CALCULATING THE GAS FLOW RATE FOR VACUUM CARBURIZATION

A proposed technique of determining the actual required flow rate of the carburizing gas into a furnace to provide the necessary amount of carbon for a given work load.

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Vacuum carburization was introduced in 1960s. Much of the original work was carried out with saturated hydrocarbons as the carburizing media. These hydrocarbon compounds required high partial pressures (greater than 10 to 15 torr) to be effective carburizing agents. Although carburizing was achieved, sooting was a problem. The sooting problem was overcome by using unsaturated hydrocarbons.

Development work led to the establishment of data for controlling many of the variables for vacuum carburization. As an example, there are data that provide case depth as a function of total carburizing time (carburizing [boost] time plus diffusion time). In addition, there is a system of parametric curves that relates carburizing temperature-total time-case depth. There is also a relationship between R, the ratio of diffusion time to boost time, to the surface carbon content. However, the foundation for the diffusion of carbon into steel goes back to Fick's differential equation for diffusion. The solution to Fick's equation yields the simple equation:

$$D = K\sqrt{t} \qquad (1)$$

where:

D = the carburized case depth
K = a constant that depends on temperature
t = total time (boost plus diffusion)

The values for the constant K can be found in the literature (ASM Handbook, Vol 4, *Heat Treating*, p. 350, ASM International, Materials Park, Ohio, 1991). As stated previously, information is available for prescribing *boost time* (carburizing time) and the *diffusion time* to achieve a given surface carbon content and case depth. However, in a search of the literature a method of determining the actual flow rate of the carburizing gas into the furnace to provide the required amount of carbon for a given work load has not been found.

This article proposes such a technique.

Carburizing Gas Flow Rate

In order to determine the flow rate of the carburizing gas, the following approach was taken:

• Determine the total surface area to be carburized.

• Establish the desired depth of the carburized layer.

• The product of the surface area and the desired depth is the volume of material to be carburized.

• Next, the amount of carbon needed to carburize the calculated volume is determined:

1. Determine the molecular weight of the carburizing gas from its chemical formula.

2. Establish the chemical dissociation reactions for the carburizing gas. This will provide the maximum amount of carbon available.

• Total boost (carburizing) time is specified.

• The theoretical flow rate of the gas is then calculated to provide the amount of carbon needed in the boost time used.

Calculations using the flow rate equation given previously assume that all the gas introduced dissociates completely, as the chemical equations for that particular gas predict. However, in practice all of the gas introduced will not dissociate completely. Therefore, the degree of dissociation

has to be determined experimentally. The flow rate as calculated above (theoretical flow rate) will then have to be corrected using the degree of dissociation. This will then provide the actual flow rate required.

Derivation of Theoretical Flow Rate

To begin with, we need to define the following terms:

D_c = carburized depth (cm)

A_s = surface area to be carburized (cm²)

V = volume to be carburized (cm³)

C_{av} = % carbon at $D_c/2$

C_{al} = % carbon of alloy at a case depth of RC 50

C_r = total carbon required (gm)

Density of iron (gm/cm³) = 7.87

TF = total flow during boost (cm³)

FR_t = theoretical flow rate of gas during boost (cm³/min)

FR_a = actual flow rate, adjusted for fraction dissociated (cm³/min)

t_b = boost time (min)

dt = diffuse time (min)

K = a constant (0.63 for acetylene at 1750°F)

Using these terms and definitions, the following calculations may be performed.

The volume to be carburized is calculated using the following equation:

$$V = A_s \times D_c \qquad (2)$$

Next we calculate the total carbon required. In making this calculation, it is assumed that the carbon gradient was linear in the carburized case. In order to verify this, carbon analyses were made, as a function of depth, by vacuum fusion analysis. These results are shown in Figure 1. It can be seen from this figure that the gradients are almost linear. Therefore, the average carbon content in the case may be represented by the carbon content at the half-case-depth.

$$C_r = V(C_{av} - C_{al}) \times 7.87/100 \qquad (3)$$

For the rest of the derivation we assume that acetylene is used as the carburizing gas. However, the calcula-

Figure 1 — Percent carbon vs. case depth for three carburizing conditions.

tions may be made for any of the carburizing gases.

