Effect of Heat Treatment on Fatigue Life of Aluminum Alloys 2024 And 7075

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Abstract

This research studies the effect of heat treatment (precipitation hardening) on fatigue life of two aluminum alloys (2024) and (7075). The alloy (2024) is hardening by natural aging, while the artificial aging is used to hardening the alloy (7075). Mechanical tests are performed to determine the mechanical properties such as yield stress, ultimate tensile strength, hardness and endurance limit of the alloys. The specimens which used in the tests are divided into eight groups according to the type of alloy, type of heat treatment, and shape. Notched and un-notched specimens are used to perform the tests. The fatigue tests are performed for different type of specimens.

The equations of fatigue life estimation are determined according to data which is obtained from the fatigue tests and endurance limit is calculated by using these equations for each type of specimens.

Keywords: fatigue life, heat treatment, endurance limit, notched specimens, Aluminum,

تأثير المعاملة الحرارية على عمر الكلال في سبائك الالمنيوم 2024 و 7075

الخلاصة

يدرس البحث تأثير المعاملة الحرارية (التصليد بالترسيب) على عمر الكلال لسبيكتين من الالمنيوم هما (2024) و (7075). السبيكة (2024) صلدت بالتعتيق الطبيعي بينما استخدم التعتيق الصناعي لتصليد السبيكة (7075). اجريت الفحوصات الميكانيكية لتحديد الخواص الميكانيكية مثل اجهاد الخضوع ، مقاومة الشد القصوى، الصلادة وحد التحمل للسبائك المستخدمة. قسمت العينات الى ثمانية مجاميع اعتمادا حسب نوع السبيكة ونوع المعاملة الحرارية والشكل. استخدمت عينات محززة وغير محززة لاجراء الفحوصات. اختبارات الكلال اجريت للانواع المختلفة من العينات. تم تحديد معادلات تخمين عمر الكلال اعتمادا على النتائج المستخرجة من الاختبارات. من هذه المعادلات تم حساب عمر الكلال للعينات وتحديد مقدار التحسن في عمر الكلال والخواص الميكانيكية بعد اجراء المعاملة الحرارية.

1- Introduction

Many machine members are subjected to repeated, reversed, or fluctuating cyclic stresses during their operation. If the number of cycles of stressing is very large, it has been observed that the failure of the member often occurs with a sudden rapture and without any pronounced amount of deformation. This phenomenon which occurs under

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cyclic stressing is termed fatigue failure. [1]

In general, fatigue is a problem that effected any structural component or part that moves. Automobiles on roads, airplanes (principally the wings) in air, ships on the high sea constantly battered by waves, nuclear reactors and turbines under cyclic temperature conditions, and many other components in motion are example in which the fatigue behavior of a material assumes a singular importance. It is estimated that 90% of service failure of metallic components that undergo movement of one form or another can be attributed to fatigue. [2]

If there is, in a mechanical component, a discontinuity such as a sudden change in cross section, a fillet, hole, groove, or notch, high-localized stresses are induced at such places. Such discontinuities are called stress raisers and the localized stress effect they produce is termed stress concentration. Stress concentration must however be considered if the component is subjected to fatigue loading. [3]

2-Fatigue:

Fatigue is the process of cumulative damage that is caused by repeated cyclic loads. Fatigue damage occurs only in regions that deform plastically under the applied cyclic load. After a certain number of load fluctuating, the accumulated damage causes the initiation and subsequent propagation of a crack. The number of cycles required to initiate a fatigue crack is the fatigue-crack initiation life, N_i. The number of cycles required to propagate a fatigue crack to a critical size is called the fatigue-crack propagation life, N_p. The total fatigue life, N_T, is the sum of the initiation and propagation lives. [4]

