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Effect of Heat Treatment on Notch Sensitivity Factor for Aluminum Alloys

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Abstract

This study is concerned with the effect of heat treatment (precipitation hardening) on notch sensitivity factor for aluminum alloy (7075). Tests were conducted on four configurations of specimens, three of them which had external circumferential notches with notch radii of 0.5 mm, 0.7 mm, and 1 mm. The fourth configuration is un-notched specimens. The alloy samples which were used in fatigue test were subjected to cold working before heat treatment. Dimensions and roughness of the specimens were measured. The fatigue tests were performed for different types of specimens. The (S-N) equation was derived for each group to estimate the fatigue life under any applied stress amplitude. In addition, the strength reduction factor (k_f)and notch sensitivity factor (q) were calculated.

The results showed that the fatigue strength reduction factor were increased after heat treatment and with decreasing notch radius. Also the notch sensitivity factor increased with increasing notch radius and after heat treatment. The enhancement percentage in notch sensitivity factor after the heat treatment for 1 mm radius notch was (22.616%).

Keywords: heat treatment, notch sensitivity, Aluminum, strength reduction factor, fatigue

تأثير المعاملة الحرارية على معامل حساسية الحز لسبائك الألمنيوم

الخلاصة

يتناول البحث تأثير المعاملة الحرارية (التصليد بالترسيب) على معامل حساسية الحز لسبيكة الألمنيوم (7075). الاختبارات أجريت على اربعة أشكال من العينات ثلاث منها تحتوي على حز محيطي خارجي بنصف قطر 0.5 ملم، 0.7 ملم، و 1 ملم, والرابعة بدون حز. العينات التي استخدمت في اختبارات الكلل معرضة إلى تشكيل بارد قبل إجراء المعاملة الحرارية عليها. تم قياس أبعاد العينات وكذلك فحص الخشونة. اجريت اختبارات الكلل للأنواع المختلفة من العينات. وتم تحديد معادلات تخمين عمر الكلل اعتمادا على النتائج المستخرجة منها. وكذلك إيجاد معامل تقليل مقاومة الكلل ومعامل حساسية الحز.

لوحظ من النتائج بان معامل تقليل مقاومة الكلل (k_f) يزداد بعد المعاملة الحرارية ويزداد أيضا كلما قل نصف قطر الحز. وان معامل حساسية الحز (q) يزداد بزيادة نصف قطر الحز وبعد المعاملة الحرارية.ان نسبة التحسن في مقدار معامل حساسية الحز بعد المعاملة الحرارية للحز بنصف القطر 1 ملم كانت (22.616%).

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1- Introduction

A fatigue failure is one that occurs under cyclic or alternating stress of an amplitude that would not cause failure if applied only once. Aircraft are particularly sensitive to fatigue. Automobile parts such as axles, transmission parts, and suspension systems may fail by fatigue. Turbine blades, bridges, and ships are other examples too. Fatigue requires cyclic loading, tensile stresses, and plastic strain on each cycle. If any of these are missing, there will be no failure. The fact that a material fails after a number of cycles indicates that some permanent change must occur on every cycle. [1] Most engineering components contain geometrical discontinuities, such as shoulders, keyways, and grooves, generally termed notches. When a notched component is loaded, local stress and strain concentrations are generated in the notch area. [2]

The early analysis of stresses of notches was based on the determination of stress concentration factor experimentally. One of the first investigations in this field was reported by Frochet in 1936 [3]. Frochet determined the stress concentration factors for holes, groove and fillets using different loading (pure tension, compression and bending).

2- Factors Affecting Fatigue Behaviour

Fatigue behaviours is dependent upon many factors and, apart from testing actual components under service condition, it is not possible to include all likely obtained in the laboratory tests [4]. Consequently when applying fatigue data obtained in laboratory to the design of actual components, account must be taken of those factors which are likely affect fatigue behaviour. It will be necessary to take account of the many influencing factors which effect fatigue behaviour, amongst the major of which are:

1- Type and nature of loading.

2- Size of component and stress or strain distribution.

3- Surface finish

4- Mean stress or strain.

5- Stress concentration

6- Environment effects.

7- Residual stress effect.

3- Notch Sensitivity Factor

Notch cannot be avoided in many structures and machines and notch effects have been a key problem in the study of fatigue. Although notches can be very dangerous they can often be rendered harmless by suitable treatment. To understand the effects of notches one must consider five parameters:

1 - Concentrations of stress and strain
2 - Stress gradients.
3 – Mean stress effects and residual stresses.
4 – Local yielding.
5 – Development and growth of crack.

