Residual Stress Effect on Fatigue Behavior of 2024- Aluminum Alloy

Dr. Ahmed N.Al-khazraji *, Dr. Farag Mahel Mohammed**
& Riyadh A. Al-Taie*

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Abstract

In the present work the effect of residual stress on the fatigue behavior of 2024 Aluminum alloy was studied experimentally and numerically using finite element method with aid of ANSYS-11 software. All the test specimens treated by annealing before any process to remove the internal stresses due to cold work. Residual stresses were imparted to the fatigue tests specimens by heat treatment, pre-strain and welding. X-Ray diffraction was used to measure the residual stress.

The heat treatment; done on the test specimens with different temperature of (420, 450, 480, and 510) ^{o}C. After heat treatment; alloy mechanical properties were improved. For the heat treated specimens as the temperature increased the compressive residual stress increased to (27.06, 41.43, 72.8 and 85.6) MPa. That leads to increase the endurance fatigue limit by (32.93%, 40.48%, 50.68% and 61.03%) respectively than other alloy as received. While in pre strain groups; the test specimens loaded to (265, 290, 315 and 340) MPa by a tension test machine. As the applied load series were increased the compressive residual stress increased to (16.51, 25.62, 51.54 and 62.44) MPa which improve the endurance fatigue limit by (7.68%, 16.19%, 24.98%, and 46.45%), respectively. An electrical arc and metal inert gas were used in welding series to weld the test specimens, that present a tensile residual stress of (76.93 and 72.66) MPa, which reduces the endurance fatigue limit by (23.45% and 16.08%), respectively. The numerical results present fatigue behavior, deflection and stress at any load, and show a reasonable agreement results with an experimental one.

Keywords: Residual stresses, Fatigue, X-Ray diffraction.

تأثير الاجهادات المتبقية على سلوك الكلال لسبيكة الالمنيوم (2024)

الخلاصة

في هذا البحث تمت دراسة تأثير الاجهادات المتبقية على سلوك الكلال لسبيكة الالمنيوم 2024 عمليا وعدديا باستخدام طريقة العناصر المحددة بمساعدة برنامج (ANSYS-11). جميع عينات الاختبار تتعرض للتلدين قبل اي اختبار لازالة الاجهادات المتبقية الناتجة من التشغيل. اضيفت الاجهادات المتبقية في عينات اختبار الكلال باستخدام المعاملات الحرارية, الانفعال مسبق واللحام. تقاس الاجهادات المتبقية بطريقة حيود الاشعة السينية. المعاملات الحرارية تمت عند درجات حرارة هي (420, 450, 480, 510)مْ. المعاملات الحرارية

* Machines & Equipments Engineering Department, University of Technology/ Baghdad
** Electromechanical Engineering Department ,University of Technology/Baghdad

ادت الى تحسين الخواص الميكانيكية للسبيكة وعند زيادة درجة الحرارة فان مقدار الاجهادات المتبقية يزداد الى (27.06, 41.43, 72.8, 85.6) MPa وهذا يؤدي الى تحسين مقاومة الكلال بنسبة (32.93%, 40.48%, 50.65%, 61.03%) على التوالي. اما في مجموعة الانفعال المسبق فقد عرضت العينات الى الاحمال التالية (265, 290, 315, 340) MPa وازدادت الاجهادات المتبقية الضغطية الى (16.51, 25.62,51.54, 62.44) MPa وادى هذا الى زيادة مقاومة الكلال الى (7.68%, 16.19%, 24.98%, 46.45%) على التوالي. بينما في مجاميع اللحام, فأن مقاومة الكلال تقل بمقدار (23.45%, 16.08%) نتيجة وجود اجهادات متبقية شدية بمقدار(76.93, 72.66) MPa ناتجة من استخدام طريقة القوس الكهربائي وغازات المعادن الخامدة في لحام العينات على التوالي. نتائج التحليل العددي لحساب سلوك الكلال والتشوه والاجهاد تظهر توافق مقبول مع النتائج العملية.

Symbols

b: Width (mm)
d: The lattice spacing (A^0).
d_0:The lattice spacing of unloading surface (A^0).
E: Modulus of elasticity (MPa).
El: Elongation (%)
L: Length (mm).
N_f: Number of cycle to failure.
P: Load (N).
t:Thickness (mm).
ε: Residual strain.
δ: Deflection (mm)
σ**:** Stress (MPa).
υ**:** Poisson's ratio.
θ**:** Diffraction angle (degree).
Ψ**:** Tilt Angle (degree).
λ: Wave length (A^0).