3- Fatigue Mechanism

Most structural metals are polycrystalline and consist of a large number of individuals ordered crystals or grains. Slip occurs in ductile metals within individual grains by dislocations moving along crystallographic planes, which slides relative to each other. Slip occurs under both static (steady) and cyclic loading. Both slip band intrusions and extrusions occur on the surface of metals when they are subjected to cyclic loading. However, a few slip bands may become more distinct, they have been called “persistent slip bands”. It has been found that fatigue cracks grow from these persistent slip bands. Fatigue life has been improved by removing the persistent slip bands by polishing. This establishes the fact that early stages of fatigue are primarily a surface phenomenon. [5]

The mechanism of fatigue involves slip followed by the formation of fine cracks that can be seen only at high magnification. These cracks continue to grow under cyclic loading and eventually become visible to the unaided eye. The cracks tend to combine and a few major cracks grow.

4- Fatigue loading Effect

Structural components are subjected to a variety of loads (stress) as following:

1-Constant amplitude loading: in this type there are many parameters which related to fatigue loading.

- Constant stress range:

$$\Delta\sigma = \sigma_{max} - \sigma_{min} \quad \text{.....(1)}$$

- Mean stress $s_m = \frac{s_{max} + s_{min}}{2}$ .... (2)

- Stress amplitude:

$$s_a = \frac{\Delta s}{2} = \frac{s_{max} - s_{min}}{2} \quad \text{...... (3)}$$

- Stress ratio: $R = \frac{s_{min}}{s_{max}}$ ..... (4)

2-Variable amplitude loading: this type can be subdivided into two types:

(a) Stable variable amplitude which repeats same sequence of stress cycle such as:

- High-low or low-high,
- Tensile overload,
- Compressive overload
- Blocks

(b) Unstable variable amplitude loading. [6]

5- Experimental Work

The tests that required in this research are hardness, tensile and fatigue tests.

The materials used in this study are aluminum alloys 2024 and 7075.

Chemical analysis of the alloys was affected by (Thermo ARL 3460, optical Emission spectrometer). The results, which is compared to the American standard, are summarized in table (1)

With regards to tensile tests, the tensile test was done using (D-6800 Mannheim MFL) testing machine that has a maximum capacity of (100KN). Three specimens with type (2024-T_4) and three specimens with type (7075-T_6) are used to perform the tensile test. The average value of three readings is recorded and used to draw the stress-strain curve.

The types of specimens was used in the experimental work is a rod for rotating bending test and tensile test. To get perfect dimensions of the specimens and to avoid mistakes, an accurate profile should be attained. All specimens were machined using programmable CNC machine. During manufacturing of the specimens, careful control was taken into consideration to produce a good surface finish and to minimize residual stresses. The test specimens are shown schematically in figure (1).

After that, machined specimens were classified into eight series, each of them correspond to appropriate materials and the heat treatment. Table (2) illustrates the different series.

After machining, all types of specimens are polished using the following steps.

1-The surface of the specimens was smoothed using different wet silicon carbide papers starting with (260) to (1200) for finishing.

2-The specimens were polished using polishing cloth and alumina.

3-Distilled water was used for three minutes to clean the specimens followed by washing them with alcohol.

With regards to fatigue test, fatigue-testing machine of type rotating bending was used with constant amplitude. the surface of the specimens is under tension and compression stresses when it rotates. The value of the stress (σ_b), measured by (N/mm^2), for a known value of load (P), measured by Newton (N) is extracted from applying the relation below [2]:

$$\sigma_b = \frac{M_b * y}{I} \qquad \text{……(3)}$$

$$\sigma_b = \frac{P * L * 32}{p * d^3} \qquad \text{…… (4)}$$

σ_b = 20 P (MPa)

Where:

σ_b : the applied stress (MPa)

M_b= the bending moment (N.mm)

y: the distance from the neutral position (mm)

I: the moment of inertia (mm^4)

d: minimum diameter of fatigue specimen (mm)

L: distance between center of notch and the center of load

For Rotating bending fatigue machine type Hi-TECH: L = 125.7mm

When dealing with fatigue test specimens preparation, two types of fatigue specimens are used.