Notch Sensitivity Factor is a measure of how sensitive a material to notches or geometric discontinuities. A notch sensitivity factor (q) can be defined as a factor which relates the strength reduction factor, k_f, and the stress concentration factor, k_t such that

$$q = \frac{K_f - 1}{K_t - 1} \qquad \text{..... (1)}$$

$$K_f = 1 + q(K_t - 1) \qquad \text{......(2)}$$

Where q=0 for no notch sensitivity, q=1 for full sensitivity. [5]

Notch Sensitivity is a very complex factor depending not only upon the material but also upon the grain size. A finer grain size results in a higher value of (q) than a coarse grain size. It also increases with section size and tensile strength thus under some circumstance it is possible to decrease the fatigue life by increasing tensile strength and as has already been mentioned. It depends upon the severity of notch and type of loading. [5]

4- Experimental Work

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

With regards to materials used in this study aluminum alloy 7075 is used. This alloy is characterized by high mechanical properties such as high strength and hardness. It has high resistance for fatigue crack prorogation and good fractures toughness. This alloy is used widely as a structural member in high speed aircraft and rocket.

Chemical analysis of this alloy is summarized in table (1). The device used in this test is (X-ray florescent).

Samples prepared for microstructure study were grinded by using different grades of wet silicon carbide papers (240, 380, 600, 800, 1200, 2400). Then the samples were polished using alumina (3μ, 1μ) and then washing by water and alcohol to clean them.

Etching was carried out with (5% HNO_3, 3%HCL, 2%HF) in water and then washing them by water and alcohol. The images were photographed with enlarges power (250X). Computerize microscope gives an ability of lighting control and resolution of the grain boundaries before and after heat treatment, was used

With regards to fatigue test, fatigue-testing machine of type rotating bending was used to execute all fatigue tests, with constant amplitude. The specimens were subjected to an applied load from the right side of the perpendicular to the axis of specimen, developing a bending moment. Therefore, 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 [6]:

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

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

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, four groups of specimens were prepared as a test standard shafts. A circumferential notch on each specimen of three groups was made by using the cutting tool with radius (0.5 mm, 0.7 mm, 1 mm).

The cutting tool was formed by using wire cutting machine to give perfect dimensions. The fourth group without notch. The specimens were classifying to eight series according to the radius of notches and heat treatment as show in the table (2). The test specimens are shown schematically in figure (1).

On finishing operation, the circumferential notches on the notched specimens were first polished with different wet silicon carbide papers starting with (240) to (1200) for finishing. This was followed by polishing with a string cloth, soaked in alumina.

The surface roughness was measured on four specimens by using portable surface roughness tester device type SRT-6210 the results are show in table (3).

Finally with regards to heat treatment, tube furnace is used for heat treatment. The maximum temperature for this furnace is 1000 °C. The furnace was calibrated before use.

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 (T_6).

5- Results and Discussion

The tensile tests of the alloy were performed to obtain the values of the ultimate tensile stress and the yield stress before and after the heat treatment. figure (2) shows the stress-strain curves of the alloy before and after the heat treatments.

The specimens were classifying to eight groups according to the radius of notches and heat treatment as shown in table (2).

The results of the stress vs. number of cycles to failure for all groups before and after heat treatment are plotted in figure (3) through (6). The fatigue strength reduction factor k_f was calculated from this equation: [7].

$$K_f = \frac{s \text{ of un-notched specimen at N cycles}}{s \text{ of notched specimen at N cycles}}$$

s = endurance limit at $N=10^6$ cycles

The value of the fatigue strength reduction factor k_f are presented in tables (4), (5) and plotted in figure (7). The theoretical stress concentration factor, k_t was founded by using the standard curve for each case [8] by using the relationship between the ratio r/d and D/d where:
r = notch radius , D = outer diameter , d = the smaller diameter. The value of k_t for each configuration of notched specimens is presented in table (4) and (5).

The notch sensitivity factor, q, was determined from the equation (1).

The values of q are presented in tables (4), (5) and are plotted against notch radius in figure (8).

