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Effect of Carburizing Temperature and Post Carburizing Treatments on Microhardness and Microstructural Evolution of Carburized Low-Carbon Steel

*Mohamed Ali Ballem, Mustafa M. Aldarwish, Abdulhamid S. Aljuroushi, Abdulwahab M. Shaka, Ali M. Abdulbakee

Department of Material Science and Engineering, Misurata University, Misurata

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ABSTRACT

This paper reports the results of an experimental investigation of the effect of carburizing temperature and post carburizing heat treatments on the structural and hardness properties of pack carburized low-carbon steel. The carburizing processes were performed at temperatures of 900°C and 1035°C for 6 hours. After that, two hardening procedures were carried out. In the first hardening procedure, the specimens were directly quenched in oil from carburizing temperatures, while in the second procedure, a double quenching method using brine as a quenching medium was applied. The resultant changes in surface hardness values, carbon content, case depth, microhardness profiles, and microstructural evolution during all processes were tracked and reported. The study showed that the hardness values and carbon content of the carburized specimens increased significantly compared to an untreated specimen, also case depth values increased by two times in some hardened specimens, the increasing in these values were correlated to the changes in microstructures. The obtained results indicated that the structure and the properties of the carburized components are strongly influenced by carburizing temperature and by post carburizing heat treatments; therefore, both variables can be used to altering or modifying surface and core characteristics of the carburized steel, which make it more suitable for engineering components that require a combination of hard surface along with ductile and tough core.

تأثير درجة حرارة الكربنة والمعالجات الحرارية التابعة لها على الصلادة والبنية المجهرية للصلب المنخفض الكربون

*محمد علي بلعم و مصطفي محمد الدرويش و عبد الحميد سالم الجروشي و عبد الوهاب محمد شاكه و علي محمد عبد الباقي

قسم هندسة وعلوم المواد، كلية الهندسة، جامعة مصراتة

الملخص

يعرض هذا البحث نتائج دراسة معملية لتأثير درجة حرارة الكربنة والمعالجات الحرارية بعد الكربنة على البنية المجهرية وكذلك الصلادة المجهرية للصلب المنخفض الكربون بعد إجراء عملية كربنة صلبة له. تم إجراء الكربنة عند درجات حرارة 900 درجة مئوية و1035 درجة مئوية لمدة 6 ساعات، واتبِعت الكربنة بعمليتي تصليد: الأولى، تم فيها إخماد العينات مباشرة في الزيت من درجات حرارة الكربنة، بينما في الثانية تم تطبيق طريقة التبريد المزدوج باستخدام محلول ملحي كوسط للتبريد. تَم تَتَبُّع التغييرات الناتجة في قيم صلادة السطح، وكذلك المحتوى الكربوني، وعمق طبقة الكربنة، وقيم الصلادة المجهرية، وتطور البنية المجهرية الدقيقة خلال الكربنة وبعد إجراء المعالجات الحرارية. أظهرت الدراسة أن قيم الصلادة والمحتوى الكربوني للعينات المكربنة زادت بشكل ملحوظ، كما زاد العمق الفعلي وكذلك العمق الكلي للطبقة السطحية المتأثرة بالكربنة بمقدار الضعف في بعض العينات، وارتبطت الزيادة في هذه القيم بالتغيرات الحاصلة في البنية المجهرية. أشارت النتائج التي تم الحصول عليها إلى أن التركيبة المجهرية وخصائص الطبقات المكربنة تتأثر بشدة بدرجة حرارة الكربنة والمعالجات الحرارية بعد الكربنة، لذلك يمكن استخدام هذين المتغيرين لتغيير أو تعديل خصائص السطح وكذلك القلب للصلب المكربن، مما يجعله أكثر ملاءمة للتطبيقات الهندسية التي تتطلب مزيجًا من صلادة في السطح ومتانة للقلب في الأجزاء المنتجة أو المصنَّعَة.