1-(V)**-**notch specimens are developed with a depth (length) of notch between (0.45-0.5) mm. The dimensions of notch were measured with a projector profile with 1µm accuracy. Figure (1) shows the dimensions of the notch.

2-Un**-**notched fatigue specimens.

The specimens are divided according to shape, heat treatment, and the type of alloy into eight groups as shown in table (2). (16) Specimens for each group are used to perform (S-N) curves, which are used to study the effect of heat treatment on fatigue life in this alloys.

Finally with regards to heat treatment, for aluminum alloy 2024, the specimens were heated in electrical furnace to (500 C°), stabilized at this temperature for (30) minutes, quenched in water and then remained in room temperature for (7) days to obtain natural aging. Alloy becomes (2024-T_4).

For aluminum alloy 7075, the specimens were heated to (465C°), stabilized at this temperature for (30) minutes, quenched in water and then heated to (165C°) for (4) hours to obtain artificial aging. Alloy becomes (T_6).

6- Results and Discussion

The tensile tests of the both alloys were performed to obtain the values of the ultimate tensile stress and the yield stress before and after the heat treatment.

From the results of the mechanical properties tests it is observed that:

1- The alloy 7075 has better mechanical properties than the 2024 before and after the heat treatment. This result coincides with the standard specification [7]. The difference in the mechanical properties between the alloys 2024 and 7075 belongs to the difference in the microstructure of these alloys.

2- The enhancement percentage of the 7075 alloy in mechanical properties due to the heat treatment is higher than the enhancement percentage of the mechanical properties of the alloy 2024, where the enhancement percentages of yield stress and the ultimate tensile stress of alloy 7075 are (54.7%) and (41.3%) respectively, while the enhancement percentage of alloy 2024 are (31%) and (34.4%) in the yield stress and ultimate tensile stress respectively.

3- It is observed that the artificial aging of alloy 7075 gives better enhancing of the mechanical properties than the natural aging of alloy 2024.

4- It is observed that the elongation of both alloys decreases after the heat treatment, and the decreasing of elongation of alloy 7075 is greater than that of alloy 2024 because of the increasing of strength causes decreasing of elongation.

5- The yield stress of both alloys is calculated from the curve of load-elongation by applying (0.1%) of gage length on elongation axis and drawing straight line parallel to elastic part of the curve to intersect with the original curve at the value of yield stress. The results are shown in the following figures.

By comparing the values of mechanical test results with the standard values of mechanical properties of these alloys [7], it is observed that the both 2024 and 7075 samples used in the test were subjected temper (T_3).

The fatigue results are presented in the forms of tables and curves. These tables and curves give indication about the variations in fatigue life after the heat treatment. From these data, the fatigue life estimation equations are determined. The fatigue endurance limit can be calculated by using these equations. Finally, the percentage of enhancement in fatigue life after the heat treatment is calculated for all groups.

The results of the stress vs. number of cycles to failure for all groups before and after heat treatment are plotted in figure (2) through (9).

From the results of fatigue test of alloy 2024 before and after the heat treatment, it can be observed that:

1- The fatigue ratio (endurance limit / ultimate tensile stress) of this alloy before heat treatment is (0.4172). This value is close to the standard values (0.3-0.4) [3]. However, it is more safely to calculate the endurance limit at higher cycles.

2- The fatigue ratio of 2024-T4 alloy is (0.3175). This value coincides with the standard value [3]. So, it is useful to use this alloy after the heat treatment.

3- It is observed that the number of cycles to failure at the stress values of less than (150MPa) is greater than the cycles to failure at the values of stress upper than (150MPa).

From the results of fatigue test of alloy 7075 before the heat treatment the followings could be observed:

1- The alloy 7075 has better fatigue strength than the alloy 2024.

2- The endurance limit of the alloy 7075 before the heat treatment is (155.95MPa). This value is greater than the value of endurance limit of alloy 2024 before the heat treatment but less than the value of endurance limit of alloy 2024 after the heat treatment. So, the alloy 2024-T_4 is more suitable use in structures and other general engineering application in comparison with 7075 before the heat treatment.

