Strain Analysis of Surface Cracked Thin Flat Plate under Cycling Impact Loading Effect

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ABSTRACT

In this work, strains and dynamic crack growth were studied and analyzed in thin flat plate with a surface crack at the center, subjected to cycling low velocity impact loading for two types of aluminum plates (2024, 6061). Experimental and numerical methods were implemented to achieve this research. Numerical analysis using program (ANSYS11-APDL) based on finite element method used to analysis the strains with respect to time at crack tip and then find the velocity of the crack growth under cycling impact loading. In the experimental work, a rig was designed and manufactured to applying the cycling impact loading on the cracked specimens. The grid points was screened in front of the crack tip to measure the elastic-plastic displacements in the x and y direction by grid method, from which the strains are calculated. The results show that the strains increase with increasing in the crack length. It was found that the cumulative number of cycles leads to increase in the strain values with increasing in crack growth velocity.

Key words: strain, velocity, crack tip, analysis, plate.

تحليل الأنفعال لشق سطحي في صفيحة رقيقة تحت تأثير حمل صدمة متكرر

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الخلاصة

في هذا العمل تم دراسة وتحليل الأنفعالات وحركة نمو الشق لصفائح رقيقه ومستوية تحتوي على شق سطحي في وسطها ومعرضة لحمل صدمة دوري ذات سرعة منخفضة ولنوعين من سبائك ألالمنيوم (2024,6061). تم استخدام طرق عملية وعددية لانجاز هذا العمل. في التحليل العددي تم أستخدام برنامج (ANSYS11-APDL) بألاعتماد على طريقة العناصرالمحددة وذلك لتحليل الأنفعالات بالنسبة للزمن عند قمة الشق ومن ثم حساب سرعة نمو الشق تحت تأثير حمل الصدمة المتكرر. في الجزء العملي تم تصميم وتصنيع جهاز لتسليط حمل الصدمه المتكرر على مركز العينه. حيث تم طباعة شبكه النقاط عند مقدمة قمة الشق وذلك لقياس الازاحات بطريقة الشبكة وبالتالي ايجاد الانفعالات المتوزعه حول قمة الشق الصدمه التكراري.

وقد أظهرت النتائج بأن الأنفعالات المتولده تزداد بأزدياد طول الشق كذلك أظهرت بأن عدد الدورات التراكمي يؤدي الى زيادة قيم الأنفعالات وبالتالي زيادة سرعة نمو الشق .

الكلمات الرئيسية : أنفعال, سرعة, قمة الشق, تحليل, صفيحة.

1. INTRODUCTION

In real life cracks may occur in some parts of structure that may lead to failure like accidental cracking of welded connection, explosion of pressure vessel, buildings and sudden failure of jet aircraft. Therefore, strain analysis and study the cracks propagation within structures is very important to improve the design against fracture, **Ayoub, 1984.** In this work, strain of surface cracked thin plate under cyclic loading was analyzed. Cycling load involved in many structures such as automobiles (piston inside cylinder), wing of aircraft, bridges, and machines structures. In general, three different fluctuating stress-time modes are possible. One is represented schematically by regular and sinusoidal time dependence. Where in the amplitude is symmetrical about mean zero stress level, alternating from a maximum tensile stress to a minimum compressive stress of equal magnitude, this is a reversed stress cycle. Another type, termed repeated stress cycle, is illustrated the maximum and minimum are asymmetrical relative to the zero stress level. Finally the stress may vary randomly in amplitude and frequency. Gears are subjected to reversed stress cycles, while the connected rod in a petrol engines and the wing of an aircraft are subjected to repeated stress cycles**, Stephens, et al., 2001.**

There are many researcher were studied the strain at crack tip with different fluctuating stress-time modes. **Toribio, and Kharin, 2009,** studied the plane-strain crack subjected to mode I cyclic loading under small scale yielding. **Sahoo, et al., 2007,** analyzed the effects of plasticity on the stress and deformation field near the crack tip, while **Boljanovic**, **2012** proposed a computational model for estimating the crack growth behavior and fatigue life of a plate with a semi-elliptical surface crack.

The aim of this work is to build up a model described the strain behavior at crack tip to thin plate under cyclic loads. A rig system will be designed and manufacturing for this purpose. ANSYS11-APDL package will be employed to build up the model and analysis the strains.

2. NUMERICAL ANALYSIS

Numerical analysis of structures subjected to various kinds of actions is an important issue for structural safety. A numerical method can be used to obtain an approximate solution; approximate numerical procedures have become very accurate and reliable for the solution with the advent of high speed digital computers**, Kareem, 1998.** Solving fracture mechanics problems involves performing a linear elastic or elastic-plastic state analysis and then using specialized post processing commands or macros to calculate desired fracture parameters. The following topics describe the two main aspects of procedure:

1. Modeling the crack region.
2. Selecting of element and meshing.
3. Calculating fracture parameters.

In this research, the ANSYS software APDL is used for solving fracture problem. Selecting of element and meshing: The element Solid185 is used for 3D modeling of solid structures. It is defined by eight nodes having three degrees of freedom at each node, translations in the nodal x, y and z directions. The element has plasticity, hyper elasticity, stress stiffening, creep, large deflection, and large strain capabilities. It also has mixed formulation capability for simulating deformations of nearly incompressible elastoplastic materials, and fully incompressible hyper elastic materials. The boundary conditions are clamped-clamped with simply supported at the other edges plate and clamped-clamped with free at the other edges plate.

2.1 The Crack Region Modeling

Stress and deformation fields around the crack tip generally have high gradients. The precise nature of these fields depends on the material, geometry and other factors. To capture the rapidly varying stress and deformation fields, use a refined mesh in the region around the crack tip. For linear elastic problem the displacement near the crack tip (or crack front) vary as $\sqrt{r}$, where (r) is the distance from the crack tip. The stresses and strains are singular at the crack tip, varying as $1/\sqrt{r}$. To produce this singularity in stresses and strains, the crack tip mesh should have certain characteristics, the crack faces should be coincident and the elements around the crack tip (or crack front) should be quadratic, with the mid side nodes placed at the quarter points. Such elements are called singular elements. **Fig.1**

2.2 Loads and Boundary Conditions

The cycling impact loading is applied at the cracked thin flat plate; the boundary conditions are clamped-clamped with simply supported at the other edges plate and clamped-clamped with free at the other edges plate. **Fig.2**

3. EXPERIMENTAL WORK

A rig system was designed and built up to achievement this work. The main purpose of rig system design to get a cycling impact loading to strike vertically at center of plate’s surface and measurement the induced deformations and calculated the strains. It consists of electric motor, control number of cycle’s equipment, gearbox, one step of pulleys and impactor arm. The specifications of electric motor were, power (100watt), voltage (220 volt), frequency (50Hz), and rotation velocity (780rpm) was reduced by gearbox that have a reduction ratio (1:40), the step of pulleys having (53mm) diameter of pinion pulley and (64mm) diameter of wheel pulley so as a reduction ratio (1:1.2), so that have a velocity for pinion pulley (19.5rpm) and suitable velocity for the wheel pulley (16.25rpm). A control number of cycle’s equipment determinates the number of cycles needed to strike a plate’s surface, for this work, the number of cycles was (1000 cycle/sec). The impactor mass (1.5kg), which have a hemispherical end (R=1.5mm), moves vertically to strike the plate’s surface. The distance between end of impactor and the surface of plate was constant (80mm). The samples were hold from four sides (clamped-clamped with simply supported at the other edges) and once again through (clamped-clamped with free at the other edges). **Fig.3** is shown the experimental rig. Two types of metals were used in this work, aluminum (2024) and aluminum (6061). The specifications of metals have shown in **tables 1 and 2.** A grid has been printed in the front of the crack tip with square grid for measuring the displacements of each point after deformation by cycling impact load.

