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Laser Treatment Effect on Fatigue Characterizations for Steel Alloy Beam Coated with Nanoparticles

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ABSTRACT

Previous work investigated the effect of nano coating for steel beams on the fatigue characterization and calculated that the coating for beams leads to modifying the fatigue life and stress. Therefore, this work modifies the fatigue characterizations for beams by using laser treatment. The main aim of this work is to modify the fatigue properties of steel materials by using a coating surface, with nanoparticle materials, in addition to the laser treatment technique, at the same time. The experimental work was divided into three parts; first, the fabricated fatigue steel samples were coated by zinc oxide (ZnO) nanoparticle; second, treatment of the fatigue sample by laser technique using (low-high) and (high–low) loading; and finally, testing the fatigue samples to calculate the fatigue life and stress, with and without laser treatment. A scanning electron microscope (SEM) was used to study the surface morphology of the samples. In addition, the numerical technique, using the finite element, was employed to evaluate the fatigue characterizations for steel samples and the results were compared. The comparison of the numerical and experimental results shows that the maximum discrepancy did not exceed about 10.86%. Finally, the treatment of nanomaterials coated steel samples shows that the fatigue characterizations were more than 35%.

Keywords: Fatigue, laser treatment, nanoparticles coating, FEM fatigue

1. INTRODUCTION

Steel has recently failed to meet functional and structural requirements in many applications due to the growth of fatigue cracks and poor maintenance, such as car axles, transmission parts, road connections, beams, and blades with high-temperature cyclic loads and mixed loads [1]. Surface conditions represent the primary influence on fatigue fracture, so different surface modifications processes have been applied to steel beams for improving their fatigue strength by techniques such as laser beam hardening, high-frequency induction hardening, shot peening, and surface rolling [2], and the deposition of thin films using coating processes, which can affect mechanical component fatigue and corrosion fatigue. The residual stresses created by the deposition technique are the primary cause. Surface compressive stresses, mainly, can protect against fatigue by preventing fracture nucleation or impeding crack propagation, and cracks of fatigue are predicted to form in which ultimate tensile stresses occur [3]. In general, in the structure, certain areas occur different damage types, in addition to the entire structure cost higher than the strengthening structure cost, [4].

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Ibrahim et al. used a low carbon steel plate with a layered TiO_2 coating, then studied the fatigue behavior of the material and compared it to non-layered materials. The results indicate that this used material's fatigue strength is much higher than that of uncoated materials [5].

The fatigue properties of AISI D2 tool steel that is TiN-coated EDM were investigated by Guu et al. The coated steel samples were noted for their high hardness, excellent adhesion and significantly reduced surface roughness. Machining parameters show significant increases in bending fatigue life, ranging from 10.9 to 29.4%. The residual stresses of compressive created by the deposition process were expected to compensate for the tensile left by the stresses on the machined surfaces by the EDM process [6]. Costa. N et al. investigated the unconventional behavior of fatigue for cast iron material with different temperatures. The temperatures of the fatigue tests were 20 ^{o}C to 400 ^{o}C. Tensile strength and fatigue limit were found to increase from room temperature to 150 ^{o}C. The fatigue life dramatically decreases at a temperature of 400 ^{o}C [7]. Al-Shammari et al. studied the fatigue behavior under high temperatures of coated steel beams with nanoparticles and showed that the low-temperature effect of fatigue could be decreased by using the nanomaterial coating of uncoated steel beams. The findings also show an acceptable difference between the numerical programs and the experimental work. Therefore, the critical results for work presented by the fatigue characterizations for steel materials were modified by nanoparticle materials coating with a value that did not exceed about 15%.

Barka et al. [8] studied the effect of various factors of the laser hardening technique of AISI 4340 steel splined shafts, such as scanning speed, the effect of laser power, flank tilt angle and tooth depth on the laser hardening process of spline shafts of various diameters. Results proved that laser hardening creates a hard, wear-resistant surface and enhances surface hardness while keeping the core ductile and soft. Case depth variations were approximately 70% due to these variables at the root and tip of steel spline teeth [9]. S. Guarino. et al. investigated the fatigue life of low carbon steel with the effect of surface hardening with a high-power diode laser. The laser treatment can significantly increase the fatigue life of radioactive components, demonstrating its suitability for industrial applications [10]. P. Ganesh et al. used laser shock peening to improve fatigue life for specimens of pre-fatigued spring steel. After laser shock peening, the fatigue life of partially damaged specimens over 15 times increased. For the increased life of fatigue of laser peened specimens, a magnitude of surface stress in the range of 600 to 700 MPa with a thick compressed surface layer of about 400 µm, unchanged surface finish and an increase in surface hardness of about 20%, are considered the contributing factors [11].

Therefore, it can be concluded that the fatigue characterizations for steel materials can be modified by using nanoparticle coating or laser treatment technique, but using the nanoparticle coating and laser treatment together can modify the fatigue characterizations more. Thus, this article aim to presents the effects of modifying the fatigue characterizations of steel materials by using both coating surface and laser treatment technique together. The zinc oxides (ZnO) nanoparticle materials are used to coat the material's surface and then the steel materials is treated by using the laser treatment technique.

2. EXPERIMENTAL WORK

The experimental work including calculating the fatigue characterization of steel sample treatment by laser after coating with nanomaterials particles. The experimental work was divided into multiple parts to estimate steel samples' fatigue behavior. So, the manufacturing of the steel samples accordant to the required fatigue machine is the first step, [12-13], as shown in Figure 1, and then, the second step, coating its samples with zinc oxides (ZnO) nanoparticle by using schematic of HVOF process, shows in Figure 2, then, after coating the sample made SEM images for coated specimens steel by SEM device, as shown in Figures 3 and 4. Also, an SEM image for the fracture surface is given in Figure 5. After this, the third step treatment of the samples by laser using the laser device, as shown in Figure 6, with different load effects, (low-high) and (high –low) loading. Then, finally, testing the fatigue samples with a fatigue machine, [14-15], as shown in Figure 7, to estimate the life of fatigue and strength for steel sample treatment by laser and coating byZnO nanoparticle.

