J. Heat Treating (1992) 9:113–123

Carburization of Steels in a Circulatory System Using Water–Gas Atmospheres

Y.C. Chen and G.S. Lu

Abstract. In order to economize on raw materials for producing controlled atmospheres and to avoid the air pollution caused by exhausted atmospheres, the feasibility of carburizing steel by using recirculated water–gas atmospheres was investigated. Water–gas was generated in a closed system and an open system respectively, and steel samples were heated under the water–gas atmospheres. Based on the heating results of steel, the relationship between the generation conditions of water–gas and its carburizing behavior was examined. In addition, the carburizing results as well as the charcoal consumption for both systems are compared with each other.

Introduction

The authors have made a series of studies on water–gas atmospheres in recent years [1–4]. In Ref. [1] they proposed a method to prepare controlled atmospheres for the heat treatment of steel by adding water–gas, generated by reacting water vapor with hot charcoal, to commercial grade nitrogen, and examined the influence of water–gas generation conditions and addition level on the carbon potential of such blends. It was concluded that the carbon potential of the blends increases with increasing the volume fraction of water–gas. So, blends to be used for carburizing must contain a large amount (generally over 40%) of water–gas.

However, to produce carburizing atmospheres by this method, two problems arise: (a) rapid consumption of charcoal and (b) the exhausted atmosphere, which contains large amounts of CO and H_2, not only leading to a waste of energy but also resulting in air pollution.

Essentially, the carbon potential of the abovementioned water–gas atmosphere comes from the hot charcoal, which reacts with water vapor to form water–gas according to the following reactions (1) and (2):

$$H_2O + C \rightarrow CO + H_2 \quad (1)$$

$$2H_2O + C \rightarrow CO_2 + 2H_2 \quad (2)$$

where C represents the carbon contained in charcoal. Water–gas has a definite equilibrium composition at a given temperature and a given pressure. For example, at 900°C and 1 atm, the equilibrium composition of water–gas is 48.6% CO, 49.3% H_2, 0.7% CO_2, 0.9% H_2O, and minor amounts of CH_4 [1]. When steel is carburized in a water–gas atmosphere, the two most important carburizing reactions are as follows:

$$H_2 + CO \rightarrow [C] + H_2O \quad (3)$$

$$2CO \rightarrow [C] + CO_2 \quad (4)$$

where [C] represents the carbon dissolved in austenite. After the carburizing reactions take place, the contents of H_2 and CO will decrease and the contents of H_2O and CO_2 will increase. As a result, the carbon potential of water–gas will decrease. If the water–gas with a decreased carbon potential repasses through the hot charcoal layer, the H_2O and CO_2 in water–gas will react with charcoal according to reactions (1) and (5) to form CO and H_2. So, the water–gas will recover its carbon potential.

$$H_2O + C \rightarrow CO + H_2 \quad (1)$$

Y.C. Chen, Associate Professor, and G.S. Lu, Graduate Student, are with National Taiwan University, Taipei 10764, Taiwan, R.O.C.

$$CO_2 + C \rightarrow 2CO \quad (5)$$

where C represents the carbon contained in charcoal. Therefore, if the water–gas atmosphere is used to carburize steel repeatedly in a closed circulative system, it can keep a constant carbon potential through reactions (1) and (5). Moreover, the amounts of CO_2 and H_2O in the used water–gas atmosphere are relatively small; therefore, the consumption of charcoal through reactions (1) and (5) is little, compared with that of generating water–gas in an open system by reacting water vapor with hot charcoal according to reactions (1) and (2).

The objective of this study is to investigate the feasibility of recycling the water–gas atmosphere after carburizing steel. First, water–gas generated in a closed circulative system, and steel samples were heated in such water–gas atmosphere under some specific conditions. Then, based on the carbon content and hardness distribution in the surface layer of treated samples and the variation of water–gas composition, both the stability of water–gas atmosphere in the closed system and its carburizing behavior are elucidated. Finally, the results of carburization employing water–gas atmospheres in the open system and closed system are compared with each other, and the benefits of the closed system on steel carburizing are shown.

Experimental Method

The schematic diagram of the experimental apparatus is shown in Figure 1. The water vapor from the heated flask reacts with the hot charcoal in the charcoal furnace to form water–gas. The oxygen partial pressure of the water–gas can be determined by passing it through the oxygen testing furnace, which contains an oxygen sensor. After flowing through an adjustable flowmeter, the water–gas was introduced into the specimen furnace, in which steel samples were heated. For comparison, two systems were adopted in this experiment, namely an open system and a closed system. For the open system, the water–gas flowing out from the specimen furnace was exhausted to the air through a bleeder, whereas for the closed system, it was passed again through the charcoal furnace with a gas pump to react with the hot charcoal again. The circulation rate of water–gas in the closed system can be regulated by controlling the rpm of the gas pump or adjusting the needle valve of the flowmeter.

The charcoal furnace, the specimen furnace, and the oxygen testing furnace all are resistance heated furnaces. A ceramic tube, with an inner diameter of 30 mm and a length of 1000 mm, was placed at the center of the charcoal furnace. Inside the tube, charcoal of 8~16 mesh, with a depth of 200 mm, was filled at the middle part of the charcoal furnace, where the temperature distribution is uniform. The oxygen sensor uses a ZrO_2 tube as a solid electrolyte and air as a reference gas. When an oxygen partial pressure was measured, the temperature of the oxygen testing furnace was kept at 950°C and the electromotive force developed at the oxygen sensor was recorded with a minivolt recorder. A ceramic tube, 1000 mm long × 30 mm I.D., was installed at the center of the specimen furnace as a heating chamber of steel samples.

