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EFFECT OF CYCLIC HEAT TREATMENT ON MICROSTRUCTURE AND MECHANICAL PROPERTIES OF C45 STEEL

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ABSTRACT

Cyclic heat treatment consisting of repeated short duration (6 minutes) holding above the Ac_3 temperature (850 ºC) followed by forced air cooling was preformed to C45 steel. Reflected light microscope (RLM), scanning electron microscope (SEM), hardness measurement, and tensile testing were used to investigate the effect of this technique of heat treatment on both microstructure and mechanical properties of this type of steel. The obtained results indicated that refinement of the microstructure and consequently modification on mechanical properties was achieved. The grain size of both proeutectiod ferrite and pearlite was decreased and the completely lamellar pearlite started in disappearance after the first cycle. By increasing number of cycles the amount of lamellar pearlite decreased and on the other hand the amount of cementite spheroids in the pearlite grains increased. Also, the inter-lamellar spacing of lamellar pearlite decreased from 0.75 to 0.28 µm by this type of heat treatment after 10 cycles. As a result of these microstructure modifications, both hardness and ultimate tensile strength improved and in the same time the high ductility was retained.

KEYWORDS: C45 Steel, Cyclic Heat Treatment, Annealing, Ferrite, Lamellar Pearlite, Cementite Spheroids

INTRODUCTION

Metals and alloys develop requisite properties by heat treatment which plays a critical role in achieving appropriate microstructure that imparts the desired characteristics in a given material. The microstructure of most steels is well known by now as well as the effect of heat treatments in changing their mechanical properties [1]. The differences in mechanical properties of given steel are the result of different microstructures formed during cooling. The highest hardness in the iron–carbon system is obtained due to a diffusionless transformation called martensite formation and the lowest hardness is obtained due to a diffusion transformation, which causes the ferrite and/or pearlite formation by the eutectoid reaction. Both martensite obtained during rapid cooling and ferrite-pearlite obtained during slow cooling or near equilibrium, come from austenite[1]. Therefore, both the steel microstructure and the steel mechanical properties are related to steel thermal history[2].

Recent investigations have established the potential of cyclic (repeated) heat treatment techniques to accelerate several solid state metallurgical processes [3-10]. The austempering process was found to accelerate bainitic transformation in 1080 steel [3]. On the other hand, an accelerated grain growth was observed in AlK grade steel using a cyclic annealing process [4].The thermal cyclic (swinging annealing) of ± 5ºC around Ac_1 temperature was known to accelerate spheroidization process in medium and high carbon steel [5]. The thermal cyclic (swinging annealing) of ± 5ºC around Ac_1 temperature facilitates the dissolution of cementite lamellae when temperature is raised above Ac_1. On subsequent cooling below Ac_1 this dissolution is interrupted and the fragmented cementite particles coagulate moreeasily and quickly [5].A cyclic heat treatment process involving repeated short duration holding above Ac_3 temperature followed by forced air cooling accelerated spheroidization process of cementite to a greater extent in 0.6 wt% C steel [6,7]. The cyclic heat treatment process generates a microstructure of spheroidized cementite in fine grained ferrite matrix that provides an excellent combination of strengthand ductility [6]. A similar microstructure with good combination of ductility and strength properties through warm deformation of 0.36 wt% C steel at 670ºC for duration of 2 h is obtained [8].

The cyclic heat treatment process consisting of repeated short duration at 910ºC (above Ac_3) followed by forced air cooling leads to a new type of microstructural development in 0.16 wt% C steel. The main features include grain refinement, dislocation generation (in early cycles) and annihilation (later cycles) and development of grain boundary cementite network and clusters through divorced eutectiodal reaction [9]. The major extent of grain refinement takes place at early stages (up to 2 cycles) through nucleation of fine austenite grains and their transformation to fine ferrite grains during forced air cooling. The growth of nucleated austenite grains is restricted by the short holding time (6 min) and the presence of undissolved cementite [9]. The strength is achieved with 2 cycles of heat treatment, not with conventional heat treatment involving single cycle. This is attributed to fine ferrite grain size, high dislocation density of ferrite grains, an adequate amount of fine lamellar pearlite and lower proportion of grain boundary cementite in the microstructure [9].

