CRACK INITIATION IN PLAIN CARBON STEELS DURING STATIC TENSION AND FATIGUE

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ABSTRACT

In this work, the effect of carbon content on static tensile and fatigue crack initiation behaviour was investigated on four different types of carbon steels with nearly equal ferrite grain sizes by the plastic replica method. Static tests and fatigue tests had been performed using the universal testing machine and the rotating bending fatigue testing machine, respectively. Fatigue tests were mainly performed under the stress level larger than the fatigue limit of each material by the same magnitude. Experimental results show that, for tensile tests, the cracks of materials with low carbon content exist in the boundaries between pearlite block and ferrite grain or in their neighborhood. On the other hand, those of materials with medium carbon content cracks also exist in pearlite. For fatigue tests, the carbon content of each material affects the crack initiation behaviour under the same stress amplitude for four types of carbon steels, comparing with that under the stress level larger than the fatigue limit of each material by the same magnitude. In addition, the carbon content of steel hardly affects the crack propagation behaviour .

1. INTRODUCTION

A plain carbon steel, being excellent due to low cost and machinability, is one of the carbon steels for machine structural use. Therefore, various types of carbon steels have been widely used and examined extensively [10]. Nevertheless, there are several problems unresolved. For example, it seems that the research on static crack initiation has not been reported. In addition, although the fatigue crack initiates from a ferrite grain, yet, it is not thoroughly clear why the fatigue limit of each material with the same ferrite grain size is dependent on carbon content .

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So, it is the purpose of the present work to investigate the effect of carbon content on static tensile and fatigue crack initiation by using four different types of carbon steels with the same ferrite grain size .

2. MATERIALS AND EXPERIMENTAL PROCEDURE

The materials used were four types of carbon steels, 0.15% C, 0.25% C, 0.35% C and 0.46% C. Tables (1) and (2) list the chemical composition, the procedure of heat treatment and the mechanical properties of the materials, respectively. The microstructures of the materials after heat treatment are shown in Fig. (1) . Fig. (2) shows the shape and dimensions of specimen for fatigue tests. Round bar tensile tests using a specimen with 6 mm diameter and 30 mm gauge length were used. The specimens were cut out from the heat treated rod. All specimens have nearly equal ferrite grain sizes of about 20 μm in diameter, according to the heat treatment conditions as shown in Table (2). After machining, the specimens were polished with emery paper and then finished by buffing. Before testing, all specimens were re-annealed at 600 ^{O}C for 1 hr to remove residual stresses. Furthermore, all specimens were lightly etched .

Every specimen for fatigue tests has a partial shallow notch at the middle of the testing part as shown in Fig. (2). This shallow notch localizes the crack initiation site and does not affect for its fatigue strength at all. The observation of micro-crack initiation and measurement of crack length were adopted by successive –taken replica method in the circumferential direction at the specimen's surface. The taken replicas of the specimens were examined using metallurgical microscope. Static tests and fatigue tests had been performed using the universal testing machine and the rotating bending fatigue testing machine (under the cyclic speed of 2880 R.P.M), respectively.

Table (1) : Chemical Composition %wt.

Material	C	Si	Mn	P	S	AL
A	0.15	0.22	0.55	0.034	0.025	-
B	0.25	0.24	0.39	0.031	0.023	-
C	0.36	0.23	0.76	0.021	0.022	0.001
D	0.46	0.20	0.73	0.029	0.017	0.018

Table (2) : Mechanical Properties

Material	Heat treatment	σ_Y MP_a	σ_u MP_a	σ_{w0} MP_a	Ψ %
A	900 °C 2hrs → A.C	283	440	205	70.8
B	900 °C 2hrs → A.C	297	496	210	64.6
C	900 °C 2hrs → F.C	312	568	225	58.6
D	990 °C 2hrs → F.C(2 times)	360	632	250	53.8

σ_Y : Yield strength σ_u : Tensile strength σ_{w0} : Fatigue limit
Ψ : Reduction of area A.C : Air cooling F.C : Furnace cooling

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Crack Formation Behaviour Under Static Tensile Loading.

Figure (3) shows stress-strain curves for tensile tests. The mechanical properties taken from these curves are summarized in table (2).