3.1 Procedure of Work

Grid method is one of the methods of strain analysis, which is whole field in nature. In order to determine displacements and strain components at given points of arbitrarily shaped surfaces a grid can be engraved on the surface to be studied. This grid acts as a reference element and the changes that the grid experiences from the unreformed to the deformed conditions can be utilized to determine either displacements or strains. Two difficulties are encountered which limit the use of grids for measuring deformations; firstly, the strains to be measured are usually very small, and in most cases the displacement readings are difficult to make with sufficient accuracy. This is particularly true in strain analysis. However, this method is very much suitable for the study of deformation in materials .Secondly, when the photographs of the grid network are magnified by microscope, the images of the grid lines are usually poorly defined introducing appreciable errors into the displacement readings. This method has the advantages that a photographic record of deformations covers the entire field of the specimen. This record can be obtained for either static, dynamic elastic or plastic deformations. The strain was measured directly. The distance between the grid lines on the model was measured by a microscope by keeping the magnification of microscope same before and after loading. The specimen was impacted vertically through a number of cycles by the impactor on the center of the sample. The number of the cycles was controlled by controlling equipment. The grid method was used to calculate the displacement in X-axis (u) and in Y–axis (v). The dimensions of grid were (30 mm×30 mm) and the length of square is (1mm) .The grid was photographic before and after the cycle of the sample and the measurements of the displacements was taken by microscope as shown in **Fig.4** for all the samples. Then the strains at the surface crack tip were calculated in the plate.

3.2 Boundary Conditions Change under Cyclic Impact Load

Two types of boundary conditions were used in this work. The first, clamped-clamped with simply supported at the other edges plate (CSCS) as shown in **Fig.5**. The second of boundary condition, clamped-clamped with free at the other edges plate (CFCF) as shown in **Fig.6.**

4. RESULTS AND DISCUSSION

The results showed substantial convergence in the numerical analysis with experimental work and illustrated the effect of cyclic impact load on the strains and crack growth velocity at surface crack tip due to number of cycles.

4.1 Numerical Analysis (ANSYS Program)

4.1.1 The effect of the crack lengths on the strains

The extension in length (deflection) is direct proportional with applied stresses that means the increasing in crack length which leads to increase the values in strain as shown in **Fig.7 to 10**. The instantaneous length of crack for aluminum 6061 is greater than aluminum 2024.Because the aluminum 6061 is more ductile than the aluminum 2024 (young modulus for aluminum 2024 greater than aluminum 6061). Increasing in the cumulative number of cycles leads to increase in the strains with nonlinear behavior so that the increasing in crack length also will be nonlinear .The yield region will be not appoint, so that there is some limiting values that strain hardening will affect the results therefor the rate of increasing curve slope will be low till nearly 600 cycles then after that, the rate of curve slope will have a high increasing. Materials especially metals tend to exhibit a yield stress, above which they deform plastically. This means that there is always a region around the tip of a crack in a metal, where plastic deformation occurs, and this plastic region is known as the crack tip plastic zone. The plastic zone size vary with the number of cycles and it increases with increase the number of cycles, because the increase in the number of cycles means increasing in the applied stresses that is leading to increase in the plastic zone size.

4.1.2 The effect of the boundary conditions on the strains

Fig. 11 to 14 show, the results of the strain values at clamped-clamped with free at the other edges boundary condition will be higher from the clamped –clamped with simply supported at the other edges boundary condition by maximum error percentage (17%) for Al-6061 and (18.9%) for Al-2024 between numerical analysis and experimental work, this is because the value of the deflection at clamped-clamped with free at the other edges will be higher from clamped-clamped with simply supported at the other edges, that is leading to the stress and strain values become higher.

4.1.3 The effect of the crack growth velocity on the strains

The crack growth velocity depends on the applied stress which increases with increase the cumulative number of cycles that means the crack growth velocity increases with increasing in the number of cycles. As shown in the **Fig. 15 and 16** noticed after 500 cycles nearly for aluminum 2024, the crack propagation values were started more increasing and faster propagate before500 cycles, while for aluminum 6061 after 525 cycles nearly the crack propagation values were started more increasing before 525 cycles, So that the plastic zone consists at aluminum 6061 before aluminum 2024 and the crack propagation at aluminum 6061 faster from aluminum 2024. The main reason of this case, the effect of ductility of material on the stress and strain values under cycling impact loading will become more clearly appeared in aluminum 6061rather than in aluminum 2024 and noticed from ANSYS program results the crack growth velocity values were increased with increasing the crack length and aspect ratio of plate. The crack propagation don’t occur under impact load only because the plastic zone due to low velocity impact with applied cyclic loading which cause crack propagation.

4.2 Experimental Work

4.2.1 The effect of the crack lengths on the strains

Fig. 17 to 20 illustrate the effect of the experimental combined load (cycling impact load) on the strains at surface crack tip due to number of cycles with crack lengths (7mm, 10mm) and constant depth (2mm) for aspect ratio (1) of aluminum plates. Maximum error percentage of strains (12.5%) for aluminum 6061 and (13%) for aluminum 2024 between experimental work and numerical analysis.

4.2.2 The effect of the boundary conditions on the strains

Fig. 21 to 24 illustrate the effect of the experimental under cycling impact load on the strains at surface crack tip due to number of cycles with boundary conditions, clamped-clamped with free at the other edges and clamped-clamped with simply supported at the other edges, with crack length (6mm) for aspect ratio (1).

5. VERIFICATION

Fig. 25 to 28 show the behavior of metal in the distribution of strains with number of cycles at different crack lengths for methods, numerical analysis and experimental work. Noticed that the behavior of metal for the ANSYS program more regularly than experimentally, because ANSYS program be more accurate while it is natural there would be an error in the proportion of experimentally. When the results of experimental work were compared with the results of the numerical analysis found the maximum error in strain (18.9%). In experimental work was found that values of displacements were higher at crack-tip and reduced when leaving the crack tip. Thus, the strains have greatest value at crack tip. The determination time of entry of the specimen in the plastic zone in experimental work was very difficult. But in the ANSYS program it was identified as the time when the specimen in the region of the plastic zone. Also it was found that in numerical analysis (ANSYS program), the strains have greatest value at crack tip.

6. CONCLUSIONS

1. Plastic zone has a significant effect on crack growth velocity under cycling impact loading for two materials used in this work. There are some specific values of strains at which strain hardening effect on the results. Therefore the rate of curve slope will be lower until about 600 cycles. After that, the rate of curve slope will back to increase.

2. The number of cycles has a significant effect on crack growth velocity specially at 400 cycles were the rate of increasing of crack growth velocity will be very high which is reflect the effect of plastic zone.

3. The effect of ductility of material on the strains under cycling impact loading will become more pronounced in aluminum 6061rather than in aluminum 2024.

