Effect of Cryogenic Treatment on the Properties of Low Carbon A858 Steel

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Abstract

This study is concerned with the effect of Deep Cryogenic Treatment (DCT) at liquid nitrogen temperature (-196 ^{o}C) on the mechanical properties and performance of low carbon steel (A858).

The tests specimens were divided in to two groups, the first group was subjected to the conventional heat treatment of normalizing, and the second group was also normalized then subjected to (DCT).

The results have shown that after (DCT), the Hardness, Tensile properties and the impact energy absorbed were all slightly increased. However the fatigue test showed some positive improvement in fatigue limit by 20(N/mm^2), and the volume wear rates at different loads were significantly decreased after (DCT).

The changes in microstructure due to (DCT) were clearly noticeable, the grain boundaries were no longer visible, and the Pearlite isles globalization was obvious.

Key Word: DCT, wear, fatigue limit; microstructure

تأثير المعاملة الزمهريرية العميقة على خواص فولاذ منخفض الكربون

الخلاصة

هذه الدراسة تتركز على تأثير المعاملة الزمهريرية العميقة عند درجة حرارة النتروجين المسال والبالغة (-196^{o}C) على الخواص الميكانيكية وخواص الأداء للفولاذ منخفض الكربون A858 .

عينات الاختبار قسمت إلى مجموعتين استنادا إلى ما قبل وما بعد المعاملة الزمهريرية ، المجموعة الأولى تضمنت المعاملة الحرارية التقليدية للفولاذ وهي التطبيع، والمجموعة الثانية تضمنت المعاملة الزمهريرية ما بعد معاملة التطبيع.تم مقارنته نتائج الخواص الميكانيكية الناتجة بالمعاملة الزمهريرية العميقة مع تلك التي لم تتم معاملتها بهذه الطريقة. أن الاختبارات الميكانيكية تضمنت اختبارات الصلادة، الشد والصدمة بينما اختبارات الأداء تمثلت باختبارات الكلال والبلى.

اظهرت نتائج الاختبارات بعد أجراء المعاملة الزمهريرية العميقة ، زيادة قليلة في قيم الصلادة وخواص الشد (جهد الخضوع، المقاومة القصوى ، الاستطالة النسبية) وطاقة الصدم.

أختبار الكلال أظهر تحسينات ايجابية في قيم حد الكلال ما بعد المعاملة الزمهريرية ، حيث انها ازدادت بمقدار20 ن/ملم2. وبالنسبة لمعدل البلى ألحجمي عند أحمال مختلفة فقد أنخفض بعد المعاملة الزمهريرية بنسبة كبيرة ، مما يعني ان المعاملة الزمهريرية العميقة تحسن مقاومة البلي للفولاذ منخفض الكربون.

التغيرات في البنية المجهرية نتيجة المعاملة الزمهريرية كانت واضحة لهذا الفولاذ، حيث ان الحدود البلورية لم تظهر وحدث تكتل للبيرلايت بشكل واضح .

1. Introduction

Cryogenic treatment is a supplementary heat treatment that is performed on some finished steel component as an effective method to improve their performance. Two types of cryogenic treatments are generally applied, the shallow cryogenic treatment which is performed between (-60 ^{o}C) and (-90 ^{o}C), and the deep cryogenic treatment that is conducted at temperatures below (-196 ^{o}C).

Meng et al [1994] studied the wear resistance and microstructure of Fe–12Cr–Mo–V-1.4C tool steel both with and without cryogenic treatment. The study reveals that cryogenically treated samples show improvement from 110% to 600% through sliding wear test. From the microstructure of the steel it is reported that the improvement in wear resistance after cryogenic treatment can be attributed to eta-carbides precipitates.

Mohan Lal et al. [2001] studied the improvement in wear resistance and the significance of treatment parameters in AISI T1, M2, and D3 tool steel. It was found that cryogenic treatment imparts nearly 110% improvement in tool life. The un-tempered samples when cryogenically treated, yield 3%, 10%, and 10.6% extra life over tempered and cryogenically treated samples, respectively. Tempered samples when cryogenically treated at 133K for 24 hrs yielded negative results, but when cryogenically treated at 93K for 24 hrs, the results were favorable. The prescribed cycle yields 20% extra life as compared to the maximum life achieved through cold treatment.