Figure. (4) shows the representative results of successive observation of crack initiation and propagation under static tensile loading. As shown in this figure, the values of plastic strain ε_p for the slip band initiation in 0.15% C steel (material A) and 0.25% C steel (material B) are about 6.3% and 3.4%, respectively. In addition, the micro-cracks of these materials initiate in the boundaries between pearlite block and ferrite grain or in their neighborhood when the plastic strain for both materials increases up to about 9.1% . Furthermore, it is clear that the crack length does not increase with increasing plastic strain. While, the slip band for 0.36%C steel (material C) and 0.46%C steel (material D) appear when plastic strain is 3.4%. Then, the crack initiation of 0.36%C steel (material C) is similar to those of 0.15%C steel (material A) or 0.25%C. steel (material B) that is to say, it initiates in the boundaries between pearlite block and ferrite grain or in their neighborhood at $\varepsilon_p = 6.3\%$. Cracks initiate when the plastic strain is about 4.8% for 0.46%C steel (material D). Cracks are formed not only in the boundaries between pearlite block and ferrite grain or in their neighborhood but also in pearlite block. From the above result, it is obvious that the critical plastic strain, in which slip bands and crack initiate, decreases according to the increase in carbon content. In addition, the crack under static tensile loading shows the tendency to exist not only in the boundaries between the pearlite block and ferrite grain but also in pearlite block with increasing carbon content. This is probably due to the difference in mechanical properties between pearlite block and ferrite grain. That is, it is considered that the plastic deformation in low carbon steels mainly meets with the elongation of ferrite grain. Therefore, the cracks in low carbon steels are initiated in the boundaries between pearlite block and ferrite grain, where appears much difference of elongation between both structures. On the other hand, the plastic deformation of medium carbon steels shares not only the deformation of the ferritic grain but also that of pearlite block because the ratio of ferrite grains decreases with increase of carbon content. Therefore the cracks in these steels are initiated not only in the boundaries between both structures but also in pearlite block.

Figure (5) shows the change in density of cracks with the nominal stress. As shown in this figure, the density of cracks of each material increases with increasing the nominal stress. The density of crack under the same nominal stress condition decreases with the increase in carbon content.
However, as mentioned above, static tensile cracks hardly propagate and only the number of cracks increases.

3.2 Crack Behaviour Under Alternative Cyclic Loading

Figure (6) shows S-N curves for fatigue tests. As shown in this figure, it can be seen the fatigue strength depends on carbon content. That is, the fatigue limit of these materials increases in accordance with carbon content, regardless of the same mean ferrite grain size. The fatigue limit of each material is listed in table (2). Fig. (7) shows the representative results of successive observation of fatigue crack initiation under the stress amplitude of $\sigma_a = 280$ MP_a, which is larger than each fatigue limit. It can be seen from this figure that the slip bands are generated in ferrite grains at an early stage of stress repetitions. Then, the grain boundary becomes like a black band in the above area, and finally turn to a micro-crack. Therefore, it is clear that the fatigue crack initiation behaviour is different from the crack behaviour in the tensile process. Namely, the cracks in the cyclic loading process initiate in ferrite grain boundaries or in its neighborhood, being irrespective of carbon content. In addition, the tensile crack length does not increase with increasing plastic strain. On the other hand, the fatigue crack increases with increasing number of cycles.

Figure (8) shows the relation between the main crack length and the number of cycles under $\sigma a = 80$ MP_a. It is known that fatigue strength is propertional to the mean grain size by Hall-Petch's equation [11]. All specimens have the same ferritic grain size in these tests. Nevertheless, it can be seen from this figure that the fatigue crack is greatly dependent on carbon content. Namely the properties for fatigue crack initiation and crack growth rate at an early stage show the tendency to be retarded in accordance with increase of carbon content.

Figure (9) shows the surface micrographs before fatigue test and at $1X10^7$ cycles under the stress amplitude of fatigue limit. For the material with low carbon content, non-propagating cracks are blocked by the boundaries of ferrite grain. On the other hand, for the material with medium carbon content, cracks show a tendency to be blocked by pearlite.

4. CONCLUSIONS

From this study, the main results obtained both for tensile tests and fatigue tests with the materials of the same ferrite grain size are as follows : -

1. For static tensile tests, the cracks of materials with low carbon content exist in the boundaries between pearlite block and ferrite grain or in their neighborhood. On the other hand, those of materials with medium carbon content also exist in pearlite .
2. For fatigue tests, the cracks of all materials initiate from the boundaries of ferrite grain, being of carbon content .
3. The main crack length under cyclic loading increases with increasing the number of cycles. In contrast, the crack length under static tensile loading does not increase with increasing plastic strain .

