EFFECT OF NOTCH SENSITIVITY ON FATIGUE STRENGTH AND FATIGUE CRACK BEHAVIOUR OF Ti-6AL-4V ALLOY

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ABSTRACT

In the present work, rotating bending fatigue tests have been carried out to investigate the fatigue strength of plain and circumferentially notched specimens of Ti-6AL-4V alloy. The purpose of this work is to evaluate fatigue strength and notch sensitivity under different stress concentrations . The notch radius of specimens changes from ∞ (plain specimen) to 1.3, 0.4, 0.2, and 0.1 mm. The fatigue cracks initiate by approximate 25% of cycle ratio in the cases of $\rho = 1.3$ and 0.4 mm while the fatigue cracks initiate by approximate 15% in the case of $\rho = 0.2$ mm. The notch sensitivity of Ti–6AL– 4V alloy is higher than that of cast iron, and lower than that of steel material. The non-propagating micro-cracks at the specimen surface are not existed for not only the plain specimen but also for all of the notched specimens including plain specimen under fatigue limit by $N = 1 \times 10^7$ cycles.

1. INTRODUCTION

It is generally known that Ti-6AL– 4V alloy has excellent properties such as the high strength to weight ratio, corrosive resistance etc. It has been used as structural material for aeroplane. Though considerable amount of studies on fatigue properties have been done until now, most of them are done on plain specimen [1]. Though the cases over 90% of failures are caused from notch (stress concentrated part), quite few reports on the notch fatigue strength under the stress concentration

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have been done. In addition, it is well know that the titanium alloy show high sensitivity for the sharp notch. In view of ensuring safety, especially, it is important that the parts which have complicated shape, is required for enough fatigue resistance at the notch. For the above reasons, the study of fatigue properties for the titanium alloy under the stress concentration should be considered as an extremely important in view of practical use for a construction material.
So, in this study, the fatigue properties of the titanium alloy with circumferential notch have been investigated using defined depth of notch by changing the radius of the notch's bottom and compared to the results of other materials.

2. MATERIALS AND EXPERIMENTAL PROCEDURE

The material used in this study is the typical Ti–6AL–4V alloy. Chemical composition is listed in table (1). The shape and dimensions of fatigue test specimen are shown in Fig (1). The specimen has constant diameter at the smallest section and constant notch depth. The notch shape is 60^{o} V type, and the notch radius of specimens is changed from ∞ (plain specimen) to 1.3, 0.4, 0.2 and 0.1 mm. After machining, all specimens were mechanically polished, annealed at 600 ^{o}C for 30 minutes afterwards to remove residual stresses, and were then lightly etched.

Fatigue tests were performed at room temperature using a rotating bending fatigue testing machine under the cyclic speed of 2880 r.p.m.

For observation fatigue crack initiation and propagation behaviour, the replica method was applied to the successive observations of specimen surface for the cases of dull notch. As, it is impossible to take the replica for the cases of sharp notch, the specimens were dismantled from the testing machine, and were examined directly using an optical microscopy, whenever necessary. All of the fatigue datum were arranged by the nominal stress at the smallest section of the specimen.

3. RESULTS AND DISCUSSION

3.1 Notch Sensitivity and Duller Notch

Table (2) shows the experimental results, in which, σ_w, is the fatigue limit for each notch. Furthermore, stress concentration factor α was calculated by Neuber's triangular law.

Figure (2) shows she S – N curves about all kind of specimens. The fatigue limit is determined by the step of 5 MP_a for the stress amplitude. The notch sensitivity is investigated for the notch of this

material on notch sensitivity factor q, which is calculated by the following formula:

$$q = (\beta - 1) / (\alpha - 1)$$

where, β is the fatigue notch factor.

It shows the effect of the stress concentration on the fatigue strength. From experimental results, it is known that the notch sensitivity factor q for $\rho = 1.3$ is the lowest in comparison to the others (see table 2).

Figure (3) shows the relationship between stress concentration factor α and notch sensitivity factor q. The datum of an annealed steel, which is practically used as a structural material, is chosen for comparing those of Ti–6AL-4V alloy. From this figure, it is clear that the notch sensitivity for $\rho = 1.3$ mm in Ti–6AL–4V alloy is much lower than that of the compared material with sharp notch. Regarding to this phenomenon, it is considered that the plastic flow would be considerably restricted for the circumferential grains, because titanium has a hexagonal close – packed lattice [1-4].

