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Effect of Austenizing and Tempering Heat Treatment Temperatures on the Fatigue Resistance of Carburized $16MnCr_5$ (ASTM 5117) Steel

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Abstract

The present investigation deals with the study of the effect of austenizing and tempering heat treatment temperatures on the fatigue resistance of carburized 16MnCr5 steel. Rotating bending fatigue specimens were machined from 16MnCr (ASTM 5117)steel rod, and pack carburized at 900°C for 2 hours soaking time.

Carburized specimens were then austenized at 900°C for one hour, water quenched, reaustenized at temperatures 750°C, 800°C and 900°C for one hour, then tempered at 200°C temperature.

Other carburized specimens were tempered by heating to 760°C temperature, water quenched to room temperature, then tempered at temperatures 200°C, 300°C, and 400°C for one hour.

Austenized and tempered steel specimens after carburization as well as uncarburized steel specimens were then tested by rotating bending fatigue machine up to fracture under different stress levels (200, 250, 300, 350, 400) Mpa.

Experimental results showed that fatigue resistance of austenized steel specimens after carburization process has been increased, and the crack length developed on the specimen surfaces was decreased with an increase in austenizing temperature up to 800°C, due to lath martensitic microstructure formation, beyond this temperature fatigue resistance was decreased and crack lengths were increased due to the grain coarsening of the lath martensite.

It was also concluded that fatigue resistance of steel specimens that have been tempered after carburization process was increased, while crack lengths due to fatigue have been decreased with an increase in tempering temperatures due to the formation of tempered martensite and troostitic microstructure.

The results also revealed that uncarburized steel specimens showed a lower fatigue resistance and a higher crack lengths than those austenized and tempered specimens after carburization.

Key words: Pack carburization, austenizing temperature, tempering temperature, fatigue resistance, crack length, lath martensite, troostite.

تأثير درجات حرارة المعالجات الحرارية لتكون الاوستنايت والمراجعة على مقاومة الكلال للصلب (ASTM 5117) 16MnCr5 المكربن

الخلاصة

تناول البحث الحالي دراسة تأثير درجات حرارة المعالجات الحرارية لتكون الاوستنايت والمراجعة على مقاومة الكلال للصلب (ASTM 5117) 16MnCr5 المكربن.

تم تحضير عينات اختبار الانحناء الدوار من عمود من الصلب نوع (ASTM 5117)16MnCr5 ، وأجريت عليها عملية كربنة صلبة عند درجة حرارة 900°م ولفترة زمنية مقدارها ساعتين.

أجريت المعالجات الحرارية على العينات المكربنة وذلك بتسخينها لمنطقة تكون الاوستنايت عند درجة حرارة 900°C ولمدة ساعة واحدة وإخمادها بالماء ثم سخنت العينات لمنطقة تكون الاوستنايت بدرجات حرارة 750°م، 800°م و 900°م ولمدة ساعة واحدة ، بعدها تم مراجعتها حرارياً عند درجة حرارة 200°م.

أجريت عملية المراجعة الحرارية على مجموعة أخرى من العينات المكربنة بتسخينها إلى درجة حرارة 760°م ومن ثم إخمادها بالماء لدرجة حرارة الغرفة، بعدها تم مراجعتها حرارياً بدرجات حرارة مقدارها 200°م ، 300°م و 400°م لمدة ساعة واحدة.

أجريت اختبارات الكلال بواسطة جهاز الانحناء الدوار و لجميع العينات المكربنة والتي تم معالجتها حرارياً عند منطقة تكون الاوستنايت والعينات المكربنة والتي تم إجراء عمليات المراجعة الحرارية عليها بالإضافة لعينات من الصلب الغير مكربن لحد الكسر تحت تأثير مستويات مختلفة من الإجهادات.

أظهرت نتائج الاختبار لعينات الصلب المعاملة حرارياً عند منطقة تكون الاوستنايت بعد كربنتها ارتفاع في مقاومة الكلال لها وانخفاض في طول الشقوق مع زيادة درجة حرارة تكون الاوستنايت ولغاية الدرجة الحرارية 800°م بسبب تكون التركيب المارتنسايتي اللوحي، بعد هذه الدرجة لوحظ انخفاض في مقاومة الكلال وزيادة في طول الشقوق بسبب زيادة حجم حبيبات المارتنسايت.

