Arab Gulf J. Scient. Res., Math. Phys. Sci., A5 (2), pp. 259-269 (1987)

Effect of Quenching Media on the Mechanical and Structural Properties of a Saudi-Steel

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ABSTRACT. The effects of austenitizing time and temperature, water, air, oil and molten lead quenching media on the mechanical and structural properties of the hot-rolled steel have been investigated using Vickers hardness testing, tensile testing and the scanning electron microscopy.

The microstructure of the as-received or the air-quenched steel consisted of proeutectoid ferrite and pearlite areas. Water quenching has produced high strength lenticular martensite but quench cracks were observed. Bainitic structures were obtained in the palm-oil quenched specimens. When Petromin oil was used as a quenching medium, a lamellar martensitic structure was produced.

From the strengthening point of view it was suggested that the rods produced after hot rolling could be cooled directly into palm oil or Petromin-type oil as this would improve the strength of the steel by about 20-60%.

The heat treatment of steel is a combination of heating and cooling operations applied to the steel in the solid state in a way that will produce the desired properties (Thelning 1984). Heat treatment of steel is normally accompanied by solid-state phase transformations (Christian 1975).

The aim of the present work was to study the effect of cooling media on the mechanical and structural properties of an austenitized 20 mm diameter Saudi-produced steel bar.

Material and Methods

Material

The steel used in our study is one of the products of Jeddah Steel Rolling Mill Company, in the form of rods, about 20 mm in diameter. The raw materials are steel billets 4.5 m long and have a cross section of 100 × 100 mm, which can be hot rolled to all sizes ranging from 14 mm to 32 mm. The average chemical analysis of the steel was given as: 0.37% C, 0.25% Si, 0.03% P, 0.03 S, 1.28% Mn, 0.16% Cr, 0.20% Cu, 0.15% Ni, 0.03% Mo and 0.04% Sn by weight (balance Fe).

Heat Treatment

In this investigation, the steel bar was cut into small specimens of about 0.7 mm in thickness. A tube furnace was used for the austenitization of the specimens. To measure the temperature of the specimen, NiCr-Ni shielded thermocouples connected to digital temperature indicators were used. Different quenching media were applied: air, water, oil and molten lead.

Vickers Hardness Testing

The Vickers hardness was measured using a Leitz-type Vickers hardness tester, supplied with a measuring eye-piece digital and a computer-counter-printer. During the present investigation, a standard 9.81 N test load was used in all the tests, to avoid errors arising from a nonlinear relationship between the applied load and the measured hardness. The duration of the indentation was taken as 30 sec for all the tests. Each specimen surface was carefully polished until it became mirror like in appearance. For each specimen, 5 to 10 impressions were made at different areas of the surface and the lengths of the diagonals of the indentations were measured photoelectrically by the eye-piece digital. The mean value of the Vickers hardness (HV) and the standard deviation were then determined.

Tensile Testing

For tensile testing, an Instron type tensile testing machine was used. The diameter of the steel was reduced to 14 mm and the gauge length was taken as 140 mm.

Scanning Electron Microscopy

To follow the microstructural changes of the heat treated specimens, a scanning electron microscope was used, type Jeol. For this purpose, the surface of the investigated specimen was etched in nital (2% nitric acid in methanol) before examination.

Results and Discussion

The Steel as Received

The Vickers hardness (HV) of the as-received steel was measured as (210 ± 10). The microstructure of the specimen, as revealed by the scanning electron microscope (SEM), is shown in Fig. 1, and consists of proeutectoid ferrite formed