3.2 Crack Initiation and Propagation Behaviour

Figure (4) shows fatigue crack propagation properties of Ti–6AL–4V alloy. The shown curves only represent the main propagating crack in the materials. From this figure, it is clear that, in the case of $\rho = 0.2$ mm, the fatigue crack propagates forward like a straight line in the smaller range N/N_f than 0.5.As shown in figure (4), there are differences in the crack propagation behaviour of each notch radius.

Figure (5) shows the results of successive observation of surface state for $\rho = 0.4$ mm and $\rho = 0.2$ mm. Fatigue crack initiates at $N/N_f = 0.25$ for $\rho = 0.4$ mm, and at $N/N_f = 0.15$ for $\rho = 0.2$ mm. From this result, it is concluded that, according to the stress concentration factor at the notch bottom being smaller, the fatigue crack initiates at lower fatigue life ratio. Furthermore, the obtained results from the successive observation of surface state indicated that as for the dull notched specimens ($\rho = 1.3$ mm and 0.4 mm), the fatigue crack almost initiates from only one point, then propagates, until failure occurs. On the other hand, as for the sharp notched ones ($\rho = 0.2$ mm), fatigue crack usually initiates in many places at the same time. These cracks propagates, and combine to a rather long and to be a discontinuous crack, and then after the final fracture occurs. In addition, in the case of dull notched specimen, the fatigue cracks slowly propagate along the circumferential direction. The number of initial cracks increases with an increasing of notch bottom sharpness. It considered that the work – hardening of the sharp notched specimen is higher than that of dull notched specimen. Therefore, initial cracks are observed in many places.

Figure (6) shows the surface state under the fatigue limit by 1 x 10^7 cycles for the case of cycles ρ = 1.3 and 0.2 mm. The non – propagating cracks are not observed.

Figure (7) shows the relationship between σ_w, and stress concentration factor $\propto$ concerning with respective notch radius. In spite of non – propagating cracks do not exist for the specimen with a sharp notch, it is well understood that the fatigue limit becomes decrease with decrease of notch radius. In this material, the reason why non – propagating cracks are not existed unlike the cases of steel [5] or cast – iron [6], is that this kind of material is hard to harden by work – hardening or harden age – hardening. The fatigue strength $\sigma_{w1}$is equal to the crack strength σ_{w2}. The branching radius in this material does not exist while it generally exists in cast – iron or steel. From the above results, it could be said that the fatigue limit of this kind of material is determinant by the crack initiating limit.

3.3 Comparison with other Materials on Notch Sensitivity

Figure (8) shows the relationship between (σ_w/σ_{w_0}) and the stress gradient χ on the notch bottom. Fig. (8) compares the relationship between $\propto$ (σ_w/σ_{w_0}) and the stress gradient in the notch bottom of this kind of material and other two kinds of compared material, S 50 C steel [7] and cast iron [8]. From this. figure (8), it is concluded that notch sensitivity concerning with crack initiation of this kind of material is higher than that of spheroidal graphite cast iron, and lower than that of S50C steel.

Figure (9) shows the relationship between fatigue limit ratio σ_w/σ_{w_0} and stress concentration factor $\propto$ among the three kinds of materials with respect to notch radius. The non – propagating crack is not observed in the case of titanium alloy even about a sharp notch, while non – propagating cracks are existed for in the case of cast – iron or S50C steel. As there exist the fatigue strength and the fatigue crack strength in the compared materials (cast-iron and S50C steel), the fatigue limit of these materials becomes constant even if increasing the sharpness of notch radius. The fatigue limit of Ti-6AL-4V alloy decreases with increasing the sharpness of notch radius, because non-propagating cracks exist in the compared materials, and do not exist in this material over the range of higher sharpness of notch radius. Finally, from the above results, the notch sensitivity of this material increases with increasing the sharpness of radius notch .

4. CONCLUSIONS

From this study, the following conclusions may be drawn :-

1. **Ti-6AL-4V alloy shows low notch sensitivity for dull notch, because this alloy has a hexagonal close-packed lattice.**
2. **The notch sensitivity of this material increases with increasing the sharpness of radius notch.**
3. **Non-propagating cracks are not observed under the stress amplitude of fatigue limit by 1×10^7 cycles, even if the notch radius becomes rather sharp, because the work-hardening effect of this material is very low.**
4. **The notch sensitivity for crack initiation of this alloy is higher than that of spheroidal graphite cast-iron, and lower than that of S50C steel.**

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Table (1) : Chemical composition of the alloy %

AL	V	Fe	O	C	N	H	Ti
6.15	4.23	0.12	0.14	0.011	0.01	0.004	balance

Table (2) : Experimental results .

