

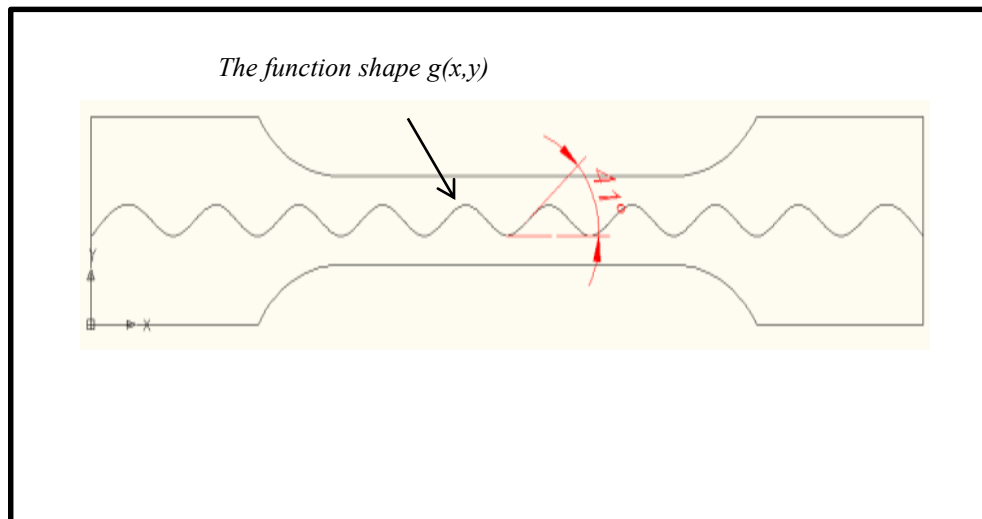


Figure 2. show the fracture surface

Figure 2 shows the crack laser shape which created according the function $g(x)$ that is predicated by curve fitting the draw in AOUTOCAD software. The angle of the crack is created to be less (41o) than the angle of shear stress which is (45o) for redirection of the crack failure expected at that angle. The redirection of crack failure growth by using crack laser is to make the crack growth path to be longer which is requiring greater stress to reach the fracture. Equation (3) represents the laser crack shape:

$$g(x)=17.27265-0.3257*x-0.0113*x^2+0.00092*x^3-2.0E-005*x^4+1.83E-007*x^5-6.073E-010*x^6 \quad (3)$$

The following equation (4) predicates the experimental result's, a relationship of the effect of conditions of laser beam on the stress-strain at laser beam speed (15 mm/sec) and different laser beam powers (40, 50 and 60) watt.

$$F_i(x,y) = y_{a1} + y_{b1} * x \quad (4)$$

Where (y) represents the equations for the curve fitting function of the relationship between constant values in the symmetric limits in equation:

$$y_{a1} = 638.0260304 + 53.85141122 * x - 2.232615722 * x^2 + 0.02113974764 * x^3 \quad (4-1)$$

$$y_{b1} = -33.62634717 + 1.458127618 * x - 0.01379198272 * x^2 \quad (4-2)$$

The following equation (5) predicates the experimental results a relationship of the effect of conditions of laser beam on the stress-strain at laser beam speed (30 mm/sec) and different laser beam powers (40,50 and 60) watt.

$$F_2(x,y) = y_{a2} + y_{b2} * x \quad (5)$$

Where (y) represents the equations for the curve fitting function of the relationship between constant values in the symmetric limits in equation:

$$y_{a2} = 638.0260304 - 100.2692261 * x + 4.407515589 * x^2 - .04855984697 * x^3 \quad (5-1)$$

$$y_{b2} = x \quad (5-2)$$

The following equation (6) predicates the experimental results a relationship of the effect of conditions of laser beam on the stress-strain at laser beam speed (45 mm/sec) and different laser beam powers (40,50 and 60) watt.

$$F_3(x, y) = y_{a3} + y_{b3} * x \quad (6)$$

Where (y) represents the equations for the curve fitting function of the relationship between constant values in the symmetric limits in equation:

$$y_{a3} = 638.0260304 + 0.405506005 * x - 0.14810265 * x^2 + 0.00222613865 * x^3 \quad (6-1)$$

$$y_{b3} = x \quad (6-2)$$

3. Experimental analysis

Table (1). shows the type of specimens according to laser power and its speed.