الكلمات المفتاحية
المحتوى الكربوني
عمق الكربنة
المعالجات الحرارية
الصلادة المجهرية
البنية المجهرية
الكربنة الصلبة

*Corresponding author:
E-mail addresses: ballem77@yahoo.com, (M. Aldarwish) mmosab@yahoo.com.au, (A. Aljuroushi) aljuroushi@gmail.com, (A. M. Shaka) a.m.shaka@gmail.com, (A. M. Abdulbakee) ali.abdulbakee@gmail.com
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1. Introduction

Steel is one of the most important engineering and construction material due to its unique properties that makes it appropriate for wide area of applications in our daily life. Generally, steel is an iron-carbon alloy that contain up to 2% by weight carbon in addition to a minor amount of other elements such as manganese, nickel, silicon, phosphorus, chromium, and molybdenum. Carbon is the main alloying element since it is significantly altering the mechanical properties of the steel, therefore based on carbon content carbon steel are classified into low-carbon steel (up to 0.25% C), medium-carbon steel (0.25% to 0.55% C), and high-carbon steel (more than 0.55% C) [1-3]. As the amount of carbon is small in low-carbon steel it is combines fair strength with outstanding ductility and fabrication properties (e.g., pressing, welding, rolling, drawing, etc.); such properties in addition to its high availability and relatively low cost makes this type of steel widely used in many applications including, buildings, bridges, pipelines, structural shapes, tin cans, and automobile bodies. However, some engineering applications as machine parts (e.g., gears, cams, valves, shafts, etc.) require a combination of hard surface along with ductile and tough core; in low-carbon steel, this combination can be achieved by so called case hardening [3], [4].

Case hardening is a chemical-thermal process by which the composition of the surface layers of steel is changed and its hardness is enhanced; it is usually done by carburizing, nitriding, cyaniding, or carbonitriding. Carburizing is the most commonly used technique for case hardening where carbon is diffused from carbon rich atmosphere (solid, liquid, or gaseous) into the surface of the steel (usually low-carbon steel) at the elevated temperature [4], [5]. Based on the carburizing compound, carburizing methods can be classified into solid or pack carburizing, liquid carburizing, and gas carburizing. All of these methods have advantages and limitations but pack carburizing is considered as cheap and simple carburizing method because it has low operating and equipment costs, and it can make use of a wide variety of furnaces, also it can be done in any workshop [3], [6].

After carburizing heat treatment is needed in order to: improve hardness and wear resistant of surfaces, refine the coarse grains developed due to high temperature and long carburizing time, to eliminate the amount of retained austenite, and to break the cementite network at the surface. Post carburizing heat treatment involves quenching the component either directly from the carburizing temperature, or after reheated it to an appropriate temperature. This treatment, however, is quite complicated because the outer surface and the inner core have different hardenability due to the variation in their carbon content [3], [6], [7].

To obtain carburized components that possessing the desirable properties, a particular attention has to be paid to the variables of carburizing process and post carburizing heat treatments as well. The main parameters influencing pack carburizing process and the following heat treatments are the carburizing temperature, the carburizing time, the quenching media, and the tempering temperature [6-10]. Several studies have been carried out with the aim of understanding the effect of these parameters on the mechanical properties and the microstructural characteristics of carburized steel [11-21]; however, there is still ongoing research in this area because controlling all these parameters is a complex and sensitive issue. The aim of this study is to keep track of the changes in microhardness, carbon content, case depth, and microstructure of low-carbon steel when it is carburized at two different temperatures. Furthermore, the effect of the following heat treatments on their characteristics is addressed.

2. Materials and Method:

Specimens with height of 15mm and diameter of 30mm were taken from low-carbon steel bar had a chemical composition given in Table 1.

Table 1: Chemical composition of the as-received low-carbon steel

Element	W %
C	0.14
Si	0.17
Mn	0.55
Cr	0.15
Mo	0.05
Ni	0.21
Cu	0.35
Sn	0.04
Co	0.01
Fe	Rem.

Pack carburizing process was performed at 900°C and 1035°C for 6 hours using a high temperature carbolite chamber furnace type RHF 1500. Briefly, after cleaning the specimens, a layer of the carburizer compound (coke) about 25 mm deep was spread on the bottom of the carburizing box (steel box with dimensions of 200×100×100 mm), and then the specimens were placed on this layer. A space of 25 mm was kept between the specimens and from the walls of the box as well; after each addition of the carburizing agent the box was tapped to remove the air voids, and to ensure that the carburizing agent is distributed more evenly and the specimens are uniformly coated with the carburizer compound. A top layer with a thickness about 50 mm was added and the box was closed with its lid and tightly sealed with fire-clay to prevent entry of air. After that, the packed box was placed in the furnace at temperature of 700°C and kept at this temperature for half an hour, and then the temperature was raised with heating rate of (10°C/min.) until reaching the carburizing temperature where counting the time is started. By the end of carburizing time the box was removed from the furnace and the specimens were subjected to hardening procedures by direct quenching in oil, and by double quenching heat treatment using brine as a quenching medium. The double quenching process consists of quenching from 890°C and re-quenching from 780°C with soaking time of 10 minutes. The carburizing and hardening process are illustrated in Fig. 1.