Other heat treatment processes such as austempering treatment of bearing steel produces an optimum duplex microstructure of bainite and martensite. It also providesan excellent combination of hardness, strength and toughness [10].Low and high carbon steels have received considerable attention in studying the effect of cyclic heat treatment on metallurgical and mechanical properties. There is lack of information about medium carbon steel in this regard. Therefore, it is aimed in this study to investigate the effect of cyclic heat treatment on the microstructure and mechanical properties of medium carbon steel C45.

MATERIALS AND METHODS

The chemical composition (in wt%) of C45 steel used in this investigation is given in Table 1. As received steel bar of 55mm diameter and 250mm length was homogenizing annealed at 1100 ºC for 1 hr. Specimens of dimensions 20mm×10mm×2mm were cut from the homogenizing annealed bar using enough flow of coolant (water) to prevent a rise in temperature and consequently microstructural changes. These specimens were subjected tocyclicheat treatment for different number of cycles. Each cycle was consisted of holding the specimen for 6 minutes in a muffle furnace at 850 ºC, then withdrawn and forced air cooled to room temperature. The air flow rate was maintained at $5m^3/h$. This flow rate was suitable to cool the specimen to room temperature in 3 minutes.

Both homogenizing annealed and cyclic heat treated specimens were mounted in epoxy, sectioned, ground with successive grades of emery papers up to 1200 grit and polished using 1µm diamond paste. The polished specimens were etched by 2% nital and examined using both Meiji reflected light microscope (RLM) and JEOL JSM5410 scanning electron microscope (SEM). The grain size was measured according to E112ASTM standard [5].

The hardness of both homogenizing annealed and cyclic heat treated specimens were measured using LECO Vickers hardness tester LV800AT. Tensile tests were carried out according to E8 ASTM standard [11].

Table 1: Chemical Composition (In Wt%) of C45 Steel Used

C	Si	Mn	Cr	Ni	Cu	S	P
0.46	0.27	0.74	0.12	0.18	0.17	0.028	0.025

RESULTS AND DISCUSSION

Microstructure

The microstructure of as-received and annealed specimens is shown in Figure (1) and (2), respectively. It is clear that the microstructure for the two specimens was more or less homogeneous and it consists of proeutectiod ferrite (43% volume fraction) and pearlite (57% volume fraction). The grain size of ferrite for as-received was 43µm and increased to be 116µm by homogenizing annealing. The pearlite grain size also increased from 64µm for as-received to be 158µm by annealing. This means that structure became coarser by homogenizing annealing. For the two specimens, as-received and annealed the pearlite phase was almost completely lamellar.

The microstructure of cyclic heat treated specimens for different number of cycles is given in Figure (3) and (8). The average grain size of proeutectiod ferrite and pearlite was measured and the obtained values are listed in Table 2. Generally, the average grain size of both proeutectiod ferrite and pearlite decreased by this type of heat treatment. The grain size of both proeutectiod ferrite and pearlite was abruptly decreased after the first cycle, and then gradually decreased with the increase in number of cycles. The completely lamellar pearlite started to disappear after the first cycle. By increasing the number of cycles, the amount of lamellar pearlite decreased and on the other hand the amount of cementite spheroids in the pearlite grains increased.

Table 2: Effect of Cyclic Heat Treatment on Average Grain Size of Both Proeutectiod Ferrite and Pearlite

Number of cycles Average Grain Size	After 0 Cycle (Annealed)	After 1 Cycle	After 2 Cycles	After 4 Cycles	After 6 Cycles	After 8 Cycles	After 10 Cycles
Average grain size of ferrite, µm	116	32	22	18	11	10	8
Average grain size of pearlite, µm	158	77	40	37	31	30	28

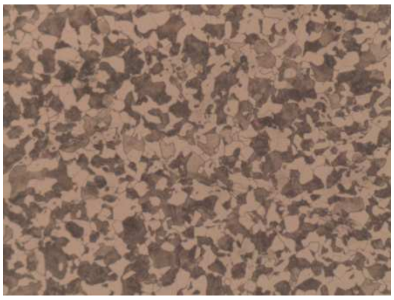

Figure 1: Microstructure of As-Received C45 Steel Specimen (200×)

Figure 2: Microstructure of As-Received Annealed C45 Steel Specimen (200×)