Spec. symbol	The spec. conditions
O	The original tensile test specimen absence of the effect of laser beam.
$g(x,y)$	The function relationship of the effect of speed laser beam and different laser beam power on stress-strain
A1	Is refer to speed 15(mm/sec) and laser power 40(watt).
A2	Is refer to speed 15(mm/sec) and laser power 50(watt)
A3	Is refer to speed 15(mm/sec) and laser power 60(watt)
A4	Is refer to speed 30(mm/sec) and laser power 40 (watt)
A5	Is refer to speed 30(mm/sec) and laser power 50(watt)
A6	Is refer to speed 30(mm/sec) and laser power 60(watt)
A7	Is refer to speed 45(mm/sec) and laser power 40(watt)
A8	Is refer to speed 45(mm/sec) and laser power 50(watt)
A9	Is refer to speed 45(mm/sec) and laser power 60(watt)

3.1. The Process of Set-up

The tensile specimens were prepared according to (ASTM D412) standard as shown in Figure 3 by using

the drawing program Auto CAD and then using the laser machine to cut the acrylic tensile specimens. The Physical properties of acrylic sheet are shown in table 2. The study uses laser machine as shown in figure 4 to create the crack in the acrylic tensile specimens. The crack in the tensile specimens is created according to the sixth degree. The crack is generated at different laser beam intensities with continuous wave (CW) CO2 at 20 kHz and powers equal to (40, 50 and 60) watt at different speeds (15, 30 and 45) mm/sec. The laser crack shape is drawn by using AUTOCAD software and it is transformed to CNC laser machine which works with dimensions (140 cm *190cm) and maximum power (80 watt) and distance from laser lens to specimen (6.5 mm).

Table (2). shows the physical properties [6].

Quantity	Value
Thermal. Expansion	50-90 μ -6/K
Thermal. Conductivity	0.167- 0.25W/m.K
Specific heat	1466 J/kg.K
Glass transition temp	105°C
Density	1170 - 1200 kg/m ³
Shrinkage	0.3 - 0.8%
Friction co-efficient	0.54
Refractive Index	1.492

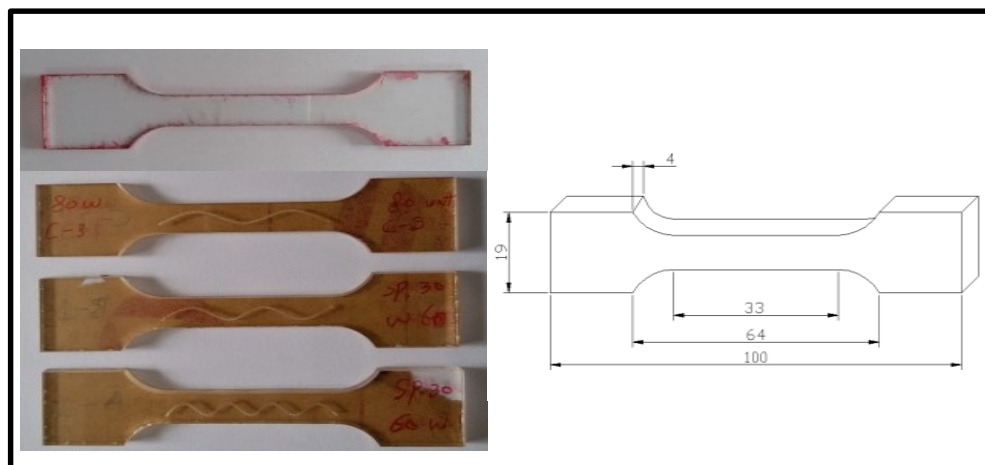


Figure 3. the tensile test specimen type (ASTM D412).