4. With cumulative number of cycles under the cycling impact loading on the plate, using clamped-clamped with simply supported at the other edges boundary condition was better than clamped-clamped with free at the other edges.

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NOMENCLUTURE

Ar = aspect ratio, dimensionless.
Lc = crack length, mm.
ϵ_x, ϵ_y = Strains at crack- tip region, dimensionless.

Table1. The specifications of aluminum 2024.

Young modulus (E)Gpa	Yield Tensile Strength (σ_y) Mpa	Ultimate tensile strength ($\sigma_{ult.}$) Mpa	Poissons ratio(ν)	Density (ρ)Kg/m^3
73	325	470	0.33	2780

Table2. The specifications of aluminum 6061.

Young modulus (E)Gpa	Yield Tensile Strength (σ_y) Mpa	Ultimate tensile strength ($\sigma_{ult.}$) Mpa	Poisson's ratio(ν)	Density (ρ)Kg/m^3
69	275	310	0.33	2700

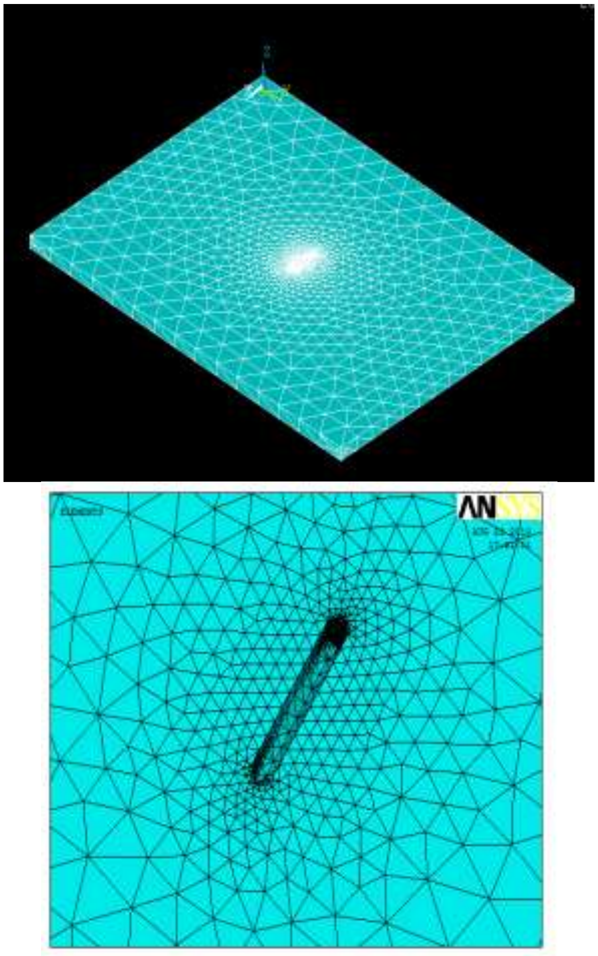

Figure1. 3D Model with solid185.

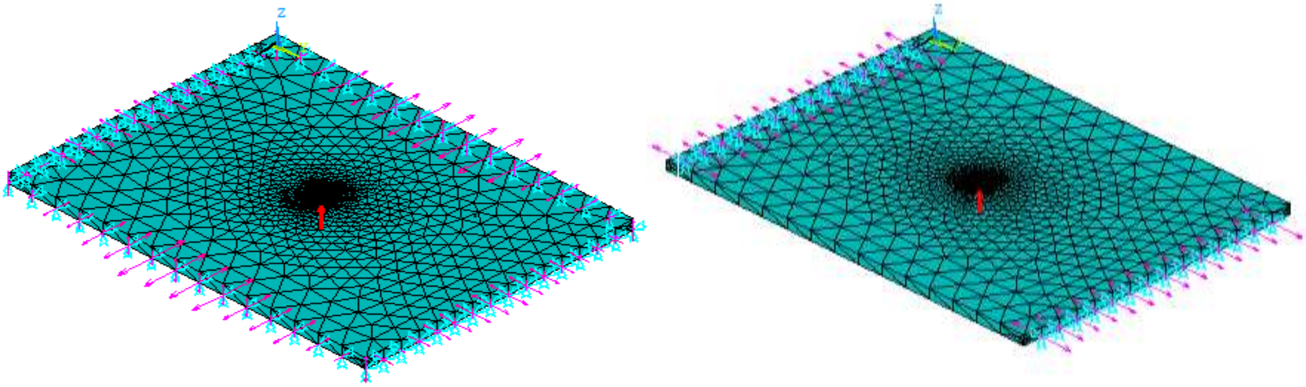

Figure2. Load and B.C.

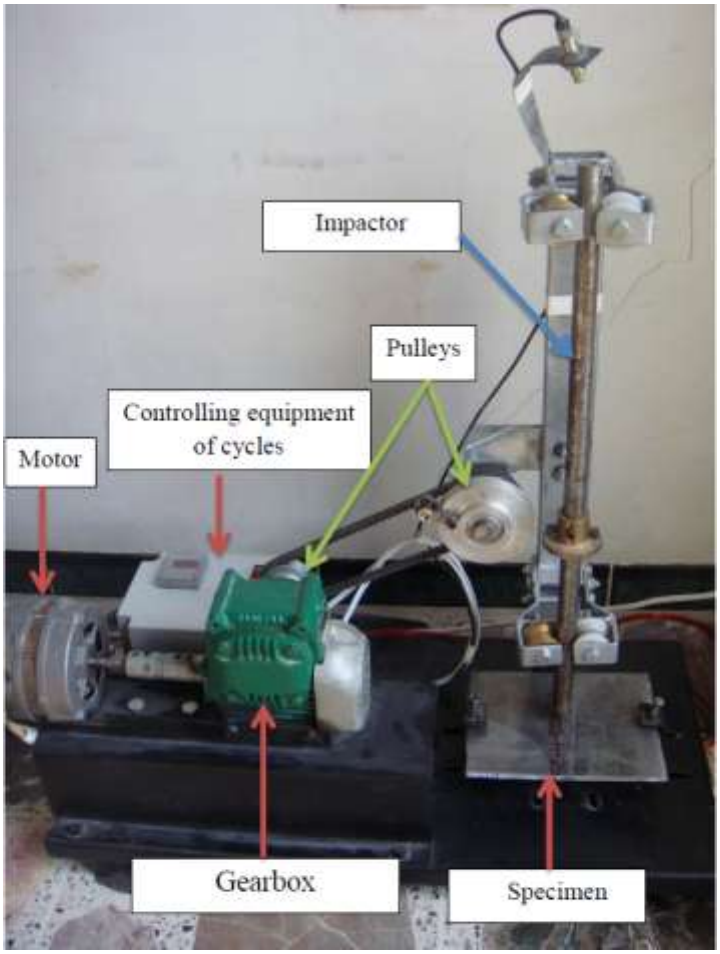

Figure3. Rig system.