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

From the results of the fatigue test of all groups it can be observed that:

1- The value of endurance limit of group **E** (specimens with 0.7 mm notch radius before heat treatment) is higher than the value of endurance limit of group **C** (specimens with 0.5 mm notch radius before heat treatment) and lower than the endurance limit of group **D** (specimens with 0.5 mm notch radius after heat treatment).

2- The value of endurance limit of group **G** (specimens with 1 mm notch radius before heat treatment) is higher than the value of endurance limit of specimens with (0.5 mm and 0.7 mm) notch radius before and after heat treatment. Because the hardness are most often lower the ductility of the alloy, so that the alloy may not be able to stretch and relive stresses around notch.

3- The value of endurance limit of this group **H** (specimens with 1 mm notch radius after heat treatment) is higher than the value of endurance limit of all groups.

7 - Conclusions

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

1. The fatigue strength reduction factor k_f increases with decreasing notch radius.
2. The experimental stress concentration factor k_f increases after heat treatment.
3. The notch sensitivity factor increases with increase notch radius and after heat treatment.
4. The enhancement percentage in notch sensitivity factor after the heat treatment for 1 mm radius notch is (22.616%).

6- References

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[8]. R. E. Peterson “Stress Concentration Factor”, 2nd Edition, John Wiley & Son 1997.

Table (1) Chemical Composition

Chemical composition							
Cu	Mg	Mn	Zn	Si	Fe	Ni	Al
1.18	2.7	0.29	6.06	0.02	0.18	0.00	rem

Table (2) Classification of the groups of specimens

Series	Heat treatment	Radius of notches (mm)
A	-	Un-notches
B	T_6	Un-notches
C	-	0.5
D	T_6	0.5
E	-	0.7
F	T_6	0.7
G	-	1
H	T_6	1

Table (3) value of surface roughness (R_a)

Specimens No.	1	2	3	4
Surface roughness μm	0.4	0.45	0.44	0.5

Table (4) value of (k_f , k_t , q) before heat treatment

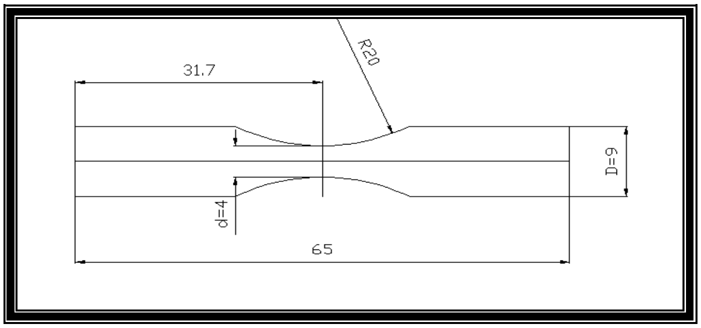
Notch radius mm	k_f	K_t	q
0.5	1.295	1.65	0.453
0.7	1.249	1.49	0.508
1	1.182	1.34	0.535

Table (5) value of (k_f , k_t , q) after heat treatment

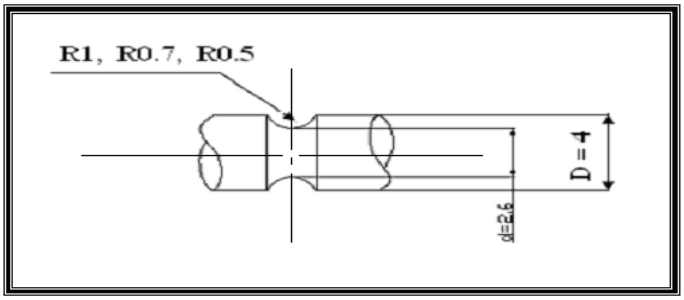
Notch radius mm	k_f	K_t	q	enhancement percentage in notch sensitivity factor due to heat treatment
0.5	1.326	1.65	0.501	10.596%
0.7	1.283	1.49	0.577	13.582%
1	1.223	1.34	0.656	22.616%

Table (6) fatigue life equation &value of endurance limit &enhancement percentage of endurance limit