استنتج أيضا ارتفاع في مقاومة الكلال للعينات التي أجريت عليها المراجعة وانخفاض في طول الشقوق الناتجة من الكلال مع ارتفاع درجة حرارة المراجعة بسبب تكون المارتنسايت المراجع والتروستايت.

بينت نتائج الاختبار أيضاً انخفاض في مقاومة الكلال وزيادة في طول الشقوق الناتجة لعينات الصلب غير المكربنة مقارنة مع تلك العينات المكربنة والتي أجريت عليها المعالجات الحرارية عند منطقة تكون الاوستنايت والعينات التي تم مراجعتها بعد عملية الكربنة.

الكلمات الدالة: الكربنة الصلبة، درجة حرارة تكون الاوستنايت، درجة حرارة المراجعة، مقاومة الكلال، طول الشق، المارتنسايت اللوحي، التروستايت.

Introduction

Carburization is the process of saturating the surface layers of steel with carbon to harden low carbon steel that not respond to quenching and tempering. Carburization results in a gradual increase in carbon content and carbide volume from the surface to the bulk resulting in a gradual alteration of mechanical properties and providing a relatively soft and tough core. Steel which has been carburized and quenched has a high fatigue limit and widely used as a material of automobiles, form implements machines, gears, spring and high strength wires [1,2].

The development of new steel led to have advances in the fatigue performance of automotive components. These advances have led to increased life by increasing the surface yield stress and introduce a residual compressive stresses to decrease the surface cyclic tensile stresses which enhances the fatigue performance of steel [3].

Most of the fatigue failures begin on the surfaces of the components and as many engineering parts work under cyclic applied stresses, cyclic failure is a major concern, and the fatigue test therefore is a useful method to evaluate the effect of carburizing process on the fatigue resistance of engineering elements working under cyclic applied load [4].

In consequence, the results of the effects of several variables on pitting life of carburized steel were analyzed by a geared roller test machine showed an improvement in contact fatigue resistance with an associated reduction of retained austenite at the surface [5].

It was shown previously that as a fatigue crack has been nucleated, its rate and direction of growth are controlled by localized stresses and by the structure of the material at the crack tip[6].Accordingly (Chakravarthula et. al. 2005)[7] showed that fatigue crack growth rate inside grains in a coarse-grained iron-silicon alloy was much higher than that at grain boundaries.

Earlier study showed that there is a linear relationship between grain diameter squared and hold time and grain growth kinetics were faster for specimens with a higher austenizing temperature. Experiments that have been conducted on AISI 4140 steel showed that the grain size after 850°Caustenizing temperature and 60 minute hold time was 0.0150 mm, while the grain size of the same material was measured to be 0.0249 mm after 900°Caustenizing temperature and 180 minute hold time. This means that the growth ratio in grains were 1.66 as the austenizing temperature and hold time were increased from 850°C and 60 minute to 900°C and 180 minute hold time [8]. As the grain diameter grows, planner slip increases, causing the grain boundaries to control the rate of cracking. Cracking initiates at grain boundaries in polycrystalline materials at high strain rates, this seems to be the preferred site for crack nucleation [6]

Osman Asi[9] analyzed fatigue failure of a hardened and tempered rear axle shaft AISI 4140 steel of an automobile was analyzed and the results of the study indicated that the axle shaft fractured in reversed bending fatigue as a result of improper welding of hardened material of low ductility in the heat affected zone, stress concentration points and inclusions in the structure that served as a nuclei for fatigue crack [9].

16MnCr5(ASTM 5117) steel are widely used for manufacturing gears, pins, shafts, clutches, plates and camshafts after quenching and tempering.

So the aim of the present investigation was to study the effects of austenizing and tempering heat treatment temperatures on the fatigue resistance and fatigue crack length of carburized 16MnCr5 (ASTM 5117)steel.

Materials and Experimental procedures

Material

The material used for the present investigation was 16MnCr5 (ASTM 5117) steel, its chemical composition as measured by Bruker S1 Turbo SD (XRF analyzer) is C:0.2, Si :0.3, Mn:1.15, Sn:0.025 and Cr:0.9 percent. Fig.1shows the microstructure of 16MnCr5 (ASTM 5117) steel before heat treatments.