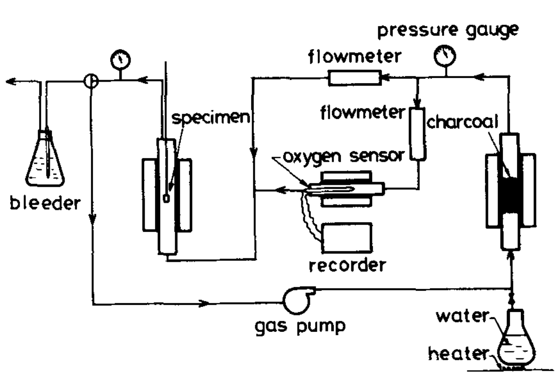

Fig. 1. Experimental apparatus.

Table 1. Experimental Conditions

	Generation Condition of Water–Gas		Steel Sample Heating Condition		
Condition	Charcoal Temp. (°C)	Generation Rate (cc/min)	Sample	Temp. (°C)	Time (min)
1	900	260	SPCE	900	1,9
2*	850,900 950	120	—	—	—
3*	900	120,260 330,480 580	SPCE	900	1–15
4	800,850 900,950	260	SPCE	900	1–15
5*	900	260	SPCE	850,900 950	1–15
6*	990	120,260 330	pure iron SAE 1020	900	60,180 300
7	800,850 900,950	260	pure iron SAE 1020	900	180
8*	950	120 260	pure iron SAE 1020	930	60,180 300
9*	850 900	180	—	—	—

*Experiments were conducted in both closed and open systems.

All specimens were suspended at the middle of the furnace for heating.

Table 1 summarizes the experimental conditions, indicating the conditions for generating water–gas and heating specimens. Steel samples used include three types: (a) Extreme low carbon steel foil, with a thickness of 0.05 mm, JIS-SPCE (0.05% C, 0.008% Si, 0.28% Mn, 0.23% P, 0.022% S). The specimen had dimensions of 20 × 10 × 0.05 mm. This type of specimen was used to test the equilibrium carbon content of steel (or the carbon potential of the atmosphere) while it was heated in the water–gas atmosphere. (b) Disk shaped pure iron specimen (0.015% C, 0.005% Si, 0.068% Mn, 0.010% P, 0.008% S) with a thickness of 5 mm and a diameter of 12 mm, (c) Disk shaped low carbon steel SAE 1020 specimen (0.21% C, 0.45% Mn, 0.04% P, 0.05% S). The specimen had the same dimensions as the pure iron specimen. Both were used to test the amount of carbon carburized, and the hardness distribution in the surface layer of steel after carburizing and quenching.

The weight change of a specimen after heating in the water–gas atmosphere can be considered to be the weight change of the carbon in the specimen if no oxidations take place. In this experiment, the carbon content of SPCE and the amount of carbon carburized into a specimen of pure iron or SAE 1020 after heating are calculated by using the following equations:

Carbon content of SPCE, %

$$= \frac{0.057 \times W_1 + 100 \times (W_2 - W_1)}{W_2} \quad (6)$$

The amount of carbon carburized into pure

$$\text{iron or low carbon steel, mg/cm}^2 = \frac{W_2 - W_1}{A} \quad (7)$$

where

W_1 = the original weight of specimen
W_2 = the weight of specimen after heating
A = the surface area of specimen

Results

Stability of Water–Gas Atmospheres During Circulation

Carbon potential stability. In order to understand if the carbon potential of water–gas is stable, experiments were performed according to condition 1 in Table 1. One piece of SPCE specimen was put into the specimen furnace for heating every 10 min interval after the circulation of water–gas atmospheres. Heating time is 1 or 9 min. The carbon content of specimens after heating is illustrated in Figure 2. The carbon content of the specimen heated for 1 min is 0.42% to 0.49%, and that heated for 9 min is 1.16% to 1.24%. From this figure, it is clear that the carburizing behavior of the water–gas atmosphere is rather stable during the period of circulation in the closed system.

Oxygen content stability. Water–gas was generated in accordance with condition 2 in Table 1, and its

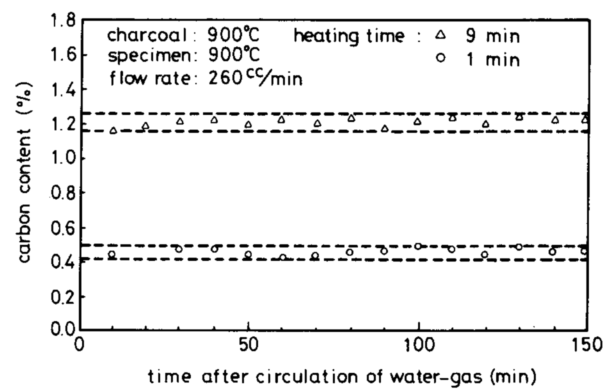

Fig. 2. Carbon content of SPCE after heating under the circulative water–gas atmosphere for 1 and 9 min, respectively.