2.1. Fatigue Specimen Preparation

The fatigue specimens were prepared based on the required fatigue machine to calculate the fatigue behavior for steel samples. Twelve specimens were used in each test to draw the S-N curve of steel samples [16-17], with ten samples for each fatigue point test of the S-N curve [18-19]. By using an accurate profile, one can get the dimensions of the perfect specimen. The CNC machine was used to machine the samples. The base material was a steel alloy rod with a diameter of 10 mm. Figure 1 illustrates the fatigue test specimen. Then, grinding and polishing were conducted for all fatigue specimens after machining. The spectrometer device was used for the chemical analysis of steel alloy. The tensile specimens' properties were obtained by using a universal machine for an average of three readings of samples tests [20-21]. The specification of ASTM E606 was used to manufacture the tensile samples with a diameter of 12.5 mm and gauge length of 50 mm. Moreover, the percentage of each element is represented in Table 1. In addition, Table 2 represents the results of the tests and lists the AISI 1020 steel standard.

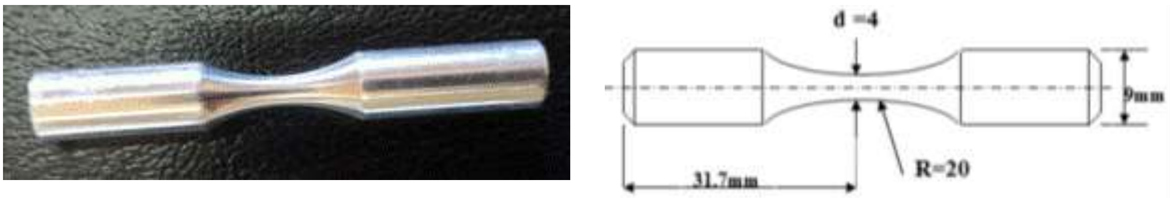


Figure 1. (a) Fatigue manufacturing sample; (b) Dimensions of fatigue test specimen.

Table 1 The composition of steel alloy-1020

Name of Item	LCS wt%
Iron (Fe)	**Bal.**
Phosphorus (P)	$\mathbf{37 \times 10^{-3}}$
Silicon (Si)	$\mathbf{311 \times 10^{-3}}$
Sulfur (S)	$\mathbf{54 \times 10^{-3}}$
Manganese (Mn)	$\mathbf{576 \times 10^{-3}}$
Carbon (C)	$\mathbf{128.8 \times 10^{-3}}$

Table 2 Tensile mechanical properties for steel-1020

Parameters	Values	AISI 1020 steel standard
Yield Strength	350 (MPa)	295 (MPa)
Young' Modulus	196 (GPa)	200 (GPa)
Tensile Ultimate Strength	590 (MPa)	395 (GPa)
Reduction of Area Percentage	63 %	66%
Elongation Percentage	22 %	36.5%

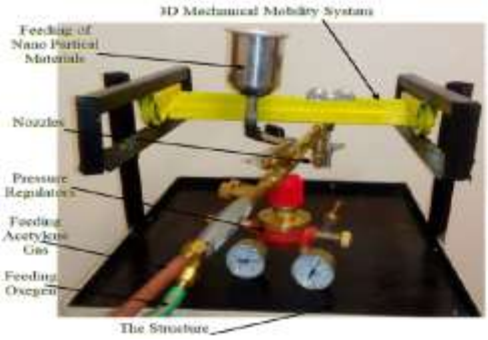
2.2. Coating Processing

A high purity zinc oxide nanoparticles/nanopowder with size (35-45 nm) was used as coating material. The density for zinc oxide nanoparticles (ZnONPs) used is (5.606 g/cm^3), and the analysis for zinc oxide nanoparticles is listed in Table 3.

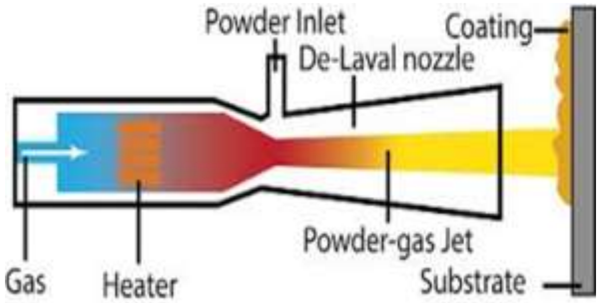
Table 3 Zinc oxide nanopowder analysis

Zinc Oxide (ZnO)	Copper (Cu)	Manganese (Mn)	Cadmium (Cd)	Lead (Pb)
> 99%	< 3ppm	< 5ppm	< 9ppm	< 9ppm

