Making Heat Treating of Steel Parts Green by Coupling Induction Heating and Intensive Quenching

Ed Ryliki and Chris Pedder
Ajax TOCCO Magnethermic Corp.

Michael Aronov
IQ Technologies, Inc.

Introduction

Induction heating is a green, environmentally friendly technology providing energy savings and much greater heating rates compared to other furnace heating methods. Other advantages of induction heating include improved automation and control, reduced floor space, and cleaner working conditions. Induction heating is widely used in the forging industry for heating billets prior to plastic deformation. Induction heating is also used for different heat-treatment operations such as surface and through hardening, tempering, stress relieving, normalizing, and annealing. The amount of steel products subjected to induction heating in the heat treating industry, however, is much less compared to that processed in gas-fired furnaces. Gas-fired heat treating equipment is a major source of carbon emissions in the industry. As shown in Reference [1], Induction Through Heating (ITH) followed by Intensive Quenching (IQ) (an "ITH + IQ" technique) eliminates the need for a gas-fired furnace when conducting through hardening and carburizing processes – the two most widely used heat treating operations for steel parts. Eliminating gas-fired furnaces will result in a significant reduction of carbon emissions.

The goal of the paper is twofold: a) to evaluate carbon emissions generated during through hardening of steel parts and carburizing processes when conducted in gas-fired furnaces, and b) to discuss how these emissions can be reduced to zero using the "ITH + IQ" process.

1. Evaluation of carbon emissions for through hardening and carburizing processes.

As known, most through hardening and carburizing operations for steel parts are conducted in batch and continuous integral quench gas-fired furnaces. Assumptions made for evaluating CO_2 emissions produced by a typical integral quench furnace are presented in Table 1. *Note: the values of carbon emissions presented below are conservative since they don't consider the amount of CO_2 produced by furnace flame screens and Endothermic gas generators used to provide a controlled carburizing atmosphere in the furnace. Also, it's assumed that the furnace walls are already heated through when loading the parts, so there are no heat losses associated with the thermal energy accumulated by the furnace walls.*

1.1 Emissions generated during the through hardening process.

A furnace time/temperature diagram for the through hardening process considered is presented in Fig. 1. Carbon emissions E_{hard} produced by the furnace considered during heating of the load to the austenitizing temperature prior to quenching is calculated by the following equation:

$$E_{hard} = k \cdot Q_{hard} \qquad (1)$$

Where:

k – emission coefficient (equal to $0.050 \cdot 10^{-3}$kg per 1kJ of released energy when burning natural gas [2]).

Q_{hard} - thermal energy required for heating up the above load from ambient to the austenitizing temperature.

Table 1 Assumption for calculating of carbon emissions by integral quench furnace.

Parameter	Value
Furnace working space dimensions	91Wx91Hx183Lcm 36Wx36Hx48L”
Furnace load	200 shafts of ø5x40cm
Load gross weight	1,135kg (2,500lb)
Furnace thermal efficiency	65%
Furnace utilization time	85%
Furnace operation	3 shifts
Initial part temperature	20^{o}C
Part heating (austenitizing) temperature for through hardening process	843^{o}C (1,550^{o}F)
Part heating temperature for carburizing process	927^{o}C (1,700^{o}F).
Furnace temperature recovery time *	1hr
Furnace soak time*	2hr
Part carburizing time*	10hr
Time for quenching parts in oil and for loading/unloading of parts*	1hr
Steel specific heat capacity	0.56kJ/kg^{o}C
CO_2 emissions coefficient when burning natural gas [2]	$0.050 \cdot 10^{-3}$kg per 1kJ (117lb per 1,000Btu)

*See Fig. 1 and 2

A value of Q_{hard} is calculated by the following formula:

$$Q_{hard} = M \cdot C \cdot (T_a - T_o) / Eff = 1,135 \cdot 0.56 \cdot (843 - 20) / 0.65 = 0.805 \cdot 10^6 kJ \quad (2)$$

Where:
M – load weight, kg
C – steel specific heat capacity, kJ/kg^{o}C
T_a – part austenitizing temperature, ^{o}C
T_o – part initial temperature, ^{o}C
Eff – furnace thermal efficiency (a ratio of the furnace thermal losses to the gross heat input)

From formulas (1) and (2), the amount of carbon emissions produced by the above furnace during one hardening operation is 40.2kg. To determine an annual amount of carbon emissions, calculate the number of hardening cycles per year N_{hard} run in the furnace. From Fig.1, a duration of one hardening cycle is 4hr (3hr for austenitizing of the parts plus 1 hour for quenching the parts in oil and unloading/ loading the furnace). Thus, N_{hard} is equal to:

$$N_{hard} = 360\text{day} \cdot 24\text{hr} \cdot 0.85 / 4\text{hr} = 1826$$

Annual CO_2 emissions from one integral quench batch gas-fired furnace is 40.2·1836 = 73,807kg, or more than 73ton.