Fatigue specimens

Rotating bending fatigue specimens were cut from 16MnCr5 (ASTM 5117) steel rod of 15 mm diameter and machined to 12 mm at gripping zone and 7.5 mm at gauge length as shown in Fig. 2.

Carburization

Rotating bending fatigue specimens were pack carburized. They were heated in powder mixture of 85% Coal and 15%$BaCO_3$ at temperature 900°C for 2 hours soaking time by using a box which was designed and fabricated for such process.

The residual air in the box combined with carbon and produced CO gas.

The unstable monoxide gas decomposes upon contacting the steel surfaces by reaction:

$2CO = C + CO_2$

The atomic carbon enters steel through the following reaction

$Fe + 2\,CO = Fe\,(C) + CO_2$

$BaCO_3$ activates the carburization process, decomposes and form carbon monoxide [2].

$BaCO_3 \rightarrow BaO + CO_2$

$C + CO_2 = 2\ CO$

As a result the specimen surface has been saturated with carbon to a depth of 0.5 mm as shown in Fig. 3.

Austenizing heat treatments

To determine the effect of austenizing temperature on the fatigue resistance and crack length, carburized specimens were austenized at 900°C temperature for one hour, water quenched reaustenized at temperatures 750°, 800°C and 900°C for one hour and tempered at 200°C.

Fig.4 shows the microstructure of 16MnCr5 (ASTM 5117) steel specimens that have been austenized after carburization.

Tempering heat treatments

The effect of tempering temperatures on the fatigue resistance and crack length were also analyzed. Carburized specimens were heat treated by heating to 760°C, water quenched to room temperature, then tempered at temperatures 200°C, 300°C and 400°C for one hour to relieve the internal stresses that have been set up after carburization process due to rapid cooling from the hardening process and to reduce their brittleness [2].

Fig.5 shows the microstructure of 16MnCr5 (ASTM 5117) steel specimens that have been tempered after carburization process.

Rotating bending fatigue machine

Austenized and tempered 16MnCr5 steel specimens were then tested by using rotating bending fatigue machine according to German standard DIN 50113 [4,10] under 200, 250, 300, 350, and 400 Mpa stress levels at stress ratio of R= –1 up to fracture and the stress (Mpa) versus Number of cycles curves were then plotted.

Crack length measurements

Crack initiation and crack growth less than 100 μm length was detected by acetate tape replication method[11,12].Surface replicas were made by using small strip of transparent acetate tape. The specimen gauge length was covered by the acetate tape, with small amount of acetone applied between the surface and the tape. Acetone partially dissolves and softens the acetate tape allowing it to flow against specimen and in to the cracks. After the acetone dries, the acetate tape was removed as a replica of the surface. The cracks that have been propagated on the specimen surface were measured and detected by filler gauge and photograph [10]. Crack length was then plotted against number of cycles.

For comparison uncarburized specimens of the same material were also tested under the same stresses.

Results and Discussion

16MnCr5 (ASTM 5117) steel specimens that have been carburized at 900ºC temperature for one hour, then austenized at 750ºC, 800ºC and 900ºC temperatures (Fig. 4) showed an increase in number of cycles to failure from $702*10^3$cycle at 750ºC to $751*10^3$ cycle at 800ºC (Table.1 and Fig.6), while the crack length was decreased from 2.8 mm at 750ºC to 2.6 mm at 800ºC austenizing temperature (Table.2). The results of crack growth rates (da/dN) have been shown to decrease from 0.008 mm/cycle to 0.00475 mm/cycle (Table.2 and Fig.8).

That increase in fatigue resistance and a decrease in the crack growth rates of the steel specimens were due to the formation of fine lath martensitic microstructure with retained austenite (Fig.4) on the surface layer of the steel specimens.

Fig.4-A clearly shows a fine lath martensitic microstructure with retained austenite at 750ºC austenizing temperature, and as austenizing temperature was increased to 800ºC the volume fraction of lath martensite was increased as shown in fig.4-B, as a result the number of cycles to failure were increased and the crack lengths with crack growth rates were decreased.

The increase in fatigue resistance and a decrease in the crack length and crack growth rate of carburized steel specimens after austenization was also due to an increase in the surface hardness of the steel specimens due to an increase in the C% and martensitic transformation which acts as a barrier for both crack initiation and crack propagation on the steel surfaces, as well as martensitic transformation decreased the strain localization and micro cracks that have been formed due to persistent slip bands which accumulate at grain boundaries on the steel surface [13] .