The equipment coating operation consists of a nozzle sprayer, heater, thermocouple and compressor device. The coating of samples by nanoparticles was done by spraying chemical pyrolysis. The furnace was 450 ^{o}C for nano coating, and the compressor mixed the air with nano-coat to specimens. The pressure was one bar with a spraying rate of 2.1 ml./min and 30 cm the distance between the nozzle sprayer and specimen, as shown in Figure 2. The dip-coating process was used to coat the metallic specimens with colloidal nanoparticles. Due to the low cost and simple coating process, many metals coat by the dip-coating technique. The nanomaterials such as ZnONPs, which to solve in water and ethanol, were used to coat in this technique to improve wear resistance, prevent corrosion, reduce the erosion of the surface, or improve or restore the surface of components. These methods are used in various applications with a range of coating materials. It is highly effective and one of the most environmentally friendly methods on the market. Like other thermal coating methods, the dip-coating method involves heating the coating material to a high temperature to accelerate towards the substrate surface. It enables the surface results of the coating to be maximized, thus providing the best finish and wear protection possible. The coating process were done by three concentrations of ZnONPs colloidal 0.25 %, 0.5 %, 1% weight fraction. The dip-coating process requires the preheating of samples to 450 ^{o}C, the dipping time of each process through 10 sec; after the dipping process, the heat treatment of coated samples was carried out inside the furnace to reach 650 ^{o}C for 90 min. A low cooling rate was used for each sample by keeping the samples inside the furnace to cool. So, can provide detailed images, with high resolution, using a scanning electron microscope (SEM), which is used to investigate the surface morphology with various magnifications for samples after and before coating, as shown in Figure 3. The SEM images for coated tensile specimens of steel samples with 0.25%, 0.5%, and 1% ZnO were indicated in Figure 4. These SEM prove that the coating layer thickness increase with increasing the concentrations of ZnO NPs because the ZnO nanoparticles tend to aggregate with each other with an increase in concentration with the presence of a heating process to 450 ^{o}C. An SEM examination of a typical fracture surface for the 0% nanoparticle indicated that the cracking originated within the specimen surface at a local inhomogeneity. Multiple separate fracture sources were visible along the specimen's edge after SEM inspection. As shown in Figure 1, distinct fracture rigions with minimum stretching were seen between the sources. The sample's surface revealed the presence of coarse grains, particularly around the fracture, which signifies the area of maximum stress the sample was subjected to upon fracture.The coating material used in this study is the ZnONP coating. HVOF is used for coating ZnONP as shown in Figure 2. Oxygen and acetylene are mixed together in the nozzle tube and spray jet to produce a flame. The spray jet contains several nozzles to specify the diameter of the flame jet.



(a) HVOF device.



(b) Schematic of HVOF Process.

Figure 2. HVOF device and process.

Figure 3. SEM device.

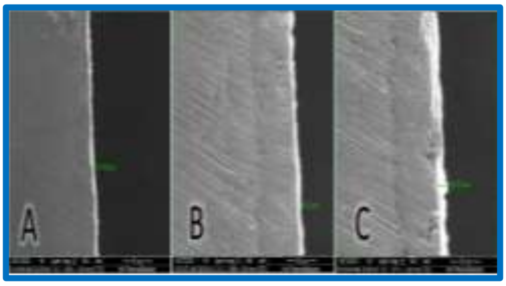
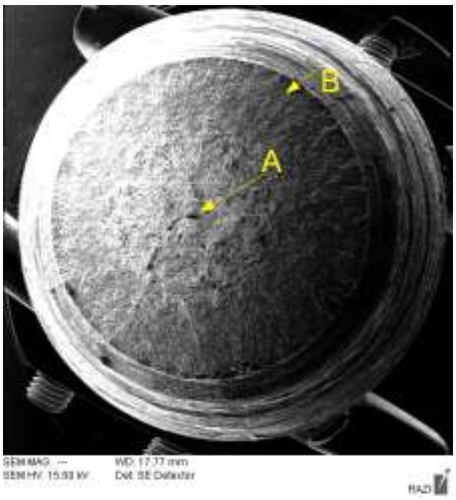
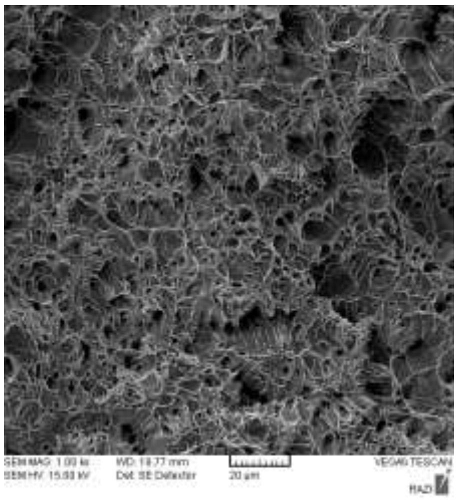


Figure 4. SEM images for coated specimens steel (a) 0.25%, (b) 0. 5%, (c) 1% ZnO nano.



(a) Fracture surface



(b) Image section fracture surface

Figure 5. SEM view of the fracture surface (0% nano) sample.

2.3. Samples Treatment and Testing

Figure 6 illustrates the laser device used in the treatment of the surface. High energy-pulsed neodymium (Nd)-YAG laser with a wavelength of 1.064 μm, the pulse energy 1 J and repetition rate was 6 Hz, and four shocks for each test with 1 mm diameter was used to investigate the laser treatment sample effect. Fatigue tests were executed by bending fatigue-testing machine (rotating type), for constant amplitude, the bending moment developed applied load perpendicular at the end of the specimen with stress ratio (R=-1). Twelve specimens performed the (S-N) curves with ten samples for each stress applied. Then the fatigue strength and life were then found from the curves obtained from the experiments done using a bending rotating fatigue machine, as shown in Figure 7. Then, the experimental fatigue results were calculated and required comparison with other results evaluated using other techniques to give the discrepancy for results calculated [22]. The numerical technique can be used by employing the finite element method to calculate the fatigue behavior for steel samples and compare the results with the experimental results evaluated [23].

Figure 6. The laser device.