3- It is observed that the overall enhancement percentage of fatigue life of this alloy after the heat treatment is (**31.86%**). This enhancement is greater than the enhancement of fatigue life of alloy 2024 after the heat treatment. This result establishes that the artificial aging of alloy 7075 gives better enhancing than the natural aging of alloy 2024.

4- The fatigue ratio of alloy 7075-T_6 is (0.296). The value of endurance limit of this alloy is lower than the standard value [7].So; this value gives safe estimation for use in engineering calculations.

From the results of the fatigue test of alloy 2024- notched specimens the following notes could be observed:

1- The first stage of fatigue crack is early coexistence of this alloy and all notched specimens.

2- The results establish that the fatigue failure begins from the surface at the zones of stress concentration.

From the results of fatigue test of alloy 7075- notched specimens before and after heat treatment the following notes could be stated:

1- The reduction percentage of this alloy is (21.114%). This value is greater than the reduction percentage of alloy 2024 before the heat treatment. So, the alloy 7075 is more sensitivity to notch than the alloy 2024.

2- The reduction percentage of 7075 alloy after heat treatment is greater than the reduction percentage of alloy 2024-T_4. This result established that the alloy 7075 is more sensitivity to stress raiser.

Table (3) shows the fatigue life equation and the endurance limit at (10^6) cycles before and after heat treatment for all groups.

7-Conclusions

1-The alloy 7075 have better mechanical properties than the alloy 2024 before and after the heat treatment. The differences in the mechanical properties between the alloys 2024 and 7075 belong to the difference in the microstructure of these alloys.

2- Artificial aging of alloy 7075 gives better enhancing of the mechanical properties and endurance limit than the natural aging of alloy 2024.

3- By comparing the values of mechanical test results with standard values of mechanical properties of these alloys, it is observed that the used samples were subjected to temper (T_3).

4- It is observed that the number of cycles to failure at the stress values of less than (150MPa) is greater than the cycles to failure at the values of stress upper than (150MPa).

5-The precipitation hardening gives better enhancement of mechanical properties than the cold working of these alloys.

6- The value of endurance limit of the alloy 7075- T_6 without notch is the highest value of endurance limit in comparison with all other groups.

7- It is observed that The overall enhancement percentage of fatigue life of the alloy 7075 after the heat treatment is (31.86%). This enhancement is greater than the enhancement of fatigue life of alloy 2024 after the heat treatment. This result establishes that the artificial aging of alloy 7075 gives better enhancement than the natural aging of alloy 2024.

8- The obtained results from the fatigue tests of all notched groups established that the fatigue failure begins from the surface at the region of stress concentration.

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Table (1) Chemical Composition

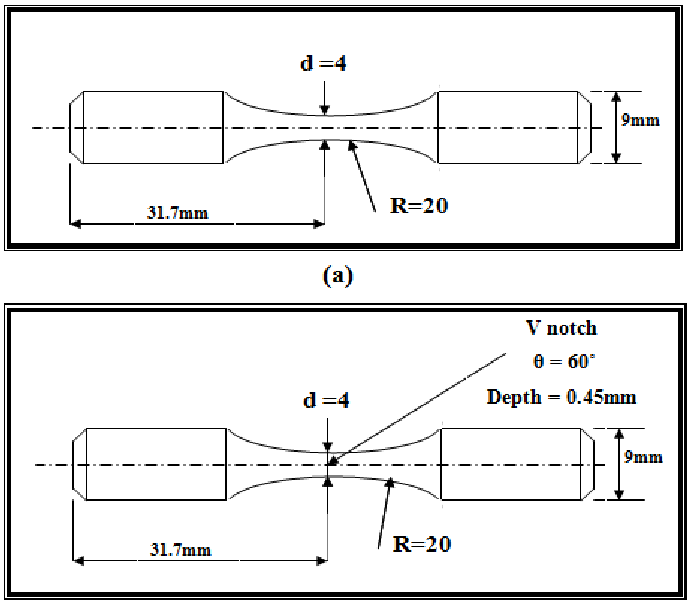
Material	Chemical composition wt%							
	Cu	Mg	Mn	Zn	Si	Fe	Ni	Al
2024	4.73	1.677	o.52	0.213	0.032	0.443	0.012	REM
7075	1.763	2.836	0.283	5.871	0.069	0.322	0.061	REM