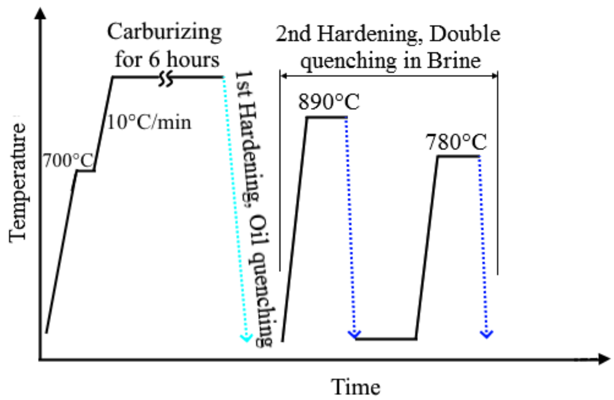

Fig. 1: Schematic illustration of the carburizing and hardening process

The characterization of the specimens was conducted through a (ARL 3460, OES Metals Analyzer) to determine the chemical composition and carbon content. Hardness Rockwell B and C [HRB and HRC] measurements were performed with (SHIMADZU Rocwell Hardness Number Testing Machine) on the specimens before and after the carburizing process and then converted to Vickers [HV] number. Surface to core microhardness measurements were carried out at load of 1000 g applied for 15 sec. using a microhardness tester (AKASHI MVK-E Hardness Tester). The microscope (Leica DM2500 Optical Microscope) was used for microstructure investigation. Before microhardness and microstructure characterization, the specimens were sectioned, mounted in epoxy mount, ground, polished, and etched with 2% Nital.

3. Results and Discussion:

Figure 2 shows the microstructure of the as-received low-carbon steel, which consists of a homogeneous coarse-grained ferrite with average grain size about 30µm (the light phase), and some pearlite structure (the dark phase). The surface hardness of this specimen was measured as 78 HRB (140 HV).

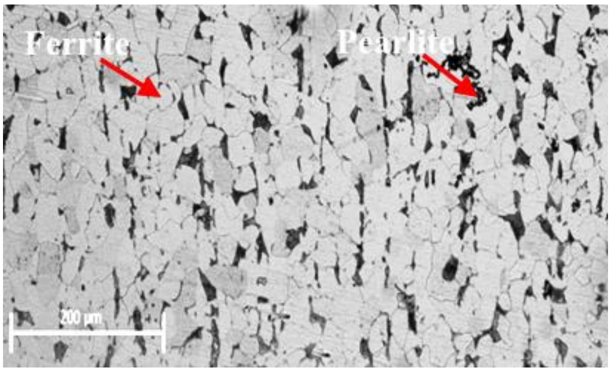

Fig. 2: Optical micrograph showing the ferrite and pearlite microstructure of as-received low-carbon steel (0.14 %C) before carburizing, Mag. 100x

The surface hardness data of the specimens before and after carburizing are shown in Fig. 3. It is obvious that the hardness values of the carburized specimens increased significantly as compared with the untreated specimen. As mentioned above the hardness of the as-received specimen was 140 HV, and after carburizing at 900°C and 1035°C and direct quenching in oil, the surface hardness increased to 530 HV and 700 HV respectively. As the carburizing process involves diffusion of carbon atoms to low-carbon steel when carbon content on steel surfaces is increased, this process of insertion of carbon atoms at grain boundaries will inhibit atomic dislocation. When the dislocation movement is slowed down or blocked, the specimen becomes harder. The increase in hardness is proportional to the increase in carbon content; the carbon content of the carburized specimens was tested with the emission spectrometer and found to be about (0.71% C) for the specimen carburized at 900°C and about (0.93% C) for the specimen carburized at 1035°C.