Johan Singh et al. [2003] investigated the effect of cryogenic treatment on the axial fatigue performance of fillet welded cruciform joints of AISI 304L stainless steel, which failed in the weld metal. It has been observed that after the deep cryogenic treatment at 88 K, the fatigue life improved almost by a factor of two. During the treatment, significant microstructural changes that occurred accounted for the improved fatigue performance. Strain induced martensitic transformation was observed. During this transformation, the weld metal tends to expanded inducing compressive residual stresses in the weld metal.

Bensely et al. [2006] studied the effect of cryogenic treatment on the wear resistance of case carburized steel-En 353. Pin on disk wear test was carried out for three different load conditions and seven sliding speeds for the samples, which have undergone three different treatment conditions, conventional heat treatment (CHT), shallow cryogenic treatment (SCT), and deep cryogenic treatment (DCT). It was found that the wear resistance had been considerably increased due to SCT and DCT when compared to CHT. The study concluded that for better wear resistance, it is advisable to go for deep cryogenic treatment.

Hao-huai Liu et al. [2007] investigated the effects of (DCT) on the microstructure, hardening and abrasion resistance of 3Cr13Mo1V1.5 high chromium cast iron. The results showed that deep cryogenically treated specimens after sub-critical treatment had an increase in hardness and abrasion resistance. This was due to abundant retained austenite transforming into martensite and secondary carbides precipitation.

Franjo Cajner et al [2009] discussed the effect of deep-cryogenic treatment on impact fracture toughness, erosion wear resistance, and the microstructure of PM S390 MC high speed steel. A set of test samples was heat treated by conventional methods (hardened and three times high temperature tempered), and the other set were deep cryogenic treated. They concluded that the application of deep-cryogenic treatment results in significantly higher wear resistance, but no significant improvements in toughness have been observed.

G.Z. Ma, D. Chen et al [2010], studied a martensitic phase transformation from the B2 to the B19'CuZr phase in the Cu-Zr-Al bulk metallic glass (BMG) composite was induced by cryogenic treatment. The martensitic transformation causes the improvements of the microhardness and the ultimate compression fracture strength. When the cryogenic treatment time was 72 h, the microhardness and the ultimate compression fracture strength of the BMG composite increased about 18.55% and 37.5%, respectively.

The present work is aimed to study the effect of deep cryogenic treatment (DCT)

on the mechanical properties and performance of low carbon steel A858. In addition a comparison study of the obtained results from mechanical and microstructure tests with specimen's conventionally heat treatment (CHT).

Table (1): Chemical composition of A858 steel.

Element%	C	Si	Mn	Fe
Composition	0.13	0.25	0.45	Bal.

2. Expermential

2.1. Sample preparation

Commercially available 30mm diameter bar stock of A858 raw material was procured. In order to confirm the composition of the material, a chemical analysis of the steels was carried out by (Thermo ARL3460, optical Emission spectrometer), the results of which are shown in Table (1).

2.2 Heat treatment

All the specimens for fatigue, wear, tensile and impact tests were normalized; it was heated to a temperature of (900 °C) for a period of 20 minutes and then air cooled.

2.3 Deep Cryogenic Treatment (DCT).

To compare the effect of the cryogenic treatment on the mechanical properties and the performance of the A858 steel, the present work involves Deep Cryogenic Treatment by soaking the steel specimens at very low temperatures (-196 ^{o}C), using liquid nitrogen as the cooling medium. To avoid thermal shock due to quick quenching, the specimens were protected by a 10 mm all around shield of paraffin wax. It took 20 minutes for the specimens to reach the (-196 ^{o}C) from ambient temperature or approximately a cooling rate of 11 °C/min. Once the soak temperature (-196 ^{o}C) is reached the components are held at that temperature for a period of 24 hours .The cryogenic treatment of the samples were done in a cryogenic chamber which is fully covered with multilayer super insulation and is filled with liquid nitrogen which is used as the cooling medium.

After cryogenic treatment, a stress relieving process was applied by heating the specimens to (200 ^{o}C) for one hour and cooled in air to room temperature.

2.4 Mechanical Tests

2.4.1 Hardness Test

Brinell hardness test (HRB) was used and the Vickers hardness number (VHN) of the samples was also calculated from tables.

2.4.2 Tensile Test

The tensile test was carried out according to American Society for testing Material (ASTM) A370-05.A rod tensile specimen of geometry and dimensions shown in Figure (1).

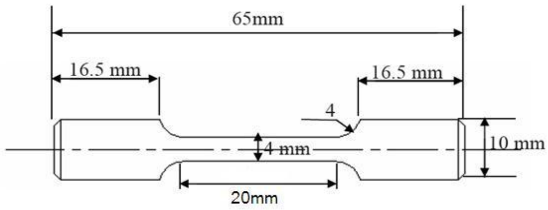

Fig. (1): Tensile Specimen.