Table (2) Classification of the groups of specimens

Series	Materials	Heat treatment	Shape
A	2024	_	Un notched
B	2024	T_4	Un notched
C	7075	_	Un Notched
D	7075	T_6	UN Notched
E	2024	_	Notched
F	2024	T_4	Notched
G	7075	_	Notched
H	7075	T_6	Notched

Table (3) fatigue life equation &value of endurance limit

Groups	Fatigue life equation	Endurance limit at (10^6) cycles (MPa)
A	$\text{Log}(\sigma_a) = 3.2 - 0.173\,\text{Log}(N_f)$	$\sigma_L = 145.211$
B	$\text{Log}(\sigma_a) = 3.222 - 0.175\,\text{Log}(N_f)$	$\sigma_L = 148.6$
C	$\text{Log}(\sigma_a) = 3.243 - 0.175\,\text{Log}(N_f)$	$\sigma_L = 155.9552$
D	$\text{Log}(\sigma_a) = 3.265 - 0.175\,\text{Log}(N_f)$	$\sigma_L = 166.341$
E	$\text{Log}(\sigma_a) = 3.114 - 0.175\,\text{Log}(N_f)$	$\sigma_L = 115.877$
F	$\text{Log}(\sigma_a) = 3.14 - 0.177\,\text{Log}(N_f)$	$\sigma_L = 119.647$
G	$\text{Log}(\sigma_a) = 3.14 - 0.175\,\text{Log}(N_f)$	$\sigma_L = 123.0268$
H	$\text{Log}(\sigma_a) = 3.163 - 0.175\,\text{Log}(N_f)$	$\sigma_L = 129.718$



(b)

Figure (1) The dimensions of specimens. (a) Fatigue test specimen (b) Fatigue test specimen with notch all dimension in (mm)

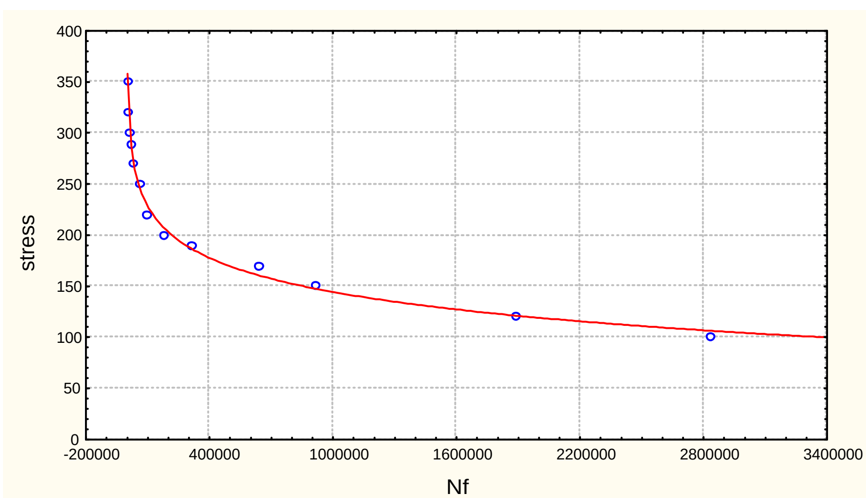


Figure (2) S-N curve of alloy 2024.