Subscript

a: Amplitude.
b: Bending.
res: Residual.
y: Yield.
u: Ultimate.

Introduction

The residual stresses are the stresses that remain in a body if all external forces or thermal gradient after yield point were removed. Various technical terms have been used to refer to residual stresses, such as: Internal stresses, initial stresses, reaction stresses and locked in stresses. Residual stresses also can be defined as stresses that are "locked-in" within a material, and exist without any external load. These "hidden" stresses can be quite large, and can have profound effects on engineering properties, notably fatigue life.

Residual stresses are presented at each stage of the life cycle in most engineering components, from original material production to final disposal. Residual stresses are created by welding, forging, casting, rolling, machining, surface treatment and heat treatment [1].

The main aims of this study are to measure the specimens residual stresses induced from different sources (heat treatment, pre strain and welding) using X-Ray diffraction and estimate the fatigue life under the effect of residual stresses. Due to the importance of this problem, many research done in the past using analytical, numerical and experimental method.

S. Spooner and E. B. S. Pardue [2] had been studied the Neutron and x-ray scattering methods of residual stress measurement

were applied to plasma arc welds made in aluminum-lithium alloy test panels as part of an evaluation of materials for use in welded structures. G. Bussu and P.E. Irving [3] explain the effects of weld residual stress and heat affected zone on the fatigue propagation of cracks parallel and orthogonal to the weld direction in friction stir welded 2024-T351 joints. D. J. Hornbach et.al [4], investigated a modified integral method as a means to nondestructive measurement the subsurface residual stress distribution. The technique has been demonstrated to be feasible in aluminum alloys by comparison to established destructive measurement methods.

M. Koc, J. Culp and T. Altan [5] explained the residual stresses developed after quenching of aluminum alloys cause distortion during subsequent machining. As a result, machined parts may be out of tolerance and have to be cold worked or re-machined. Tanner and J.S. Robinson [6] demonstrated a closed die forgings manufactured from 2014 aluminum alloys subject to both standard and non-standard heat treatments in order to reduce the as-quenched residual stress magnitudes.

Experimental Work

There are many steps done to achieve the experimental work that:

1. Material selection: an aluminum alloy 2024 was selected. The 2024 aluminum alloy being partially the first heat- treatable alloy to be discovered (duralumin) still find wide application for many engineering and aircraft structure purposes in the form of forging, extruded bars and section sheets, plates, tubes and rivets. An alloy chemical composition and mechanical properties test were done in the General Company for Mechanical Industries, and the results of tests are shown in tables (1) and (2) respectively. The fatigue test specimens are shown in figure (1); all the specimens were annealed before any process to remove the internal stresses due to cold work.
2. Heat treatment: the specimens series were heated to (420- 450- 480- 510) ^{o}C stabilized at this temperature for (30) minutes, quenched in water and then remained at room temperature for (7) days to obtain natural aging. Heat treatments were performed in the Department of Materials Engineering / University of Technology.

3. Pre Strain: the region between the point of plastic deformation (yield point) and ultimate strength were determined by tensile test for the alloy as received. A four points located between them selected and the stresses of these points estimated. The stress values applied on the fatigue specimens by tensile test machine are (265, 290, 315, 340) MPa.

4. Two types of welding (electrical arc and metal inert gas (MIG)) used to weld the specimens. Welding process done in the General Company for Mechanical Industries.

5. Residual stress measurement: The x-ray diffraction (XRD) technique exploits the fact that when a metal is under stress (applied or residual), the resulting elastic strains can cause the atomic planes in the metallic crystal structure to change their spacing. The angular position (2θ) of the diffracted beam is used to calculate the distance (d-spacing) between the parallel planes of atoms using Bragg's law [7]. The slope of the least squares fit on a graph of the d-spacing versus sin2Ψ is used to calculate the stress and strain as [8]: nλ = 2d sin

$$\varepsilon_{res} = \frac{d - d_o}{d_o} \qquad \ldots(1)$$

$$\sigma_{res} = \left(\frac{E}{1+\upsilon}\right)\frac{1}{d_o}\left(\frac{\partial d}{\partial \sin \psi^2}\right)$$

The X-Ray diffraction tests were done in the Ministry of Science and Technology by X-Ray diffraction machine, with supplied voltage of (40Kv) and current of (20mA). The target is Copper with wave length (λ=1.5406 A^0) and filter is Nickel.