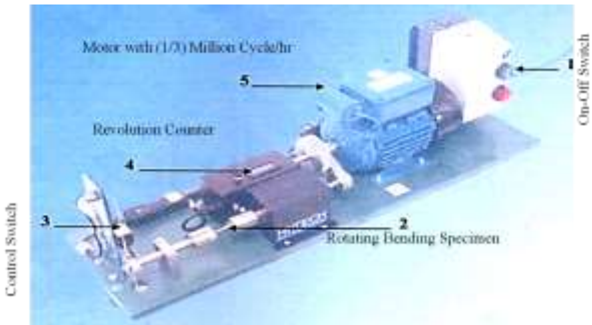


Figure 7. Bending rotating fatigue test machine.

3. NUMERICAL INVESTIGATION

The numerical technique (finite element method) was used to calculate steel material samples' fatigue life and strength with various parameters effect using finite element methods [24]. So, the parameters studied were the nanomaterials volume fraction and the laser treatment effect. Therefore, the first step used to analyze the fatigue problem for materials required selected the element type was must be used, [25-26], which can be using (element type solid 187) element type, as shown in Figure 8. Therefore, the element solid 187 is a 3-D higher-order with ten nodes and can be used to analyze the stress, creep, large deflection and strain, plasticity and hyperelasticity application. Then, the analysis required meshing the molding for the fatigue sample, shown in Figure 9 (a), by using the mesh generation technique to calculate the best element and nodes number [27-28], as shown in Figure 9 (b), which can give the best fatigue results. So, about 75000 elements and about 750000 nodes can be used to analyze the fatigue sample to give the best results. Finally, the solution problem by inputting required information from experimental results calculated [29-30], then, the mechanical properties for steel materials were presented in Table 2 can be used as input data for numerical technique [31-33]. So, the numerical technique application to reversed stress ratio R=-1 to calculate the fatigue behavior. Also, the clamped supported at the two ends were used to support the materials sample, with zero displacement values for all displacements. There, the results calculated by numerical and experimental results were compared together, and calculating the discrepancy of the results to evaluate the agreement for experimental work was used.

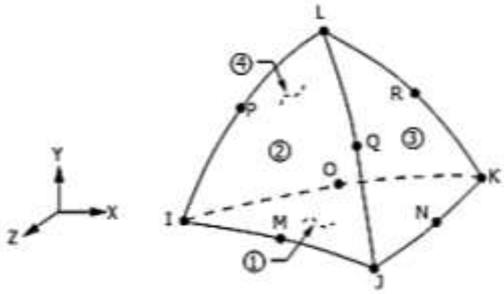
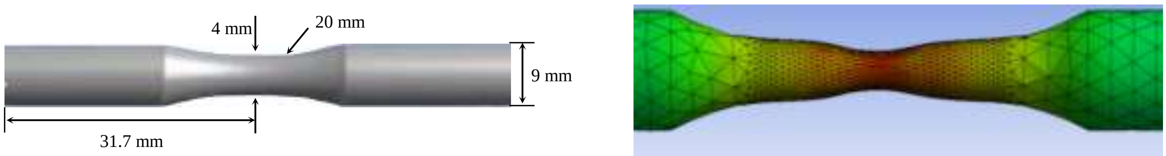


Figure 8. Element type solid 187.



a. Sample dimensions b. Fatigue fracture sample

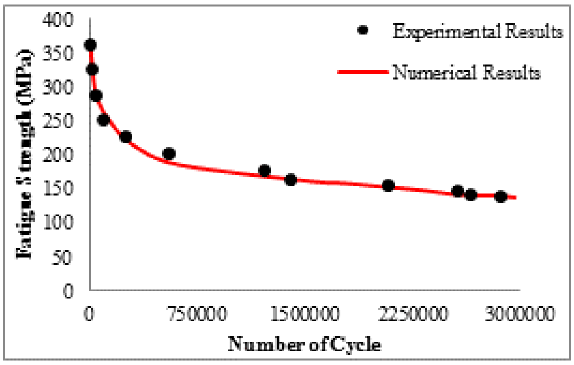
Figure 9. Fatigue sample mesh and stress distribution.

4. RESULTS AND DISCUSSION

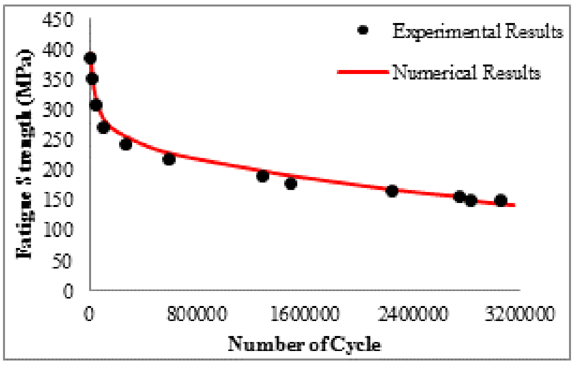
The results for the laser treatment effect on the fatigue characterization for steel materials coating by nanomaterials included calculating the strength and life fatigue of steel material with various nano and laser treatment effects. So, the experimental work was used to evaluate the fatigue characterization and used numerical techniques to compare the experimental results were calculated. Therefore, the comparisons between experimental and numerical results are presented in Figures 10 and 11, with various parameters effects, nanoparticle additives, and laser treatment effects. So, the effect of different nanoparticle ZnONPs coating, with weight fraction 0.25 %, 0.5 %, 1%, and with and without laser treatment effect, in addition to the fatigue for steel material without nano effect, was shown in Figure 12. Also, the effects of nanoparticle additive and laser treatment on the fatigue characterizations are shown in Figure 13. All these figures show that the additive for nanomaterials leads to modifying the fatigue life and strength of steel materials. Also, it can be shown that the laser treatment leads to modifying the life and strength fatigue with high about lead to about 40%.