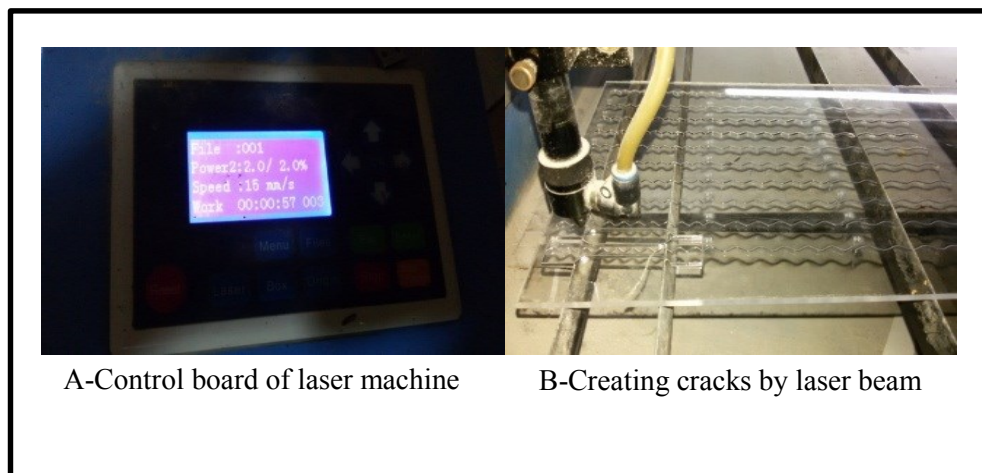


Figure 4. shows the CNC laser machine to create different types of cracks

The microscopic images are obtained by using microscopic type (Bel-X1600) as shown in figure 5. The microscopic images of cracks created by laser show the microscopic structure of the laser cracks at different locations of it as shown in figure 6.



Figure 5. shows microscopic type (Bel-X1600)

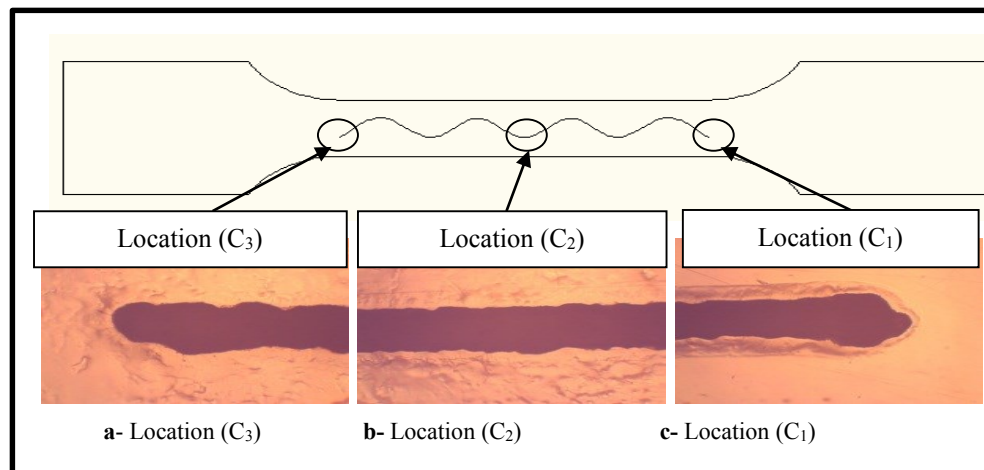


Figure 6. shows microscopic images of the laser crack created at speed (30mm/sec) and laser power (60 watt)

4. The Results and Discussions

4.1. The effect of laser beam on the microstructure

The scanning electron microscope (SEM) shown in figures 7, 8, and 9 of the laser crack created at speeds (40 mm/sec) and (15 mm/sec) show that the lateral surface of the slit at low-energy cutting energies is a uniform and regular surface compared to the surfaces at medium cutoff powers (50 watt) and (60 watt) at speed (15 mm / sec). This is due to the fact that the high temperature generated by the high intensity of the laser beam causes the melting of the cutting area and distortion of the side surfaces of the slit. Therefore, these surfaces will decrease their resistance to crack growth and failure. When surfaces have low energies they are more resistant. The microstructure of the acrylic specimens shows a significant change in the use of a high laser capability that deforms the microscopic structure due to the high temperatures generated by the laser beam.