6. Fatigue test: the fatigue tests carried out in the Mechanical Engineering Department/ University of Technology. The type of fatigue testing machine is Alternating bending fatigue machine (HSM20) with constant amplitude. The specimens subjected to deflection perpendicular to the axis of specimens at one side of the specimens, and the other side was fixed, developing bending stresses. So, the surfaces of the specimens are under tension and compression stresses when the machine rotates. A dial gauge was used to measure the deflection; their values were used to determine the load and bending stress as:

$$\delta = \frac{4PL^3}{Ebt^3} \qquad \ldots (2)$$

$$P = \frac{bt^2\sigma_b}{6L}$$

Numerical analysis

The Finite Element Method with aid of ANSYS-11 software is used as a numerical tool to demonstrate the residual stress effect on the fatigue behavior in a structure element [9]. The solid-45 element with 8 nodes was used in this work. The meshing process has been done by choosing the volume and the number of elements in each body, as shown in Figure (2-a). The number of elements in each specimen is (2400) elements with (12389) nodes. The load in the ANSYS workbench software will be at one side, and the other side was fixed support, as shown in Figure (2-b). All the material properties required in numerical analysis are imported from the experimental tests results.

Results and discussion

An experimental and numerical analyses were done to investigate the influence of residual stress on the fatigue behavior of 2024 Aluminum alloy. Thus fatigue tests were performed on the fatigue specimens with residual stresses imparted to them. The residual stress imparted to the specimens test using heat treatment, pre-strain and welding. The experimental tests present the mechanical properties, residual stresses, and the fatigue behavior while the numerical analyses show the fatigue behavior.

The X-ray diffraction tests; done on the specimens to measure the diffraction angle of unloaded and loaded specimens at different tilting angles. Apply Bragg's law on the recorded data to determine the lattice space, slope, strain and stress as shown in tables (3) and (4) with the all cases study. The results show that the compressive residual stress increased to (27.06, 41.43, 72.8 and 85.6) MPa than other alloy as received, with increased the temperature of heat treatment group. In pre strain group as the applied load increased the compressive residual stress increased to (16.51, 25.62, 51.54 and 62.44) MPa. But in welding group a tensile residual stress of (76.93 and 72.66) MPa present when using an electrical arc and metal inert gas respectively.

Figure (3) represents the experimental fatigue behavior of the heat treatment group. The heat treatment; done on the test specimens with different temperature of (420, 450, 480, and 510) ^{o}C. The fatigue life improved with the temperature of heat treatment increase, leading to increase the endurance fatigue limit by (32.93%, 40.48%, 50.68% and 61.03%). And, the failure occurs at the number of cycles greater than the number of cycles compare with received alloy at the same load due increase the yield strength, and these appeared as compressive residual stresses. In which the compressive residual stress leads to delay the crack propagation and improve the mechanical properties as shown in table (5).

The fatigue behavior of pre strain series shown in Figure (4). The test specimens loaded to (265, 290, 315 and 340) MPa by a tension test machine. The alloy fatigue life increased with the increase of applied load. Because, when load is applied between yield and ultimate strength. A compressive residual stress remains in the specimens after load removed, and the residual stresses reverse the applied stress which decrease the lattice spacing, and leading to improve the endurance fatigue limit by (7.68%, 16.19%, 24.98%, and 46.45%).

In welding test group; using an electrical arc and metal inert gas present an increase in the lattice spacing as compared with the received alloy, that lead to tensile residual stress as shown in tables (3 and 4). The tensile residual stress decreases the yield stress. Therefore, the fatigue curve drops and the failure occurs at the number of cycles less than the number of cycles of received alloy at the same load , as shown in Figure (5). That led to reduces the endurance fatigue limit by (23.45% and 16.08%) respectively.

The fatigue endurance limit calculated using fatigue life estimation equation for these series at million cycles. Table (6) shows the value and enhancement of fatigue endurance limit for all series. Figure (6) represent the experimental results of fatigue endurance limit and residual stress for each series.