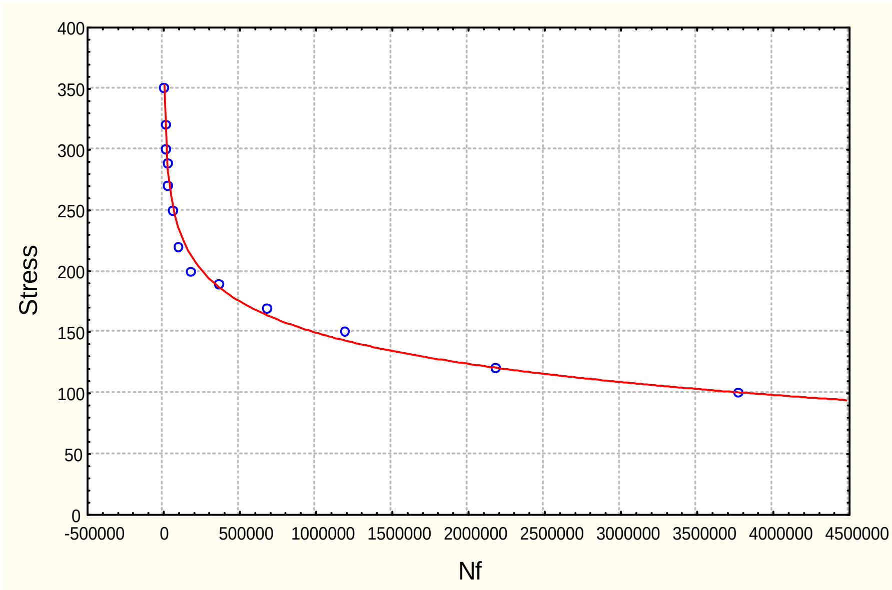


Figure (3) S-N curve of alloy (2024-T_4)