Then, the conclusion for the effect of nanoparticle additive and laser treatment are shown in Table 4 and Figure 14, where the results show that the fatigue strength for materials modified by about 20% by nanoparticle coating and increasing to about 38% by using laser treatment together with nanomaterial. Also, the fatigue life was modified to about 25% by coating steel materials with nanoparticles and increasing to 40% with treatment materials with laser treatment. The curve fitting to calculate the fatigue equations for steel materials with different nanoparticle effects and without laser treatment was presented in Figure 15; in addition, Figure 16 has shown the curve fitting for experimental fatigue results with nanoparticle and laser treatment effects. So, from Figures 15 and 16 can be seen that the good agreement for curve fitting results and can be used to calculate the fatigue characterizations for materials with different parameters effect. In addition, the effect of the stress ratio and the shaft shoulder radii on the fatigue characterizations were can be presented in Figures 17 and 18, respectively. Then, the following equation can be listed for fatigue characterizations with different effects:

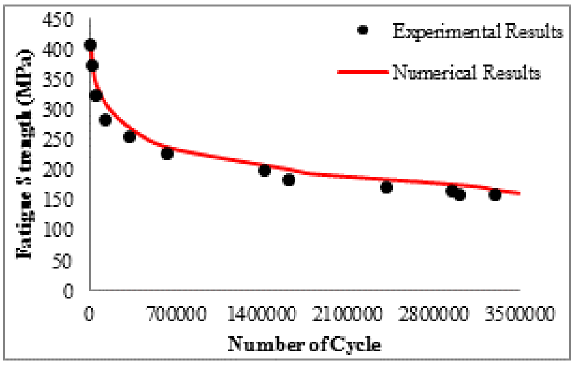
- $\sigma_f = 1631.4N^{(-0.163)}$ for 0% Nanoparticle without laser treatment effect
- $\sigma_f = 1768.4N^{(-0.163)}$ for 0.25% nanoparticle without laser treatment effect
- $\sigma_f = 1973.6N^{(-0.166)}$ for 0.5% nanoparticle without laser treatment effect
- $\sigma_f = 2156.5N^{(-0.165)}$ for 1% nanoparticle without laser treatment effect
- $\sigma_f = 1979.4N^{(-0.164)}$ for 0% nanoparticle with laser treatment effect
- $\sigma_f = 2044.6N^{(-0.163)}$ for 0.25% nanoparticle with laser treatment effect
- $\sigma_f = 2290.5N^{(-0.166)}$ for 0.5% nanoparticle with laser treatment effect
- $\sigma_f = 2469.4N^{(-0.165)}$ for 1% nanoparticle with laser treatment effect



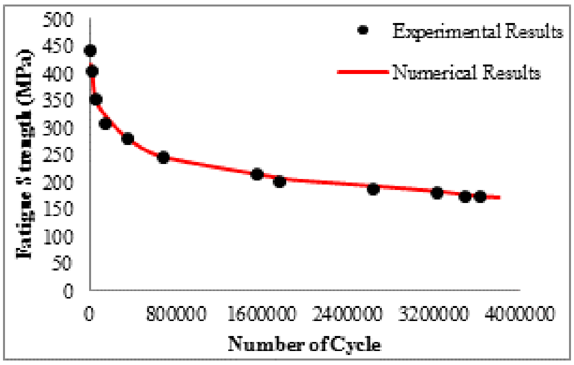
a. 0% Nano Effect



b. 0.25% Nano Effect

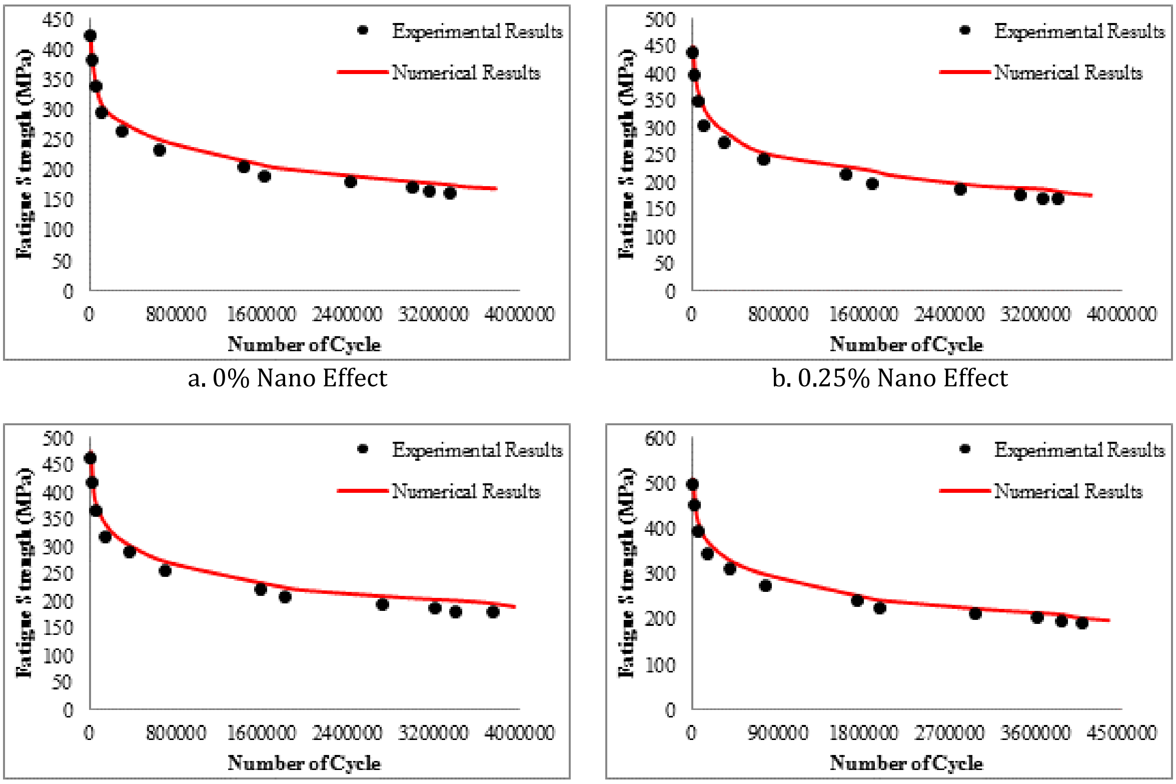


c. 0.5% Nano Effect



d. 1% Nano Effect

Figure 10. Numerical and experimental fatigue results comparison for steel materials with nanomaterial.