Numerical solutions were done to simulate fatigue behavior and estimate deflection and stress at any load. Table (7) presents the expermental and numerical results of deflection and stress. Figure (7) shows a comparison between the numerical and experimental fatigue behavior. The comparison get a good agreament results between them.

Conclusions

The following conclusions may be drawn from the results obtained in this work:

1. The compressive residual stress of heat treatment group increases with the temperature increase to (27.06, 41.43, 72.8 and 85.6) MPa, which leads to increase the endurance fatigue limit by (32.937%, 40.481%, 50.682% and 61.03%), respectively.
2. In pre strain series, the compressive residual stresses increases with the increasing the applied load to (16.51, 25.62, 51.54 and 62.44) MPa leading to increase endurance fatigue limit by (7.689%, 16.197%, 24.958%, and 46.453%), respectively.
3. Using an electrical arc and metal inert gas welding present increasing tensile residual stress to(76.93 and 72.66) MPa, which reduces the endurance fatigue limit by (23.45% and 16.08%), respectively.
4. The numerical results show a good agreement with the experimental results for fatigue life, stress, and deflection.

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Table (1): 2024 Aluminum alloy chemical composition.

	%Si	%Fe	%Cu	%Mn	%Mg	%Cr	%Zn	%Ti	%other	%Al
Standard(41)	**≤0.5**	**≤0.5**	**3.8-4.9**	**0.3-0.9**	**1.2-1.8**	**≤0.1**	**≤0.25**	**≤0.15**	**≤0.2**	Reminder
Actual	**0.25**	**0.09**	**4.53**	**0.81**	**1.51**	**0.014**	**0.13**	**0.014**	**0.065**	Reminder

Table (2): Mechanical properties of 2024 Aluminum alloy.

σ_y (MPa)	σ_u (MPa)	El%
240	348	20

Table (3): X-Ray diffraction test results.

Series	Cases	d_o (µmm)	θ_0 (degree)	$\Psi=0^0$		$\Psi=25^0$	
				d (µmm)	θ (degree)	d (µmm)	θ (degree)
A	As received	1.602553	28.18833	1.60255	28.72926	1.602548	28.72931
B	Heat to 420 ^oC	1.633461	27.60887	1.633381	28.13811	1.633231	28.14092
C	Heat to 450 ^oC	1.571641	28.79402	1.571531	29.35103	1.571331	29.35513
D	Heat to 480 ^oC	1.57871	28.65311	1.57847	29.20949	1.57808	29.21741
E	Heat to 510 ^oC	1.618009	27.89541	1.617719	28.43518	1.617249	28.4442
F	Apply 265 MPa	1.606234	28.11799	1.606194	28.65804	1.606104	28.65979
G	Apply 290 MPa	1.609887	28.04853	1.609797	28.58797	1.609657	28.59069
H	Apply 315 MPa	1.60071	28.2237	1.60053	28.76891	1.60025	28.77441
I	Apply 340 MPa	1.604391	28.15317	1.604111	28.69871	1.603771	28.70655
J	Electrical arc weld	1.60871	28.60907	1.60896	28.60422	1.60938	28.59606
K	Metal Inert Gas weld	1.58163	29.14551	1.58186	29.14086	1.58225	29.13299

Table (4): Strain, slope and Stress of X-Ray diffraction.

Series	Strain	Slope	Stress(MPa)
A	$-3.12*10^{-6}$	$-1.1198*10^{-5}$	-0.368
B	$-1.4081*10^{-4}$	$-8.3984*10^{-4}$	-27.0604
C	$-1.9725*10^{-4}$	$-1.2374*10^{-3}$	-41.4384
D	$-3.9906*10^{-4}$	$-2.1836*10^{-3}$	-72.8
E	$-4.6971*10^{-4}$	$-2.6315*10^{-3}$	-85.6
F	$-8.0935*10^{-5}$	$-5.03902*10^{-4}$	-16.5114
G	$-1.4287*10^{-4}$	$-7.8385*10^{-4}$	-25.6262
H	$-2.8737*10^{-4}$	$-1.5677*10^{-3}$	-51.5462
I	$-3.8644*10^{-4}$	$-1.90363*10^{-3}$	-62.448
J	$4.16483*10^{-4}$	$2.35154*10^{-3}$	76.9345
K	$3.92*10^{-4}$	$2.18358*10^{-3}$	72.6626

Table (5): mechanical properties variation with heat treatment.