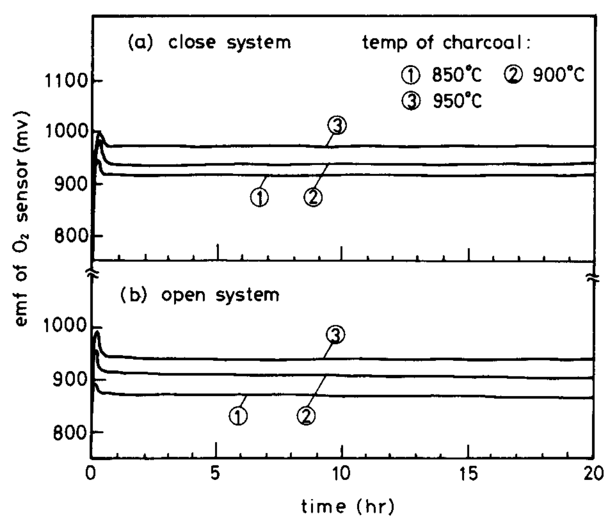

Fig. 3. Variation of the electromotive force developed at oxygen sensor while it was detecting the oxygen partial pressure of water–gas generated in (a) closed system and (b) open system.

oxygen partial pressure was determined with an oxygen sensor by passing it through the oxygen testing furnace. The partial pressure of oxygen is correlated with the electromotive force (EMF)(millivolts) developed at the oxygen sensor; that is, the lower the oxygen partial pressure, the higher the EMF [5]. Figures 3(a) and (b) show the EMF as a function of time from the moment that water–gas was introduced into the oxygen testing furnace for the closed system and open system, respectively. From these curves, it is known that the EMF for either system reaches its individual steady value in 20 min and does not change significantly thereafter. This indicates that the oxygen partial pressure of the water–gas generated in either system is quite stable.

Equilibrium Carbon Content of Steel Heated under the Water–Gas Atmosphere in the Closed System

Influence of the circulation rate of water–gas on the equilibrium carbon content of steel. Experiments were conducted in the closed system according to condition 3 in Table 1; that is, SPCE specimens were heated in water–gas atmospheres, with various circulation rates, at 900°C for period from 1 to 15 min. The relationships between heating time and carbon content of specimens heated are indicated by the solid lines in Figure 4. For a given circulation rate, carbon content of the specimen increases with time, and reaches some equilibrium level after about 10 min of heating. Comparing curves in this figure, we know that the greater the circulation rate of water–gas, the higher the equilibrium carbon content of steel.

Influence of charcoal temperature on the equilibrium carbon content of steel. In order to understand the relationship between charcoal temperature and the equilibrium carbon content of steel, experiments were performed in the closed system according to condition 4 in Table 1. The result, as shown in Figure 5, indicates that the higher the charcoal temperature, the higher will be the equilibrium carbon content of steel or the carbon potential of the water–gas.

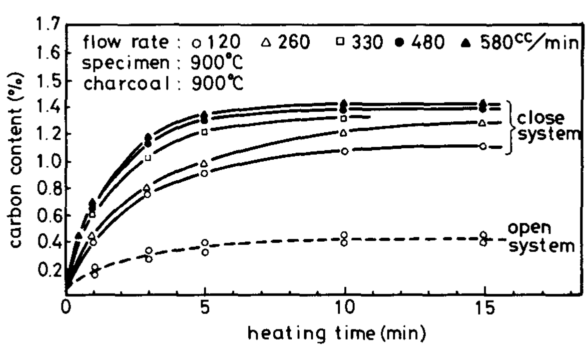

Fig. 4. Relationship between time and carbon content for SPCE heated at 900°C under the water–gas atmosphere with various flow rates.

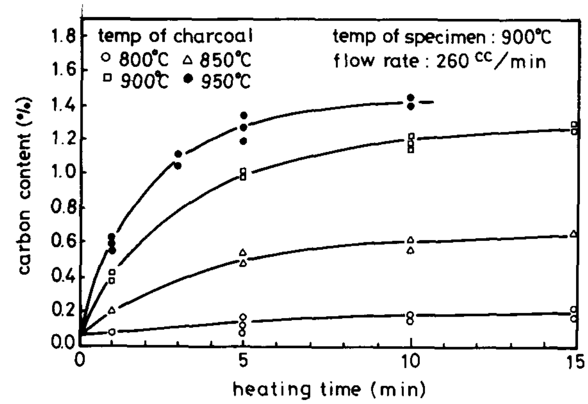

Fig. 5. Relationship between time and carbon content for SPCE heated at 900°C under the water–gas atmosphere generated at various charcoal temperatures in the closed system.

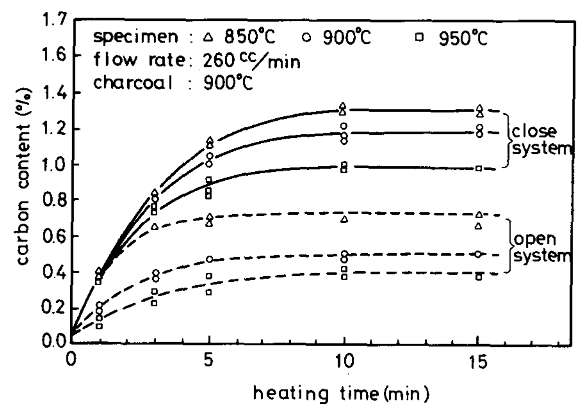

Fig. 6. Relationship between time and carbon content for SPCE heated at various temperatures under the water–gas atmosphere.

Influence of heating temperature on the equilibrium carbon content of steel. In order to understand the effect of temperature on the equilibrium carbon content of steel heated in the closed system, experiments were carried out according to condition 5 in Table 1. The result is shown by the solid lines in Figure 6, that is, the higher the heating temperature, the lower the equilibrium carbon content of the steel after heating. This implies that the carbon potential of the water–gas, generated in the closed system under a specific condition, decreases with increasing temperature of steel.