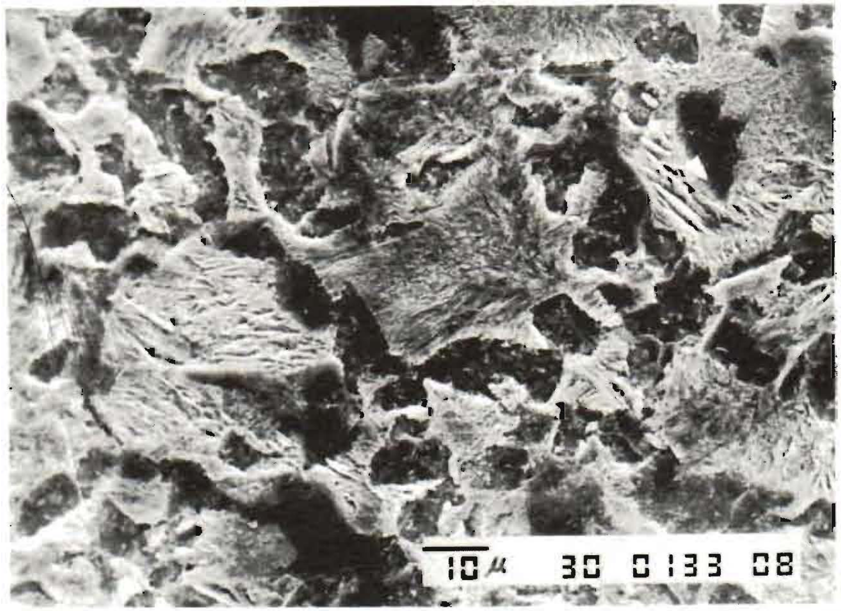

Fig. 1. Pearlite and proeutectoid ferrite in the as received steel.

at grain boundaries and pearlite inside the grains. During the manufacturing of the steel bar, the billet was hot rolled in successive stages and the produced bars were then air cooled from about 800-850°C. On continuous air cooling of the hypoeutectoid steel bar, a structure consisting of pearlite and proeutectoid ferrite would therefore be produced, both normally being soft constituents. Manganese and chromium in the steel would have a retarding effect on the austenite to pearlite transformation due to their selective partitioning during the transformation (Razik *et al.* 1974, 1976, and Razik 1980) and fine pearlite could therefore be formed in the steel during air cooling, Fig. 1.

Water Quenching

The first step in the heat treatment of steel is to heat the material to some temperature in order to form austenite. One of the specimens was austenitized at 1000°C for 20 min and was then quenched into water at room temperature (about 30°C). The HV of the specimen was measured as (505 ± 14).

Figure 2 is a SEM micrograph showing the microstructure of the water quenched specimen. It consists of lenticular martensite. However, on scanning the water quenched specimen by the metallurgical microscope, a quench crack was observed. It is well known that when a piece of steel is cooled in such a way as to form martensite, two basic dimensional changes occur: the normal thermal contraction due to cooling and the expansion of the metal as it transforms from the austenite lattice to the martensite lattice. When there is a big difference between the cooling rates of the surface and the interior of the steel, residual stresses due to volumetric changes may be produced which can cause localized fractures or quench cracks. The water quenched steel, although its hardness is high, is therefore practically not useful.