Series	σ_y %	σ_u %	El%
B	7.5	10.92	-15
C	26.67	19.54	-17.5
D	40	37.93	-30
E	45.83	42.53	-40

Table (6): Fatigue endurance limit and it is enhancement.

Series	Fatigue Limit (Exp)(MPa)	Enhancement %
A	104.714	___
B	139.204	32.937
C	147.103	40.481
D	157.785	50.682
E	168.621	61.03
F	112.762	7.686
G	121.674	16.197
H	130.849	24.958
I	153.355	46.453
J	80.157	-23.452
K	90.203	-16.087

Table (7): comparison between the experimental and numerical analysis.

load	Deflection (mm)		Stress(MPa)	
	Exp	Num	Exp	Num
102	3	3.4142	309	332.89
93.5	2.75	3.1297	283.25	305.15
85	2.5	2.8451	257.5	277.41
76.5	2.25	2.5606	231.75	249.67
68	2	2.2765	206	221.93
59.5	1.75	1.9916	180.25	194.19
51	1.5	1.7071	154.5	166.45
42.5	1.25	1.4226	128.75	138.71
34	1	1.1381	103	110.96
25.5	0.75	0.85354	77.25	83.223

Figure (1): Fatigue test Specimens.

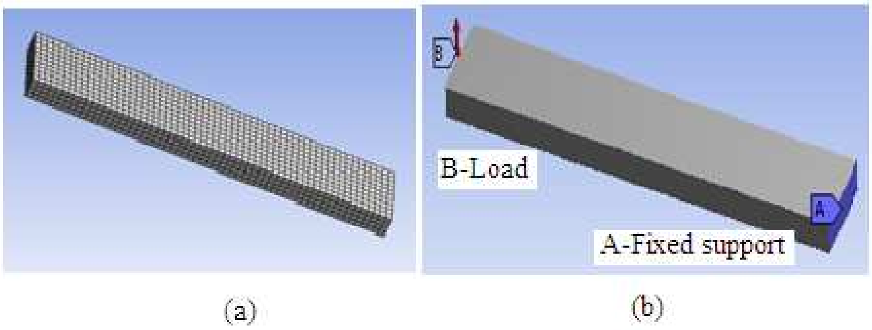

Figure (2): The model mesh and boundary condition.

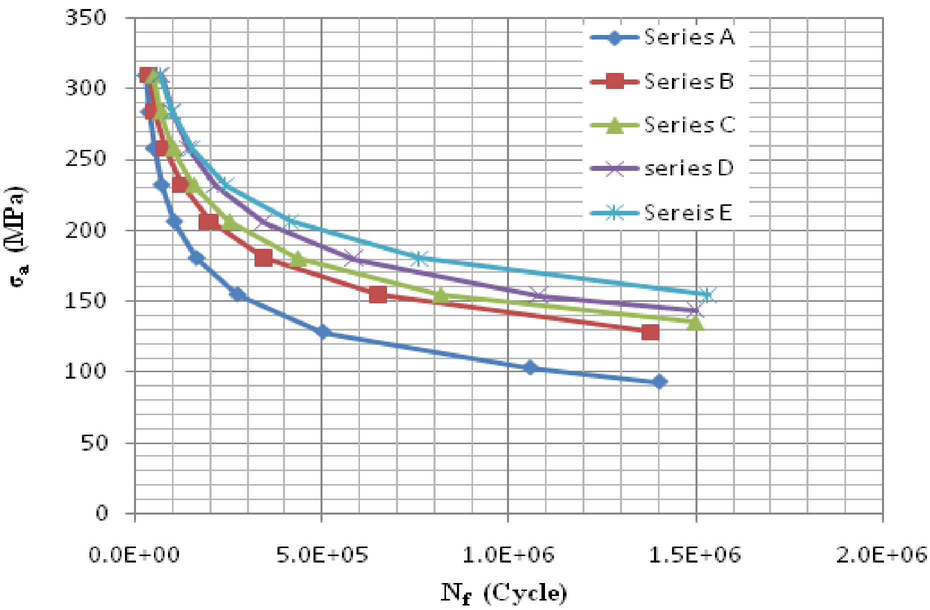

Figure (3): S-N curve of heat treatment group test specimens.