Amount of Carbon Carburized for the Steel Heated under the Water–Gas Atmosphere in the Closed System

Influence of the circulation rate of water–gas on the amount of carbon carburized. Experiments were conducted in the closed system according to condition 6 in Table 1, and the results are shown in Figures 7(a) and (b). The solid lines in Figure 7(a) indicate the relationship between heating time and the amount of carbon carburized per unit surface area for pure iron heated in water–gas with circulation rates of 120, 260, and 330 cc/min. As can be seen from the plot, the carburized carbon of pure iron increases with increasing the circulation rate of water–gas. For low carbon steel SAE 1020 treated under identical conditions, a similar result was obtained as indicated by the solid lines in Figure 7(b).

Influence of charcoal temperature on the amount of carbon carburized. In order to compare the amount of carbon available for carburizing steel heated in the water–gas generated at various charcoal temperatures in the closed system, experiments were carried out according to condition 7 in Table 1. The result, shown in Figure 8, indicates that the weight of carbon available for carburizing per unit of surface area increases with increasing charcoal temperature. Furthermore, by comparing the weight gain per unit area for pure iron with that for low carbon steel, it is known that the total diffused carbon of pure iron is slightly greater than that of low carbon steel treated under the same conditions.

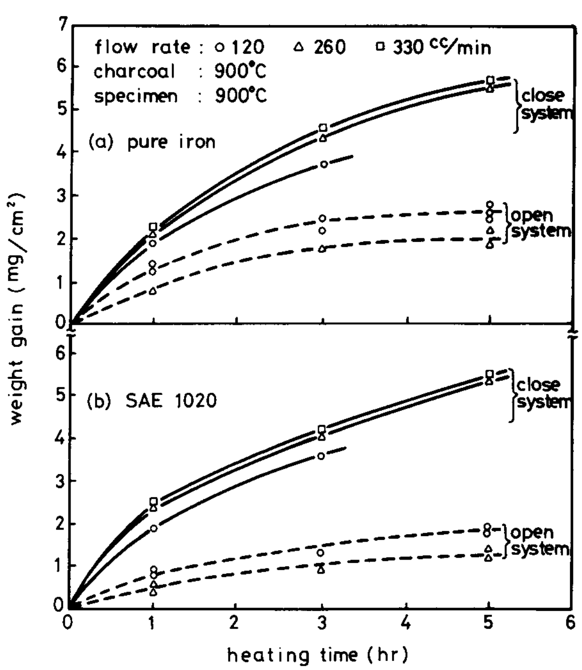

Fig. 7. Relationship between time and the weight gain per unit area due to carburization for (a) pure iron and (b) SAE 1020 heated in water–gas with various flow rates.

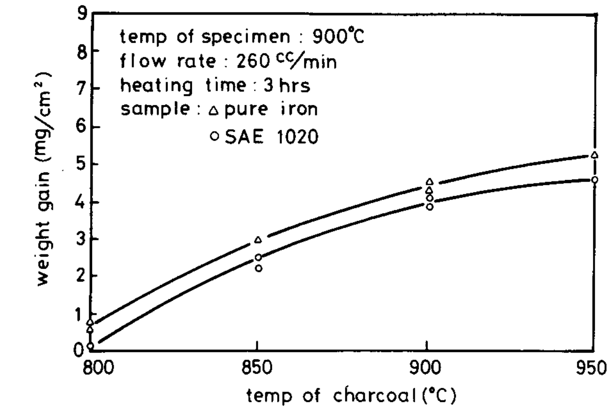

Fig. 8. Relationship between charcoal temperature and the weight gain per unit area for pure iron and SAE 1020 heated in the water–gas generated in the closed system.

Hardness Distribution in the Carburized Layer

In order to understand the case hardness distribution for steel carburized in the water–gas atmosphere and quenched in water, experiments were performed according to condition 8 in Table 1. After being heated for a specific period of time in the water–gas atmosphere, the specimen was quenched into water. Then the disk shaped specimen was cut into two parts through the diameter with a low speed diamond saw. After the section was polished, the hardness of the surface layer was tested every 0.1 mm interval from the surface by a microhardness tester. The results are shown in Figures 9, 10 and 11.

Figures 9(a) and (b) indicate the case hardness distribution for the carburized and water quenched pure iron treated in the closed system and open system, respectively. As shown in the plots, a longer carburizing time results in a harder case and a deeper case depth. By comparing the curves in Figure 9(a) with those in Figure 9(b), it is clear that the hardness of the case produced in the closed system is much higher than that produced in the open system for pure iron. A similar result was obtained for low carbon steel SAE 1020, as shown in Figures 10(a) and

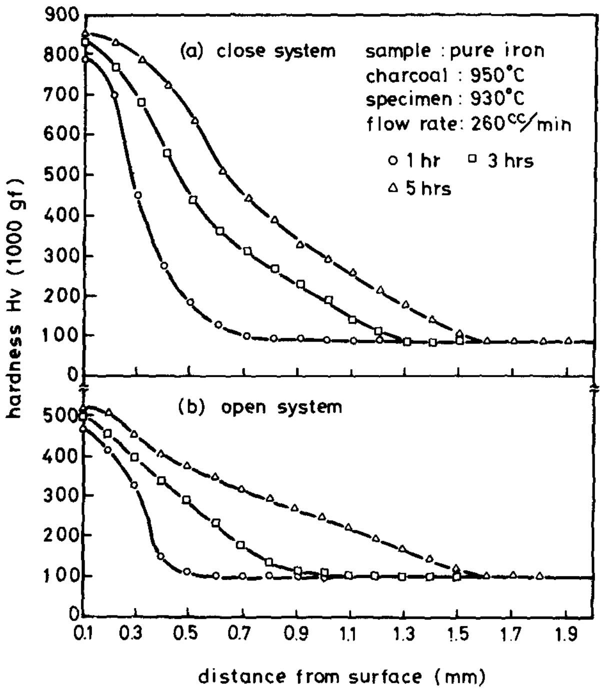

Fig. 9. Variation of case hardness with distance below the surface for pure iron heated at 930°C for various time under the water–gas atmosphere in (a) closed and (b) open systems, and followed by water quench.