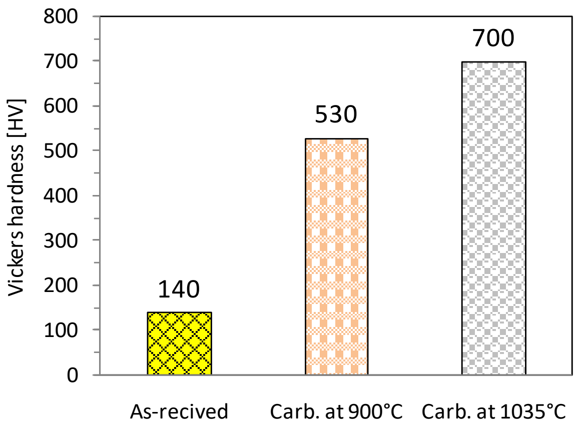

Fig. 3: Vickres hardness of the studied specimens before and after carburizing at 900°C and 1035°C

In order to understand and analyze the obtained results, metallographic examination and microhardness measurements were carried out on the specimens. All specimens were prepared as mentioned above to retain the edge precisely to facilitate the measurement of the total case depth and the effective case depth. The hardness (HV) versus the distance from surface to core (mm) for the carburized specimen at 900°C and direct quenching in oil is represented in Fig. 4, the drop in hardness values can be determined from the graph. The inset optical micrograph shows the cross-sectional microstructure, the variation in hardness indentation from the outer layer (case) to the interior layer (core) can be observed clearly. Form the microhardness profiles of this specimen, the depth from the surface to where the hardness becomes constant (total case depth) is found to be 0.75mm, where the distance from the surface to where the hardness is 550 HV (the effective case depth) is about 0.25mm.

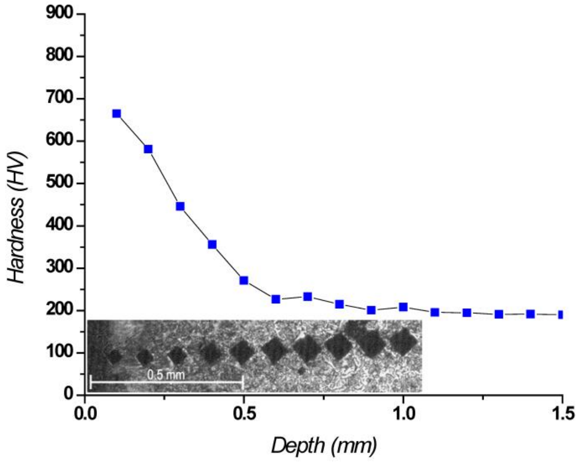

Fig. 4: Cross-section microhardness profiles and optical micrograph at 50x (inset) of the carburized specimen at 900°C after direct quenching in oil

The reported drop in hardness values for the carburized specimen can be attributed to microstructural evolution; Fig. 5 (a) and (b) show a high magnification view (200x) of the case and core locations respectively; the microstructure of the case appears as a mixture of bainite and lamellar martensite in a lower proportion, where the core microstructure consists of a coarse pearlite.

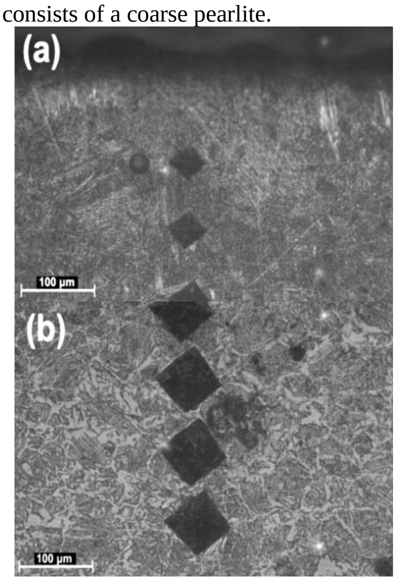

Fig. 5: Optical micrograph at 200x magnification: (a) case and (b) core of the carburized specimen at 900°C after direct quenching in oil

For the specimen that was carburized at 1035°C and directly quenching in oil, the microhardness profiles as well as the variation in hardness indentation (inset) are shown in Fig. 6, from the presented profiles the total case depth is determined to be 1.5mm, where the effective case depth is about 0.4mm.