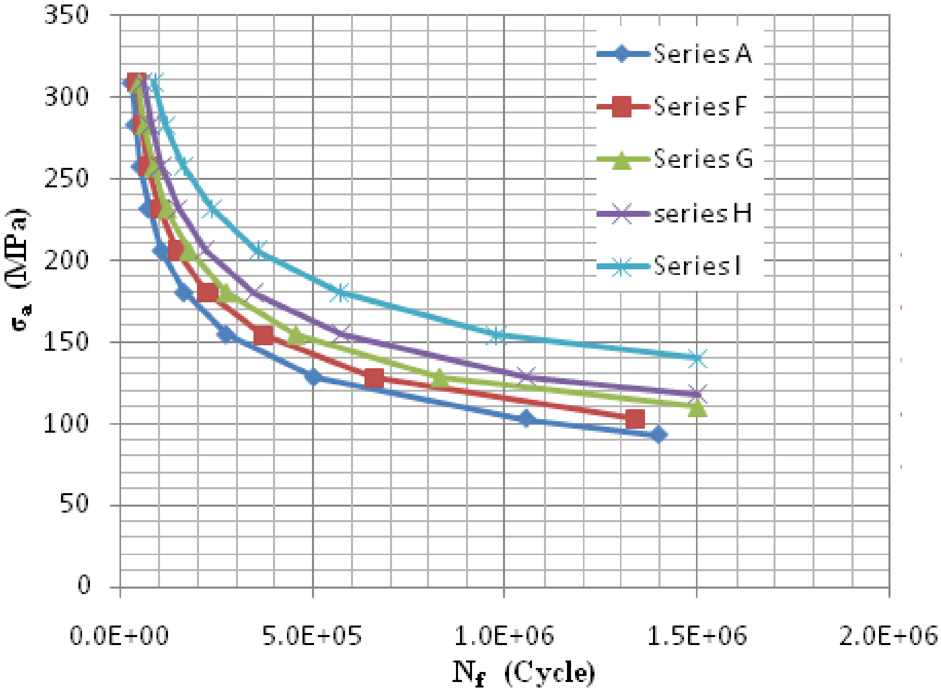

Figure (4): S-N curve for pre strain group test specimens.

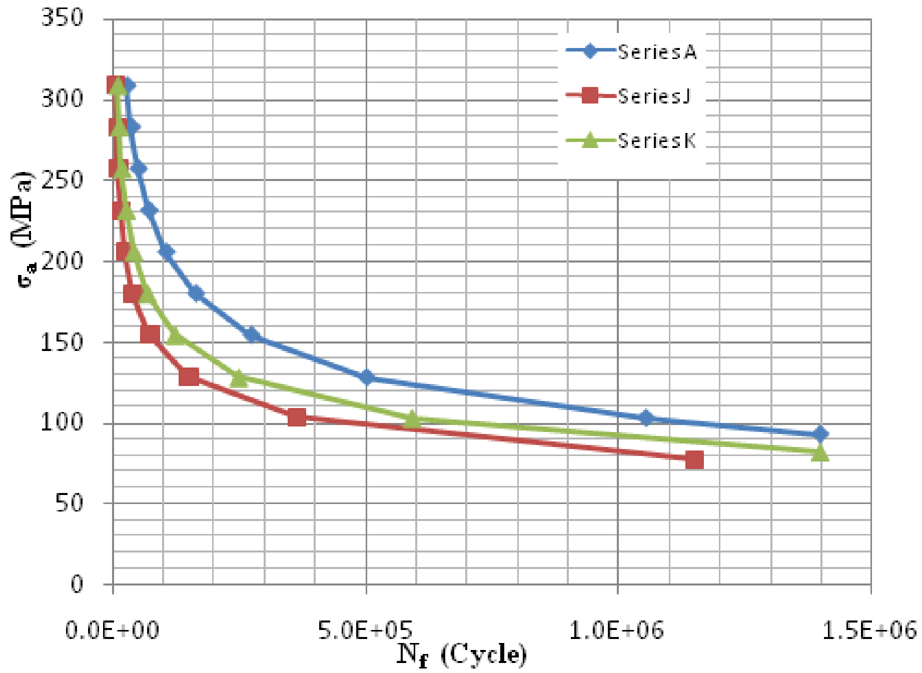

Figure (5): S-N curve for welding group test specimens.