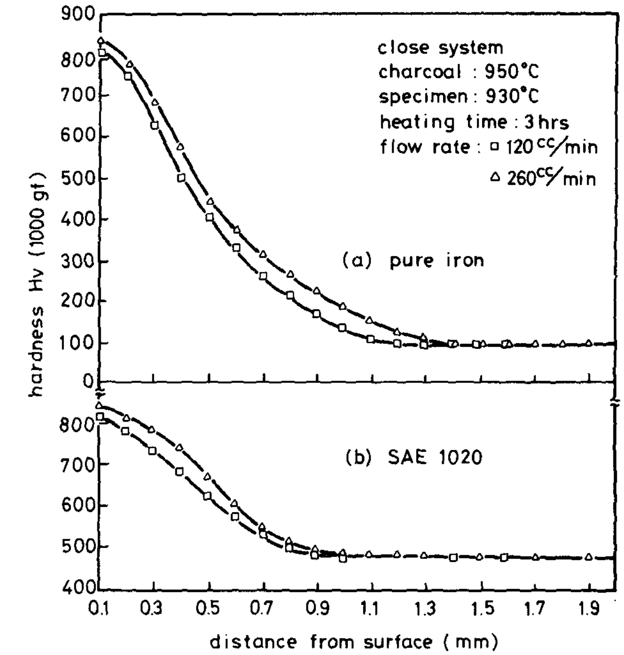

Fig. 11. Variation of case hardness with distance below the surface for (a) pure iron and (b) SAE 1020 heated at 930°C for 3 hr under the water–gas atmosphere with various circulation rates in the closed system, and followed by water quench.

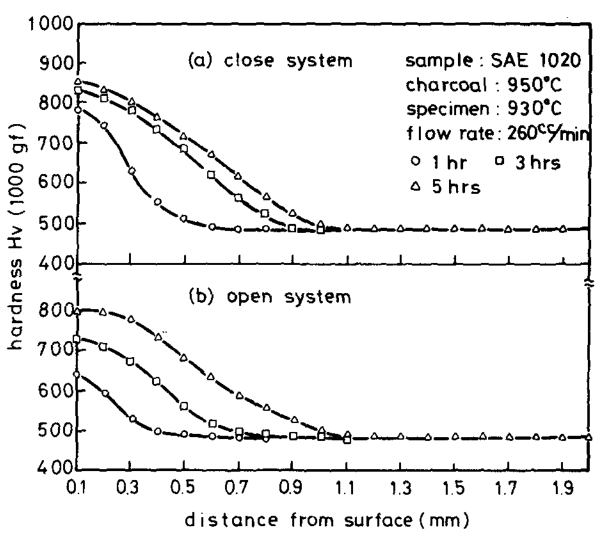

Fig. 10. Same as Fig. 9 except that the steel involved is low carbon steel SAE 1020.

(b). Figure 11(a) indicates the case hardness distribution for pure iron carburized for 3 hr at 930°C in water–gas with various circulation rates. Comparing the two curves in the plot, we know that a greater circulation rate of water–gas results in a higher hardness of the surface layer for pure iron. A similar result was also obtained for low carbon steel SAE 1020, as shown in Figure 11(b).

Comparison of the Carburizing Result between the Closed System and Open System

Comparison of the equilibrium carbon content. In order to compare the equilibrium carbon content of steel carburized in the closed system with that in the open system, experiments were conducted in both systems according to condition 3 in Table 1. The equilibrium carbon content of SPCE carburized in the closed system is indicated by the solid lines in Figure 4, as mentioned previously. For example, the equilibrium carbon content of SPCE heated at 900°C is 1.05% when the circulation rate of water–gas is 120 cc/min. However, that of SPCE carburized under identical conditions in the open system is only about 0.4%, as indicated by the dashed line in Figure 4. It can be concluded that the carbon potential of the water–gas generated in the closed system is much higher than that generated in the open system.

The dashed lines in Figure 6 indicate the result of the experiments conducted in the open system according to condition 5 in Table 1. The heating temperatures of SPCE are 850°C, 900°C, and 950°C, and the corresponding equilibrium carbon contents are 0.73%, 0.52%, and 0.42%. Apparently, the higher the heating temperature of steel, the lower is its equilibrium carbon content. This tendency is similar to that in the closed system. However, comparing this result with that of the closed system, indicated by the solid lines in Figure 6 where the corresponding equilibrium carbon contents are 1.31%, 1.18%, and 0.96%, it is known that the specimen treated in the closed system reaches a higher equilibrium carbon content. This proves again that the carbon potential of the water–gas in the closed system is higher than that in the open system for the identical generation conditions.