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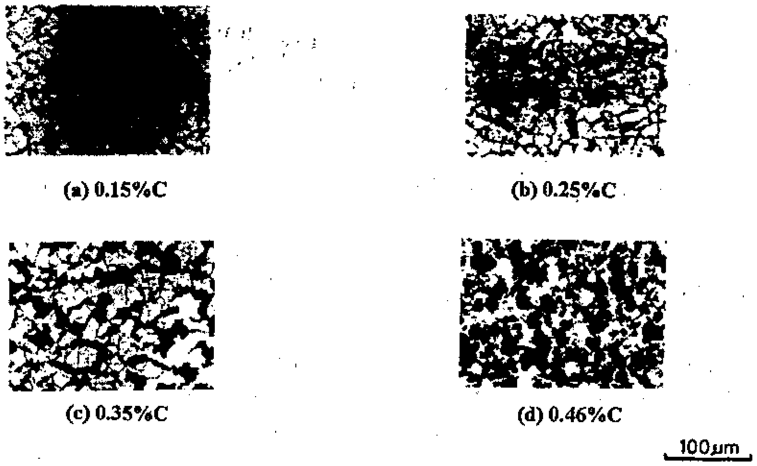

(a) 0.15%C

(b) 0.25%C

(c) 0.35%C

(d) 0.46%C

Fig. 1 Microstructures of the Materials used after Heat treatment.

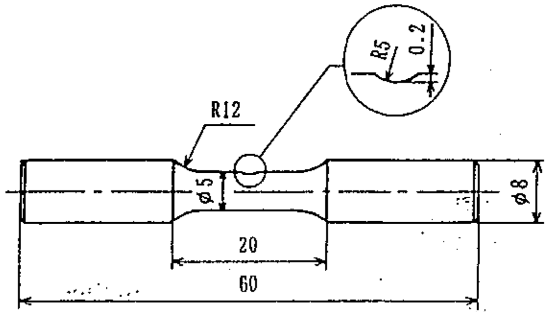


Fig. 2 Shape and dimensions of specimen for fatigue tests. mm.

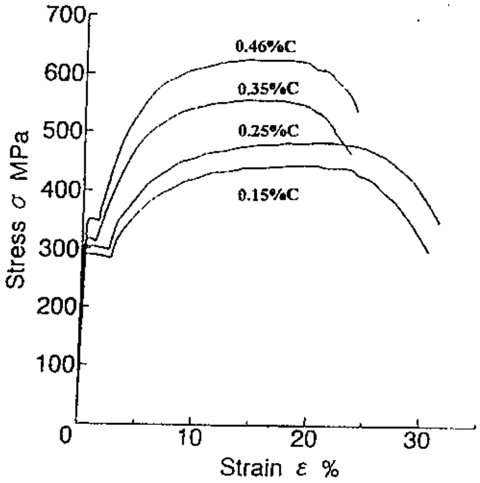
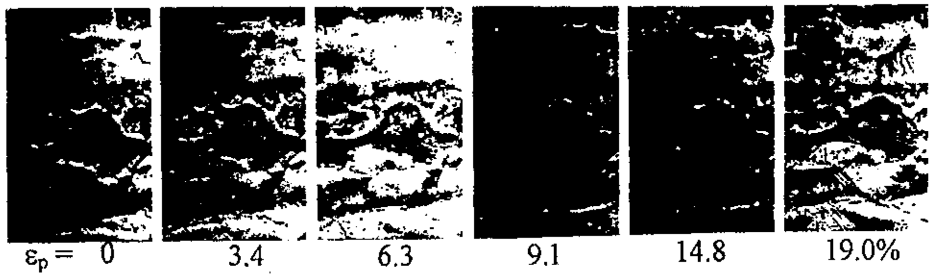
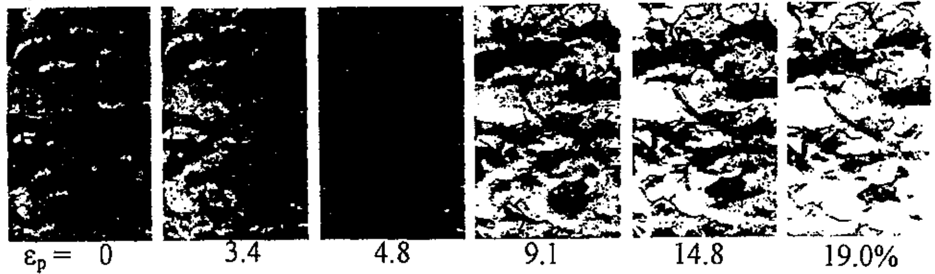