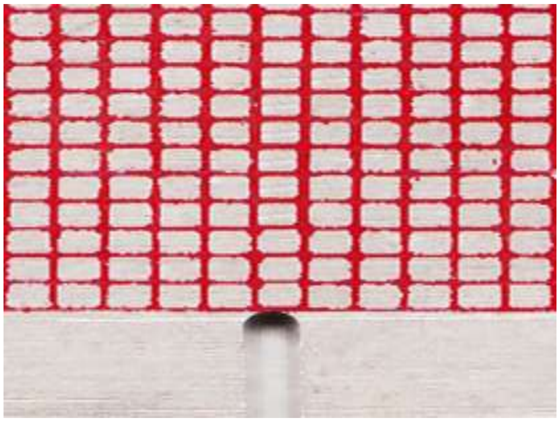

Figure4. Crack with grid.

Figure5. CSCS-Boundary Condition.

Figure6. CFCF-Boundary Condition.

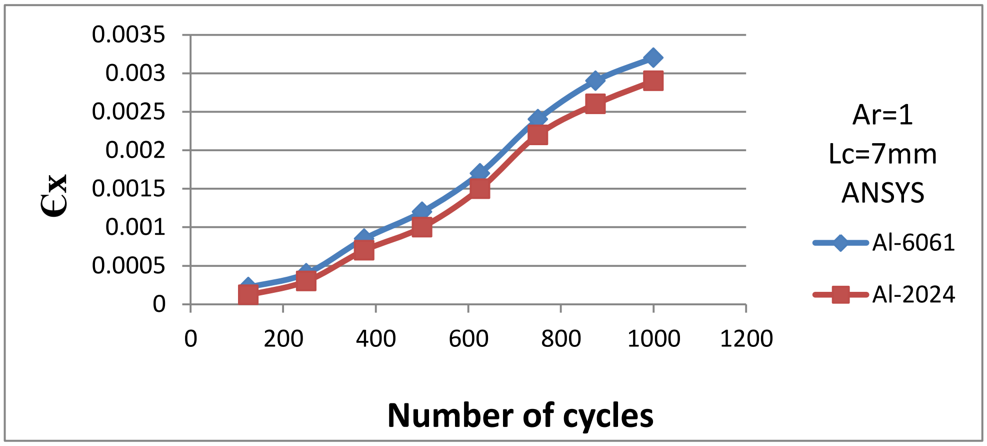

Figure7. ϵ_x Numerical with number of cycles (Ar=1&Lc=7mm).

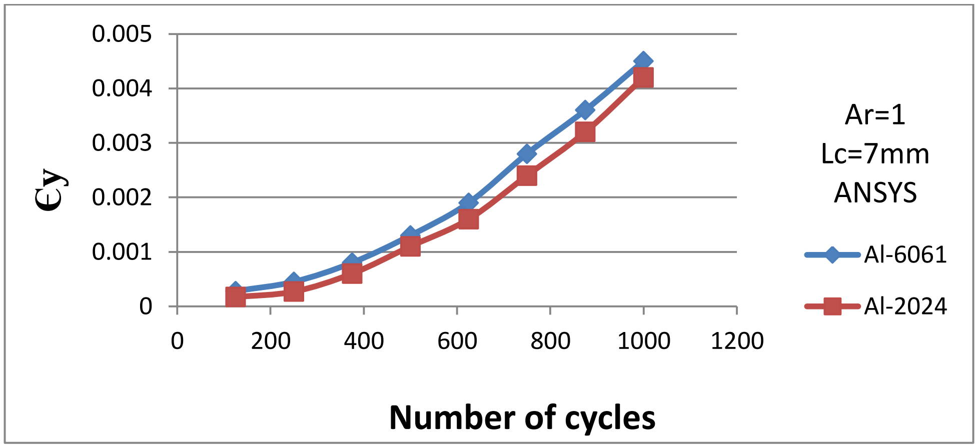

Figure8. ϵ_y Numerical with number of cycles (Ar=1&Lc=7mm).

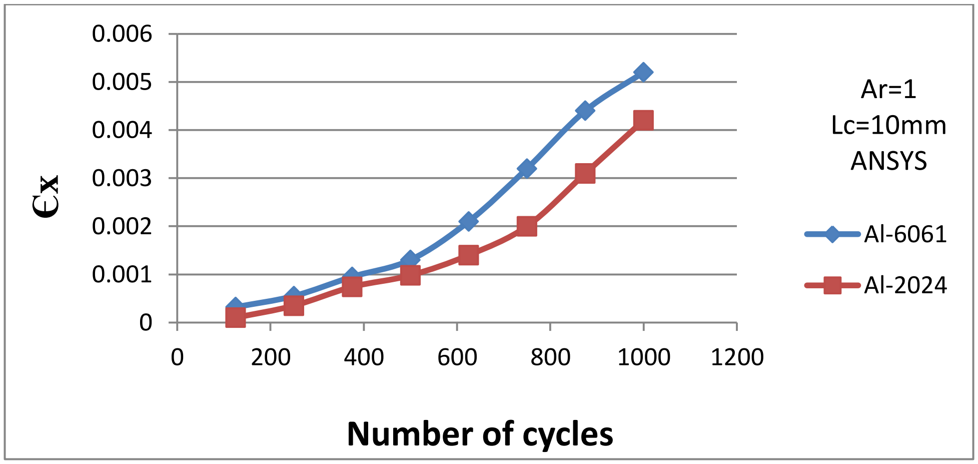

Figure9. ϵ_x Numerical with number of cycles (Ar=1&Lc=10mm).

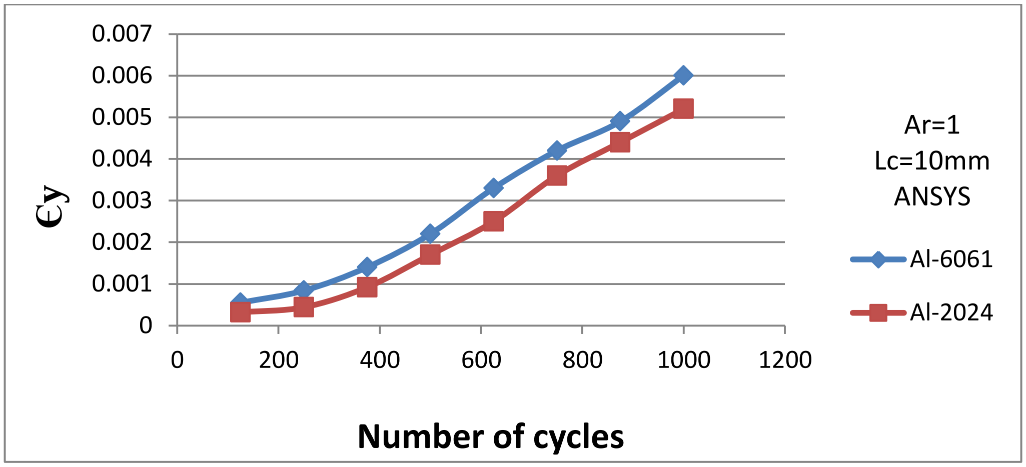

Figure10. Є$_y$ Numerical with number of cycles (Ar=1&Lc=10mm).