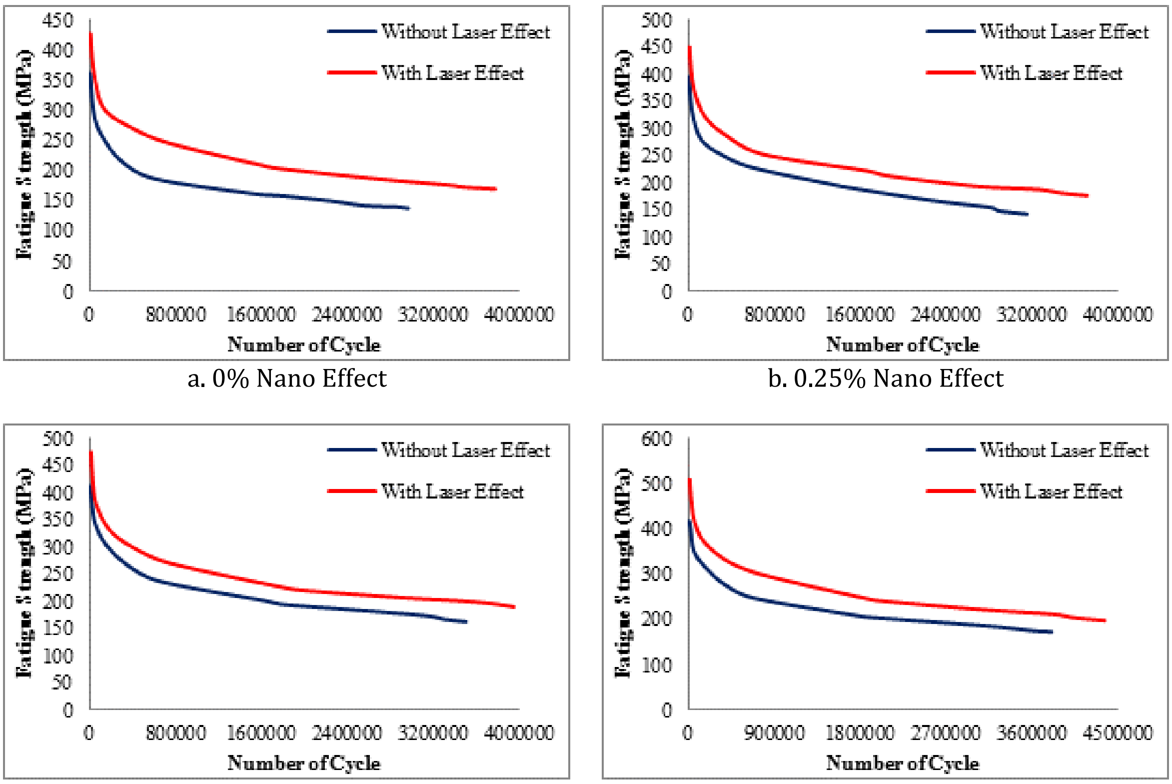
a. 0% Nano Effect

b. 0.25% Nano Effect

c. 0.5% Nano Effect

d. 1% Nano Effect

Figure 11. Numerical and experimental fatigue results comparison for steel materials with nanomaterial and laser treatment effect.