Groups	Fatigue life equation	Endurance limit at (10^6) cycles (MPa)	Enhancement percentage in endurance limit due to heat treatment
A	$\sigma=1616*N_f^{-0.1741}$	$\sigma_L = 145.83$	7.98%
B	$\sigma=1653.5*N_f^{-0.1702}$	$\sigma_L = 157.472$	
C	$\sigma = 1489*N_f^{-0.1869}$	$\sigma_L = 112.59$	5.43%
D	$\sigma = 1483.5*N_f^{-0.1828}$	$\sigma_L=118.71$	
E	$\sigma = 1497.4*N_f^{-0.1847}$	$\sigma_L = 116.72$	5.15%
F	$\sigma = 1531.8*N_f^{-0.1827}$	$\sigma_L = 122.74$	
G	$\sigma = 1542*N_f^{-0.1828}$	$\sigma_L = 123.39$	4.364%
H	$\sigma = 1589.4*N_f^{-0.1819}$	$\sigma_L = 128.755$	



(a)



(b)

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

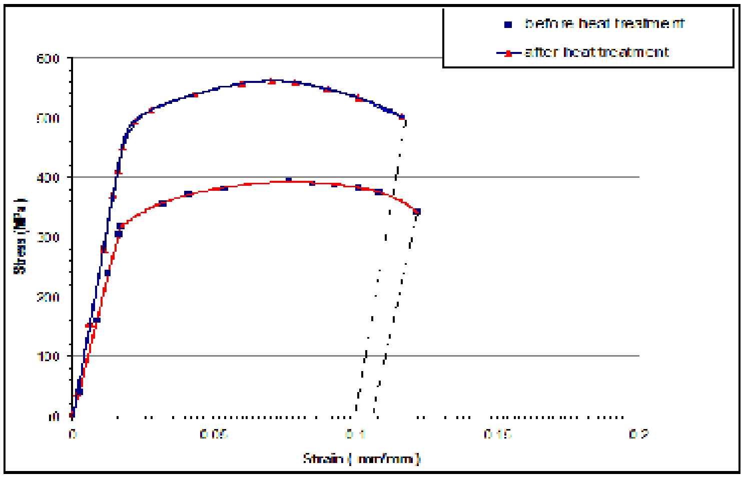


Figure (2) Stress–strain curves of alloy 7075 before and after heat treatment

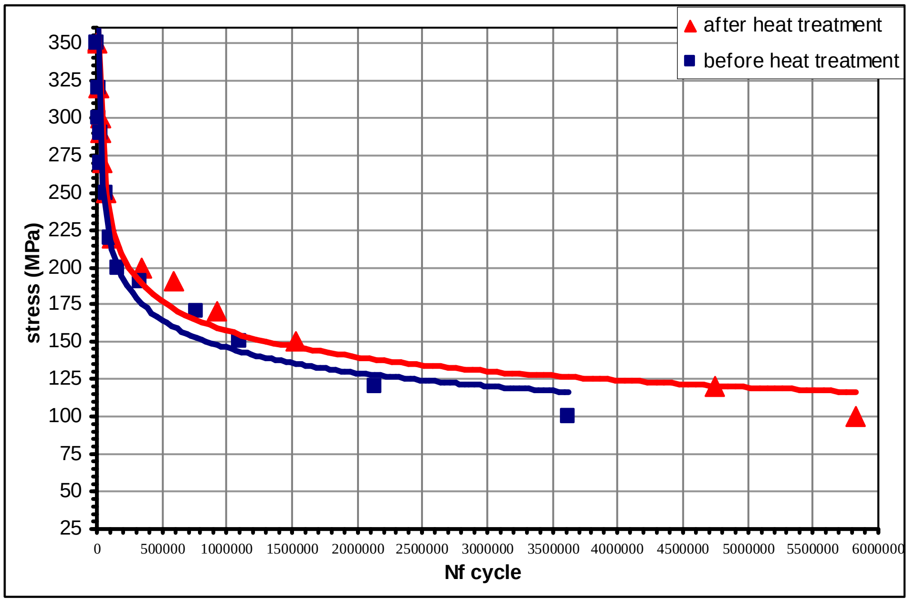


Figure (3) S-N curve for un-notch specimens before and after heat treatment groups (A&B)

