Economic Aspects of Vacuum Carburizing

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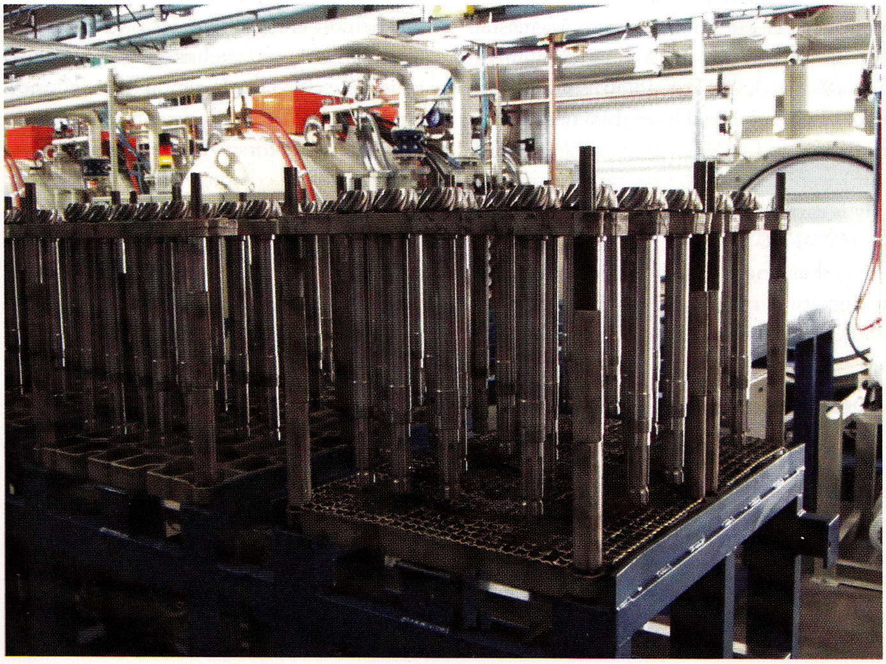
There is increased interest in vacuum furnace carburizing due to the demand for products having optimum metallurgical quality and lowest unit cost. The economic efficiency of vacuum carburizing can be considerably more competitive than traditional gas carburizing.

Vacuum carburizing technology produces work with minimum distortion, the direct result of being cooled down using gas. Surface metallurgy is superior because the carburization process is carried out in a vacuum environment. Vacuum furnace systems provide "cold-to-cold" (cold work going in, cold work coming out) and fully automatic operation, which reduces the amount of operator involvement, thus minimizing labor costs. Considering upstream and downstream costs, vacuum carburizing provides a total reduction of processing costs and is a natural fit in a lean manufacturing cell. An additional advantage is that vacuum furnace technology is a green manufacturing process with no negative impact on the environment.

The rate of vacuum carburizing

Vacuum carburizing is characterized by an extraordinarily high coefficient of carbon transfer at the phase interface, which results in a high carbon transfer. In the initial phase of carburizing, for example, at the temperature of 1740°F (950°C), the carbon stream directed at the charge surface reaches the rate of 250 g/m^2h. Therefore, in the case of thin carburization layers, the process is considerably faster than the gas carburizing process. The advantage is smaller in the case of thick layers that exceed, for example, 0.00315 in. (0.8 mm), where carbon transfer is much more dependant on the diffusion coefficient (D_C).



Vacuum carburizing may easily be carried out even at temperatures of up to 1900°F (1040°C), within the natural temperature range of a vacuum furnace. The process temperature range increases to 1700-1800°F (930-980°C) compared with traditional gas carburizing processes that typically operate within a temperature range of 1600-1700°F (870-930°C). Operating at higher temperatures results in shorter carburizing cycles due to the considerably higher diffusion coefficient. Both the increased amount of carbon in the carburizing atmosphere and faster diffusion are responsible for the increase in vacuum carburizing efficiency compared with traditional gas carburizing.

Reduction of processing time and energy-related factors

Vacuum carburizing technology differs considerably from gas carburizing in the method of delivering the carbon stream to the charge surface, process regulation and in the completion of the entire cycle. There also are differences in furnace construction, the results of heat and chemical treatment and in the consumption of energy, and therefore, process costs. The technology consistently reduces and/or eliminates part deformation, eliminates internal oxidation and reduces exhaust gas emissions into the atmosphere.