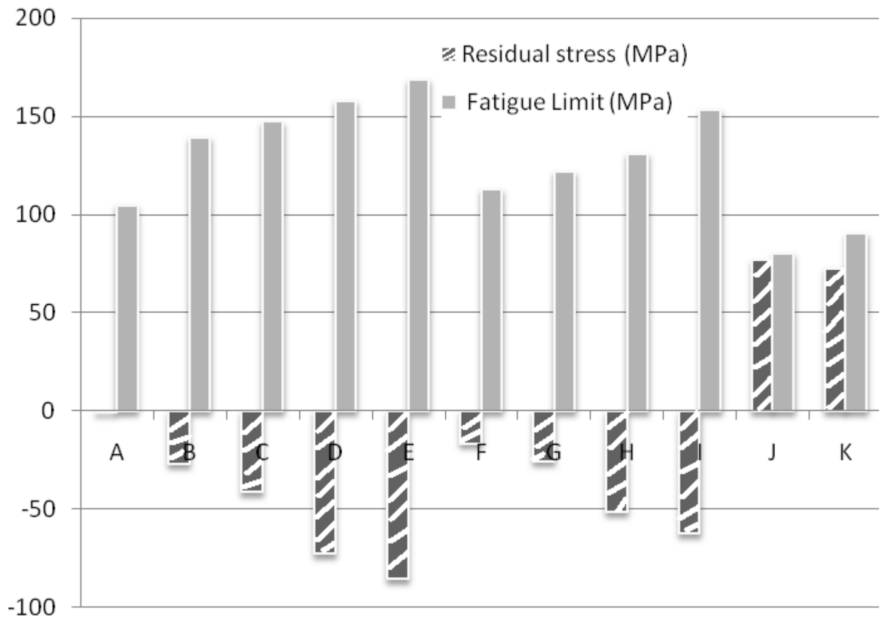

Figure (6): The value of residual stress and endurance fatigue limit for all series.

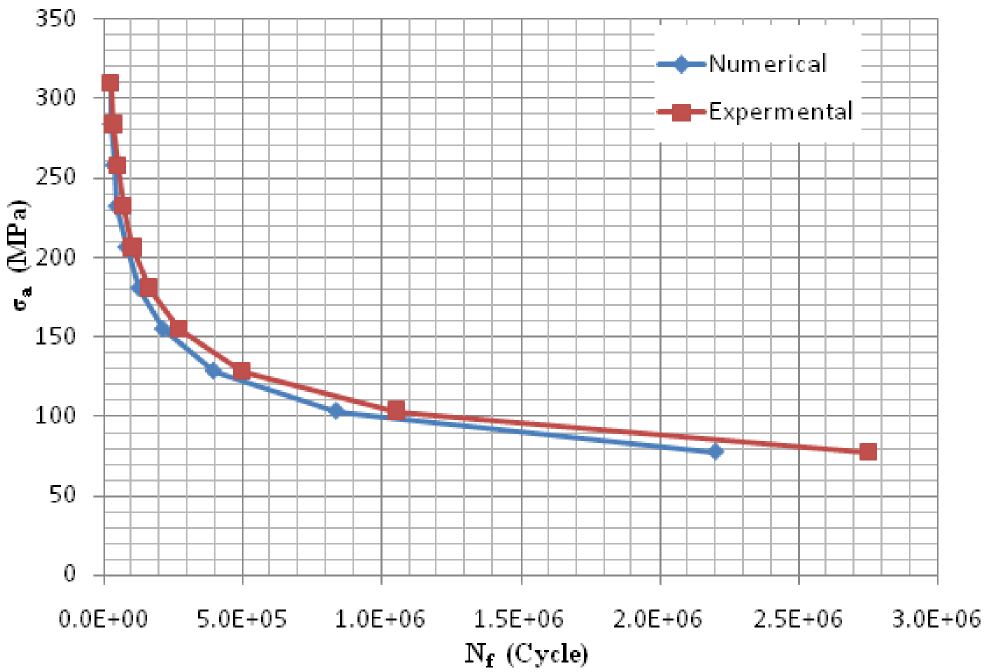

Figure (7): S-N curve for series A.