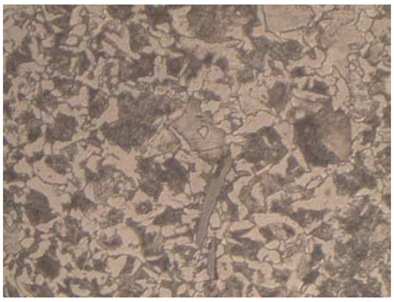

Figure 3: Microstructure of Cyclic Heat Treated Specimen, 1 Cycle (200×)

Figure 4: Microstructure of Cyclic Heat Treated Specimen, 2 Cycles (500×)

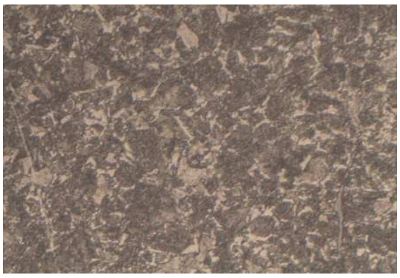

Figure 5: Microstructure of Cyclic Heat Treated Specimen, 4 Cycles (200×)

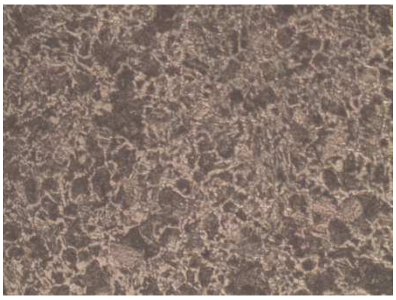

Figure 6: Microstructure of Cyclic Heat Treated Specimen, 6 Cycles (200×)

Figure 7: Microstructure of Cyclic Heat Treated Specimen, 8 Cycles (200×)

Figure 8: Microstructure of Cyclic Heat Treated Specimen, 10 Cycles (200×)

Figure (9) and (10) represent the scanning electron microscope (SEM) photomicrographs of annealed and cyclic heat treated specimens for 10 cycles, respectively. In general it is clear that grain refinement has taken place for both ferrite and pearlite phases by cyclic heat treatment. For annealed specimen the pearlite was more or less lamellar. Figure (11) represents the SEM photomicrograph of cyclic heat treated specimen for 10 cycles at higher magnification. It is clear that the amount of lamellar pearlite decreased and cementite spheroids appeared. This photomicrograph also exhibits fragmented cementite lamellae surrounded by fine pearlitic regions. From SEM photomicrographs of annealed and cyclic heat treated specimens for 10 cycles at different magnifications the inter-lamellar spacingof lamellar pearlite decreased from 0.75 to 0.28µm by this type of heat treatment.

The mechanism of structure modification (grain refinement) occurred during cyclic heat treatment of C45 steel can be explained according to two findings;firstly, the transformation of α-iron to γ-iron is a diffusionless massive allotropic transformation that occurs extremely fast[12], secondly, the dissolution of cementite in austenite during austenitization is a diffusion controlled slow process [12, 13]. During the short time holding at 850°C (6 min) the coarse proeutectiod ferrite grains transform to austenite fine grains quite rapidly[6, 7]. These austenite fine grains contain less than 0.02% carbon and during forced air cooling to room temperature, they transform to ferrite of very fine grains. This is the cause of abrupt decrease in the average diameter of proeutectiod ferrite grains after the first cycle of heat treatment. On the hand, the austenitization in pearlite region starts at the interface of ferrite-cementite lamellae. The ferrite to austenite transformation occurs and the cementite lamellae begin dissolving into austenite, whereas the cementite dissolution in austenite is a slowerprocess [6], and because the holding time at 850°C is short, the cementite dissolution remains incomplete.

The presence of undissolved cementite (fragments) is reported to impede the growth of austenite grains [13]. The austenite regions which surround the undissolved cementite fragments are enriched with carbon, and during forced air cooling to room temperature, they transform to proeutectiod ferrite fine grains and fine pearlite with lower inter-lamellar spacingcompared to the original pearlite. This process repeats on each heat treatment cycle to produce after 10 cycles a very fine structure containing very fine grains from proeutectiod ferrite, very fine pearlite with inter-lamellar spacing of 0.28µm, and cementite spheroids as shown in Figure (10) and (11).