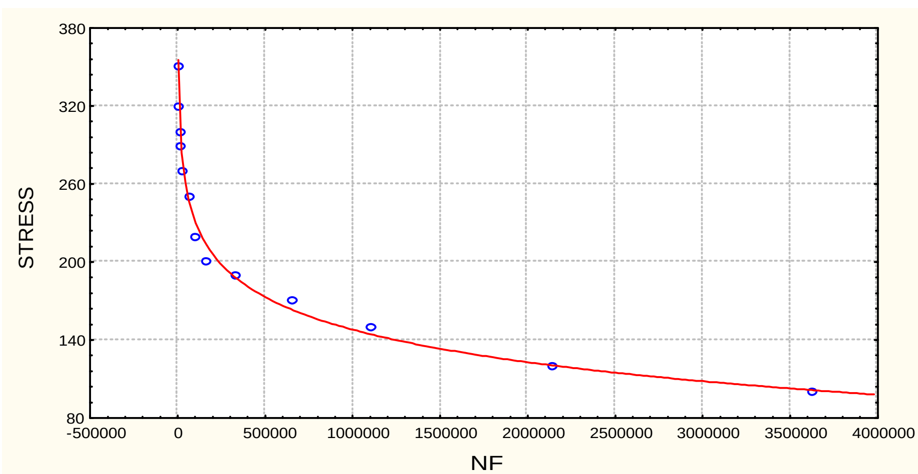


Figure (4) S-N curve of alloy 7075

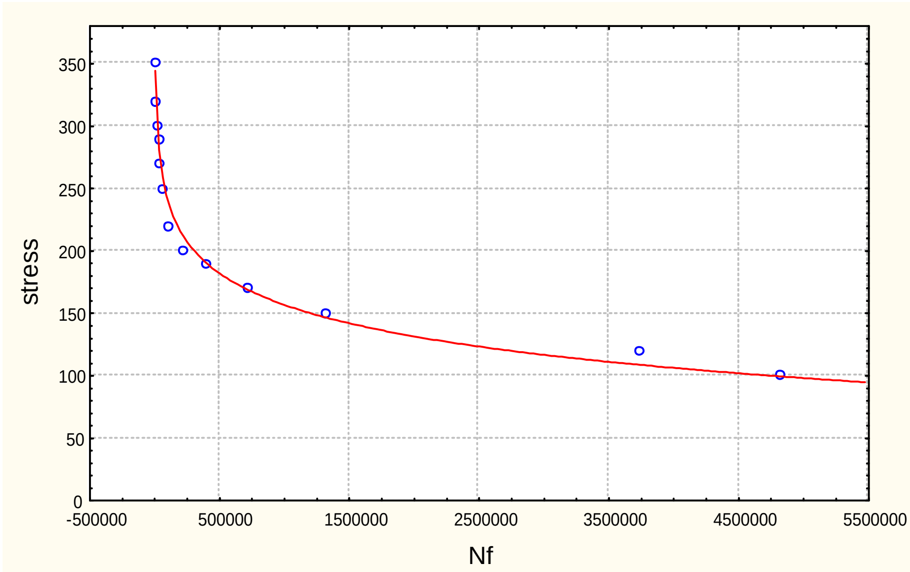


Figure (5) S-N curve of alloy 7075-T_6

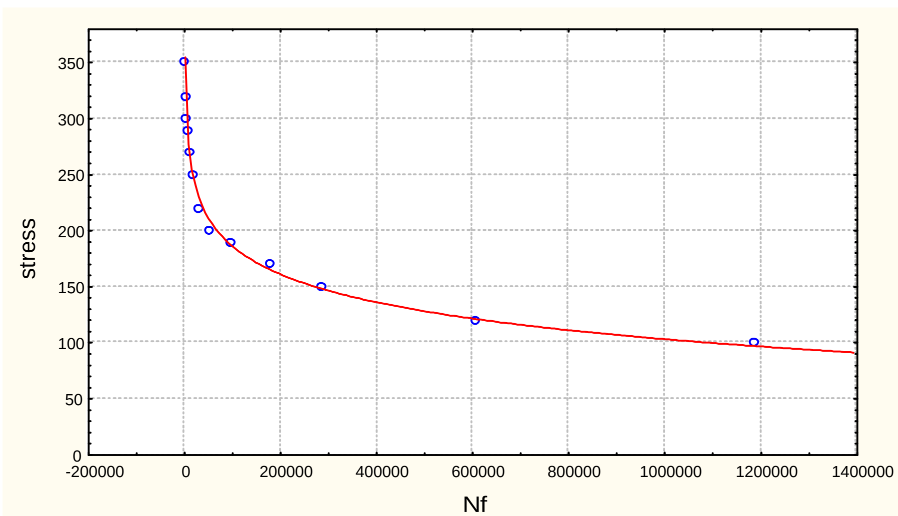


Figure (6) S-N curve of alloy 2024, notched specimens