ρ mm	α	β	χ mm-1	q	σ_w MPa
∞	1.00	1.00	0.40	—	420
1.3	1.42	1.14	1.98	0.33	370
0.4	1.96	1.79	5.26	0.82	235
0.2	2.44	1.71	9.25	0.49	245
0.1	3.47	2.27	21.54	0.51	185

α : Stress concentration factor

χ : Stress gradient .

σ_w : Fatigue limit .

β: Fatigue notch factor .

q : Notch sensitivity factor .

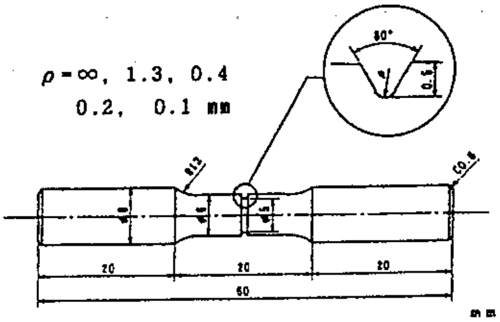


Fig. 1 Shape and dimensions of specimen.

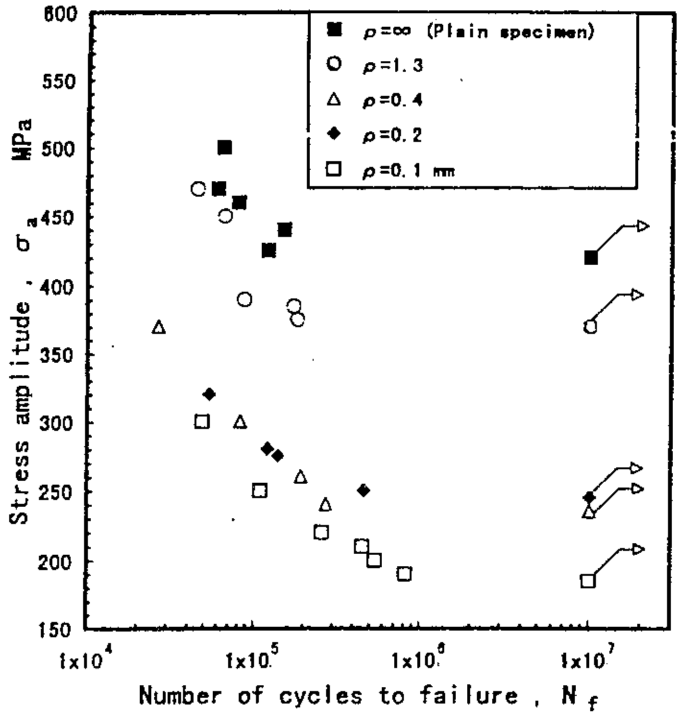


Fig. 2 S-N curves.

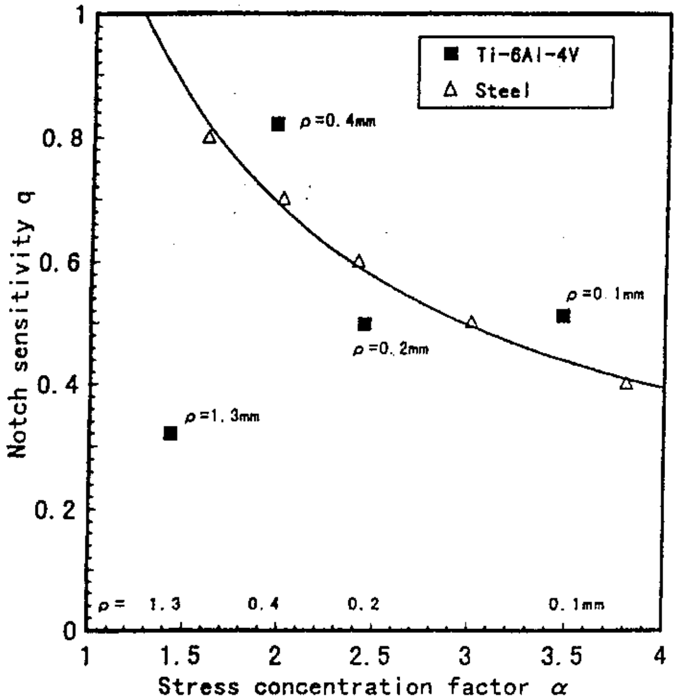


Fig. 3 Relationship between α and q.