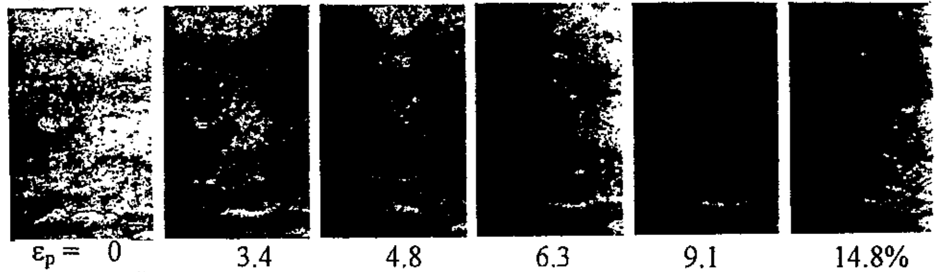
Fig. 3 Stress-strain curves.



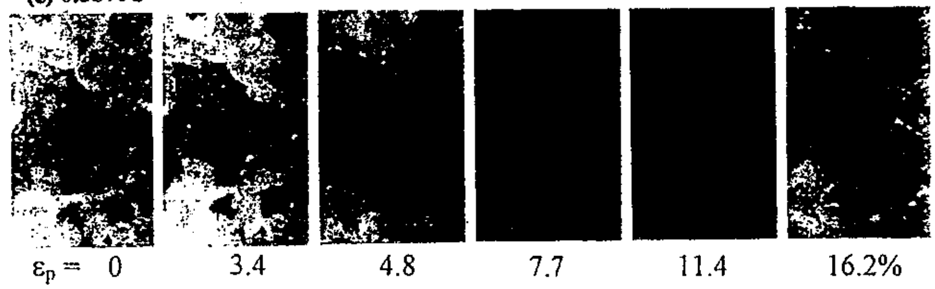
(a) 0.15%C



(b) 0.25%C



(c) 0.35%C



(d) 0.46% C

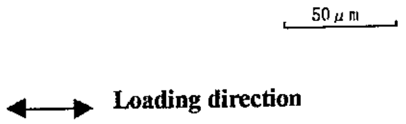


Fig. 4 Successive observation results of crack initiation under static tensile loading.

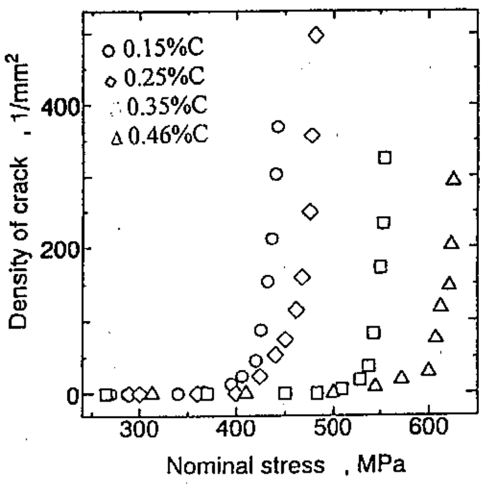


Fig. 5 change in density of crack with nominal stress.