Comparison of the amount of diffused carbon. In order to compare the amount of diffused carbon for steel heated under the water–gas atmosphere in the closed system with that in the open system, experiments were conducted in both systems according to condition 6 in Table 1, and the results are shown in Figure 7, where the solid lines indicate the result for the closed system and the dashed lines for the open system. By comparing the solid lines and dashed lines in the figure, it is known that the amount of diffused carbon for the closed system is much greater than that for the open system. For example, at a charcoal temperature of 900°C and water–gas circulation rate of 260 cc/min, the amounts of diffused carbon for pure iron and low carbon steel are 4.3 mg/cm^2 and 4.0 mg/cm^2, respectively after heating in the water–gas at 900°C for 3 hr; however, under the identical conditions, except for heating in the open system, the amount of diffused carbon for pure iron and low carbon steel is just about 1.7 mg/cm^2 and 1.0 mg/cm^2, respectively.

Comparison of the case hardness. In order to compare the hardness distribution of the case produced in the closed system with that produced in the open system, experiments were practiced in both systems according to condition 8 in Table 1. For the convenience of comparison, the case hardness distribution curves for both systems were plotted in the same figure, as shown in Figure 12. Figure 12(a) indicates the case hardness distribution of the pure iron after 3 hr of carburizing and water quenching. From the two curves in this figure, it is clear that the case hardness obtained in the closed system is much higher than that obtained in the open system. For example, at the point of 0.1 mm below surface, the former is HV 835; however, the latter is only HV 490. Figure

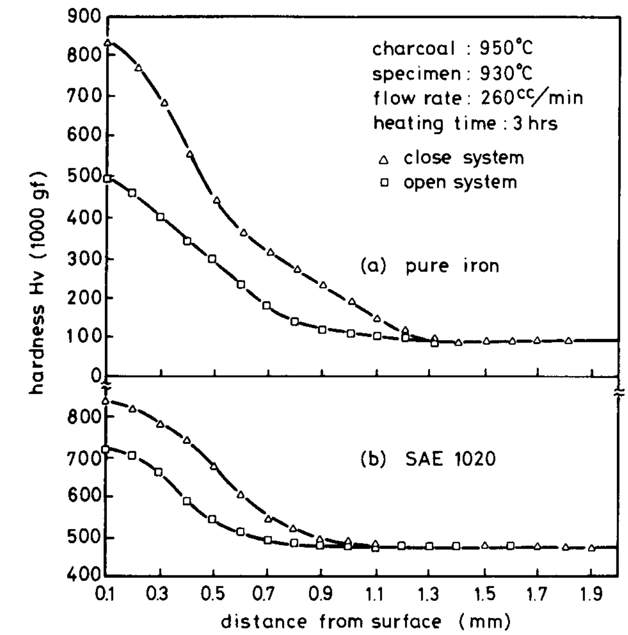

Fig. 12. Comparison between the case hardness distributions obtained in the closed and open systems for (a) pure iron and (b) SAE 1020, heated at 900°C for 3 hr under the water–gas atmosphere and followed by water quench.

12(b), the result for low carbon steel SAE 1020, also indicates that the case hardness obtained in the closed system is higher.

Comparison of Charcoal Consumption between the Closed System and Open System

In order to understand the consumption rate of charcoal for the closed system and open system, experiments were carried out in both systems according to condition 9 in Table 1. The weight decrease of charcoal was recorded after generating a given amount of water–gas. The results are shown in Figure 13, where the horizontal axis denotes the volume of water–gas at room temperature under 1 atm, and the vertical axis denotes the consumption of charcoal. From this figure it is known that there is an approximately linear relationship between the charcoal consumption and the volume of water–gas generated for both systems.

For the open system, the slope of this line is 0.33 g/L; however, for the closed system, the slope of this line is 0.011 g/L. In other words, generating 1 L of water–gas in the open system needs 0.33 g of charcoal; however, generating 1 L of water–gas in the closed system needs only 0.011 g of charcoal, which is 1/30 of that required in the open system. Clearly,

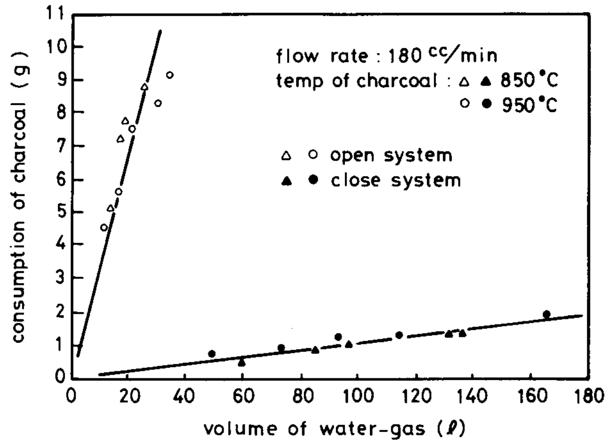

Fig. 13. Comparison of charcoal consumption for generating water–gas in the closed and open systems.

the closed system minimizes charcoal consumption in comparison with the open system.

Discussion

Electromotive Force and Carburizing Capability of Water–Gas Atmospheres

From the result in Figure 3(a), it is known that the EMF developed at the oxygen sensor for the water–gas generated under a specific condition can remain unchanged for a long time. On the other hand, the EMF is closely related with the oxygen content and carbon potential of water–gas; that is, the higher the EMF, the lower the oxygen content and the higher the carbon potential of water–gas [5,6]. Thus, from Figure 3(a), it can be reasoned that the carburizing capability of water–gas during circulation is quite stable. This is consistent with the result of Figure 2. By comparing curves ①, ② and ③ in Figure 3, it is known that the higher the charcoal temperature, the higher is the EMF of water–gas. In other words, water–gas generated from charcoal with a higher temperature possesses a higher carbon potential. This is consistent with the results of Figure 5 and Figure 8. In addition, by comparing the curves in Figure 3(a) with the corresponding ones in Figure 3(b), it is known that the EMF for the closed system is higher than that for the open system if charcoal temperatures for both systems are identical. It can be inferred that for the same charcoal temperature and the same generation rate, water–gas generated in the closed system possesses a higher carbon potential than that generated in the open system.