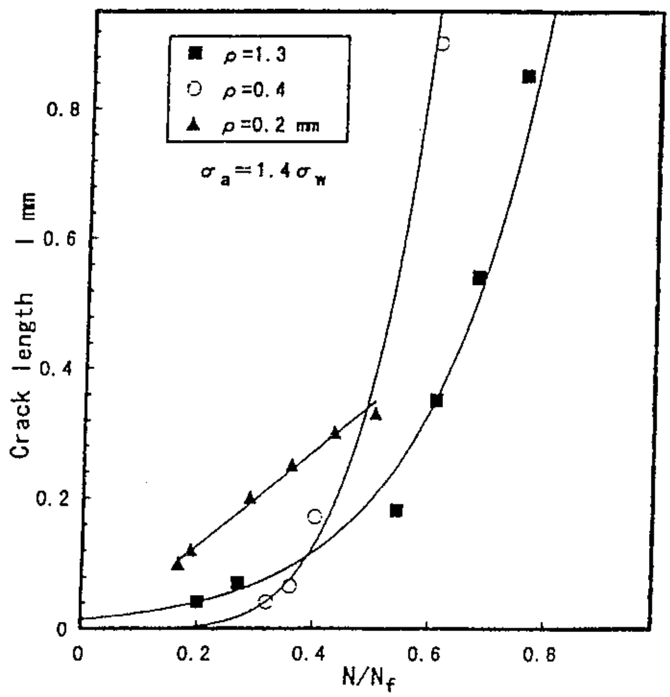
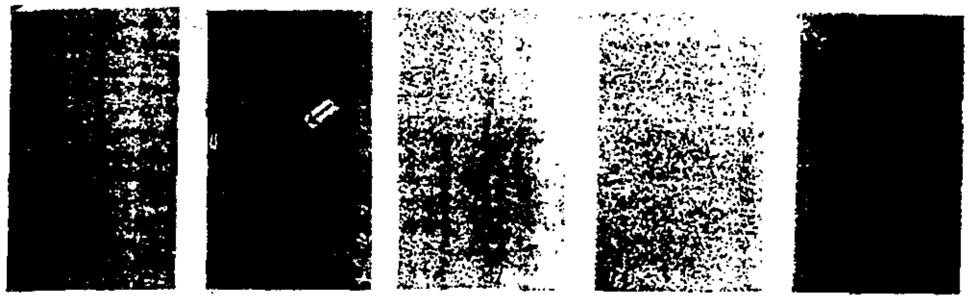


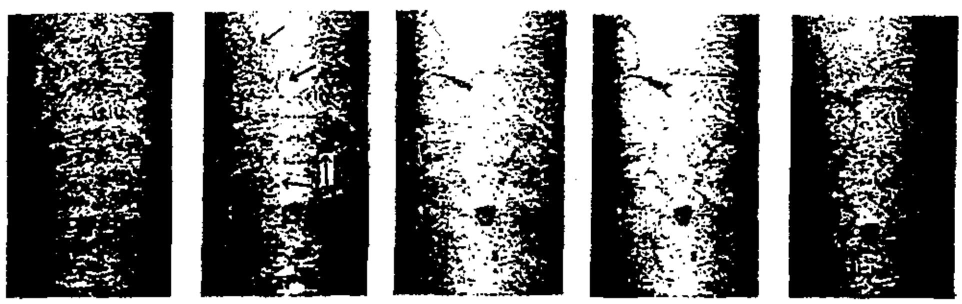
Fig. 4 Fatigue crack propagation properties.