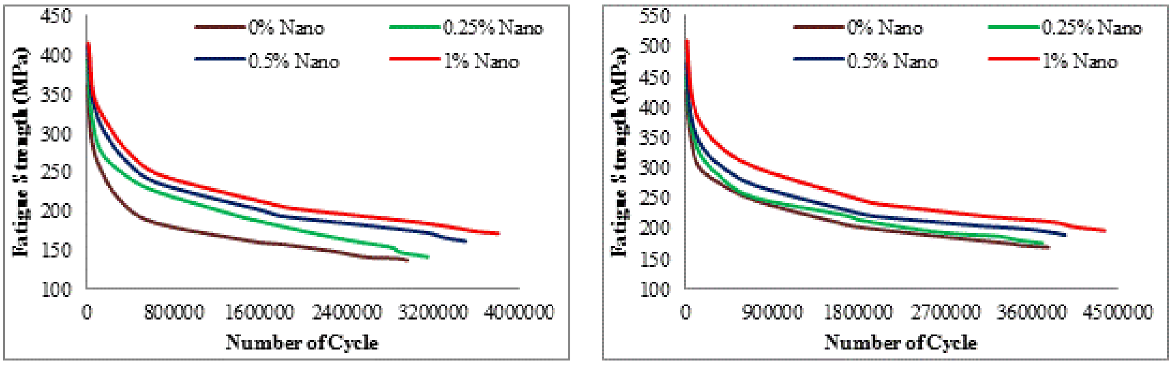
a. 0% Nano Effect

b. 0.25% Nano Effect

c. 0.5% Nano Effect

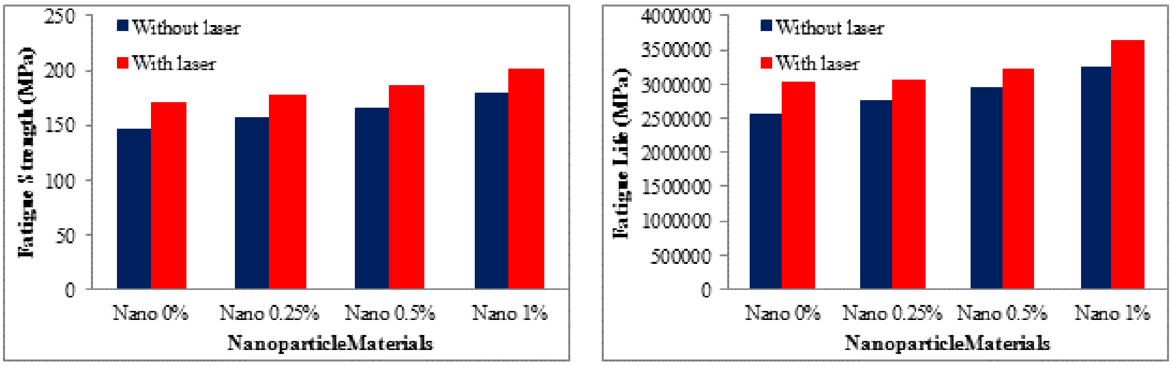
d. 1% Nano Effect

Figure 12. Results for laser treatment and nano effect on the fatigue characterizations for materials.



a. without laser treatment effect b. with laser treatment effect

Figure 13. Fatigue characterizes material with and without laser treatment and nano effects.

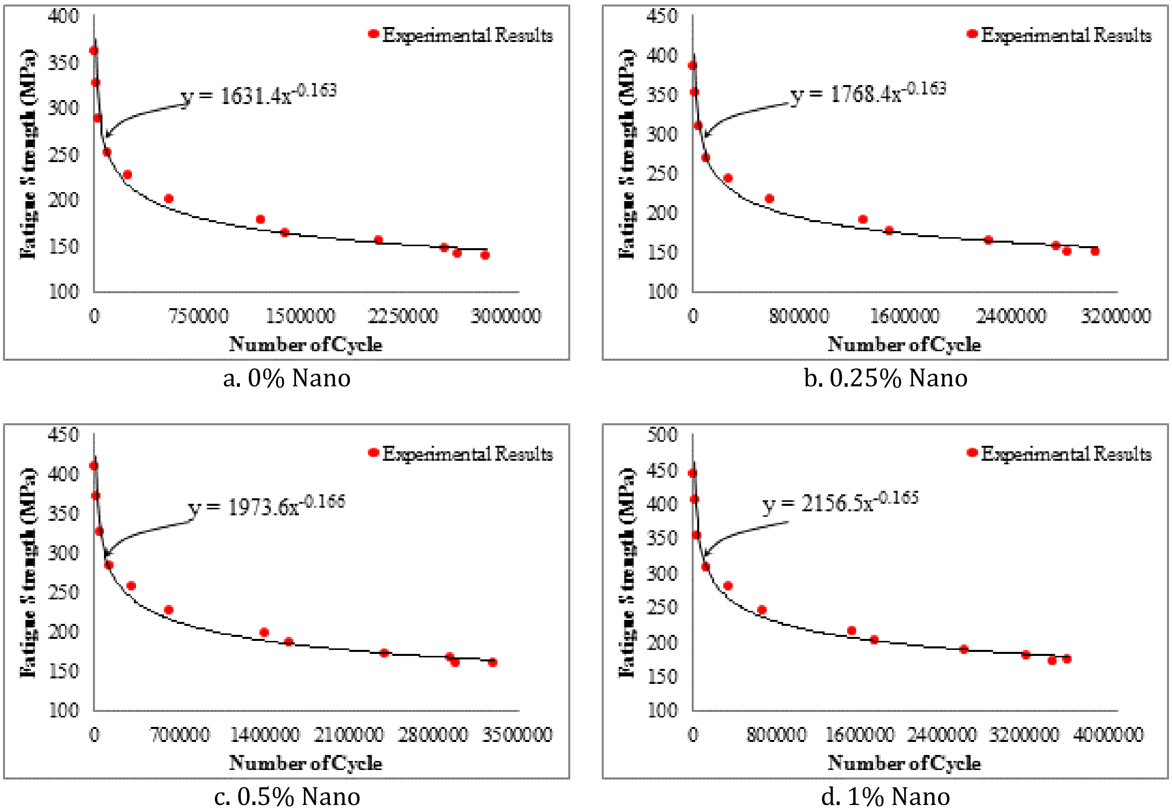


a. Fatigue strength (MPa) b. Fatigue life

Figure 14. Fatigue strength and life for steel samples with nanoparticle and laser treatment effect.

Table 4. Fatigue strength and life for steel material with coating and laser treatment effect

Nanomaterials	Fatigue strength (MPa)		Fatigue life	
	without laser	with laser	without laser	with laser
0%	145.2	169.74	2568201	3009931
0.25%	155.95	176.9	2750543	3061354
0.5%	164.52	185.42	2947467	3204743
1%	177.85	200.62	3233372	3621376