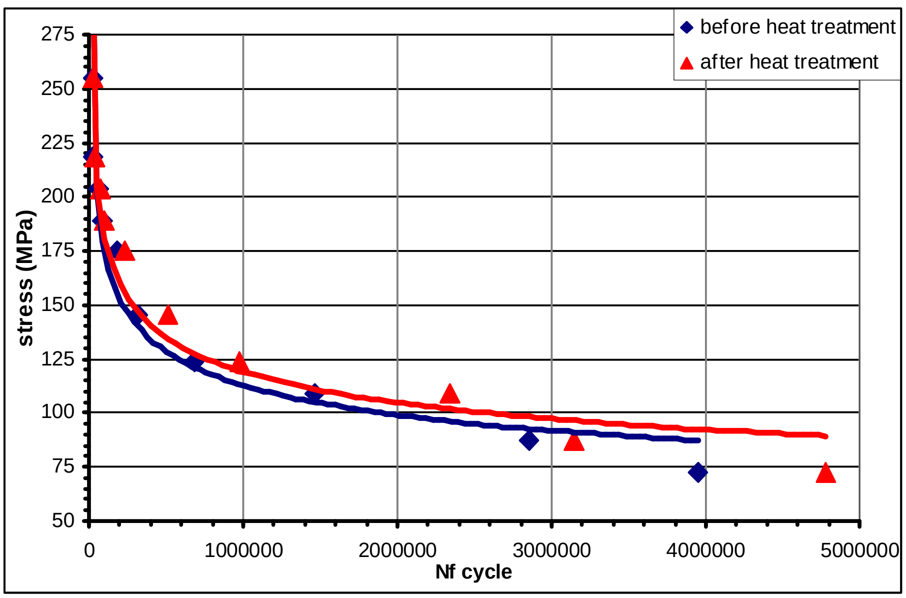


Figure (4) S-N curve for specimens with 0.5mm notch radius before and after heat treatment groups (C&D)

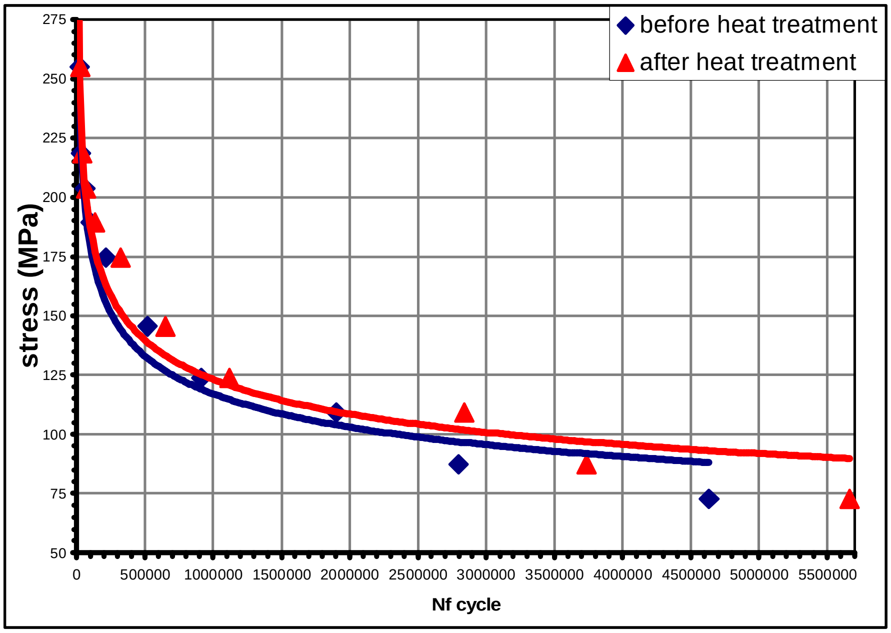


Figure (5) S-N curve for specimens with 0.7mm notch radius before and after heat treatment groups (E&F)