1.2 <u>Emissions generated during carburizing process.</u>

A simplified furnace time/temperature diagram for the carburizing process considered is presented in Fig. 2. Carbon emissions E_{carb} produced by the above furnace during the carburizing process is calculated by the following equation:

$$E_{carb} = k \cdot Q_{carb} \qquad (3)$$

Where Q_{carb} is a thermal energy expended by the furnace during the carburizing process A value of Q_{carb} amounts to two components:

$$Q_{carb} = Q_{carb1} + Q_{carb2} \qquad (4)$$

Where:

Q_{carb1} - energy required for heating up the load to the carburizing temperature.

Q_{carb2} - energy needed for maintaining the furnace temperature during the remaining duration of the carburization process (for compensating of the furnace thermal losses since the parts are already heated up to the carburizing temperature).

A value of Q_{carb1} is calculated using formula (2) where the part carburizing temperature T_c is used instead of part austenitizing temperature T_a (see Table 1):

$$Q_{carb1} = 1{,}135 \cdot 0.56 \cdot (927 – 20) / 0.65 = 0.887 \cdot 10^6 kJ$$

A value of Q_{carb2} is a sum of the flue gas losses and losses of the thermal energy through the furnace walls by heat conduction. Q_{carb2} is evaluated from the following considerations. Since the assumed furnace thermal efficiency is 65%, the furnace heat losses are equal to 35% of the gross heat input to the furnace. Hence, the furnace heat losses Q_{loss1} during the load heat up period (the first 3hr of the carburizing cycle, see Fig. 2) are the following:

$$Q_{loss1} = Q_{carb1} \cdot 0.35 = 0.887 \cdot 10^6 \cdot 0.35 = 0.31 \cdot 10^6 kJ.$$

The furnace heat losses during the remaining 8hr of the carburizing cycle Q_{loss2} are proportionally greater and are equal to:

$$Q_{loss2} = Q_{loss1} \cdot 8hr /3hr = 031 \cdot 10^6 \cdot 8 /3 = 0.827 \cdot 10^6 kJ$$

Thus, the total amount of the thermal energy expended by the furnace during the carburizing cycle is $Q_{carb} = 0.887 \cdot 10^6 + 0.827 \cdot 10^6 = 1.71 \cdot 10^6$kJ. The total amount of the CO_2 emissions from carburizing of the load in the furnace considered according to equation (3) is: $E_{carb} = 0.050 \cdot 10^{-3} \cdot 1.71 \cdot 10^6 = 85.7$kg. To determine an annual amount of carbon emissions from one carburizing furnace, let’s calculate the number of carburizing cycles run in the furnace per year. Per Fig. 2, a duration of one carburizing cycle is 12hr (1hr for the furnace recovery plus 10hr for carburizing of parts at 927ºC plus 1hr for quenching parts in oil and for unloading and loading the furnace). Thus, the number of carburizing cycles per year N_{carb} is:

$$N_{carb} = 360day \cdot 24hr \cdot 0.85 / 12hr = 612$$

<u>Annual CO_2 emissions from one integral quench batch carburizing furnace is about 85.7·612 = 52,448kg, or more than 52ton.</u>

2. Reducing carbon emissions using the "ITH + IQ" process.

Reference [1] presents results of two case studies of the "ITH + IQ" process on automotive input shafts and drive pinions. The study was conducted with a major US automotive part supplier. A two-step heat treating process was used for the input shafts, consisting of batch quenching parts in oil or polymer using an integral quench gas-fired furnace for core hardening followed by induction hardening. This two-step method of heat treatment is widely used in the industry for many steel products. It provides parts with a hard case and tough, ductile core. Substituting the "ITH + IQ" method for the two-step heat-treating process not only eliminates the batch hardening process but also requires less alloy steel for the shafts that don't require annealing after forging. Thus, in this case, applying the "ITH + IQ" technique eliminates two furnace heating processes for the input shafts resulting in the reduction of the CO_2 emissions to zero for the shafts' heat treatment. Per customer evaluation, as mentioned in Reference [3], the hardness profile in the intensively quenched input shafts was similar to that of the standard shafts. Residual surface compressive stresses in the intensively quenched shafts were greater compared to that of the standard input shafts, resulting in a longer part fatigue life of up to 300%.

Per Reference [1], the environmentally unfriendly carburizing process can be fully eliminated for automotive pinions when applying the "ITH + IQ" method and using limited hardenability (LH) steels that have a very low amount of alloy elements. A case study conducted for drive pinions with one of the major US automotive parts suppliers has proven that the intensively quenched drive pinions met all customer's metallurgical specifications and passed both the ultimate strength test and the fatigue test. It was shown that the part fatigues resistance improved by about 150% compared to that of standard carburized and quenched in oil drive pinions. In addition, distortion of the intensively quenched drive pinions is so low that no part straitening operations were required.

3. Conclusion.

Coupling Ajax TOCCO's induction through heating method with the intensive quenching process, creates a significant reduction of CO_2 emissions produced during heat treatment operations for steel parts. For the through hardening process, eliminating just one batch integral quench gas-fired furnace will reduce carbon emissions by more than 73ton per year. For the carburizing process, eliminating just one batch carburizing furnace will reduce carbon emissions by more than 52ton per year. Note that for continuous gas-fired furnaces, the carbon emission reduction will be much greater due to higher continuous furnaces production rates (hence a much higher fuel consumption). Per our experience, the "ITH + IQ" process can be applied to at least 20% of the currently through hardened and carburized steel parts. Per two major heat treating furnace manufacturers in US, there are thousands of atmosphere integral quench batch and continuous furnaces in operation in US. That means hundreds of gas-fired heat treating furnaces can be potentially eliminated, drastically reducing carbon emissions in the US, supporting a lean and green economy.