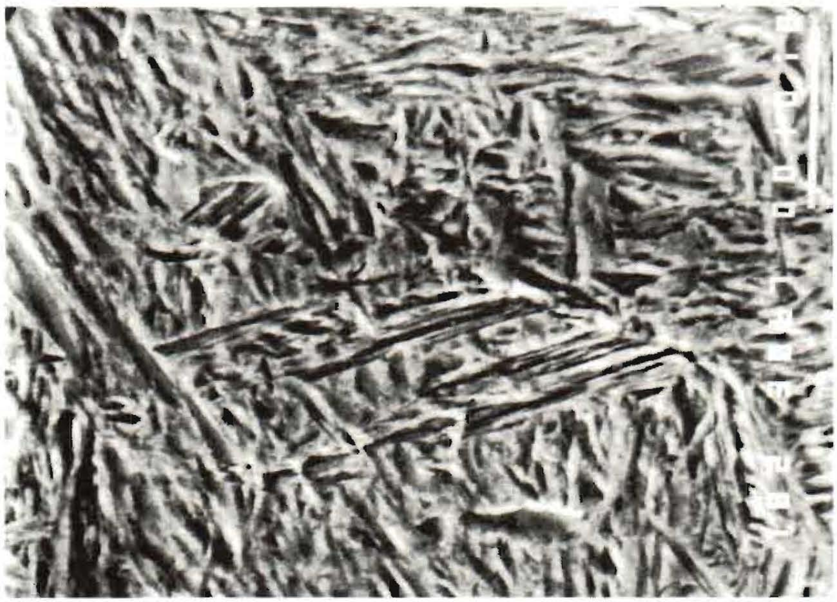

Fig. 2. Lenticular martensite structure in a water-quenched specimen.

Effect of Austempering

The austempering heat treatment process is intended to obtain a structure which is completely bainite. It is accomplished by first austenitizing followed by quenching directly into a molten lead bath kept at a temperature somewhat above that at which the austenitic structure of the steel starts to transform to martensite (*i. e.* the M_s-temperature). Using the empirical formula of Andrews (1965), the M_s temperature for this steel was calculated as 339°C. A steel specimen was austenitized at 1000°C for 20 min and was then quenched directly into the lead bath at 394°C, where it was kept for 4 min before air cooling. The HV of the specimen was measured as (254 ± 1) and was thus higher than that of the as-received steel. However, a practical limitation for molten lead quenching is that a more expensive equipment is required.

Palm-Oil and Air Quenching Media

Four specimens were austenitized at 850°C for different times: 5, 10, 20 and 30 min, and were then quenched into palm-oil at room temperature (about 30°C). Another four specimens were given the same austenitization treatment but were air cooled. Figure 3 shows the relationship between HV and the austenitizing time at 850°C. It can be seen that for all the austenitizing times used, palm oil quenching has improved the strength of the steel and that 5 min were adequate for austenitization at 850°C.