N=0 | $8x10^4$ | $9x10^4$ | $1x10^5$ | $1.5x10^5$ cycles

◀ ▶ Axial direction   100 μm

ρ =0.4 mm (σ_a=360 MP_a, N_f=$2.5x10^5$ cycles)

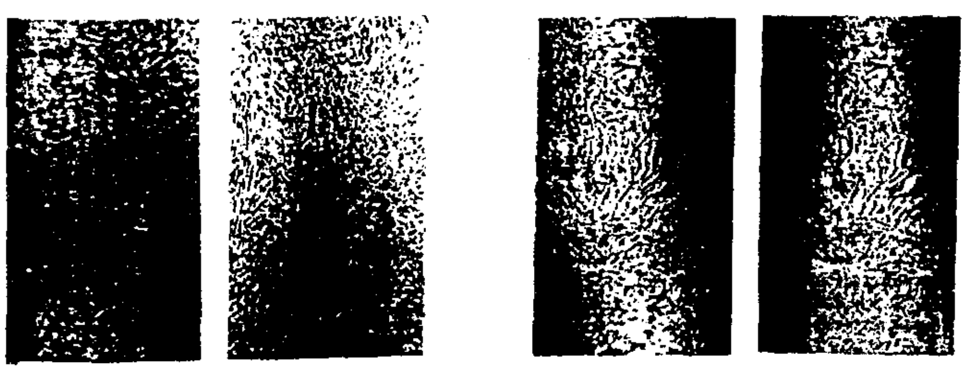


N=0 | $1x10^4$ | $1.5x10^4$ | $2x10^5$ | $2.5x10^5$ cycles

◀ ▶ Axial direction   100 μm

ρ =0.2 mm (σ_a=320 MP_a, N_f=$5.4x10^4$ cycles)

Fig.5 Successive surface observation of crack initiation for ρ =0.4 and 0.2 mm.



N=0 | $1x10^7$ cycles | N=0 | $1x10^7$ cycles

(a) ρ =1.3 mm (σ_a=370 MP_a)   (b) ρ =0.2 mm (σ_a=245 MP_a)

◀ ▶ Axial direction   100 μm

Fig.6 Surface state under the fatigue limit by $1x10^7$ cycles for ρ =1.3 and 0.2 mm.

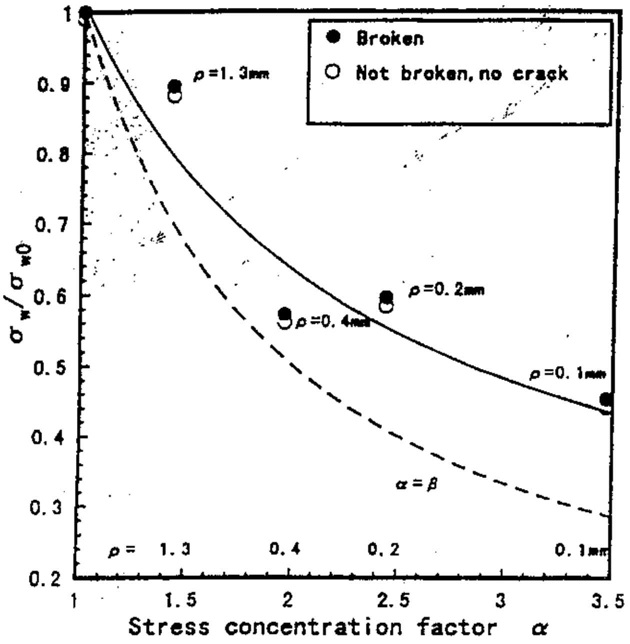


Fig. 7 Relationship between σ_W and stress concentration factor α concerning with respective notch radius.

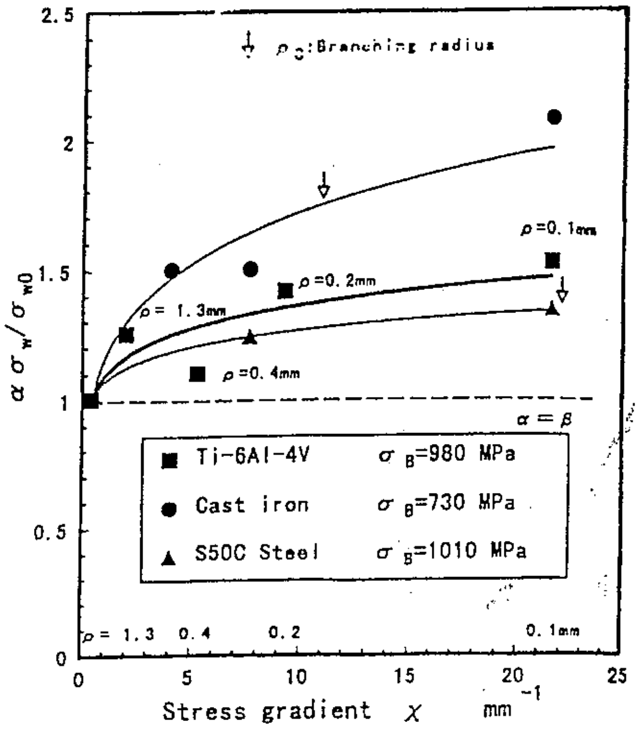


Fig. 8 Relationship between $\alpha\sigma_w/\sigma_{w0}$ and the stress gradient χ on the notch bottom.