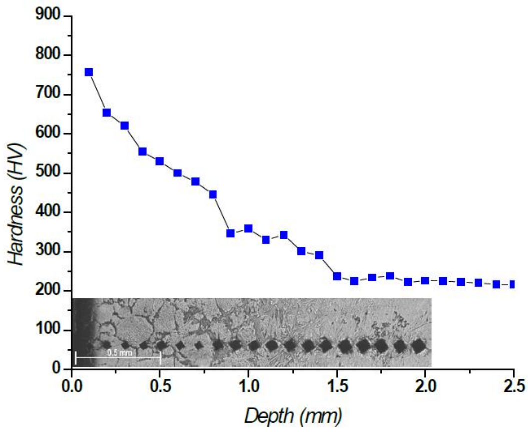

Fig. 6: Cross-section microhardness profiles and optical micrograph at 50x (inset) of the carburized specimen at 1035°C after direct quenching in oil

It is obvious that the hardness values, total case depth, and effective case depth for this specimen is higher than the previous specimen, and that is because the increase in carburizing temperature will enhance the diffusion of carbon atoms from carburizing agent to the surface of the carburized steel. To have a close view on the microstructural evolution of this specimen, Fig. 7 represents two micrographs taken at 200x magnification for case and core zone respectively, the case zone (Fig. 7a) shows a mixture of martensite, cementite, and retained austenite. The cementite phase is located at the boundaries of the grains forming a cementite network. The core of the specimen (Fig. 7b) consists of a lamellar pearlite.

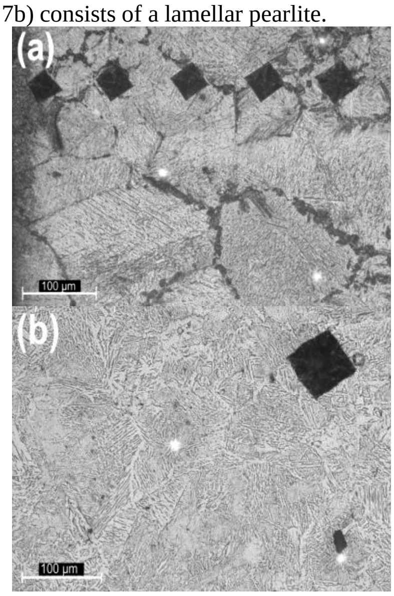

Fig. 7: Optical micrograph at 200x magnification: (a) case and (b) core of the carburized specimen at 1035°C after direct quenching in oil.

The presence of retained austenite and undesirable brittle cementite networks in the case of the carburized specimens may lead to higher probability of surface cracks formation. Therefore, in order to improve the properties of both the case and the core, double quenching heat treatment using brine as a quenching medium was performed. Such treatments are usually following the carburizing process for the purpose of refining the grain size and improving the mechanical properties of both surface and the core. Fig. 8 shows schematic illustration of double quenching heat treatment, as illustrated in the figure the first stage is to improve the properties of the core, where the second one is to improve the properties of the case.

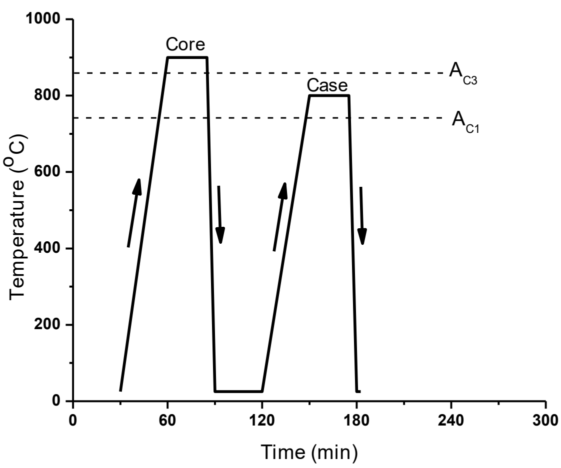

Fig. 8: Schematic illustration of double quenching process

Double quenching process was applied in both specimens that carburized at 900°C and 1035°C; the microhardness profiles for both specimens are shown in Fig. 9 and Fig. 10 respectively. From the microhardness profile represented in Fig. 9 the total case depth for the specimen carburized at 900°C after double quenching treatment is about 1mm, where the effective case depth is about 0.4mm, the maximum hardness value achieved at the surface of the specimen was 822HV, where the hardness of the core was about 250HV. From Fig. 10 the total case depth for the specimen carburized at 1035°C after double quenching treatment is about 2mm, where the effective case depth is about 0.75mm, the maximum hardness value achieved at the surface of the specimen was 867HV, where the hardness of the core was about 300HV.