Earlier study showed that initiation of fatigue cracks are in close relation to surface and subsurface material properties [14].

Also austenization process after carburization led to an increase in the time period of crack initiation and retard crack nucleation [6].

Carburization also enhanced the compressive residual stresses in the surface regions of the steel and act in a reverse direction to the tensile stresses induced on the surfaces due to applied load, which are primarily responsible for both crack initiation and crack propagation on the steel surface [10], more over carburization led to the formation of a dispersed carbides in the surface regions of the steel which acts as a barrier to the dislocation movement that have been responsible for the extrusion and intrusion process in the surface layers of the steel specimens, as a result an increase in the fatigue resistance and a decrease in both crack length and crack growth rates have been gained [10].

As austenizing temperature was more increased to 900°C, the number of cycles to failure have been decreased to $454*10^3$ (Table.1 and Fig.6), while both the crack length and crack growth rate were increased to be 3.27 mm and 0.00525 mm/cycle respectively (Table.2)(Fig.7 and Fig.8), which clearly reveal a decrease in the fatigue resistance of the steel at 900°C austenizing temperature. That decrease in the fatigue resistance and increase in crack length and crack growth rate were due to grain coarsening of the lath martensite in the retained austenite case of the steel (Fig.4 – C) at 900°C austenizing temperature, due to its lower strength to fatigue as compared to a fine lath martensite as a result the cracks were grown under the cyclic load of constant amplitude due to increased crack tip stress intensity [15].

Rotating bending fatigue tests were also conducted on tempered specimens to analyze the effect of tempering temperatures on the fatigue resistance and crack length of 16MnCr5 carburized steel.

Quenched steel after carburizing, consist of plate martensite and retained austenite case as shown in Fig.3 [3,16,17]. The steel is harder than needed and brittle, also severe internal stresses are set up during the rapid cooling from carburizing temperature, all that affect the fatigue strength and crack length of carburized steel specimens. To relieve the internal stresses, reduce brittleness, decrease hardness and increase ductility and impact fatigue strength, steel specimens were tempered after carburization [2,18].

Carburized 16MnCr5 steel specimens were heat treated by heating to 760°C, water quenched to room temperature, then tempered at 200°C, 300°C and 400°C for one hour. Tempered specimens were then tested by rotating bending fatigue machine under (200, 250, 300, 350 and 400) Mpa, stress levels up to fracture and Tables. 3 and 4 were listed, and Figs.9 to Fig.11 were plotted. Fig.9 represents the variation between stress level (Mpa), with number of cycles for uncarburized 16MnCr5 steel specimens and those specimens that have been tempered at different tempering temperatures.

As tempering temperature was increased from 200ºC to 400ºC, the number of cycles to failure were found to increase from $853*10^3$ cycle (at 200ºC) to $900*10^3$ cycle (at 300ºC) (Table.3 and Fig.9), while the crack length was decreased from 2.53 mm (at 200ºC) to 2.5 mm (at 300ºC) tempering temperatures (Table.4 and Fig.10), and the results of crack growth rates (da/dN) were found to decrease from 0.003425 mm/cycle (at 200ºC) to 0.002875 mm/cycle (at 300ºC) (Table.4 and Fig.11). That increase in the fatigue resistance and a decrease in the crack growth rate of the steel with tempering temperature were due to tempered martensitic microstructure (Fig.5-A) that has been formed on the steel surface.

As tempering temperature was increased to 300ºC, a surface regions of troostitic microstructure was found (Fig. 5-B), and at 400ºC tempering temperature, a uniform troostitic microstructure (Fig. 5-C) was distributed on the surface area of the steel which increased the number of cycles to failure to $950*10^3$ cycle (Table.3 and Fig.9), while the crack length and the crack growth rate were decreased to 2.55 mm and 0.002125 mm/cycle respectively (Table.4) (Fig.10 and Fig.11).

That increase in fatigue resistance (Fig.9) and a decrease in both crack length (Fig.10) and crack growth rate (fig.11) of tempered steel specimens were also due to internal stress relief that have been set up due to rapid cooling of 16MnCr5 steel specimens after carburization process and the brittleness reduction, which led to a definite improvement in the steel physical properties [2].