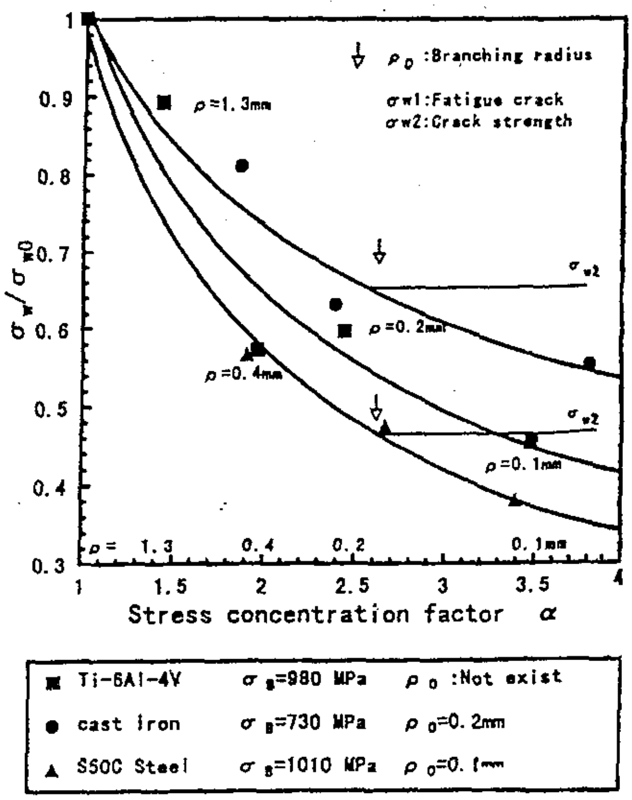


Fig. 9 Relationship between fatigue limit ratio σ_w/σ_{w0} and stress concentration factor α.

تأثير حساسية النقر (الحز) على مقاومة الكلال
وسلوك شرخ الكلال لسبيكة Ti-6AL-4V

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الملخص العربي:

يهدف البحث إلى دراسة تأثير حساسية النقر (الحز) على مقاومة الكلال (التعب) وسلوك شرخ الكلال لسبيكة Ti-6AL-4V . وتم في البحث استخدام عينات اختبار كلال منقورة (تحتوي على حز) على هيئة حرف V بزاوية ٦٠° . واشتمل البحث على استخدام أربعة أنواع من العينات بقيم مختلفة لنصف قطر الحز ρ. وأجريت اختبارات الكلال باستخدام ماكينة اختبار الكلال الانحنائية الدوارة. واشتمل البحث على استخدام الـ Replication technique لفحص منشأ ونمو شرخ الكلال على أسطح العينات أثناء اختبارات الكلال . كذلك اشتمل البحث على مقارنة النتائج بنتائج تجارب سابقة أجريت على كلٍ من الحديد الزهر الجرافيتي والصلب ٥٠.

ولقد خلص البحث إلى النتائج التالية:-

١. تنشأ شروخ الكلال عند ٢٥% لنسبة الدورة Cycle ratio (N/N_f) عندما يكون نصف قطر الحز (ρ) ١,٣ ، ٠,٤مم. بينما تنشأ عند ١٥% لنسبة الدورة عندما يكون نصف قطر الحز ٠,٢مم.
٢. حساسية النقر (الحز) تتزايد بتزايد حدة نصف قطر النقر.
٣. أظهرت نتائج الفحص لأسطح كل العينات المختبرة إلى عدم تواجد الشروخ الدقيقة والتي لا تنمو Non-propagating micro-cracks وذلك عند تحميل العينات بإجهاد حد التعب لعدد دورات ١×١٠^٧ دورة. وقد فسرت النتائج على انخفاض تأثير التصليد الانفعالي لهذه السبيكة.
٤. أظهرت نتائج المقارنة إلى أن حسايسة النقر (الحز) لمنشأ شروخ الكلال في هذه السبيكة أعلى من حساسية النقر للحديد الزهر الجرافيتي وأقل من حساسية النقر للصلب ٥٠ .