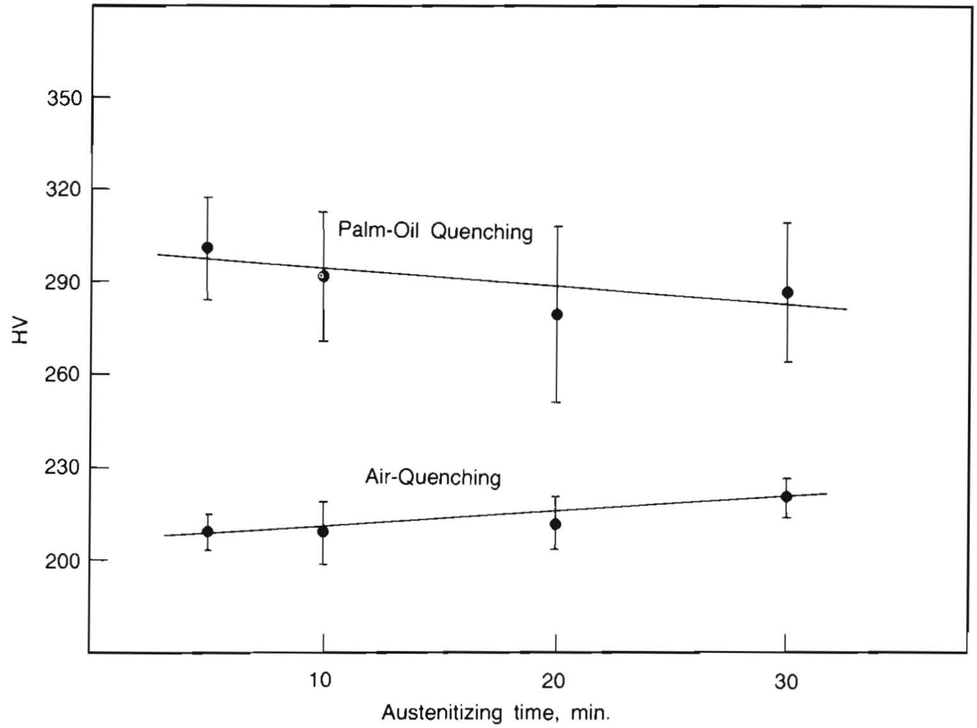

Fig. 3. Vickers hardness *versus* austenitizing time at 850°C

Figure 4 shows the microstructure of a specimen, austenitized for 5 min and air cooled, as revealed by SEM. It consists of pearlite and ferrite phases, similar to the microstructure of the as-received steel. Also, the hardness of the air cooled steel was found to be similar to that of the as-received steel.

To study the effect of palm-oil quenching temperature, five specimens were austenitized for 5 min at 850°C and were quenched, successively, into palm oil at

30, 53, 101, 150 and 202°C, kept there for 5 min and then air cooled. The relationship between the measured HV values of the specimens and the temperature of the quenching oil is shown in Fig. 5.

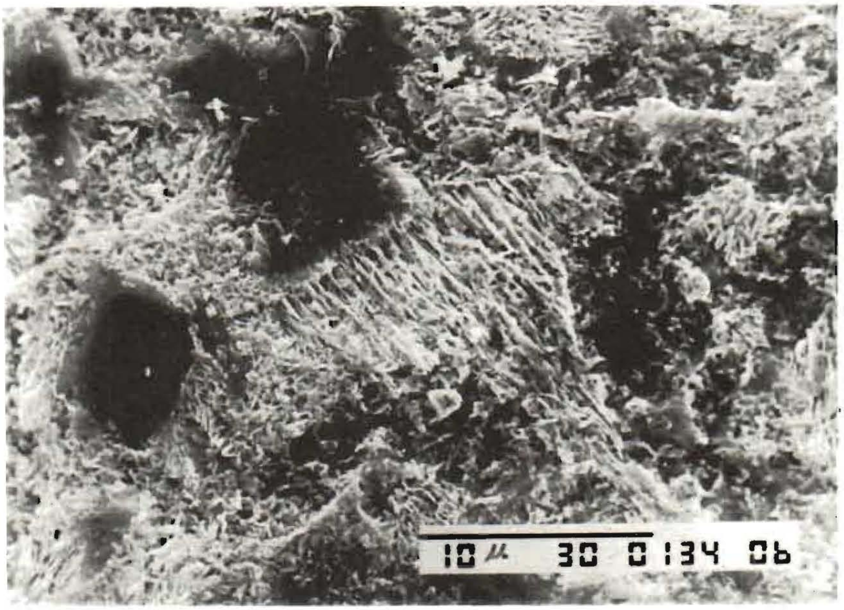

Fig. 4. The microstructure of an air-quenched specimen, showing pearlite and proeutectoid ferrite areas

Figure 6 shows the microstructure of a specimen after palm oil quenching at 53°C, as revealed by SEM, which consists mainly of lower (acicular) and upper bainite structures (Ohmori and Honeycombe 1971, and Honeycombe and Pickering 1972). During the quenching of a steel specimen in oil media, heat is extracted in distinct stages (Thelning 1984): vapour blanket, boiling and convection stages, which depend upon the physical properties of the oil used. The microstructure of the palm oil quenched steel, Fig. 6, indicates that the cooling rate of the specimen was relatively slow in the range of the bainite transformation and fast above this range. The scatter in hardness measurements which can be observed in Fig. 5, could be due to the presence of two structures in the steel, upper bainite and lower bainite, possessing different HV. As the temperature of the oil rises, the cooling rate decreases and the amount of upper bainite in the steel would consequently increase.