The shape change of the microscopy is due to the laser beam at the high-energy which creates the cavities on the surface of the laser crack, which are caused by the changing in the stress concentration at applying tensile stress to the specimens due to increase of stress resistance to failure.



Figure 7. shows scanning electron microscope (SEM) of the laser crack created at speed (15 mm/sec) and laser power (40 watt).

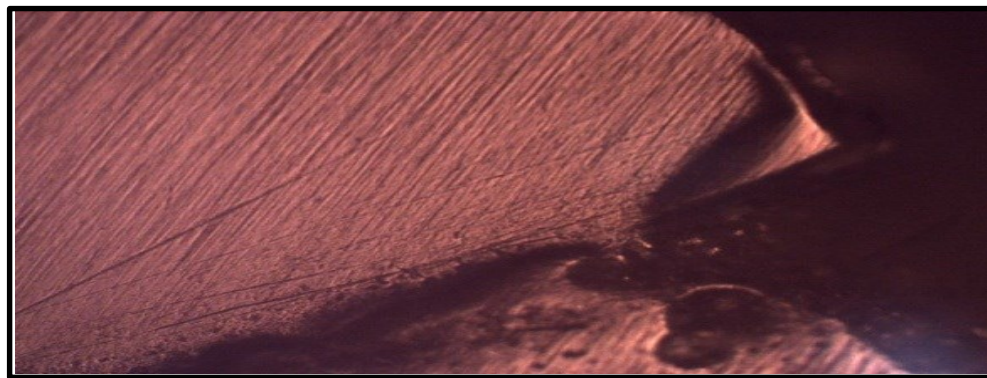


Figure 8. shows scanning electron microscope (SEM) of the laser crack created at speed (30 mm/sec) and laser power (50 watt).

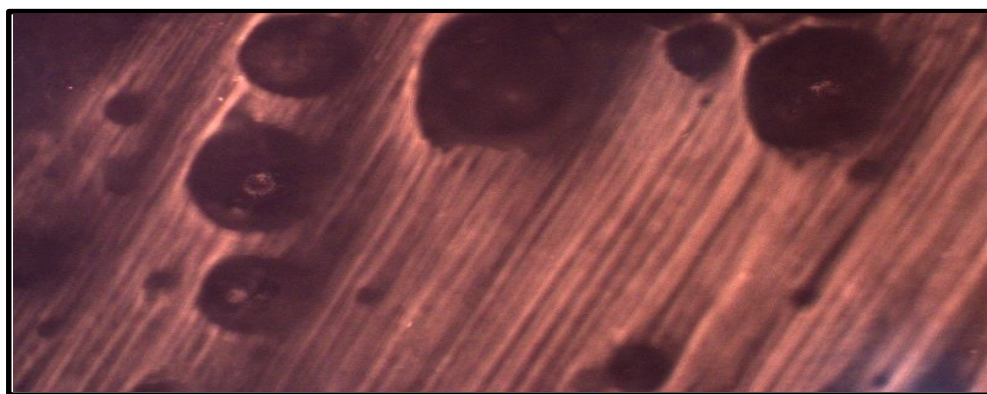


Figure 9. shows scanning electron microscope (SEM) of the laser crack created at speed (45 mm/sec) and laser power (60 watt).

4.2. The effect of laser crack on the tensile stress of acrylic properties

The heat of laser beam creates the crack's edge in acrylic specimens which has impeded the crack failure growth through the acrylic specimen which is caused by tensile stress. It has affected the specimen's

resistance to failure compared to the original specimen (O-type) due to absence of laser beam effect. The crack laser beam is created according to the function which is consisting of an angle (41o) to redirection the crack failure path.