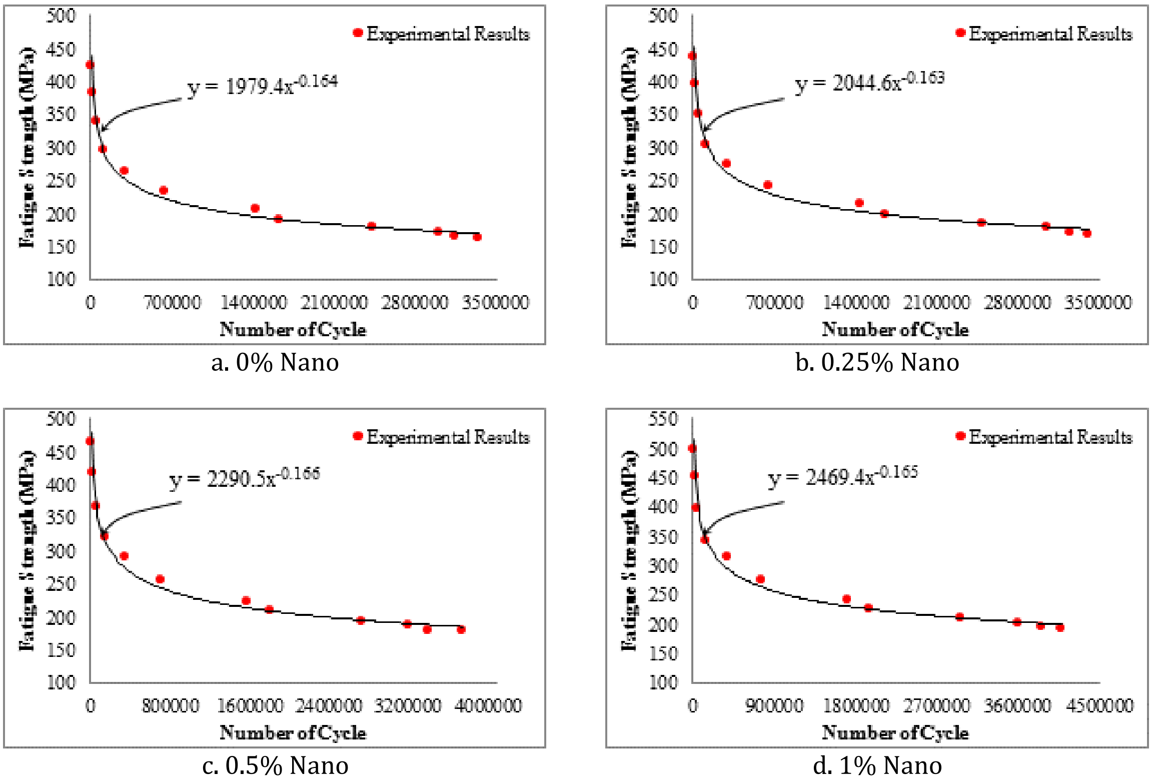
a. 0% Nano

b. 0.25% Nano

c. 0.5% Nano

d. 1% Nano

Figure 15. Curve fitting for experimental fatigue results with nanoparticle effect, without laser treatment.



a. 0% Nano

b. 0.25% Nano

c. 0.5% Nano

d. 1% Nano

Figure 16. Curve fitting for experimental fatigue results with nanoparticle coating and laser treatment.

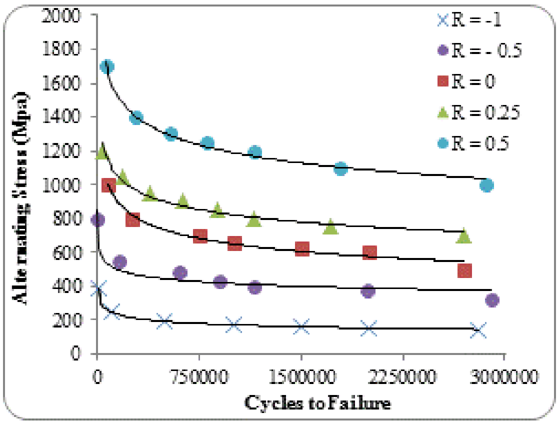


Figure 17. Influence of stress ratio on fatigue life characteristics (0% nano).

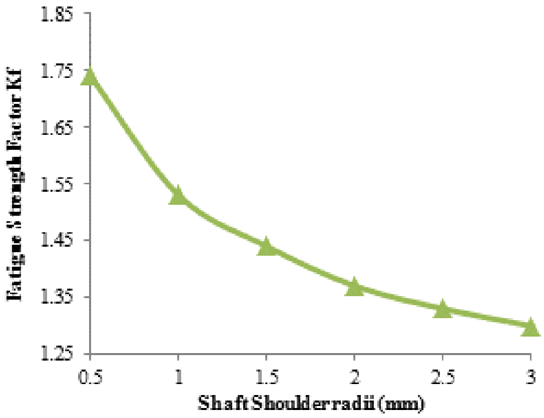


Figure 18. Fatigue strength factor for reversed bending samples (0% nano).

5. CONCLUSION

From the experimental and numerical techniques used to calculate the fatigue behavior strength and life, with nanomaterials and laser treatment effect, the following important points can be concluded:

1. The experimental technique can calculate the fatigue characterizations for materials with various effects, nanomaterials and laser treatment.
2. The comparison between the numerical, using finite element technique and experimental work for fatigue life and strength gave a good agreement for results with maximum discrepancy not exceeding about 10.86%.
3. Based on the practical and experimental results, we can conclude that the fatigue strength and fatigue life improve with coating with nanoparticles compared to the samples without coating. With the increase in the weight fraction of added nanoparticles, the fatigue strength also increases. In the case of coating with nanoparticles and laser treatment, the fatigue strength and fatigue life are improved, and when the weight fraction of added nanoparticles is increased, the fatigue life is significantly increased. It was found that laser surface treatment caused an improvement in fatigue strength and life of about 40%. The experimental results match the numerical results.
4. The modification of the fatigue strength and life with the effect of nanoparticle coating and leaser treatment effect together was more than the effect of nanoparticle coating or laser treatment effect on fatigue strength and life for steel materials.

5. The results showed that the fatigue strength for materials was modified by about 20% by nanoparticle coating and increased to about 38% using laser treatment and nanomaterial. Also, the fatigue life was modified to about 25% by coating steel materials with nanoparticles and increasing to 40% with treatment materials with laser treatment.

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