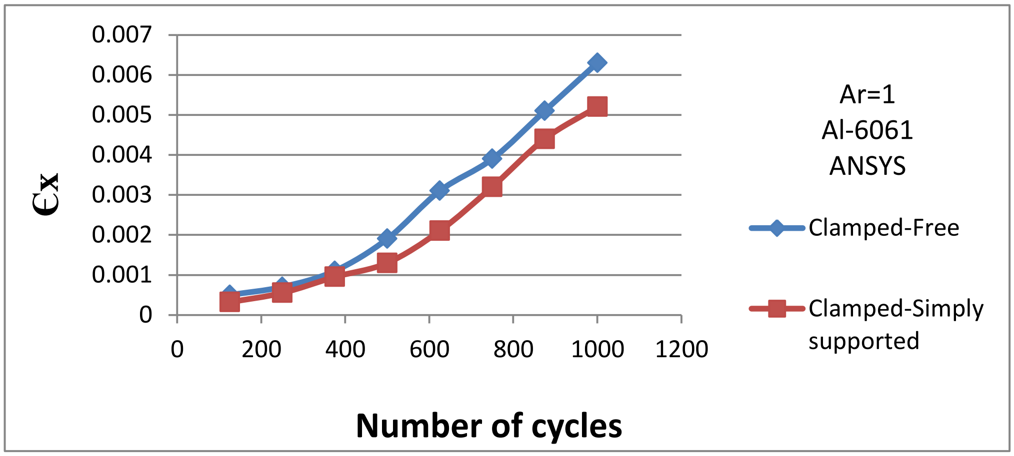

Figure11.Є$_{x.}$ Numerical with number of cycles (B.C for Al-6061).

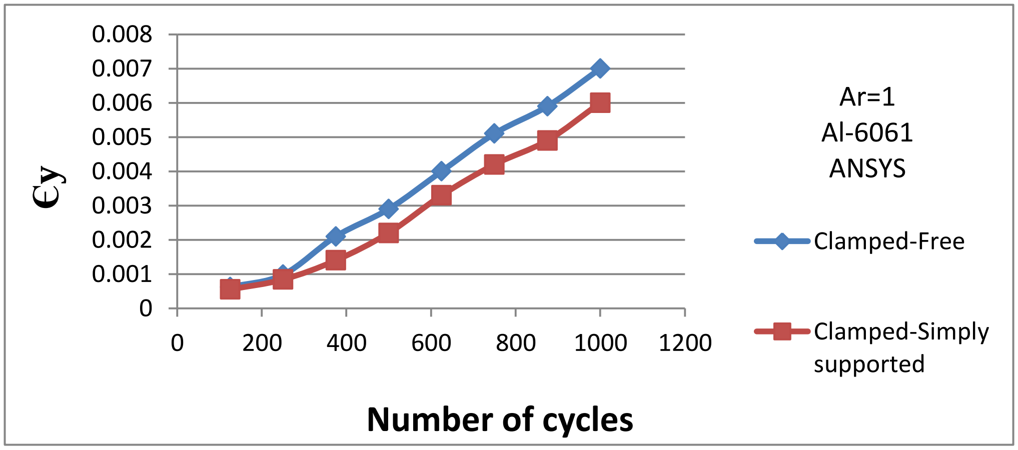

Figure12. Є$_y$ Numerical with number of cycles (B.C for Al-6061).

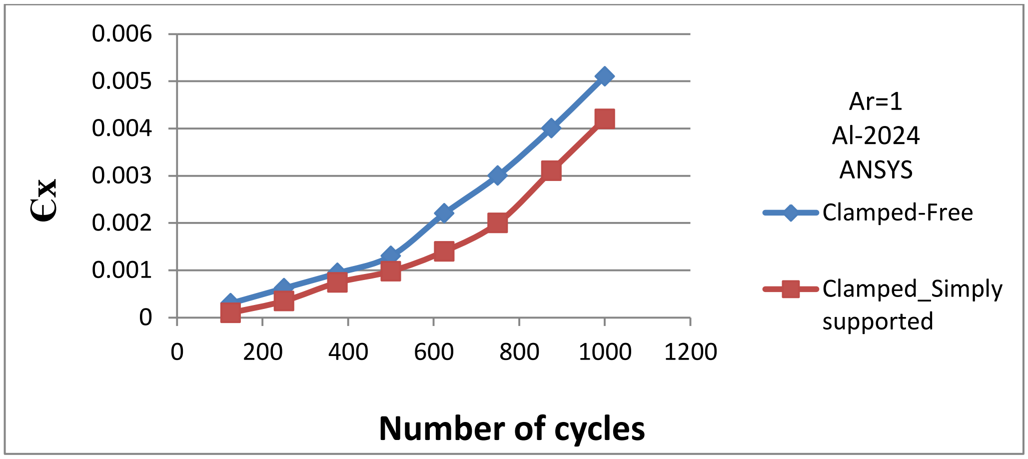

Figure13.€$_x$ Numerical with number of cycles (B.C for 2024).

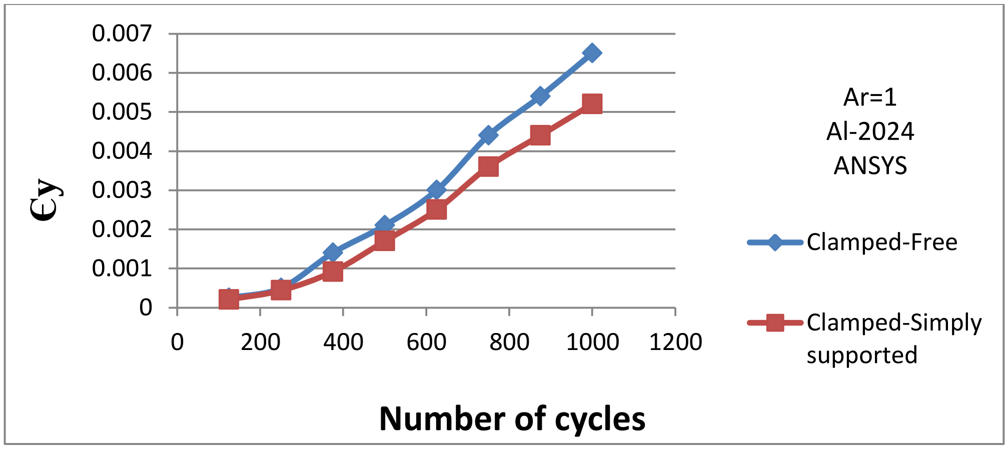

Figure14.€$_y$ Numerical with number of cycles (B.C for 2024).

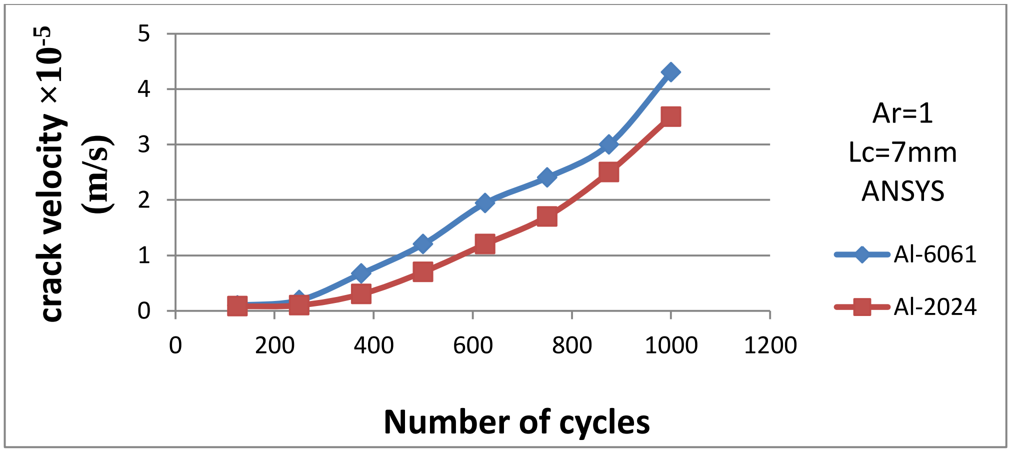

Figure15. Crack velocity numerical with number of cycles (Ar=1&Lc=7mm).