The laser's cracks are created according to polynomial's function (eq.3) contributed to prolonging the path of crack failure growth thus for increasing the tensile stress required for failure. The experimental results shown increased tensile stress on the tensile test specimens exposed to the laser beam compared to the original acrylic specimen (O-type). Figure 10 shows the experimental results comparison of tensile stress-strain of acrylic specimens (O, A1, A2, and A3) at constant laser speed (15 mm/sec) and different laser powers (40, 50 and 60) watt. The experimental results show increasing in tensile stress with increasing in average rate (12.25%).

The laser speed is increased to be equal (30 mm/sec) at different power levels of laser (40, 50 and 60) watt as shown in figure 11. The comparing of the experimental results of specimens type (O and A4) shows improving in tensile stress at average rate (12.87%) and comparing the experimental results of specimens type (O, A5 and A6) shows increasing in the tensile stress with average rate (14.088%).

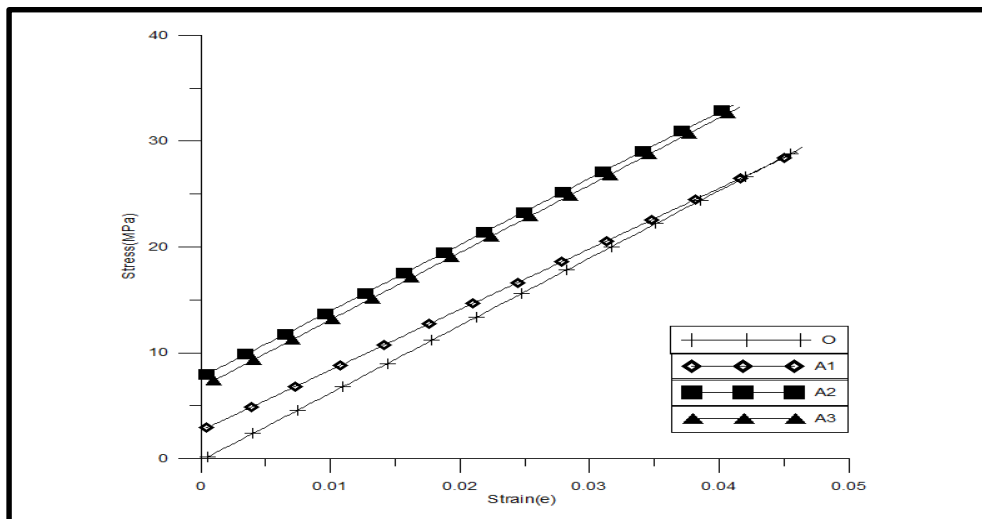


Figure 10. show the compare the tensile stress-strain results of acrylic specimens (O, A1, A2, and A3) (ASTM D412).