References.

1. Aronov, M., Rylicki, E., Pedder, C., Two Cost-Effective Applications of Intensive Quenching Process for Steel Parts, Heat Treat Today, October 2021.
2. U.S. Energy Information Administration, www.eia.gov/energyexplain/natural-gas-and-environment.

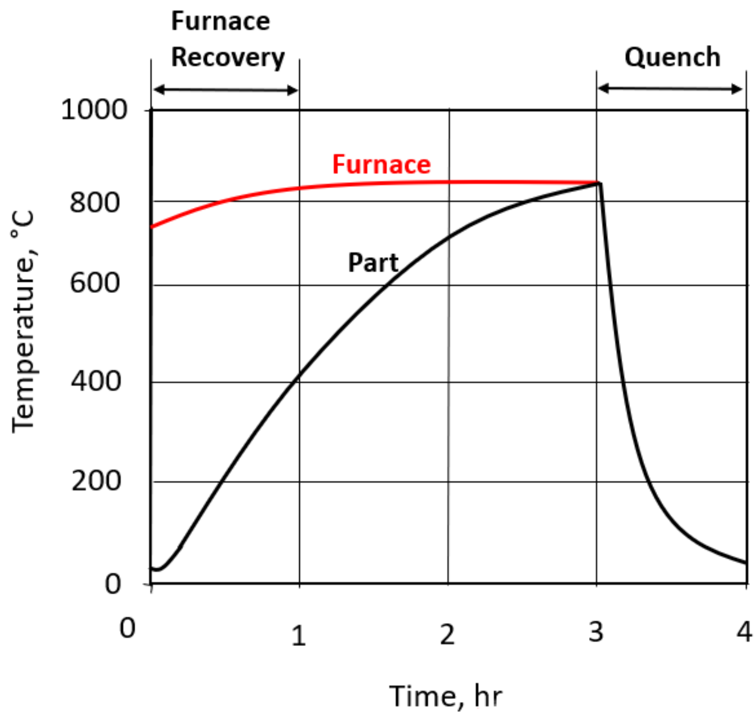

Fig 1. Furnace time/temperature diagram for the through hardening process

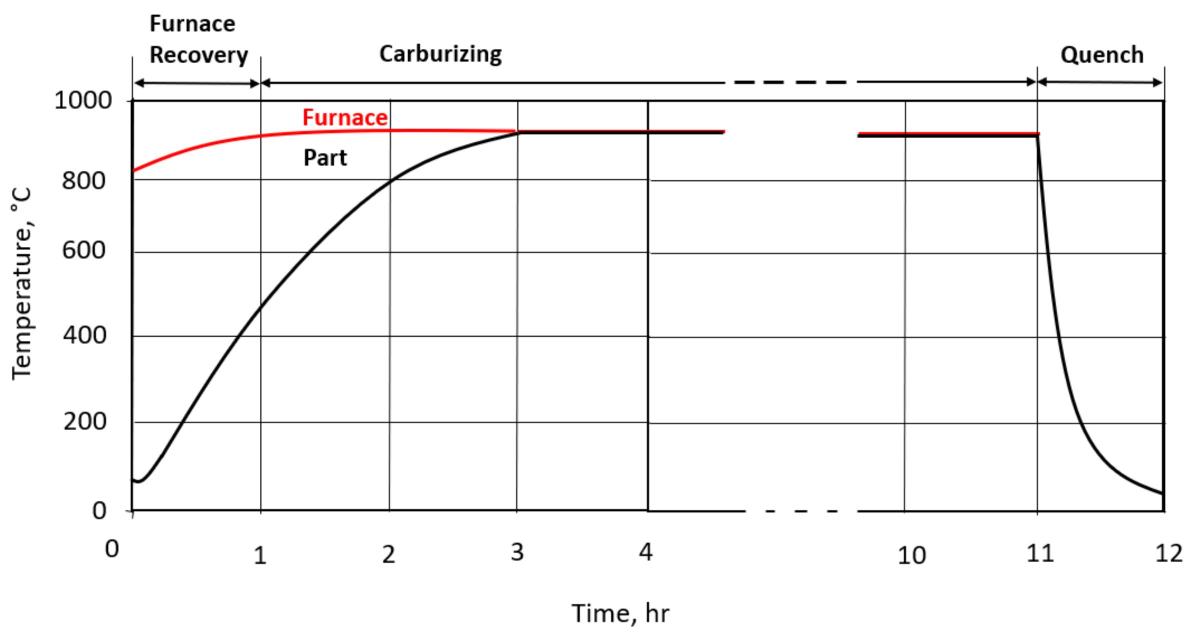

Fig 2. Furnace time/temperature diagram for the carburizing process