The results listed in Table.1 to Table.3 and plotted in Fig.5 to Fig.10 show that the maximum number of cycles to failure for uncarburized steel specimens was $474*10^3$ (Table.1 and Fig.6) and the maximum crack length was 7.5 mm with crack growth rate value (da/dN) of 0.01375 mm/cycle (Table.2 and Fig.7), which best reveals a lower fatigue resistance of uncarburized specimens as compared to those austenized and tempered steel specimens after carburization. This is because the microstructure of uncarburized steel specimens was ferrite and pearlite (Fig.1) and the affinity of cracks to grow through interface of ferrite and pearlite microstructure of uncarburized specimens [19], which result to intergranular cracking in the specimens due to direct quenching after carburization [15, 16, 17].

As rotating bending fatigue tests were continued those cracks propagate as stable transgranular cracks, which eventually reach critical length and propagate as unstable intergranular cracks, which led to a large increase in crack length of uncarburized specimens [3,16].

Conclusions

1. Fatigue resistance of carburized then austenized 16MnCr5 (ASTM 5117) steel specimens have been increased with an increase in austenizing temperature up to 800°C due to lath martensitic microstructure formation.
2. Carburized steel specimens that have been austenized at 900°C, showed a lower fatigue resistance and a higher crack length than those specimens austenized at 750°C and 800°C due to the grain coarsening of lath martensite .
3. Fatigue resistance of uncarburized steel specimens, were much lower than those carburized and then austenized specimens.
4. Crack length of carburized and austenized steel specimens have been decreased with an increase in austenizing temperature up to 800°C.
5. Crack length of uncarburized steel specimens were much higher than both carburized and then austenized and carburized and then tempered steel specimens due to the formation of tempered martensite and troostitic microstructure.
6. Fatigue resistance of carburized and tempered steel specimens have been increased with an increase in tempering temperature.
7. Carburized and tempered steel specimens, showed a lower crack length and a higher fatigue resistance than those carburized and austenized steel specimens.

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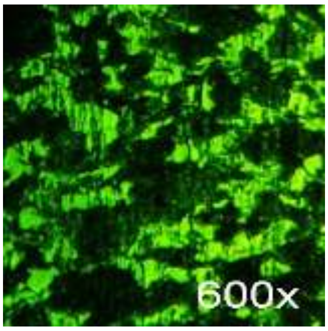


Fig(1) The microstructure of 16MnCr5 (ASTM 5117) steel before heat treatments.

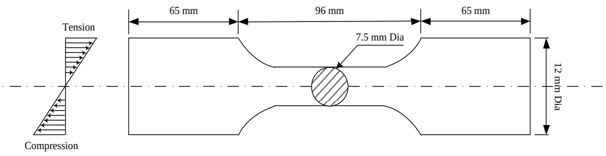


Fig.(2) Rotating bending fatigue specimen.

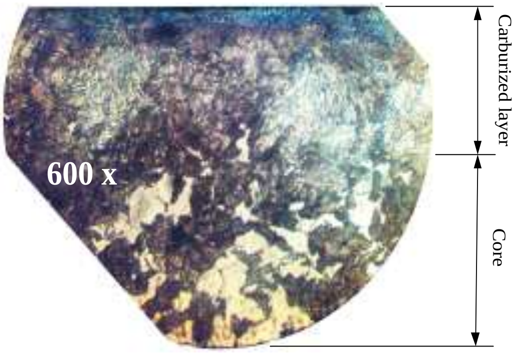
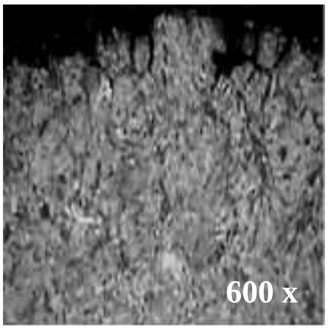
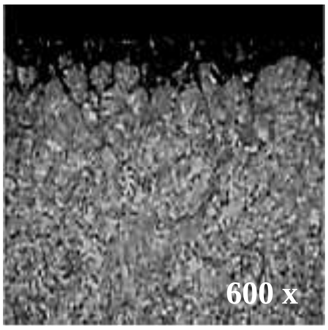


Fig.(3) The microstructure of carburized 16MnCr5 (ASTM 5117) steel before heat treatments.