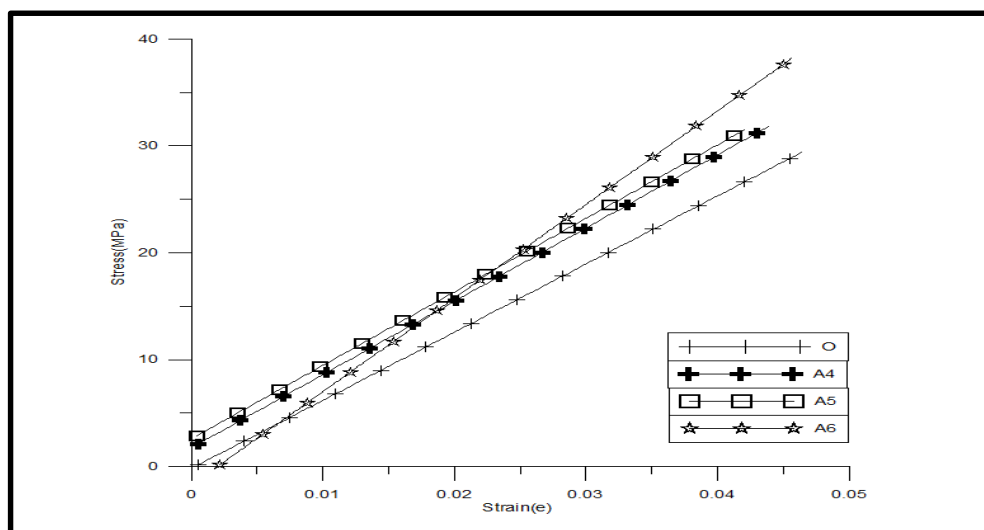


Figure 11. shows the compare the tensile stress-strain results of acrylic specimens (O, A4, A5, and A6)

Figure 12 shows the comparing of the experimental results of acrylic specimens type (O, A7, A8 and A9) at different laser beam powers (40, 50 and 60) watt and laser beam speed equals to (45 mm/sec). The experimental results show increasing in tensile stress at rates (6.85, 17.488 and 22.95%), respectively. This is caused as a result of increasing the laser beam power at constant speed (45 mm/sec) which increases the heating created by the laser beam on the surface of the acrylic specimens due to change the microstructure in it.

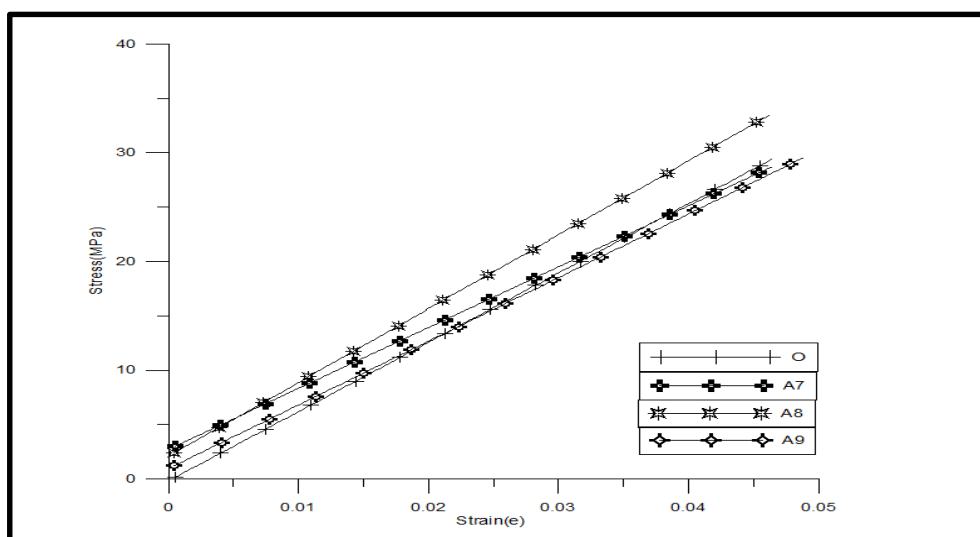


Figure 12. shows the compare the tensile stress-strain results of acrylic specimens (O, A7, A8, and A9)

5. The Conclusions:

The study concluded that the laser beam crack according to the function of the $g(x)$ post increases the tensile stress of the acrylic specimens by (12.25%) at (15mm / sec) and different laser powers (40, 50, 60) watt and the stress increases by (14.088%) when comparing the results of the type of specimens (O and A5). The tensile stress of the type of acrylic specimens (A7, A8 and A9) at the laser beam powers (40, 50 and 60) watt and speed (45 mm / sec) when compared to the O-type specimen shows increases by (6.85, 17.488 and 22.95 %) respectively. The study creates three relationship functions $f_{1,2,3}(x,y)$ at different conditions of speed and laser beam power. The study explains the increase in tensile stress due to a change in the microstructure of the acrylic material on the edges of the laser beam caused by the heat of the laser beam that resists and redirects the progress of the crack failure to follow the longer path. In microstructure pictures creates the cavities on the internal surface of the laser beam crack due to dispersion of the stress concentration points which led to increase the failure resistance.

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