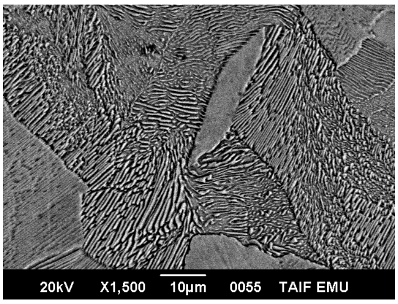

Figure 9: Scanning Electron Microscope (SEM) Photomicrograph of Annealed Specimen

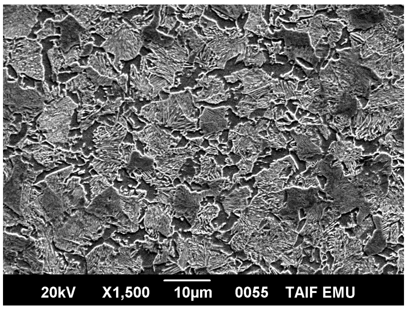

Figure 10: Scanning Electron Microscope (SEM) Photomicrograph of Cyclic Heat Treated Specimen for 10 Cycles

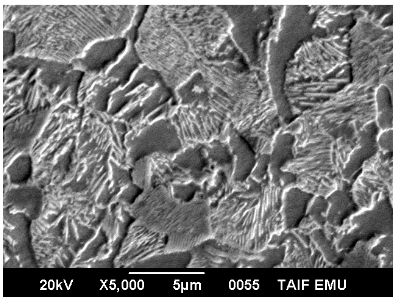

Figure 11: Scanning Electron Microscope (SEM) Photomicrograph of Cyclic Heat Treated Specimen for 10 Cycles

Mechanical Properties

The effect of cyclic heat treatment on mechanical properties is given in Table 3. The hardness decreased from 177Hv for as-received specimen to 167Hv by homogenizing annealing. This is due to sintering and consequently the increase in the average grain size of both proeutectiod ferrite and pearlite as shown from microstructures given in Figure (1) and (2). Hardness increased in general by cyclic heat treatment. It increased gradually by the increase in number of cycles to reach a maximum value after 4 cycles, and then slightly decreased. The increase in hardness is attributed to grain refinement taken place on both proeutectiod ferrite and pearlite, fragment of cementite lamellae and decrease on the inter-lamellar spacing of lamellar pearlite. The decrease in hardness for the specimens treated for more than 4 cycles can be attributed to the increase on the amount of cementite spheroids.

In general the ultimate tensile strength (UTS) increased by cyclic heat treatment. It increased from 547 MPa for annealed specimens to 824 MPa for cyclic heat treated ones after 4 cycles. This means that the strength increased by more than 50%, and in the same time the decrease in % elongation did not exceed 5%. After 10 cycles the UTS increased to 792

MPa compared to the annealed one. This means that the strength increased by more than 33% and in the same time the decrease in % elongation did not exceed 4%.Generally, the increase in (UTS) is attributed to refinement in the structure which is taken place during cyclic heat treatment. The decrease in improvement in the (UTS) by increasing number of cycles from 4 to 10 cycles is attributed to the increase in the amount of cementite spheroids which leads to increase in ductility (% elongation).

Table 3: Effect of Cyclic Heat Treatment on Mechanical Properties

Number of Cycles Property	As-Received	Annealed (After 0 Cycle)	After 1 Cycle	After 2 Cycles	After 4 Cycles	After 6 Cycles	After 8 Cycles	After 10 Cycles
Hardness HV	177	167	204	234	246	236	233	230
Ultimate Tensile Strength (MPa)	--	547	--	--	824	--	--	792
% Elongation	--	32	--	--	30.5	--	--	31

CONCLUSIONS

From the current research the following concluded remarks can be drawn

- The average grain size of both proeutectiod ferrite and pearlite increased by homogenizing annealing.
- The average grain size of both proeutectiod ferrite and pearlite decreased by cyclic heat treatment.
- The amount of lamellar pearlite decreased and cementite spheroids increased by increase in number of heat treatment cycles.
- The inter-lamellar spacingof lamellar pearlite decreased by cyclic heat treatment.
- Both hardness and ultimate tensile strength improved by cyclic heat treatment. This is attributed to refinement in the structure which is taken place during cyclic heat treatment.

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