2.4.3 Impact Test

An Izod impact test was carried out according to American Society for testing Material ASTM (E23) Izod cantilever beam type Y. Three specimens for each group were used to perform the Impact test. The average value of three tests was recorded. Figure (2) shows the impact test specimen.

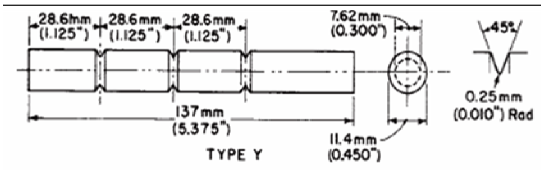

Fig.(2): Izod Impact Specimen.

2.5 Performance Test

2.5.1 Fatigue Test

A rotating bending fatigue machine was used to carry out the fatigue testing . A maximum capacity of (+800 N/mm^2) and a speed of (6000 rpm) were available with a capability of applying different stress levels with zero mean stress(stress ratio equal to (-1).Al the tests were performed at room temperature. The specimens are subjected to an applied load from the right side perpendicular to the axis of specimen and hence a bending moment is developed. The shape and dimensions of fatigue specimens used in the experimental work are as shown in figure (3). During manufacturing of the specimens, careful control was taken to produce a good surface finish and to minimize residual stresses. The outer surface at the reduced section of all fatigue specimens was polished to eliminate the effect of surface roughness caused by machining, hence all specimens obtained similar surface finish by using different grades of emery papers (400,600,800, 1200m1800 and 2000) .

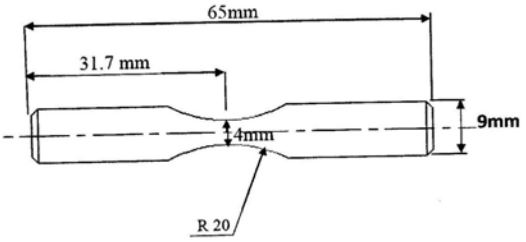

Fig.(3): Fatigue test Specimen.

2.5.2 Wear Test

Dry sliding wear tests were carried out on a pin on disc wear testing machine. The rotating friction disc was made of tool steel (surface hardness ≈385 VHN) , The wear tests were carried using three different normal loads :15 N, 25N and 40N at a constant linear sliding velocity of 2 ms−1, in dry condition at a room temperature of ~25°C and the time used was 10 min for each run. The specimens were prepared according to ASTM (G99-05) standard, where 10mm diameter and 30mm length were used as static pins. The faces of the pin specimens were polished by emery papers and cleaned prior to wear test. The weight method was used to calculate the wear resistance, where the specimens was weighted before and after applied load, the volume losses is given by relation:

$$WRv = \frac{\Delta w}{2\pi r n t \rho} \quad \ldots\ldots\ldots \ (1)$$

Where:

WRv= volume wear rate in cm^3/cm

Δw =weight before applied load - weight after applied load.

ρ= Steel density =7.085 gm/cm^3

r= Effective disc radius=70 mm.

n= Friction disc rotational speed (277.4 rpm).

t= Time of applied load (10 min).

2.6 Micostructure Test

Samples for microstructure examination were ground using different grades of wet emery papers (220, 400, 800 and 1000), then polished using two grades of diamond paste (1um and 0.3 um). Distilled water and alcohol were used to clean the samples in succession. Etching was carried out using Nital etching solution (2% HNO3 in alcohol), followed by washing them with water and soup to remove stains, then rinsed with alcohol and dried. The microstructure examination is performed with an optical microscope which has a photo digital system and computerized by special imaging software. The images were photographed with a magnification of (800X).

3. Results

3.1 Hardness Test resilts

Table (2) shows the results of Rockwell Hardness tests (and its conversion to Vickers hardness) of the steel. The improvements caused by the DCT were calculated. It can be noticed that the

hardness increases after cryogenic treatment for this steels is only 2.66%.

Table (2): Results of Hardness test
(The results are averages of five tests).

Treatment	Impact energy (Kgf.m)	Improve %
Normalized	80.8333	
Normalized +DCT+T	82.8333	2.47%

3.2 Tensile test results

The tensile test results are presented in table (4) and figure (3). After DCT, the improvement in ultimate tensile strength (UTS), yield strength (σy) and elongation (ϵ %) are only moderate.

Table (3): The results of Impact test.
(Each is an average of three tests).