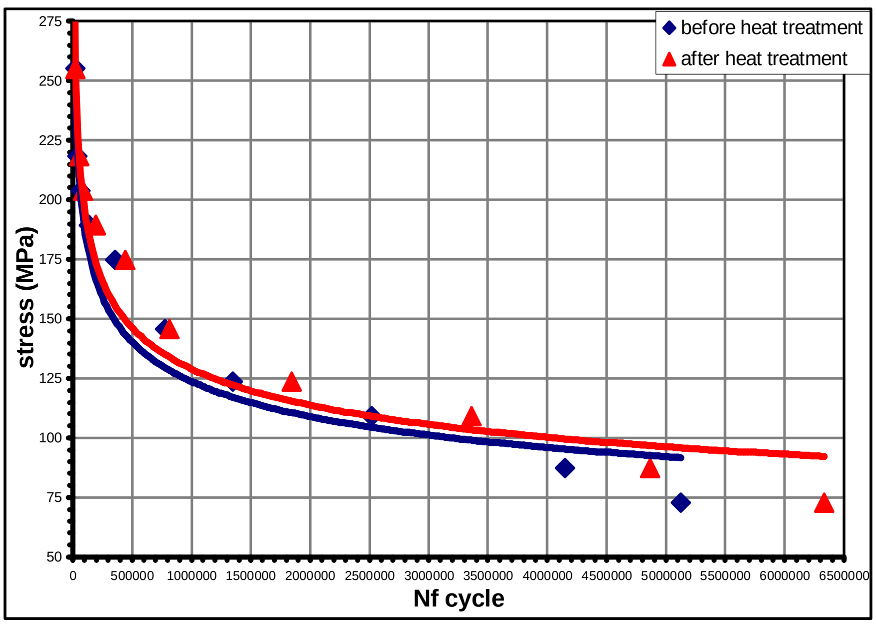


Figure (6) S-N curve for specimens with 1 mm notch radius before and after heat treatment groups (G&H)

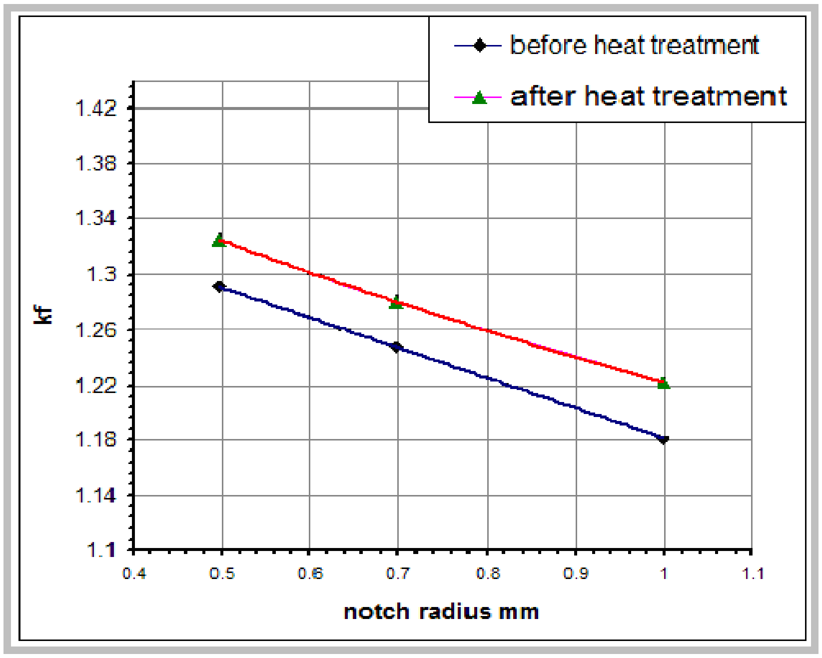


Figure (7) fatigue strength reduction factor (k_f) against notch radius

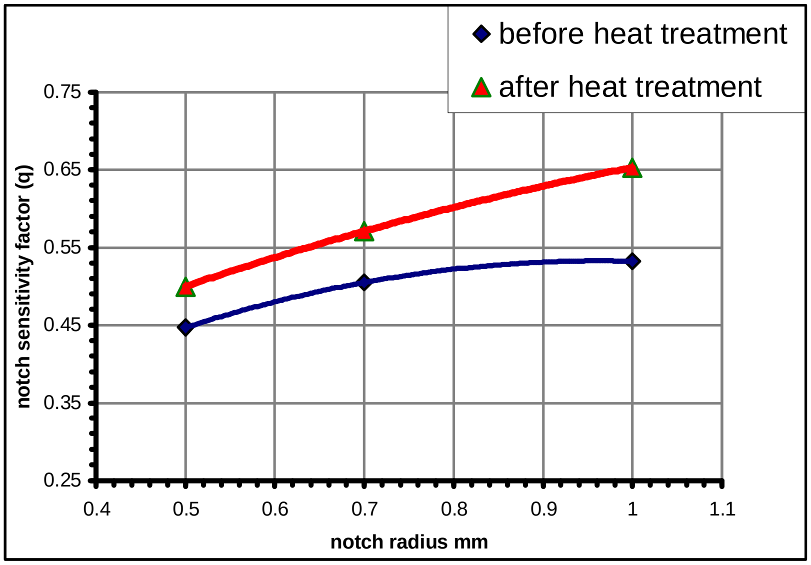


Figure (8) notch sensitivity factor (q) against notch radius