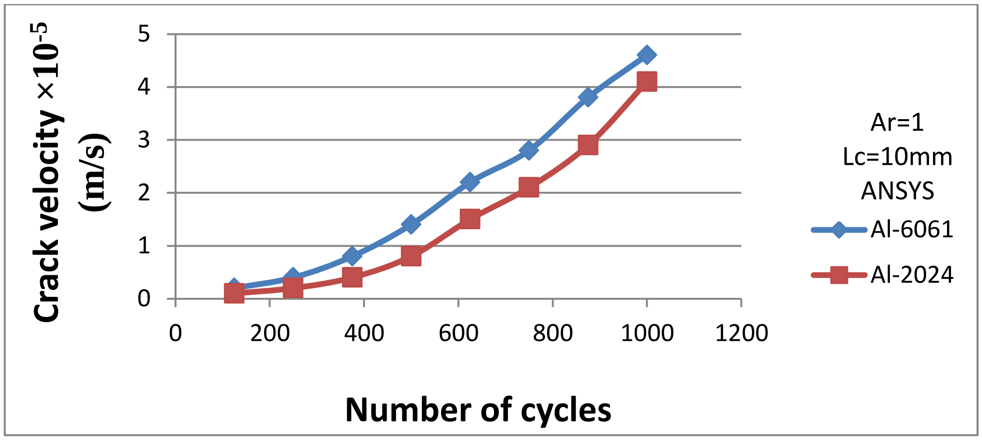

Figure16. Crack velocity numerical with number of cycles (Ar=1&Lc=10mm).

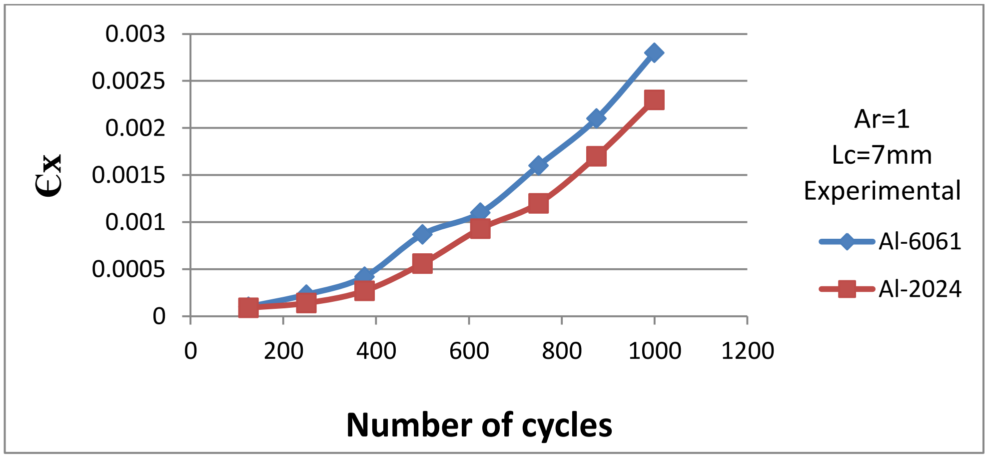

Figure17. ϵ_x Experimental with number of cycles (Ar=1&Lc=7mm).

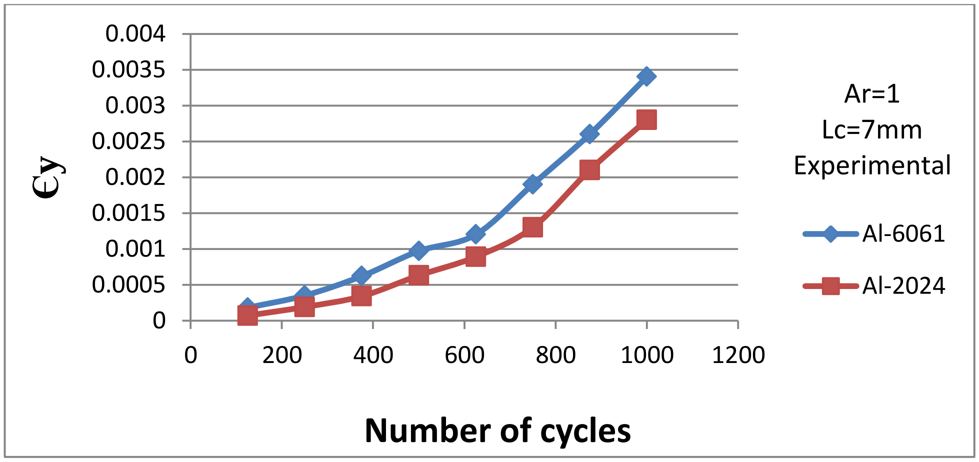

Figure18. ϵ_y Experimental with number of cycles (Ar=1&Lc=7mm).

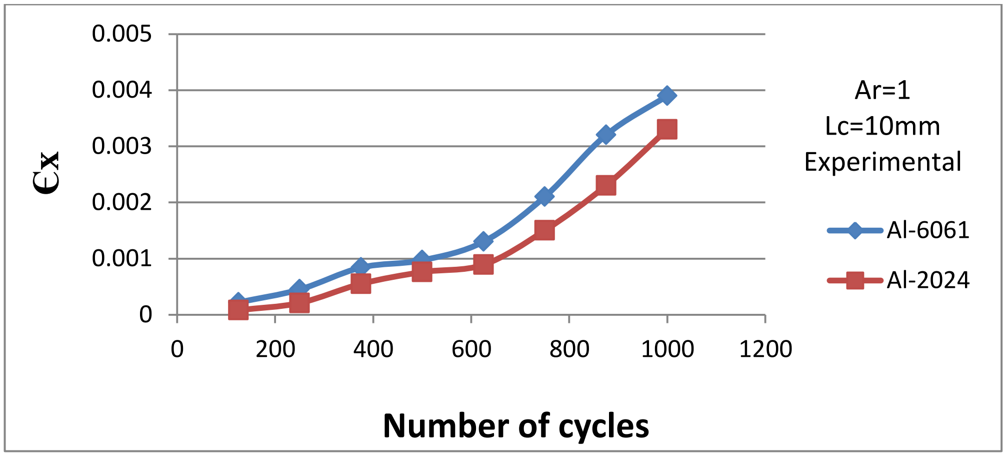

Figure19.ϵ_x Experimental with number of cycles (Ar=1&Lc=10mm).