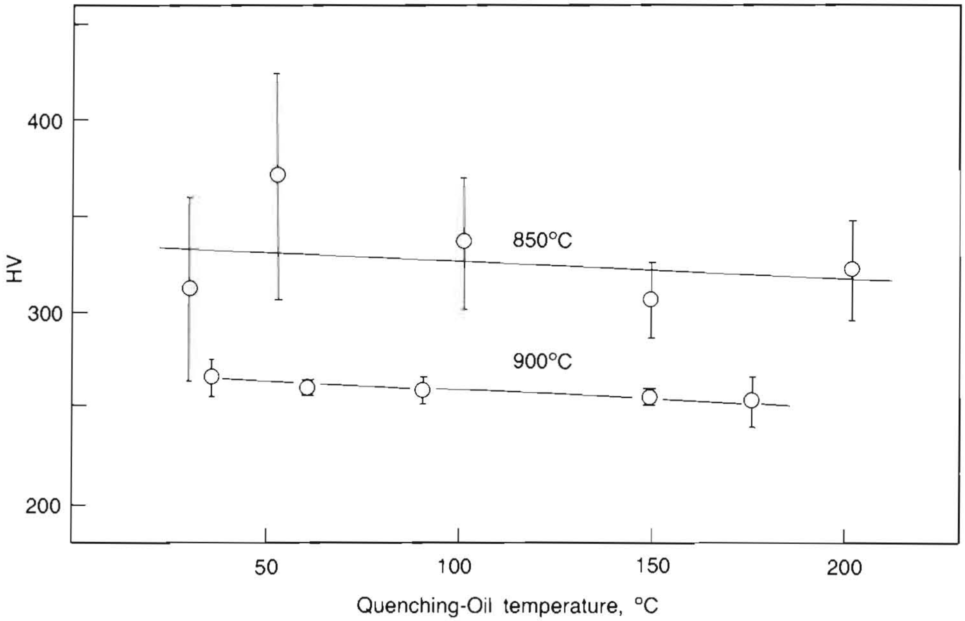

Fig. 5. Effect of palm-oil quenching temperature on the hardness of the steel

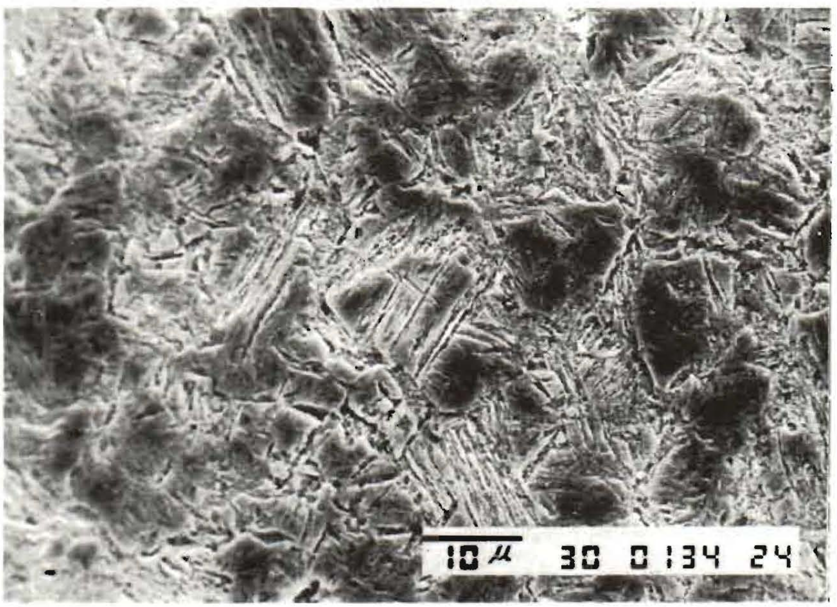

Fig. 6. Showing lower and upper bainite in a palm-oil quenched specimen

When the austenitizing temperature was increased to 900°C, the increase in hardness of the steel was less. Figure 5 shows also the relationship between HV and the quenching palm oil temperature for specimens which were austenitized at 900°C. The lower HV values, for this austenitizing temperature, suggests that the cooling rates of the specimens were relatively slow at the upper bainite formation region. The strength of the upper bainite is normally less than that of the lower bainite structure.

