Experimental and Numerical Investigation of Shot-Peening and Solidification Effects on the Endurance Limit of Composite Material

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Abstract: This work studied experimentally and numerically the effect of the shot-peening on the properties of fatigue of composite materials during the solidification period of composite material. Different two type of composite material have been investigated, woven (matt) reinforcement E-fiber glass with matrix epoxy resin, the second type made from random reinforcement E-fiber glass with matrix epoxy resin. Different shot peening times and also different times of solidification have been studied in this work. The experimental work includes calculating the mechanical properties (modulus of elasticity and the ultimate tensile stress) using the tensile test, also calculating the fatigue stress using the fatigue test. The numerical verification was done using ANSIS Workbench.15 to obtain the S-N curves of the composite material. The result shows, the best enhancement in fatigue strength had been 59% and 33.78% for matt reinforcement material and random reinforced material respectively, both types have the best improvement at 6 minutes shot peening time (SPT) and on two days of solidification. The numerical verification shows an agreement with the experimental results of the S-N curves, in which the maximum percentage error between the experimental and numerical results does not exceed 12 % and 15.12% for the matt reinforced material and for the random reinforced material respectively.

1. Introduction
Every shot hits the surface of the material like as a small hammer creating a tiny dimple in material surface’s part. Those tiny dimples provide similar residual stress’s layer. The compressive stresses resulted from the shot peening treatment provide great increases in part life [1]. J. Chuanhai et. al., [2] (2009) evaluated effect of the shot peening of 1 (minute) to mechanical properties of surface of the (TiB2/6351Al). Micro-structures have been observed using X-ray diffraction line profile analyses. Also, their outcomes displayed that, the increase in hardness was about 50% in the surface layer. They draw conclusions that the shot peening is an influential treatment in enhancing the strength of the surface of TiB2/6351Aluminum composite. H.A. Ruaa [3] (2012) evaluated properties (mechanical and physical), and wear. Classic, crossbred composite have been manufactured using casting by lay-up. Composite material ingredient was unsaturated polyester resin, a volume fraction 3% and 6% of carbon fiber as reinforced material, 3% of Al2O3, 3% of Aluminum, locally Gypsum and Cement as particles. The result shows that, the tensile stress for unsaturated polyester reinforcement with 3 % Al particles were 38 MPa.

F. S. Abdel-jabbar ET. al., [4] (2013) investigated effect of the shot-peening process to the fatigue creep performance on Aluminum (7075-T651). Results showed, the fatigue-creep and shot-peening
mixture may utilize successfully to increase endurance limit for the specimens exposed to a cumulative damage of fatigue. The increasing SPT by (38 %) causes increasing in magnitude of hardness to (387 HV) at (15minute). A. N. Abood et.al [5] (2013) evaluated the influence of shot-peening at various time of shot peening (5, 10, 15, 20 and 30) minute. At the time of 15 minute, these properties reached the highest value and then they decreased. The results of the tests displayed that, un-peened AA2024-T4 had better resistance especially at ranges below 9X103 cycles. Ahmed N. Al-Khazraji [6] (2014) investigated the shot-peening effect on endurance limit of two types of composites: aluminum powder with unsaturated polyester and E-glass with unsaturated polyester. Results shows, the shot-peening enhance fatigue strength for first material, the maximum decreases in endurance life had been (29%), the percentage of maximum improvement had been (25%) for the second material at 6minute of shot-peening.

T. Bhopathy and T. Ganapathy, [7] (2015) studied the effect of the shot-peening on 7075-T6 aluminum alloy layers to enhance the endurance limit and the stress resistance on corrosion cracking at different types of glass beads and different methods of shot peening. Then, after those components have a load in bending or tension to some level of stress in ranges under desired to yield, real tensile strength at surface was less than what studied on basics of cross-sectional area or loading. S. Kanchidurai et. al, [8] (2017), evaluated the improvement in endurance limit on high stressed aluminum alloy, welded connection and steel by shot-peening process. The result showed preferable difference in layer of the surface of the metals, al. alloy provided an endurance limit improvement of (15–250%), steel plain member provided an endurance limit improvement of (6-200%), and welded connection provided an endurance limit improvement of (50-75%).