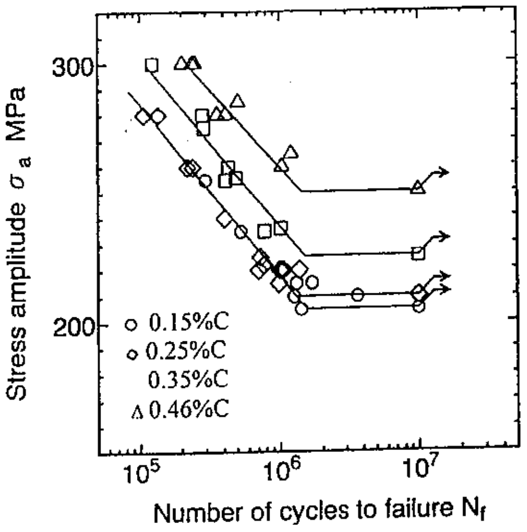
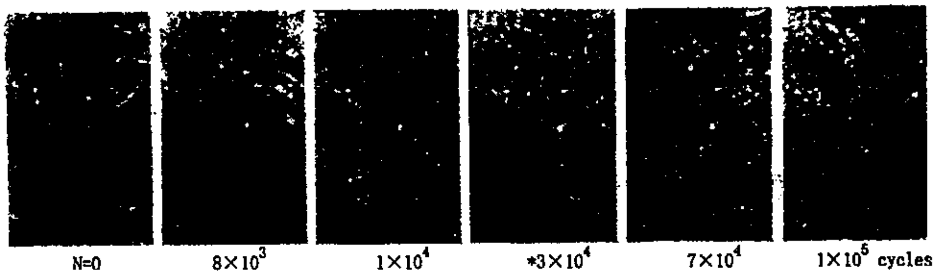
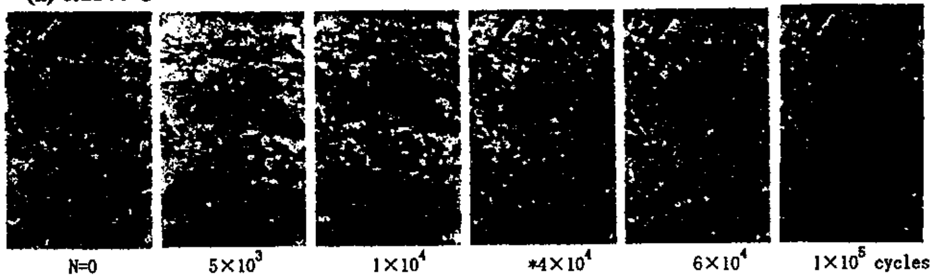


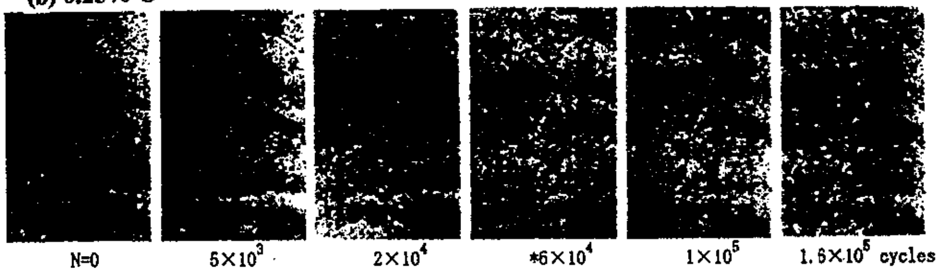
Fig. 6 S–N curves.



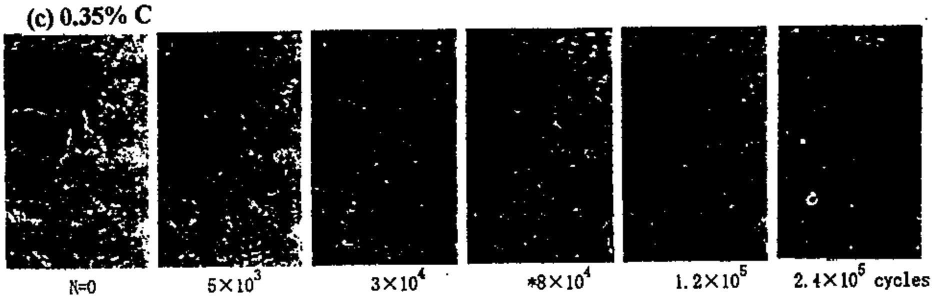
(a) 0.15% C



(b) 0.25% C



(c) 0.35% C



(d) 0.46% C

50μm

* Crack initiation ←→ Axial direction

Fig. 7 Successive observation results of crack initiation under cyclic loading (σ_a=280MPa)