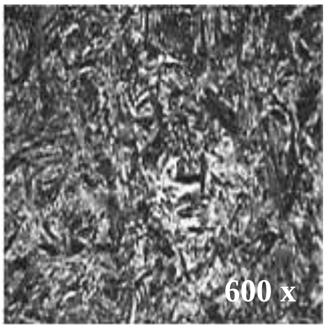
A

750ºC Austenizing temperature. (Fine lath martensitic surface with retained austenite).



B

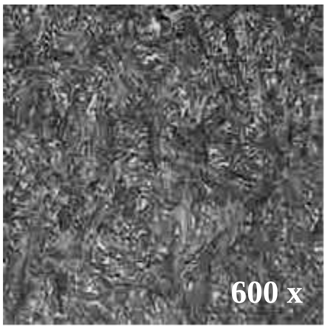
800ºC Austenizing temperature. (lath martensitic surface with retained austenite).



C

900ºC Austenizing temperature. (Coarse lath martensitic surface with retained austenite).

Fig.(4) The microstructure of austenized 16MnCr5 (ASTM 5117) steel after carburization.



A

200°C Tempering Temperature. (Tempered martensite)

B

300°C Tempering temperature. (Troostite)

C

400°C Tempering temperature. (Troostite)

Fig.(5) The microstructure of Tempered 16MnCr5 (ASTM 5117) steel specimens after carburization.

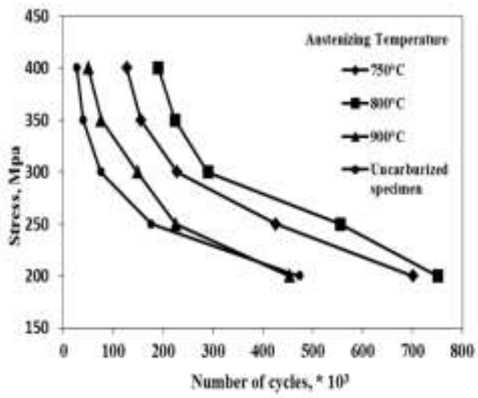


Fig.(6) Stress versus number of cycles for austenized 16MnCr5 (ASTM 5117) steel specimens after carburization process.

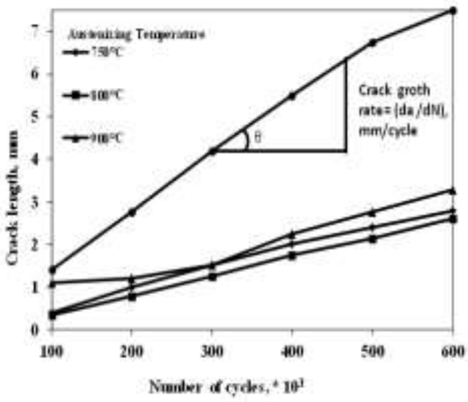


Fig.(7) Crack lengths versus number of cycles for austenized 16MnCr5 (ASTM 5117) steel specimens after carburization.

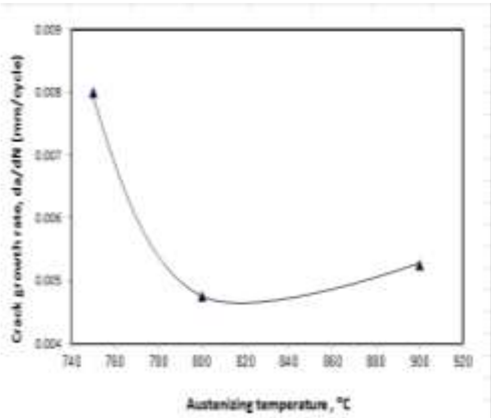


Fig.(8) Crack growth rate as a function of austenizing temperature for tempered 16MnCr5 (ASTM 5117) steel specimens.

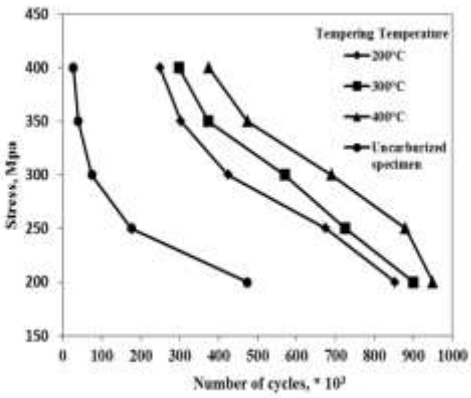


Fig.(9) Stress versus number of cycles for tempered 16MnCr5 (ASTM 5117)steel specimens after carburization.