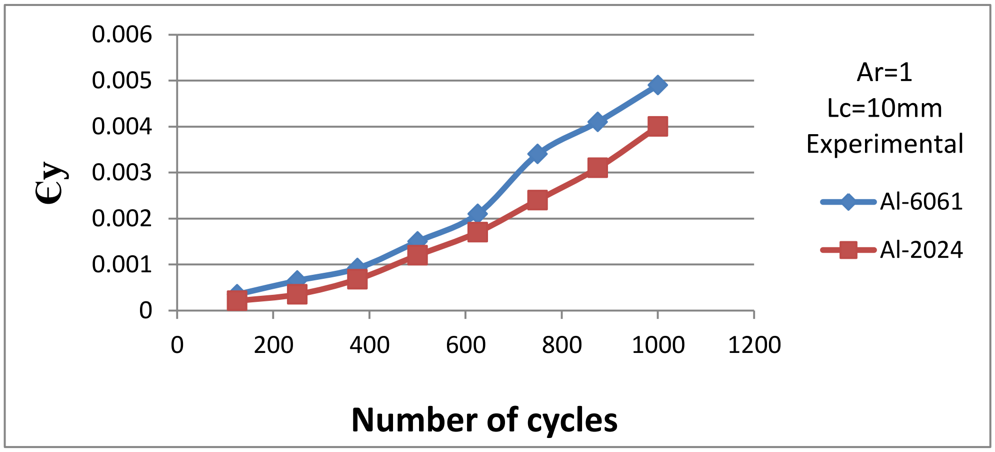

Figure20 .ϵ_y Experimental with number of cycles (Ar=1&Lc=10mm).

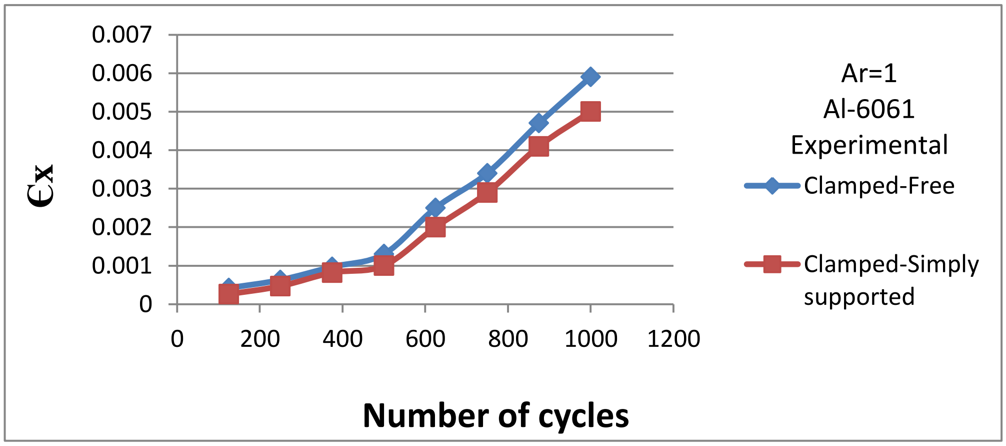

Figure21. ϵ_x Experimental with number of cycles (B.C for Al-6061).

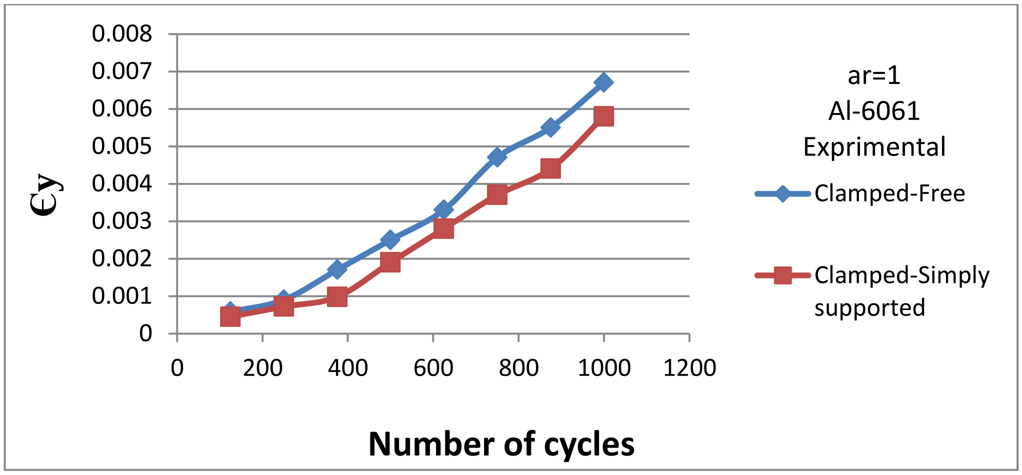

Figure22. Є$_y$ Experimental with number of cycles (B.C for Al-6061).

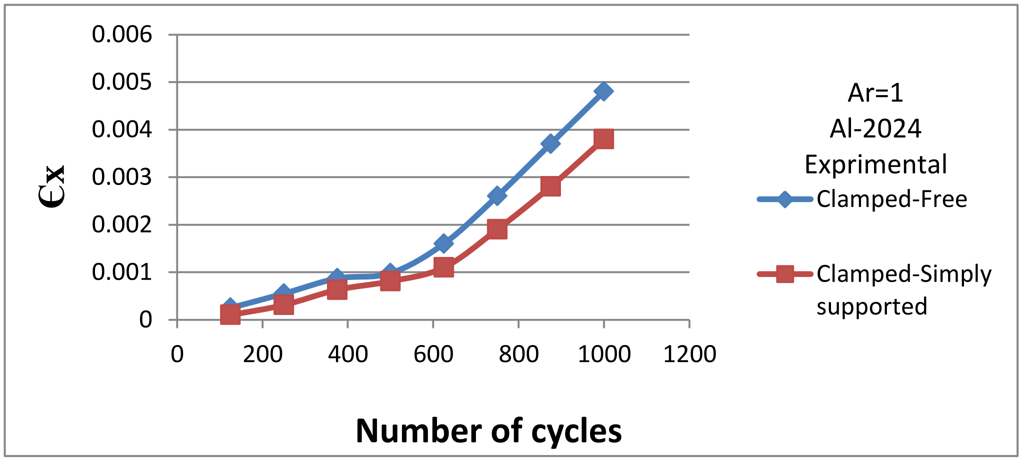

Figure23.Є$_x$ Experimental with number of cycles (B.C for 2024).

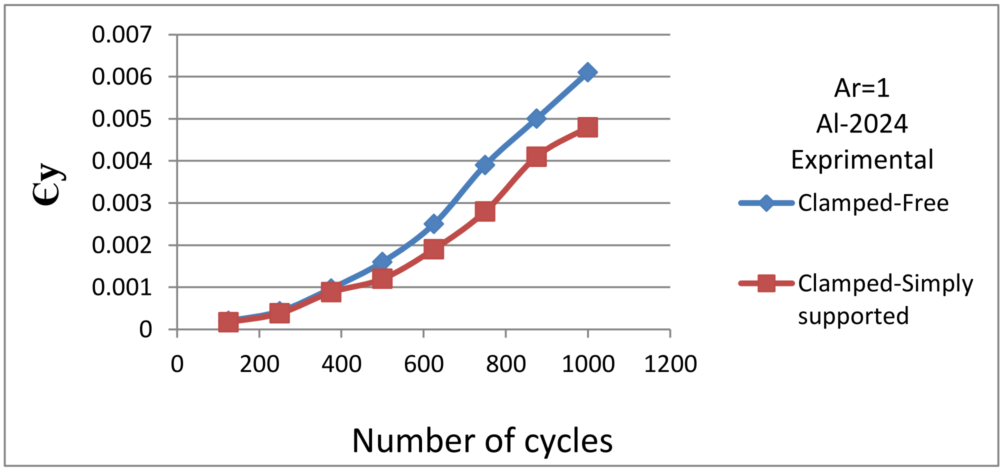

Figure24.Є$_y$ Experimental with number of cycles (B.C for 2024).