It is commonly believed that shortening the cycle period according to the assump-

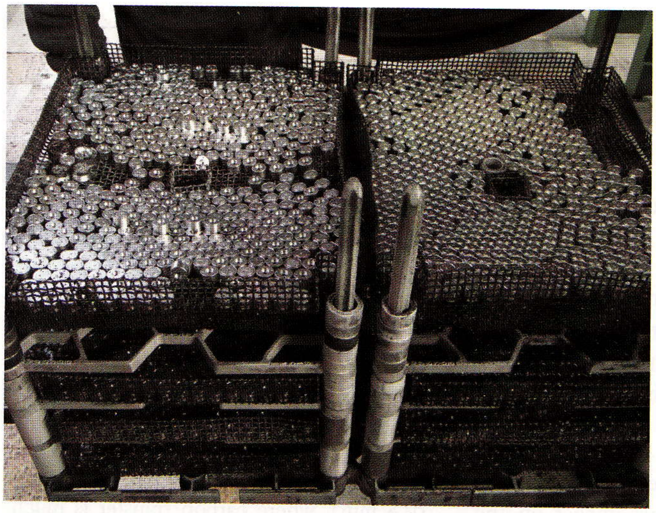


Fig. 1. Injector elements made of EN39B and 17HNM steels

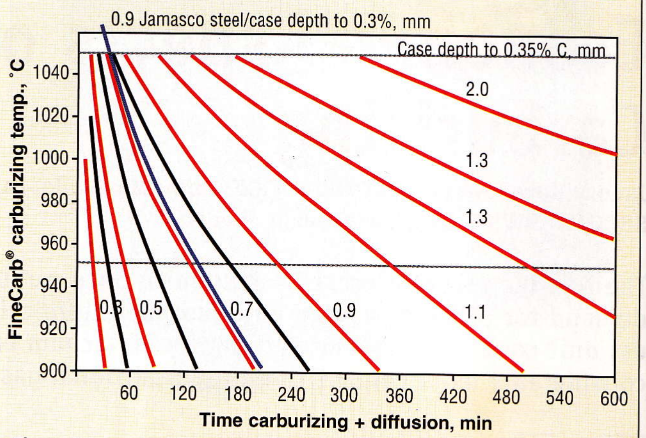


Fig. 2. Approximate vacuum carburizing process cycle time for 16MnCr5 steels with respect to temperature and required thickness of AHT layer

tions above can reduce process cost, but it should be remembered that the reduction of process duration is higher for the same temperature in the case of thin carburized layers than thicker layers, where the impact of the diffusion coefficient is dominant. For thin layers, especially those produced at high temperatures in steel grades having higher hardening capacity, the vacuum cycles are very competitive compared to gas carburizing. The following implementation examples illustrate the efficiency of vacuum carburizing.

Example 1

Vacuum carburizing allows producing a uniform carburized layer in small diameter openings of considerable depth, such as diesel injectors made of materials such as EN32B and 18CrNiMo7-6 (17HNM). The vacuum carburizing cycle (typically performed in a temperature range of 1540-1690°F, or 840-920°C) requires 11 minutes of carburizing to produce a 0.01969 in. (0.5 mm) thick layer and 120 minutes of diffusion. An analogous cycle in an atmospheric furnace requires a temperature range of 1540-1560°F (840-850°C) for a triple period to achieve comparable quality. The conspicuous impact of the process temperature difference is possible for thin layers (CCAT 550 HV 0.5 mm) produced in the steel types where the Grossman coefficient (*H*) has negligible impact on CCAT 550HV (Fig. 1).

Example 2

A comparison of gas carburizing and FineCarb vacuum carburizing was carried out to demonstrate the differences in the process cycle for typical carburized materials. The tests were carried out for the 770 lb (350 kg) net charge consisting of 16MnCr5 and 15CrNi6 steels. The tests of 16MnCr5 steel were carried out in a Casemaster® integral-quench (IQ) furnace having a 24 in. × 24 in. × 36 in. (609 × 609 × 914 mm) load capacity and in a double-chamber Seco/Warwick NVPT 24 in. × 24 in. × 36 in. furnace. Tests of 15CrNi6 steel were carried out in the same Casemaster IQ furnace and in a single-chamber Seco/Warwick VPT 4035/36 vacuum furnace. Two carburized layer thickness values (0.02362 and 0.04724 in., or 0.6 and 1.2 mm) were compared. Gas carburizing usually is carried out in the temperature range of 1690-1700°F (920-930°C), while vacuum carburizing is usually carried out in the temperature range of 1760-1800°F (960-980°C). Therefore, the comparison was carried out at temperatures of 1690°F and 1760°F, respectively. Moreover, the time of heating up to carburization temperature for a given charge is assumed to be 50 minutes, and the time of burn-in after cool-down for hardening is assumed to be 30 minutes.