Relationship between Charcoal Temperature and the Carbon Potential of Water–Gas

Both Figures 5 and 8 indicate that the higher the charcoal temperature, the higher the carburizing capability of water–gas. As mentioned previously, the constituents of water–gas are CO, H_2, and small amounts of CO_2, H_2O, CH_4, etc. The higher the charcoal temperature, the higher the percentage of carburizing constituent, CO, and the lower the percentage of decarburizing constituents, CO_2 and H_2O, among the equilibrium constituents of water–gas [1], and accordingly, the higher the carbon potential of the water–gas atmosphere. The fact that the CO content increases and the CO_2 content decreases with increasing charcoal temperature can be proved by the gas analysis data given in Table 2.

Relationship between the Carburizing Capability and Generation Rate of Water–Gas

The generation rate of water–gas influences a carburizing process two ways, namely, by affecting the flow velocity of water–gas and the residence time of water–gas in the charcoal layer. More precisely, the higher the generation rate of water–gas, the higher the velocity as it passes by the specimen, and the shorter its residence time in the charcoal layer. A rapid flow velocity for water–gas passing by the specimen favors a carburizing reaction; however, a short residence time in the charcoal layer will lower the carburizing capability of water–gas.

From the results of Figure 4, it is known that the equilibrium carbon content of a specimen carburized in the closed system increases with increasing the circulation rate of water–gas. The reason can be deduced as follows. When steel is carburized in water–gas, decarburizing gases, CO_2 and H_2O, will be generated by reactions (3) and (4). If these CO_2 and H_2O adhere on the surface of the steel, the subsequent carburizing reaction will be retarded because

Table 2. Chemical Composition of the Dehumidified Water – Gas Generated in the Closed System

Charcoal Temp. (°C)	Generation Rate (cc/min)	Chemical Composition (%)			
		CO	H_2	CO_2	CH_4
950	120	50.53	48.34	0.14	0.98
	260	50.41	48.49	0.16	0.95
900	120	49.46	48.63	0.60	1.30
	260	48.79	49.40	0.65	1.16
850	120	47.20	50.49	1.08	1.22
	260	45.80	51.20	1.79	1.21

Table 3. Chemical Composition of the Dehumidified Water-Gas Generated in the Open System

Charcoal Temp. (°C)	Generation Rate (cc/min)	Chemical Composition (%)			
		CO	H_4	CO_2	CH_4
950	120	49.92	48.82	0.28	0.98
	260	49.04	49.61	0.31	1.03
900	120	48.72	49.54	0.32	1.43
	260	48.66	49.06	0.85	1.43
850	120	45.37	50.91	2.03	1.69
	260	39.44	54.42	4.44	1.69

the carbon potential of the atmosphere near the surface of the steel will decrease owing to the accumulation of CO_2 and H_2O. The furnace atmosphere with a high flow velocity tends to remove the CO_2 and H_2O from surface of the steel, and avoids the subsequent decrease of carbon potential. Thus, for the atmosphere with a definite composition, the greater the flow rate, the higher the equilibrium carbon content of steel after heating in it. Moreover, when the flow rate of an atmosphere increases, the collision frequency between steel and the atmosphere will increase; consequently, the amount of carbon carburized per unit area of the steel will increase as well. This point is illustrated by the solid lines in Figure 7.

The dashed lines in Figure 7 indicate that increasing the generation rate of water–gas in the open system will result in a decrease of carburized carbon of steel. This is because the water–gas in the open system is generated by reacting water vapor with hot charcoal, and it takes more time to complete this reaction. If the residence time of water vapor in the charcoal layer is insufficient, the percentages of decarburizing constituents, CO_2 and H_2O, in the water–gas will increase markedly. As a result, the carburizing capability of water–gas will decrease. This can be proved by the data of gas analysis given in Table 3.

Carburizing Results for the Closed System and Open System

All the results in Figures 9, 10, and 12 indicate that the hardness of the carburized and hardened case treated in the closed system is higher than that treated in the open system. Because the water–gas generated in the closed system possesses a higher carburizing capability, as reasoned previously, the carbon content of the case produced in the closed system is higher as well. After quenching, the microstructure of the case is mainly martensite, the hardness of which increases with increasing carbon content. Thus, the hardness of the case produced in the closed system is higher. From this it can be concluded that the result of carburizing conducted in the closed system is superior to that in the open system.