Next we calculate the carbon available from acetylene. One mole (gram-molecular weight) of any gas at standard conditions occupies 22.4 liters. The molecular weight of acetylene (C_2H_2) is 26 (carbon 12 + 12, hydrogen 1 + 1). Thus there are 24 grams of carbon in each mole of acetylene. Or, 24 g. in 22,400 cm³ of acetylene, since the dissociation of acetylene is given by:

$$C_2H_2 = 2C + H_2 \qquad (4)$$

From this we calculate that there are 0.0011 grams of carbon in each cm³ of acetylene. The total flow required and the theoretical flow rate can then be calculated:

$$TF = C_r/0.0011 \ (cm^3) \qquad (5)$$

$$FR_t = TF/t_b \ (cm^3/min.) \qquad (6)$$

or,

$$FR_t = \frac{A_s D_c (C_{av} - C_{al}) \times 0.0787}{t_b (0.0011)} \qquad (7)$$

Remember that equation (7) assumes the acetylene dissociates completely. However, the dissociation is not complete, and equation (7) must be divided by the fraction that dissociates to provide the actual flow rate required.

Amount of Acetylene that Dissociates

Most of our experimental work was carried out in the laboratory furnace shown in Figure 2. RGA (residual gas analysis) readings for acetylene were made as a function of time while the furnace was at room temperature. Under this condition there would be no dissociation of acetylene, and thus an indication of the total amount of acetylene introduced per unit time. Another run was made with a work load at 1750°F. The RGA readings at 1750°F represent the amount of acetylene left after dissociation. These data are plotted in Figure 3. The space between the two curves represents the amount of acetylene that dissociated. The fraction of acetylene dissociated as a func-
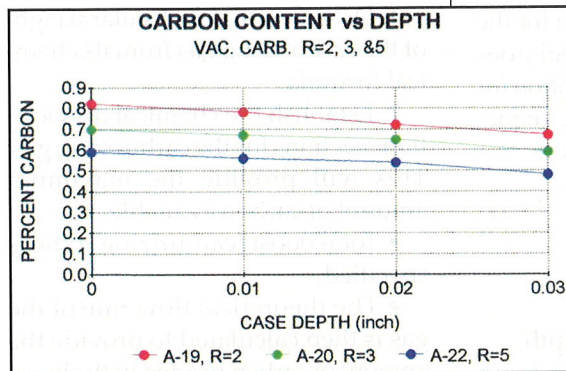
tion of time data obtained from Figure 3 is plotted in Figure 4. It can be seen from Figure 4 that the fraction dissociating is a maximum of 0.55 at 2.5 minutes, and decreases to about 0.14 at 40 minutes for this particular run.

Assuming a boost time of 40 minutes, then the area under the curve, up to this point in Figure 4, is indicative of the total amount of acetylene that dissociated. This area was determined to be 9.53 square units. The area on this plot that represents the total amount of acetylene introduced, has an ordinate value of 1.0 and an abscissa value of 40; providing an area of 40 square units. Thus, the total fraction of acetylene that dissociated is:

$$total\ fraction\ dissociated = \\ 9.53/40 = 0.238 \qquad (8)$$

Dividing equation (7) by 0.238 provides the actual flow rate, which for this example is:

$$FR_a = \frac{A_s D_c\ (C_{av} - C_{al})\ \times\ 300}{t_b} \qquad (9)$$

The reader is cautioned that equation (9) is only for the case cited and is not to be used in general. Reducing the flow rate of the gas will result in a larger fraction being dissociated. Therefore, making RGA measurements as illustrated here for a given furnace system and using these data in a progressive regression will provide an appropriate "fraction dissociated" factor. This can then be used in equation (7) to provide the actual flow rate required for a given furnace system. Using this procedure should provide the minimum gas flow for a given furnace load, resulting in the most efficient utilization of the carburizing gas.