In this work, the endurance limit influence under shot-peening effect was investigated for (woven and random reinforcement composite). Also, the solidification effect of samples was investigated.

2. Experimental Work

2.1. Preparation Processes for Specimen,

These processes include the following procedures:

1. Manufacturing a (300*300*3) mm glass mold (see plate (1)).
2. Preparing two types of fiber glass as reinforce material had been prepared with epoxy matrix, the first type was matt fiber reinforcement, while the second one was random fiber reinforcement [9].
3. The plate of composite had been provided by putting the sheets of fiber one above another (5 layers) in glass mold with the matrix mixed and poured above a fiber in the mold, at a volume fraction of (41%).
4. Specimens stay in mold for 24 hours [10]. After that sample is extracted from the mold (see plate 2). Using a CNC machine, cut the tensile specimens depending on the standers of (ASTM-d638-I) [11], plates (3, 4) and also cut the specimens for the fatigue depending on the machine manual [12], (plate (5)).

3. Solidification

Using the hardness test of the composite plate ( which is need sex day for full solidification) by Digital Hardness Tester for composite material and polymer , every day after extracting composite plate from the glass mold till it be stationary (no obvious difference in the reading between current day reading and reading in next day) [13].

4. The Shot Peening device

The Sintokogio LTD machines device was used in this work. This machine is located in the Institute of Technology in Baghdad, the diameter of ball is 2 mm, and the velocity of ball is 42 m/sec.
5. The Tensile Test
Micro computer controlled electronic universal test machine is the type of machine that used in this test in which the test has been achieved in the Production and Metallurgy faculty at University of Technology, Iraq (see figure 1). This test was used after shot peening and before it, and for each case.

6. Fatigue Test
The fatigue action of composite materials can be obtained from laboratory tests. HI-TECH alternating bending fatigue (HSM20) was the fatigue testing machine used in this work with a constant amplitude [12], where the tests was accomplished in Materials Engineering Department in AL-Mustansiriya University College of Engineering (see figure 2). Samples had been submitted to deflection perpendicular to their axe at the free part’s side, the other part’s side has been fixed, inducing stress in bending like cantilever beam.
7. Numerical Verification
One of the most powerful numerical procedures is the Finite Element Method (FEM) which may be used to get the solutions of a large number of engineering problems, particularly in the area of solid mechanics [14,15,16]. In this research, FEM by the help of Analysis Systems ANSYS.15 program was utilized as the numeric tool for obtaining the shot peening influence on the endurance limit properties. The major reason for using a FEM analyses was to simulate numerically how the real engineering system will behave.

8. The Results and the Discussions

8.1. Hardness Results
Hardness test was performed to obtain the time that the composite material needed to reach the full solidification state. Figures (3 and 4) observe the time needed to reach the full solidification for the woven reinforcement composite material random reinforcement composite material, respectively. From these two figures it can be seen that the solidification period for the two composite material types (woven reinforcement type and random reinforcement type) could be divided into, two, four and six (full solidification) days.

![Figure 1. Machine of Tensile Test](image1)

![Figure 2. Machine of Fatigue Test](image2)
8.2. Tensile Test Results
The purpose for using the tensile test in this work was to obtain the mechanical properties (modulus of elasticity E and the ultimate tensile stress σult) of the two composite materials (matt reinforced type and random reinforced type). Table (1) shows these mechanical properties for each type of composite material.

8.3. The Fatigue Results
Fatigue test had been done before and after shot-peening and its attitude clarified as fatigue strength with numbers of cycle to failure, like figures (5, 6 and 7) for matt reinforced material and figures (8, 9 and 10) for random reinforced material. Equation for defining these curves is the power law equation (equation 1) and the equations of S-N curve for all cases are listed in Tables (2) and (3).

\[ \sigma_a = A \cdot N^B \] basquin equation [6] … (1)

Where
\( \sigma_a \): fatigue strength (MPa).
\( N \): numbers of cycles to fail (cycle).
\( A \) and \( B \) constant depends on the material.