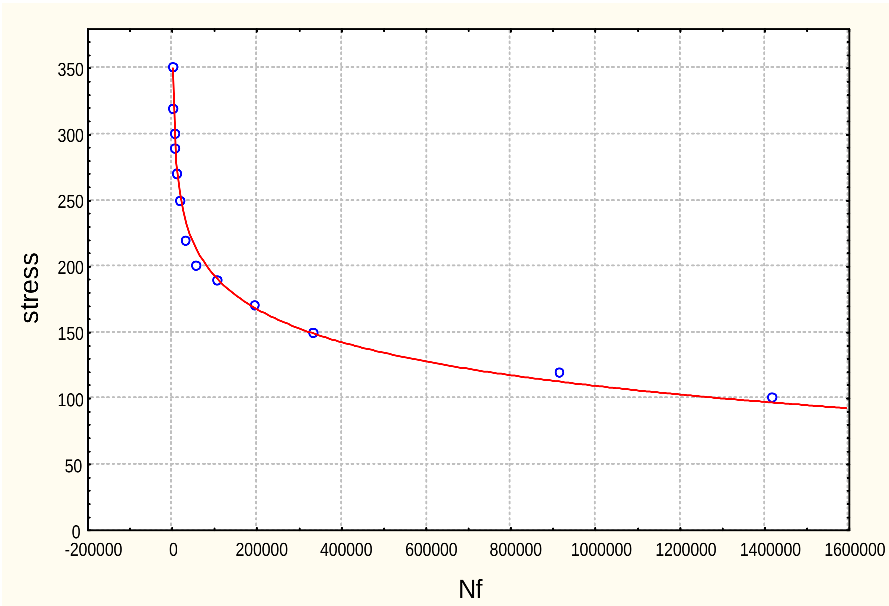


Figure (7) S-N curve of alloy 2024-T_4, notched specimens

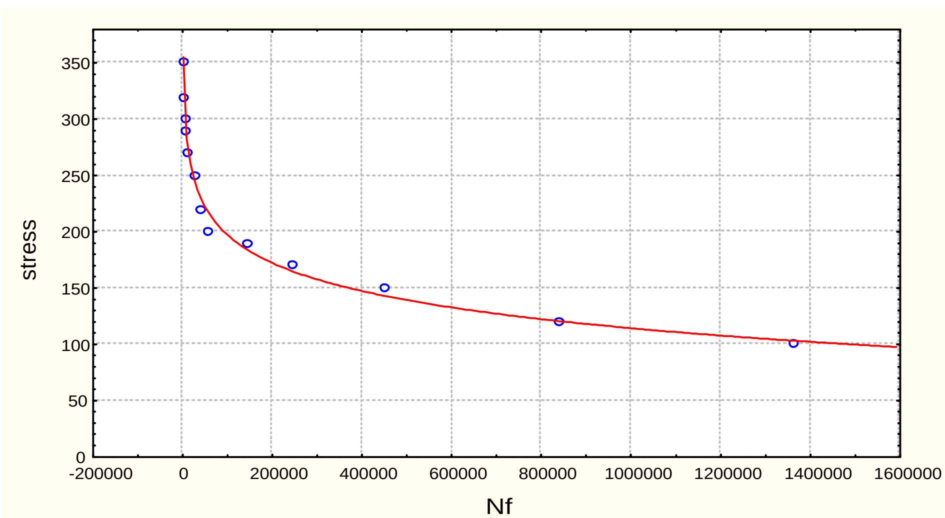


Figure (8) S-N curve of alloy 7075, notched specimens

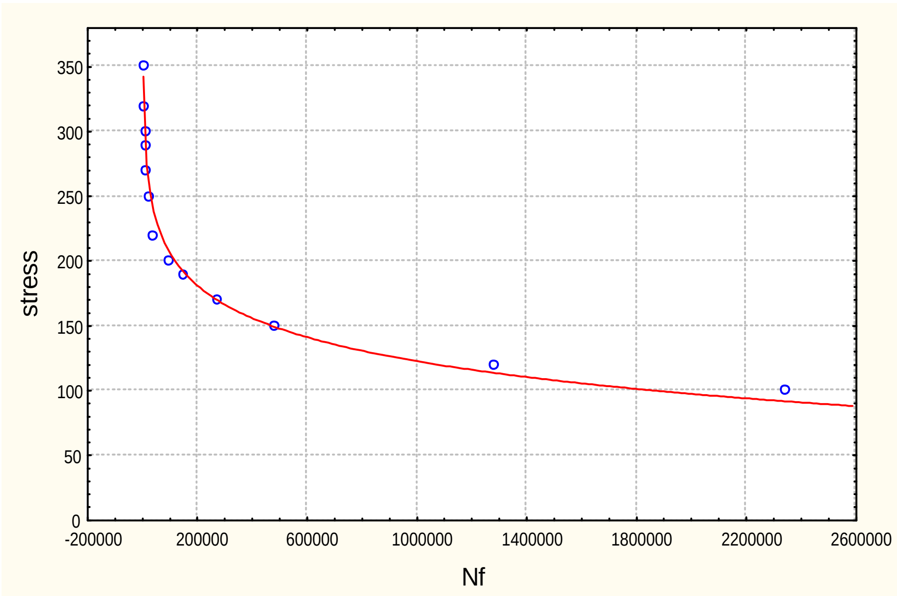


Figure (9) S-N curve of alloy 7075-T_4, notched specimen