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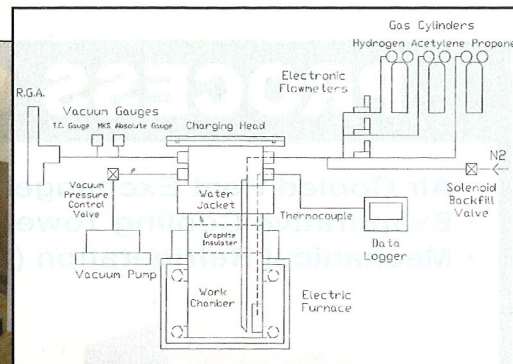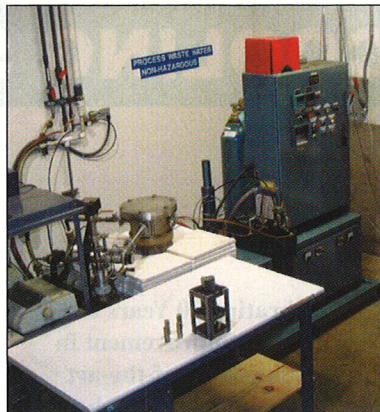

Figure 2 — Solar laboratory furnace for carburizing studies: Actual furnace, inset, schematic.
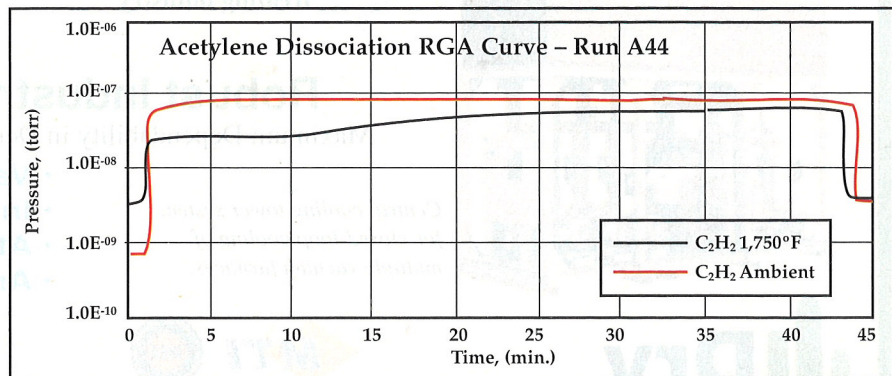

Figure 3 — RGA data for acetylene pressure vs. carburizing time at room temperature and 1750°F.
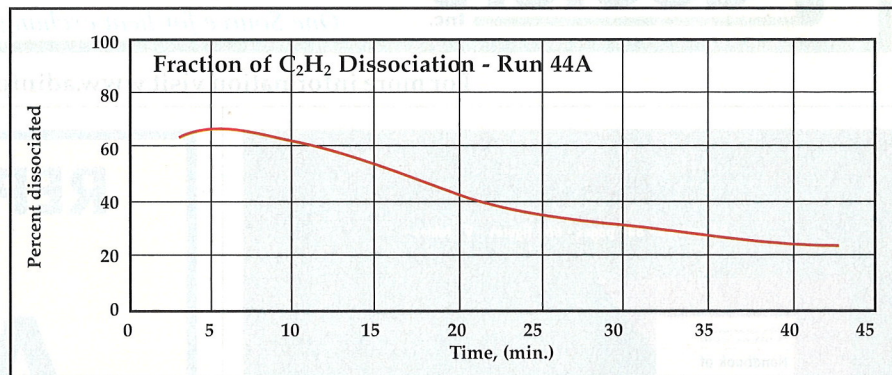

Figure 4 — Fraction of acetylene dissociated during 40-minute carburization.

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