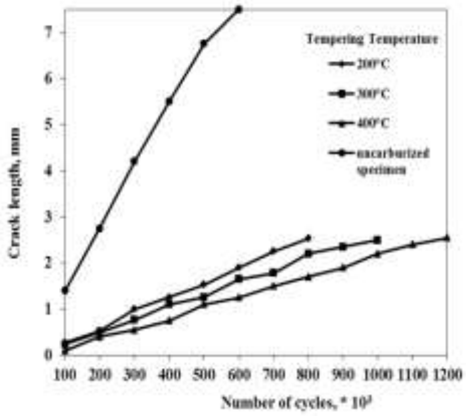


Fig.(10)Crack lengths versus number of cycles for tempered 16MnCr5 (ASTM 5117) steel specimens after carburization.

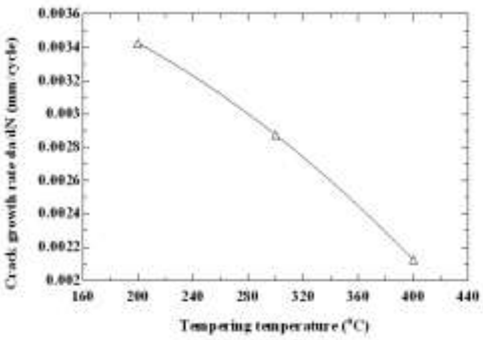


Fig.(11) Crack growth rate as a function of tempering temperature for tempered 16MnCr5 (ASTM 5117) steel specimens.

Table.(1) The values of stress and number of cycles up to fracture for austenized 16MnCr5 (ASTM5117) steel specimens at different austenizing temperatures.

Stress, Mpa	Number of cycles * 10^3			
	750°C Austenizing temperature	800°C Austenizing temperature	900°C Austenizing temperature	Uncarburized specimens
400	127	190	50	27
350	155	224	76	40
300	228	290	149	75
250	426	555	225	176
200	702	751	454	474

Table.(2) The values of crack length and number of cycles for austenized 16MnCr5 (ASTM 5117) steel specimens at different austenizing temperatures.

Number of cycles, * 10^3	Crack length, mm			
	750°C Austenizing temperature	800°C Austenizing temperature	900°C Austenizing temperature	Uncarburized specimens
100	0.4	0.35	1.1	1.44
200	1	0.79	1.2	2.75
300	1.5	1.25	1.52	4.2
400	2	1.74	2.25	5.5
500	2.4	2.15	2.76	6.75
600	2.8	2.6	3.27	7.5
Crack growth rate da/dN, mm/cycle	0.008	0.00475	0.00525	0.01375

Table(3) The values of stress and number of cycles to fracture for tempered 16MnCr5 (ASTM 5117) steel specimens at different tempering temperatures.

Stress, Mpa	Number of cycles * 10^3			
	200°C Tempering temperature	300°C Tempering temperature	400°C Tempering temperature	Uncarburized specimens
400	250	298	375	27
350	304	374	475	40
300	425	570	690	75
250	675	725	880	176
200	853	900	950	474

Table(4) The values of crack length and number of cycles for tempered 16MnCr5 (ASTM 5117) steel specimens at different tempering temperatures.

Number of cycles, * 10^3	Crack length, mm			
	200°C Tempering temperature	300°C Tempering temperature	400°C Tempering temperature	Uncarburized specimens
100	0.27	0.24	0.1	1.4
200	0.53	0.5	0.4	2.75
300	1	0.76	0.55	4.2
400	1.26	1.1	0.75	5.5
500	1.53	1.26	1.1	6.75
600	1.9	1.65	1.25	7.5
700	2.25	1.78	1.5	
800	2.53	2.2	1.7	
900		2.35	1.9	
1000		2.5	2.2	
1100			2.4	
1200			2.55	
Crack growth rate da/dN, mm/cycle	0.003425	0.002875	0.002125	0.01375