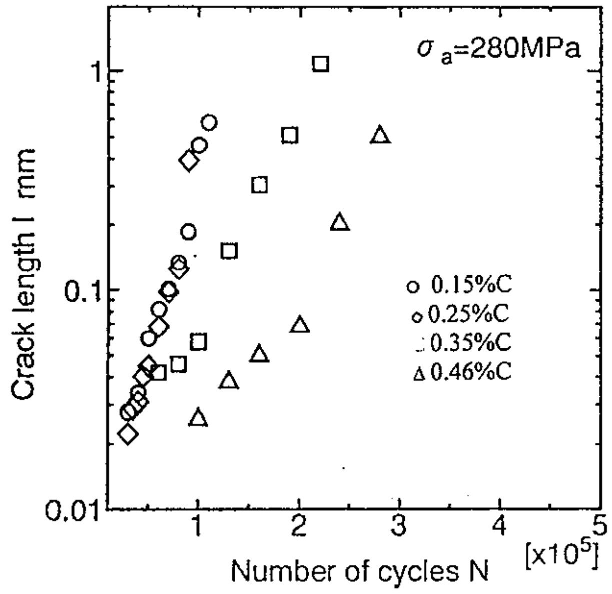
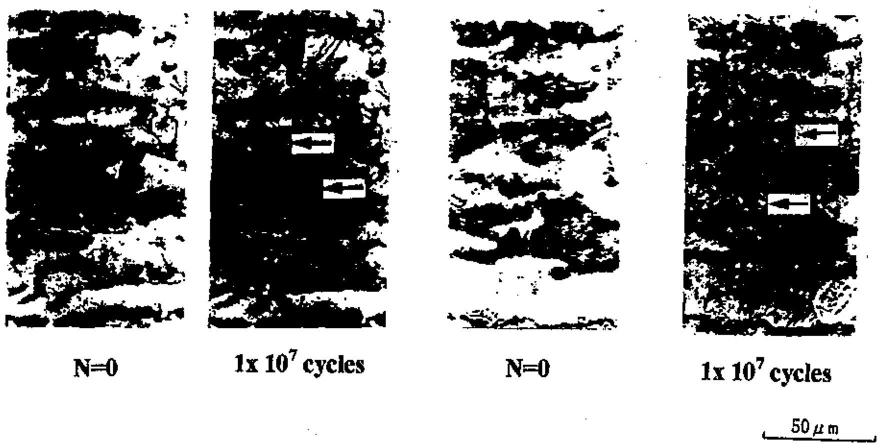


Fig. (8) Relation between the main crack length and number of cycles.



N=0 | 1x 10^7 cycles | N=0 | 1x 10^7 cycles

(a) 0.15% C (σ_{wo} = 205 MP$_a$) **(b) 0.35% C (σ_{wo}=225MP$_a$)**

Arrow mark: Non-Propagating crack ↔ Axial direction

Fig. (9) Surface state by 1x 10^7 cycles under the stress amplitude of fatigue limit.

“CRACK INITIATION IN PLAIN CARBON STEELS DURING STATIC TENSION AND FATIGUE”

"منشأ الشرخ في الصلب الكربوني أثناء اختبارات الشد الاستاتيكية والكلال"

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ملخص البحث :

يهدف هذا البحث إلى دراسة تأثير محتوى الكربون في الصلب على سلوك الشرخ أثناء اختباري الشد الاستاتيكي والكلال. وتم في البحث استخدام أربعة أنواع مختلفة من الصلب الكربوني . كذلك اشتمل البحث على إجراء اختبارات الشد الميكانيكية . وأجريت اختبارات الكلال على ماكينة اختبار الكلال الانحنائية الدوارة . واشتمل البحث على استخدام الـ **Replication technique** لفحص منشأ ونمو الشرخ أثناء الاختبارين السالفي الذكر .

ولقد خلص البحث للنتائج الآتية:

1. في اختبارات الشد الاستاتيكية فإن الشروخ المتكونة في الصلب الكربوني تتواجد عند الحدود المتاخمة بين البرليت والفيريت أو في المنطقة المجاورة . بينما في الصلب المتوسط الكربون فإن الشروخ تتواجد في البرليت .
2. في اختبارات الكلال، فإن الشروخ تنشأ من الحدود المحددة لحبيبة الفيريت وذلك لكل أنواع الصلب المستخدمة.
3. طول الشرخ الرئيسي أثناء اختبار الكلال يتزايد بتزايد دورات التحميل بينما لا يتزايد طوله بتزايد الانفعال اللدن أثناء اختبار الشد الاستاتيكي .