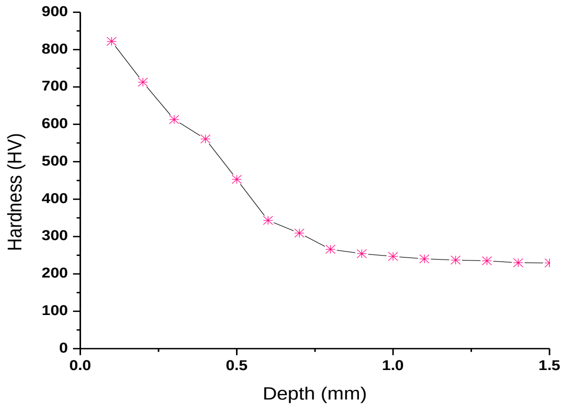

Fig. 9: Cross-section microhardness profiles of the carburized specimen at 900°C after double quenching in brine

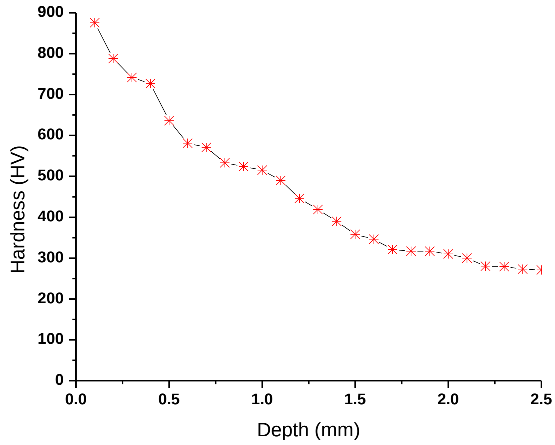

Fig. 10: Cross-section microhardness profiles of the carburized specimen at 1035°C after double quenching in brine

As mentioned above the outer surface zone for both specimens after double quenching process has hardness of approximately 800HV and that reflects the microstructures of these specimens which is consists of mainly martensite with no evidence of retained austenite as shown in Fig. 11 (a); and the hardness of the core zone for the specimens is falls to about 300HV, the microstructure consists of some martensite and pearlite as shown in Fig. 11 (b).

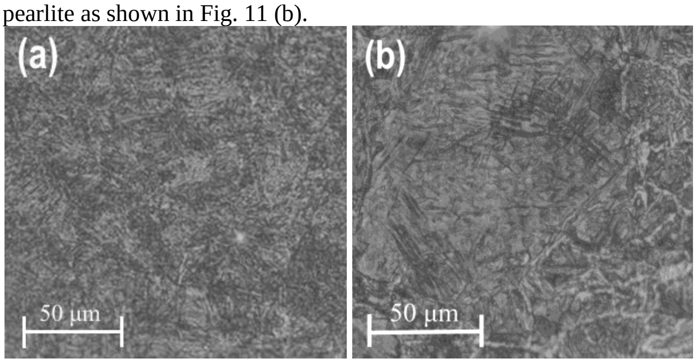

Fig. 11: Optical micrograph at 200x magnification: (a) case and (b) core of the carburized specimens after double quenching process

To summarize the results of the current study, table 2 represents a comparison between the carburized specimens after direct quenching in oil and double quenching in brine.

Table 2: Comparison between the carburized specimens after direct quenching and double quenching treatments

Treatment	Carburizing temperature (°C)	Effective case depth (mm)	Total case depth (mm)	Max. Surface Hardness (HV)	Core Hardness (HV)	Case Microstructure	Core Microstructure
Direct quenching in oil.	900	0.25	0.75	665	200	mixture of bainite and lamellar martensite in a lower proportion	coarse pearlite
Double quenching in brine.	900	0.4	1	822	250	mainly martensite	some bainite and pearlite
Direct quenching in oil.	1035	0.4	1.5	757	225	mixture of martensite, cementite, and retained austenite	lamellar pearlite
Double quenching in brine.	1035	0.75	2	867	300	mainly martensite	some bainite and pearlite

4. Conclusion

Based on the obtained results the following conclusions can be drawn:

1. The surface hardness and the microstructure of low carbon steel are strongly influence by carburizing process.
2. It is possible to develop useful layer thickness on the low carbon steel by a conventional pack carburization treatment.
3. Carburizing temperature and post carburizing heat treatments strongly influence the hardness values and the microstructure evolution of the carburized steel.
4. The values of hardness, carbon content, effective case depth and total case depth increase by increasing the carburization temperature.
5. The highest value of hardness is obtained on carburized specimens after double quenching in brine.
6. Double quenching process effectively refined the structure of the carburized specimens compared with traditional direct quenching process.

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