Table 1 shows the carburizing results, which confirm the claimed efficiency of vacuum carburizing, especially in the case of thin layers. Figure 2 shows the general time estimates of the FineCarb process at the high temperature range (easy to obtain in a vacuum furnace) for 16MnCr5 steel and the most common layer thickness values.

The cost competitiveness of the process (installation cost excluded) is a separate issue. The above cycle periods have considerable impact on the consumption of energy-related factors. While disregarding detailed list of components of the process (i.e., furnace downtime, the time of maintaining the furnace during weekends, etc.), the energy consumption for a 15CrNi6 charge and 0.6 mm and 1.2 mm layers is presented in the following table.

Table 1 Comparison of gas and vacuum carburizing process times for two steels

EHT, mm	Total cycle, min 16MnCr5 (16H)	Total cycle, min 15CrNi6 (15HN)	(N+D) cycle, min 16MnCr5 (16H)	(N+D) cycle, min 15CrNi6 (15HN)
Gas carburizing				
0.6	315	250	176	109
1.2	660	495	520	352
FineCarb vacuum carburizing				
0.6	210	220	63 (13 min carb.)	50 (9 min carb.)
1.2	525	450	380 (27 min carb.)	280 (19 min carb.)

Energy consumption to carburize 15CrNi6 steel		
Carburized layer thickness, mm	Power consumed, kW	
	Gas carburizing	FineCarb vacuum carburizing
0.6	200 (incl. 65 to heat the charge)	180 (incl. 65 to heat the charge)
1.2	290	315

The table shows the vacuum carburizing method to be competitive in the case of thin layers, while gas carburizing is slightly more cost effective in the case of thicker layers, which is due to larger heat loss of the insulation of the heating chamber in a vacuum furnace.

Vacuum carburizing is much more competitive with respect to the consumption of the process atmosphere. The atmosphere consumption for both 0.6 mm and 1.2 mm layers is presented below.

Atmosphere consumption	
Gas carburizing	FineCarb vacuum carburizing
Feeding time ~4.5 h Endo atm consumption = 35 Nm³/cycle	Feeding time ~ 9 min. Gas (ethylene/acetylene/hydrogen) consumption = 0.45 Nm³/cycle
Feeding time ~8.5 h; 65 Nm³	Feeding time = 19 min.; 0.95Nm³

As a consequence, post-processing gas emission is considerably lower in vacuum carburizing technology, which is particularly important for toxic CO and CO_2. Vacuum carburizing also involves consumption of cooling gas used in the gas quenching (hardening) step (the cost of about 0.4 PLN/Nm^3 times the cooling chamber volume times process pressure). In the case of 15CrNi6 steel hardened in the VPT 4035/36 furnace at a pressure of 10 bar, the cost of nitrogen consumed is about 20 PLN per cycle. For a modular furnace installation where the demand for cooling gas is much higher, incorporation of a recycling system with a 98% efficiency considerably improves gas cost.

Explaining vacuum carburizing benefits

Tests results from a specially equipped furnace explain the reason for such low consumption of carburizing gases in the FineCarb technology. A vacuum carburizing furnace was modernized to carry out a series of measurements for the processing atmospheres shown in the table below.

Processes and atmosphere compositions examined			
Process	Atmosphere composition, %		
	C_4H_4	C_2H_2	H_2
A	80	0	20
B	70	5	25
C	55	13	32
D	33	23	44
E	27	27	46
F	0	40	60

Additional furnace equipment (Fig. 3) allowed the chemical composition of output gasses to be constantly measured during the run. Knowing the proportions of the atmosphere being introduced into the furnace allowed determining both the most probable directions of chemical reactions occurring during the process and their kinetics.

A capillary tube (2) was connected to the furnace (1) to allow sampling of the carburizing atmosphere for analysis via mass spectrometer (3). Particles were ionized in the ionization chamber (6) inside the spectrometer, detected by a detector (7) and analyzed in the quadruple analyzer (5), the results converted into a measurable signal registered by the computer (8).