Figure (5) shows that increasing shot-peening time (SPT) at 2days solidification for matt reinforced composite material will be increases the endurance limit of composite material and the max. Increment had been 59% (6minute shot-peening) and that was because of minimized the inter particle distance of the composite plat due to shot peening effect, and deliver of compressive residual stress from the surface of composite plate.

Figure (6) show the S-N curve for different times of shot peening at four days of solidification for composite reinforcement woven at low cycle fatigue. Increase of SPT decreases the endurance limit and the max. decrement was 43% (6minute shot-peening), the reason for that was that the shot-peening changed and ruined the arrangement of molecular of the composite plate particles and this issue affected more than the effect of the compressive residual stress.

Figure (7) shows S-N curve for different times of shot peening at six days of solidification for composite reinforcement woven at low cycle fatigue. S-N curves shows, increase SPT will be causes increase in the endurance limit, that’s due to delivered of the residual stress from the surface composite plate and the max. increase in endurance limit had been 53%.

Figures (8, 9 and 10) give the S-N Curve for different times of shot peening at (2, 4, and six) days of solidification respectively for composite reinforcement random. It has a similar behavior like the first composite (woven reinforced). Figure (8) (2days solidification) the endurance limit increases with the increase of the SPT and the max. increment in endurance limit had been 33% (6minute shot peening). On figure (9) (4days solidification) the max. decrement in endurance limit had been 28% (6-minute shot peening). On 6 days of solidification, figure 10 show that, the max. increment had been 14% (6-minute shot peening).

8.4. Numerical Results
The most important parameter that can be inferred from the numerical analysis is the fatigue life. The comparison between experimental S-N curve results and numerical S-N curve results was done after determining the fatigue life estimation for each case (experimental or numerical) using the power law equation (equation 1) and they are listed in tables (2) and (3). In these tables, the percentage of difference of fatigue stress between the experimental work and the numerical work is also listed, and it is calculated using (equation 2),

\[ \text{Percentage Error} = \frac{\sigma_{\text{max}} - \sigma_{\text{min}}}{\sigma_{\text{max}}} \times 100\% \] … (2)
Figure 3. the Increase in the Hardness during the Solidification State for Woven Reinforcement with Epoxy Resin.

Figure 4. the Increase in the Hardness during the Solidification State for Random Reinforcement with Epoxy Resin.

Table 1. Mechanical Properties for the Two Composite Material (matt Reinforced Type and Random Reinforced Type).

| Composite Material Type          | Mechanical Properties |
|---------------------------------|-----------------------|
|                                 | E (MPa)    | \( \sigma_{ult} \) (MPa) |
| Woven (matt) Reinforcement      | 1211       | 130                      |
| Random Reinforcement            | 973        | 86                       |
Figure 5. S-N Curve for Different Times of Shot Peening at Two Days of Solidification for Composite Reinforcement Woven at Low Cycle Fatigue.

Figure 6. S-N Curve for Different Times of Shot Peening at Four Days of Solidification for Composite Reinforcement Woven at Low Cycle Fatigue.

Figure 7. S-N Curve for Different Times of Shot Peening at Six Days of Solidification for Composite Reinforcement Woven at Low Cycle Fatigue.
Figure 8. S-N Curve for Different Times of Shot Peening at Two Days of Solidification for Composite Reinforcement Random at Low Cycle Fatigue.

Figure 9. S-N Curve for Different Times of Shot Peening at Four Days of Solidification for Composite Reinforcement Random at Low Cycle Fatigue.