The tensile properties of a steel rod austenitized for 10 min at 900°C and quenched into palm oil at 60°C were measured as:

Tensile strength R_m	= 825 N/mm^2
Yield point $R_{p0.2}$	= 536 N/mm^2
Elongation A_{10}	= 16% (in 137 mm)

For the as-received steel rod, the corresponding properties were determined as:

Tensile strength R_m	= 692 N/mm^2
Yield point $R_{p0.2}$	= 462 N/mm^2
Elongation A_{10}	= 19% (in 140 mm)

It was not possible to carry out further tensile tests since the steel rods of the same production number had already been consumed. However, a conversion table (Table 2.2, Thelning 1984) for hardness-tensile strength of the steel was found consistent with the present data.

Petromin-Oil Quenching

One specimen was austenitized at 850°C for 5 min. and was then quenched into Petromin motor oil at room temperature (about 30°C). The specimen was held for 5 min. in the quenching oil before air cooling. The HV of the specimen was measured as (335 ± 20). The tensile strength corresponding to this value can be deduced (Table 2.2, Theling 1984) as (1065 ± 64) N/mm^2. When the austenitizing temperature was raised to 900°C, the HV for a Petromin-oil quenched specimen was measured as (343 ± 18).

The high strength of the Petromin oil quenched specimens suggests that their cooling rates were fast above M_s and slow below it. The structure of the steel was mainly lamellar martensite as can be seen from Fig. 7. The lamellar martensite consists of packets of parallel laths (Marder and Krauss 1967). When the Petromin oil quenched steel was tempered in oil at 195°C, the hardness of the steel had not changed appreciably up to about 160 hrs of tempering, as shown in Fig. 8.