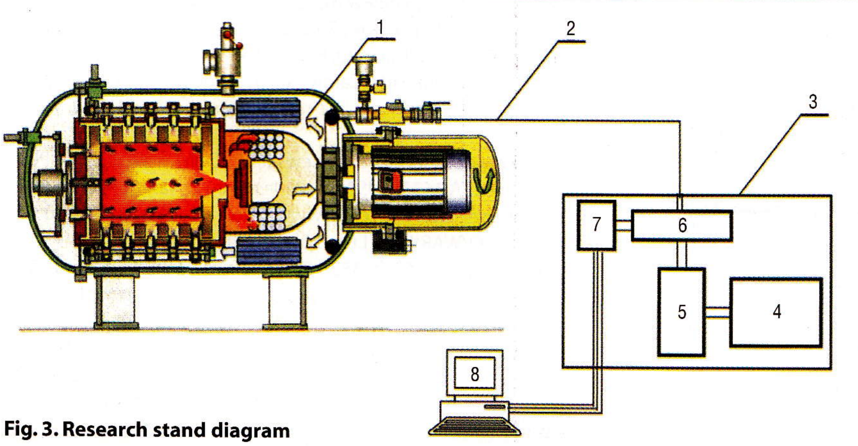


Fig. 3. Research stand diagram

Peak intensities of particular masses were plotted from measurements taken during vacuum carburizing at 1740°F (950°C) using the different atmospheres mixtures listed in the table above and compared with the input level of the processing atmosphere. Figures 4 and 5 show the values obtained from ethylene and acetylene decomposition, while Fig. 6 shows the increase of the amount of hydrogen in the processing atmosphere.

Test results show that the relative decomposition of ethylene proceeds faster if its content in the mixture is lower (Fig. 4). The highest intensity of acetylene decomposition occurs for mixtures D and E. However, it should be noted that the results obtained for acetylene are burdened with a certain error due to partial decomposition of ethylene into acetylene (which is subsequently partly decomposed), while it is also partly responsible for the increased level of C_2H_2 in the output gases. Therefore, the decomposition percentage presented in Fig. 5 can be slightly underrated.

The decomposition of hydrocarbons results in the emission of hydrogen, and its level in the output gasses increases compared with the expected atmosphere. Figure 6 shows the percentage increase of observed hydrogen. Maximum values are observed for mixtures D and E, which correlate well with the data for the hydrocarbons used. The behavior of mixtures D and E covered by the Seco/Warwick Ltd. Group Poland patent can be explained by the synergistic operation of C_2H_4, C_2H_2 and H_2 for the proportions of the atmosphere used in this discussion, which ensures optimum conditions for the process aimed at achieving the desired quality of carburized layers and short processing times.

Conclusions

There is a synergistic impact of the mutual interaction of acetylene and ethylene in connection with hydrogen resulting in a decidedly higher carbon supply, which

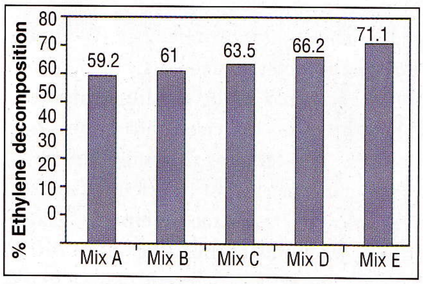


Fig. 4. Ethylene decomposition as a function of mixture type

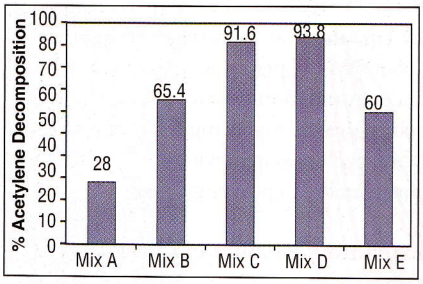


Fig. 5. Acetylene decomposition as a function of mixture type

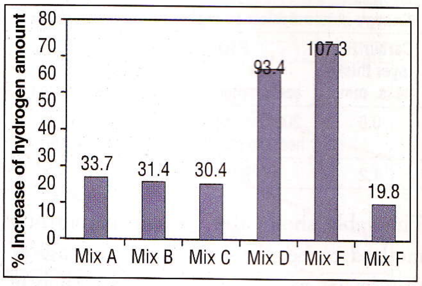


Fig. 6. Increase in hydrogen as a function of mixture type

leads to the intensification of vacuum carburizing process, and consequently to shortening the treatment time, reduction of gas consumption and negative environmental impact.

The economic efficiency of vacuum carburizing can be considerably more competitive than traditional gas carburizing. Currently, the use of vacuum carburizing concentrates on materials with better hardening capacity and/or on details with a limited cross section, where the use of this technology brings measurable economic benefits. The implementation results of this technology will continue to be supported by other factors that influence the final cost including reduction of hardening distortion, reduced emission of post-processing gases, limitations of gas carburizing resulting from the use of hardening oil and associated problems, and the development of process automation, etc. When viewing the entire process (both upstream and downstream), vacuum carburizing is an economical solution that produces optimum quality work with lower unit cost. **IH**

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