Figure 10. S-N Curve for Different Times of Shot Peening at six Days of Solidification for Composite Reinforcement Random at Low Cycle Fatigue.
Table 2. the Experimental and Numerical Equation of S-N Curve for each Case of Woven Reinforcement Epoxy Matrix Composite Materials with the Percentage Difference between the Experimental and Numerical endurance limit Results.

| Solidification time (day) | SPT (min) | Experimental (S-N curve) equation | Numerical (S-N curve) equation | Percentage Difference eq. 2 (%) |
|--------------------------|-----------|-----------------------------------|---------------------------------|--------------------------------|
| Full solidification      | 0         | $\sigma = 1596 \cdot N^{-0.4906}$ | $\sigma = 1162 \cdot N^{-0.4601}$ | 11.99                          |
|                          | 2         | $\sigma = 500 \cdot N^{-0.323}$  | $\sigma = 776 \cdot N^{-0.3746}$ | 11.18                          |
| Two                      | 4         | $\sigma = 13860 \cdot N^{-0.0354}$ | $\sigma = 17090 \cdot N^{-0.66}$ | 5.49                           |
|                          | 6         | $\sigma = 200248 \cdot N^{-0.6354}$ | $\sigma = 151270 \cdot N^{-0.849}$ | 11.37                          |
| Four                     | 4         | $\sigma = 320 \cdot N^{-0.3716}$  | $\sigma = 405 \cdot N^{-0.3993}$ | 6.11                           |
|                          | 6         | $\sigma = 2510 \cdot N^{-0.5766}$ | $\sigma = 2803 \cdot N^{-0.5858}$ | 5.18                           |
| Six                      | 4         | $\sigma = 201 \cdot N^{-0.2306}$  | $\sigma = 268 \cdot N^{-0.2588}$ | 10.3                           |
|                          | 6         | $\sigma = 1106 \cdot N^{-0.3914}$ | $\sigma = 826 \cdot N^{-0.3536}$ | 5.55                           |

Table 3. Experimental and Numerical Equation of S-N Curve for each Case of Random Reinforcement Epoxy Matrix Composite Materials with the Percentage Difference between the Experimental and Numerical endurance limit Results.

| Solidification time (day) | SPT (min) | Experimental (S-N curve) equation | Numerical (S-N curve) equation | Percentage Difference eq. 2 (%) |
|--------------------------|-----------|-----------------------------------|---------------------------------|--------------------------------|
| Full Solidification      | 0         | $\sigma = 158 \cdot N^{-0.2362}$  | $\sigma = 205 \cdot N^{-0.2654}$ | 7.61                           |
|                          | 2         | $\sigma = 212 \cdot N^{-0.2591}$  | $\sigma = 232 \cdot N^{-0.2662}$ | 4.41                           |
| Two                      | 4         | $\sigma = 2006 \cdot N^{-0.4857}$ | $\sigma = 1171 \cdot N^{-0.4255}$ | 15.12                          |
|                          | 6         | $\sigma = 257793 \cdot N^{-0.9723}$ | $\sigma = 188694 \cdot N^{-0.9386}$ | 9.75                           |
| Four                     | 4         | $\sigma = 101 \cdot N^{-0.2279}$  | $\sigma = 135 \cdot N^{-0.2652}$ | 5.23                           |
|                          | 6         | $\sigma = 654 \cdot N^{-0.4251}$  | $\sigma = 734 \cdot N^{-0.4367}$ | 4.23                           |
| Six                      | 4         | $\sigma = 127 \cdot N^{-0.2113}$  | $\sigma = 97 \cdot N^{-0.1811}$ | 7.19                           |
|                          | 6         | $\sigma = 131 \cdot N^{-0.2052}$  | $\sigma = 108 \cdot N^{-0.1835}$ | 6.24                           |

9. Conclusions
The main conclusions from this work for two types of composite materials (matt type and random type) may be summarized as:
1- The suitable shot peening time for composite materials is equal or less than 6 min.
2- For the matt reinforcement, the maximum enhancement in the endurance limit was 59% (2 days of solidification, 6 minute shot peening). The random reinforcement the max. enhancement in endurance limit had been 33% (also at 2 days of solidification, 6 minute shot peening).
3- at four days of solidification, the fatigue stress decreases with increasing shot-peening and the maximum decrease in endurance limit at 6 minute shot-peening had been (43%) and (28%) for matt and random composites respectively.

4- Numerical verification was done using ANSIS/Workbench.15 to obtain the S-N curves for the composite material. From comparison it can be seen that the maximum percentage difference between the experimental and numerical values of the S-N curves for the matt reinforced composite and for the random reinforced composite does not exceed 12 % and 15.12% respectively.

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