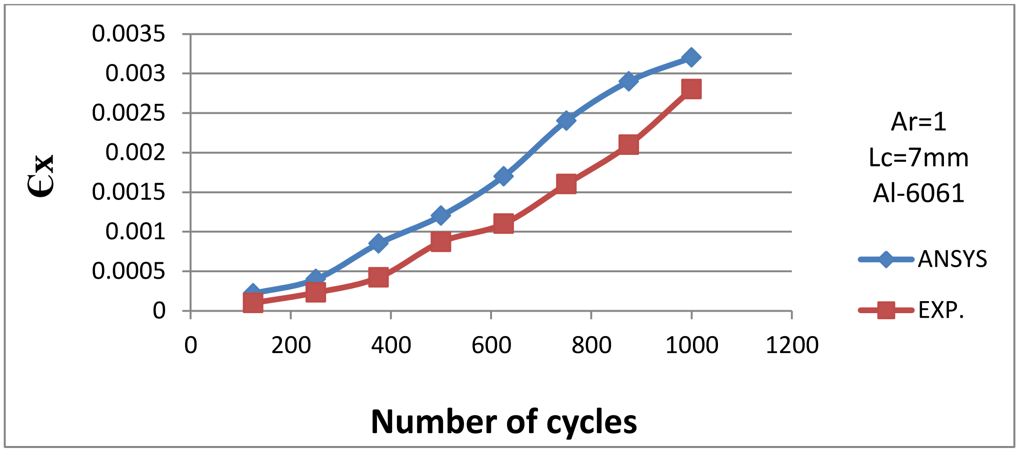

Figure25.Є$_x$ Numerical and experimental with number of cycles (Ar=1&Lc=7mmforAl-6061).

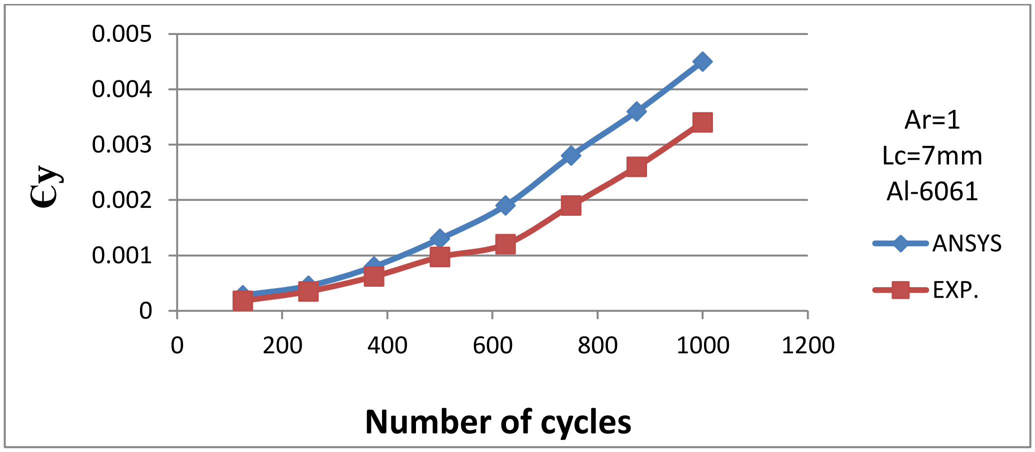

Figure26.Є$_y$ Numerical and experimental with number of cycles (Ar=1&Lc=7mm forAl-6061).

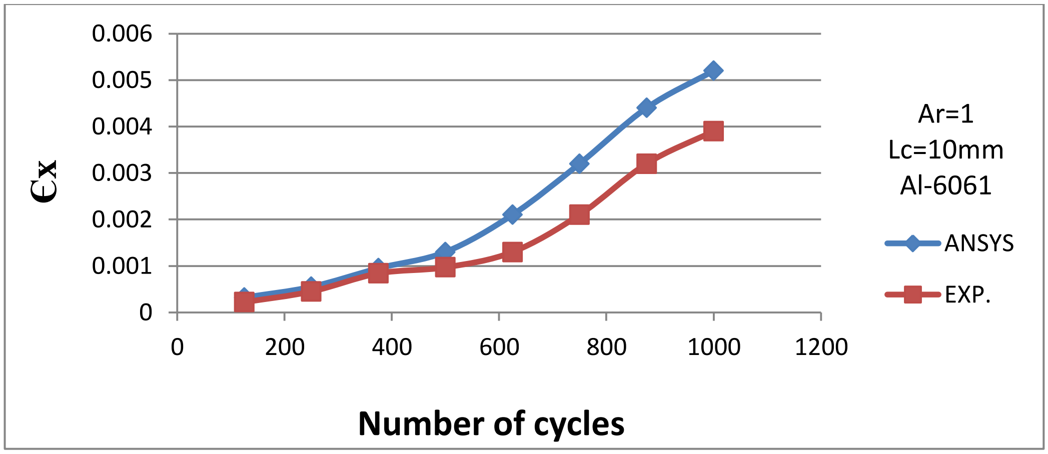

Figure27. Є$_x$ Numerical and experimental with number of cycles (Ar=1&Lc=10mm for Al-6061).

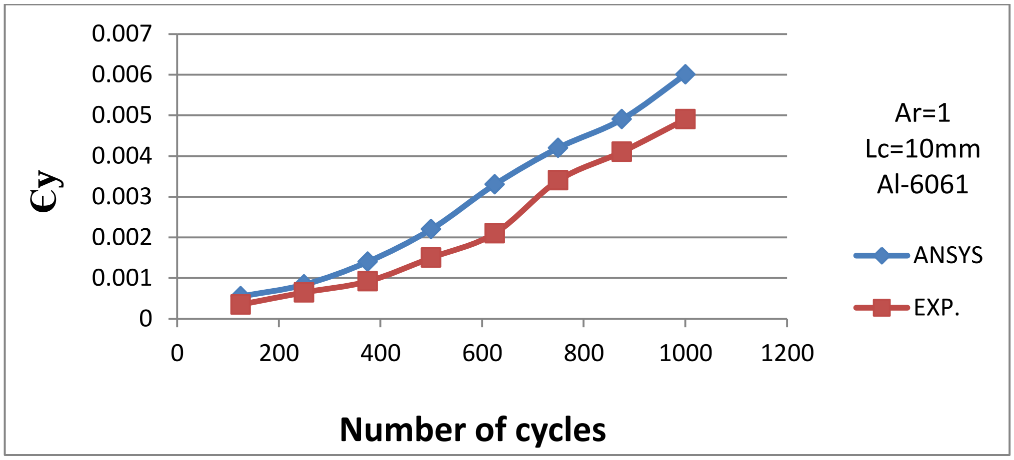

Figure28. ϵ_y Numerical and experimental with number of cycles (Ar=1&Lc=10mm for Al-6061).