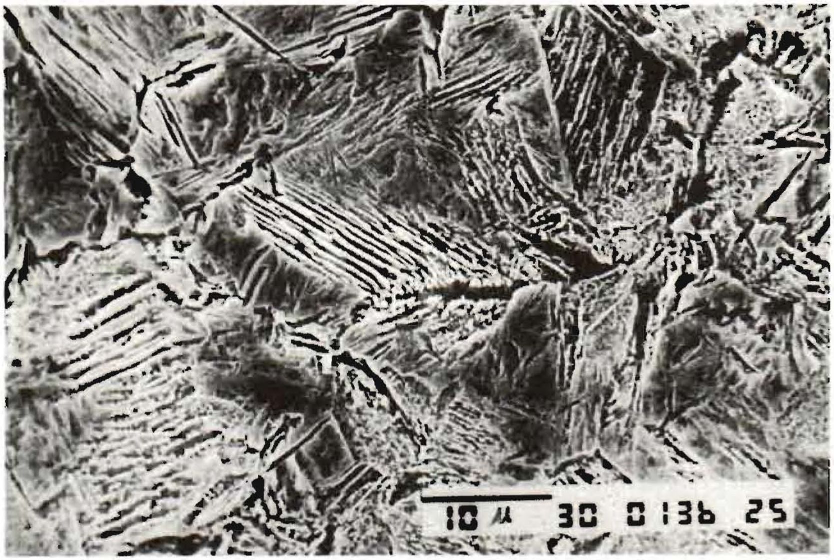

Fig. 7. Lamellar martensite formed in a Petromin-oil quenched specimen

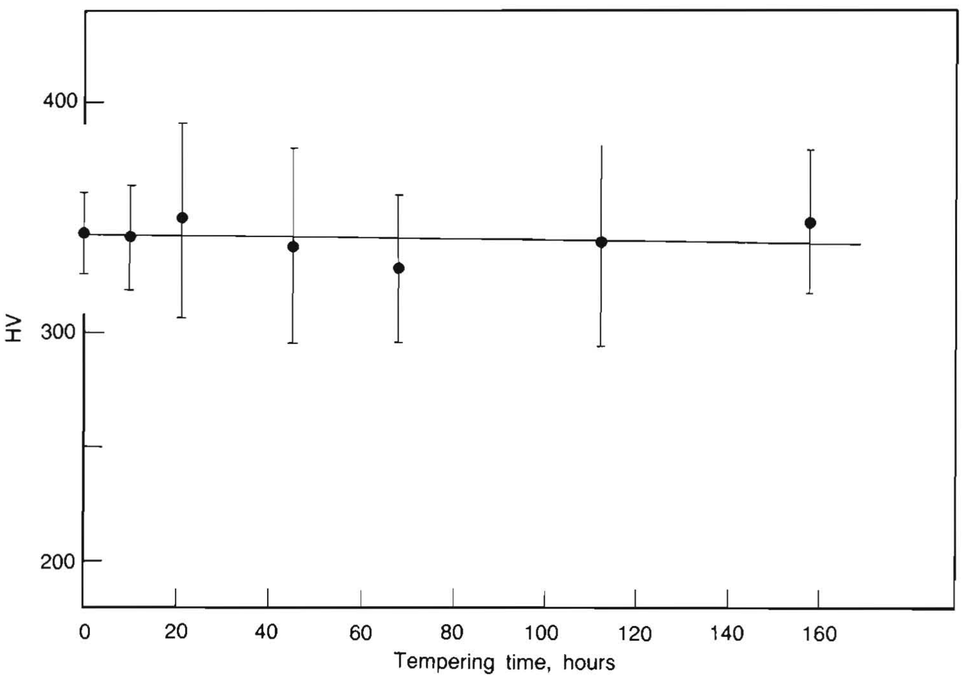

Fig. 8. Effect of tempering time at 195°C on the hardness of a Petromin-oil quenched specimen

Conclusion

From the strengthening point of view, palm oil or Petromin oil can be used as a quenching medium for the hot-rolled steel. This could improve the strength of the as-produced steel by about 20-60%. From the economic point of view, Petromin oil is produced in Saudi Arabia from its natural oil resources and may therefore be more favourable economically taking into consideration that lower quality refined oils are cheaper and can be used for this purpose.

Acknowledgement

This research was sponsored by the Faculty of Science, King Abdulaziz University, and we wish to thank the Dean of the Faculty and the Committee of Research and Higher Studies. We would like to thank Mr. Al-Hiniti, Mr. Banerjee, Mr. Arnous and Mr. Dabbour at the Faculty of Science, Mr. Mokhtar and Mr. Farouk at the Faculty of Engineering for their technical assistance.

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(Received 16/03/1986;
in revised form 06/09/1986)

تأثير الوسط المبرد على الخواص الميكانيكية والتركيبية لصلب سعودي

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أستخدم في هذا البحث قضيب من الصلب منتجاً بالدرفلة على الساخن في مصنع جدة لدرفلة الصلب، وقد درس تأثير زمن ودرجة حرارة التحول للأوستنايت والتبريد في الماء وفي الهواء وفي الزيت وفي الرصاص المنصهر، على الخواص الميكانيكية والتركيبية؛ وأستخدم لدراسة تلك الخواص كل من: مقياس الصلادة لفيكرز ومقياس الشد والمجهر الالكتروني الماسح.

وقد تبين أن التركيب الدقيق للصلب المنتج أو المبرد في الهواء يتكون من مناطق من أطوار الفيرايت والبيرلايت. أما الصلب المبرد في الماء فيتركب من المارتنزايت العدسي. والصلب المبرد في زيت النخيل يتركب من البينايت، بينما يتركب الصلب المبرد في زيت بترومين من المارتنزايت اللوحي.

ولتحسين صلابة الصلب المنتج فقد أقترح أن تبرد القضبان مباشرة عقب الدرفلة الساخنة في زيت النخيل، أو زيت من نوع بترومين، إذ يؤدي ذلك إلى تحسين الصلابة بنسبة ٢٠٪ - ٦٠٪ تقريباً.