Heat treatment	HRB	VHN	change %
Normalized	90.2	184	
Normalized+ DCT+T	92.6	201	2.66

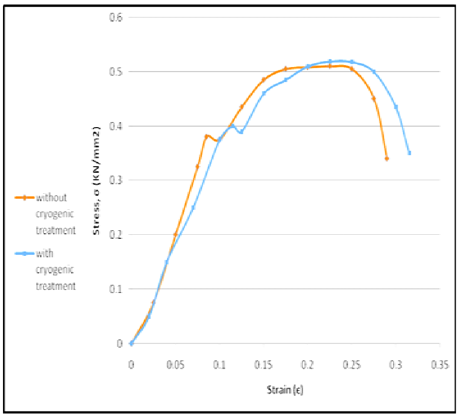

Fig.4: Tensile test profiles before and after DCT.

3.3 Impact test results

The impact test results are shown in table (5). The results show an increase in impact energy for this steel after DCT. The percent improvement is 2.47%. This improvement in this case can be attributed to the densification of the metal atoms and removal of residual stress.

Table (4): The results of tensile test.

treatment	UTS KN/mm^2	σy KN/mm^2	ϵ%
Normalized	0.49	0.365	29.5
Normalized +CD+T	0.514	0.385	32

3.4 Fatigue test results

The fatigue test results for the normalized steel before and after DCT are presented in the forms of (S-N) curves as shown figure (5).Seven specimens were used to construct each curve.

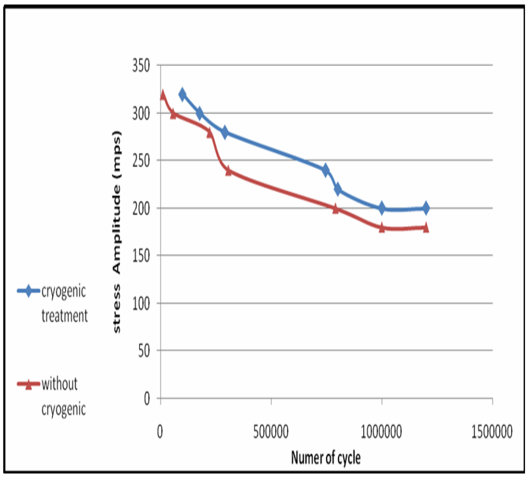

Fig. 5: S-N Curves before and after DCT.

3.5 Wear test results

The wear rates (WR) have been calculated as volume wear loss (cm^3) per unit sliding distance (cm) corresponding to the steady-state wear regime. The relation between the load and volume wear rate are shown in figures (6) and (7).They indicates a clear and significant improvement in wear resistance after DCT at all loads.

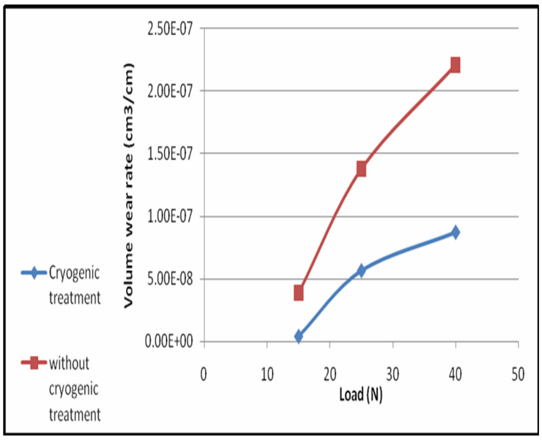

Fig. (6): The relation between the load and Volume wear rate.

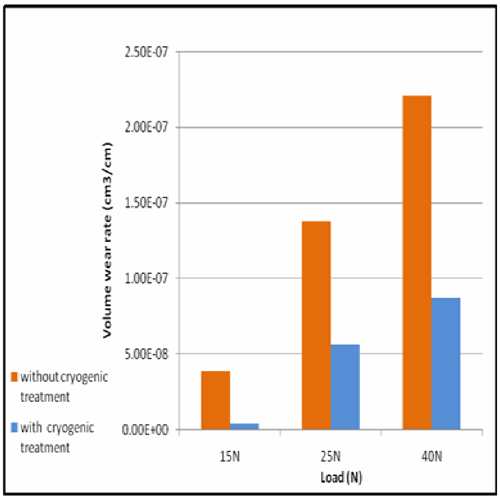

Fig. (7): Histogram showing the effect of DCT on wear rate.