Relationship between the Chemical Composition and Carbon Potential of Water–Gas

Water–gas may be regarded as an H_2 + CO + CO_2 + H_2O + CH_4 gas mixture. Its carbon potential is proportional to the value of P^2_{CO}/P_{CO_2} [1,5,6], where P_{CO} and P_{CO_2} denote the partial pressure of CO and CO_2, respectively. Tables 2 and 3 present the chemical composition of the dried water–gas generated under various conditions in the closed system and open system, respectively. From the two tables, it is known that the higher the charcoal temperature, the higher the CO content and the lower the CO_2 content for the water–gas generated at a definite generation rate. In other words, the rise of charcoal temperature will increase the value of P^2_{CO}/P_{CO_2}, and consequently increase the carbon potential and carburizing capability of the water–gas generated. This is consistent with the results of Figures 5 and 8. Moreover, by comparing the corresponding data in Table 2 and Table 3, it can be found that for the same charcoal temperature and the same generation rate, water–gas generated in the closed system contains more CO and less CO_2 than that generated in the open system. Thus, the former possesses a higher carbon potential than the latter. In addition, if the temperature of charcoal keeps constant, increasing the generation rate of water–gas will decrease the volume percentage of CO and increase the volume percentage of CO_2, and accordingly lower the value of P^2_{CO}/P_{CO_2}, for both systems. However, the decrease in the value of P^2_{CO}/P_{CO_2}, for the open system is more serious than that for the closed system. This implies that increasing the circulation rate of water–gas in the closed system does not affect the chemical composition and carbon potential so much. For this reason, when the circulation rate of water–gas increases, the positive effect on carburizing due to the increase in its flow velocity probably exceeds the negative effect on carburizing due to the slight change in its chemical composition. Thus, if the circulation rate of water–gas increases, both the equilibrium carbon content and the amount of carbon carburized per unit area of steel will increase as well. The solid lines in Figure 4 and Figure 7 indicate this situation.

On the other hand, increasing the generation rate of water–gas in the open system will lower its carbon potential pronouncedly owing to the marked change of its chemical composition. For this reason, when the generation rate of water–gas increases, the positive effect on carburizing due to the increase in its flow velocity can't offset the negative effect due to the change in its chemical composition. Thus, for the open system, when the generation rate of water–gas increases, the amount of carbon carburized per unit area of steel decreases, as indicated by the dashed lines in Figure 7.

Consumption of Charcoal

From Figure 13, it is known that the consumption of charcoal for generating a given amount of water–gas in the closed system is far smaller than that for generating the same amount of water–gas in the open system.

In the open system, the main reaction for generating water–gas is as follows:

$$H_2O + C \rightarrow H_2 + CO \qquad (1)$$

That is, one mole of carbon reacting with water vapor will produce two moles of water–gas. One mole of carbon weighs 12 g and the volume of two moles of water–gas is about 49 L at room temperature under 1 atm. Calculating from these data, we know that 0.24 g of carbon is needed to produce 1 L of water–gas by reacting carbon with water vapor. However, by experiment, 0.33 g of charcoal is consumed to generate 1 L of water–gas in the open system. The experimental value is greater than the calculated value because charcoal is not pure carbon, but also contains moisture, ash, and other impurities.

As stated in the introduction, the water–gas of the closed system is generated by reacting the used water–gas from the specimen furnace with hot charcoal. In the specimen furnace, the main reactions are the carburizing reactions of Eqs. (3) and (4), whereas in the charcoal furnace, the main reactions are the carbon potential recovering reactions of Eqs. (1) and (5). During carburizing, these reactions repeat unceasingly. Thus, water–gas may be regarded as a carrier gas of carbon, which carries carbon from charcoal to steel. Theoretically, the weight decrease of charcoal should be equal to the weight increase of steel due to carburizing, if one neglects the soot formed in furnaces and the impurities contained in charcoal. Therefore, the charcoal consumption in the closed system is minimal compared with that in the open system.

Conclusions

1. The carburizing capability of water–gas atmospheres in a closed circulative system is rather stable. For a definite charcoal temperature and a given circulation rate, the carbon potential of the water–gas can remain unchanged for a long period of time.
2. The equilibrium carbon content of steel heated under the water–gas atmosphere in the closed system depends on the temperatures of steel and charcoal, and the circulation rate of water–gas. If both the temperature of charcoal and the circulation rate of water–gas keep unchanged, the higher the heating temperature of steel, the lower its equilibrium carbon content after heating in the water–gas. If the heating temperature of the steel keeps constant, either increasing the temperature of charcoal or increasing the circulation rate of water–gas will result in an increase in the equilibrium carbon content of the steel.
3. If both the temperature of charcoal and the generation rate of water–gas are definite, the water–gas generated in the closed system possesses a higher carbon potential than that generated in the open system.
4. The hardness of the carburized and hardened case obtained in the closed system is higher than that obtained in the open system under the same conditions.
5. Carburizing of steel by using water–gas atmospheres in a closed system can (a) avoid the air pollution caused by the exhausted atmosphere, (b) markedly economize the raw material for preparing the atmosphere (charcoal consumption rate cut by about 97% for the apparatus used in this experiment) and (c) get a better carburizing result.

Acknowledgments. The authors wish to acknowledge the National Science Council of Taiwan, R.O.C. for the financial support for this research under grant No. NSC-79-0401-E002-17. In addition, particular thanks are due to Professor C. H. Hwang for his continued advice and encouragement.

References

1. Y.C. Chen and C.H. Hwang: *Heat Treatment of Metals*, 1984, No. 4, pp. 96–101.
2. Y.C. Chen, K.C. Chi, and C.H. Hwang: *Chinese Jour-*

nal of Materials Science, 1987, Vol. 19, No. 4, pp. 262–278.
3. Y.C. Chen, C.C. Wu, and C.H. Hwang: *Chinese Journal of Materials Science*, 1989, Vol. 21, No. 1, pp. 45–59.
4. Y.C. Chen, B.S. Yu, and C.H. Hwang: *Chinese Journal of Materials Science*, 1989, Vol. 21, No. 3, pp. 169–181.
5. M.J. Bannister: *Industrial Heating*, March 1984, pp. 24–26.
6. F.E. Harris: *Metal Progress*, January, 1945, Vol. 47. No. 1, pp. 84–89.

Received September 27, 1991.