5. Microstructure Tests

Figure (8) shows the microstructure of the normalized steel, and figure (9) shows the microstructure of the normalized steel after DCT, It can be observed that the microstructure contains usual phases which are present in this type of steel i.e. Ferrite (α-iron) and Pearlite (Fe_3C+α-iron).However there are clear difference between them in which after DCT, the morphology of both phases are completely different, in which no grain boundaries can be seen and the Pearlite became globules.

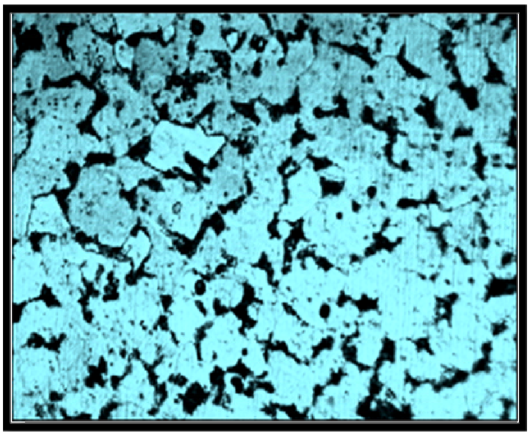

Fig.(8):Microstructure of normalized Steel before DCT, showing normal ferrite and pearlite(Dark) at grain boundaries.

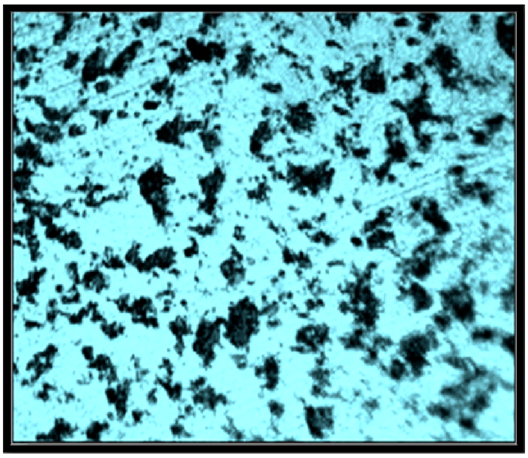

Fig.(9):Microstructure of normalized Steel after DCT. Showing (globalization) of Pearlite and no grain boundaries are visible.

6. Discussion

The main general aim of DCT is to improve the performance of the component, the result of all inspection showed significant improved performance in respect to fatigue and wear resistance .These are the most important aspects of

the mechanical parts, which are subjected to dynamic loading. The tested steel showed noticeable increase in fatigue limit, hence it can be concluded that DCT does improve the fatigue life of low carbon steel.

As for wear resistance improvement, the result was positive, and best performance was found at lower load (15N), this is a low carbon steel containing only (0.13%C) in normalize condition contains ferrite and Pearlite which is regarded a stable structure, yet it showed high response to DCT in which a major structure change occurred as shown in figure (9), although the increase in hardness was only 2%, which means that the improvement in wear resistance could be attribute to structure changes such as the (globalization) of Pearlite.

Figure (8) shows atypical structure of normalize low carbon steel, the grain and the grain boundaries are clearly shown and the Pearlite isles are distributed around the grains, generally on grain boundaries. But figure (9) in which the specimens was subject to DCT, the structure is completely different, in which the grain boundaries are no longer visible and the Pearlite isles are seem to be (globalized).

The disaperance of the grain boundary may attributed to the removal of the grain boundaries defects such as vacancies, and to the rearrangement of the grain boundary atoms, this could make the grain boundaries less vulnerable to etching solution.

As for the globalization of the Pearlite isles, a possible explanation is that due to sever contraction during DCT, the Pearlite which consist layers of hard Cementite and soft Ferrite will be squeezed by the contraction of the Ferrite matrix. However after warming up, the homogenous ferrite matrix will return back to its original shape, but the Fe3C lamella may have (cracked) hence the Pearlite can no longer regain its original shape. This may explain the (globalization) shape of the Pearlite. For this type of structure, no mention was found in the literatures.

6- Conclusions

From the results of the present investigation on the effect of cryogenic treatment on properties and structure of A858 steel, the following conclusions were drawn:

1-The hardness, ultimate tensile stress, yield stress, percentage elongation (є) and impact energy for A858 steel were all moderately increased after DCT.

2- The fatigue limit of the steel increased by 20 KN after DCT.

3-The volume wear rate decreased significantly or wears resistance increased after DCT and best wear resistance was at (15N) load.

5- The grain boundaries after DCT were no longer visible, and the Pearlite isles were globalized.

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