United
PROCESS CONTROLS

TECHNICAL PAPER

Better Parts Faster with Embedded, Real-Time Control of Carbon Diffusion

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UNITED PROCESS CONTROLS

ABSTRACT

By using modern process controllers it is possible to optimize a gas carburizing furnace such that ideal carbon profiles can be achieved in less time compared to traditional controllers. Traditional controllers, which today dominate the industry, can be easily replaced with advanced instrumentation capable of providing exact control of carburizing depth and surface carbon. With these types of advanced controllers, variations in heating gradients as well as variable load sizes no longer influence the process results since the actual readings for temperature and carbon potential are used to calculate the carbon profile. Moreover, it is possible to predict the residual hardness curve by taking characteristics of the workpiece and the quench conditions into account.

MECHANISMS IN CARBURIZING

When referring to case hardening of steel parts, we usually think about a carburizing process with quenching afterward. The hardness that can be achieved is mainly caused by carbon, which diffuses from the process atmosphere into the steel surface (Fig 1.)

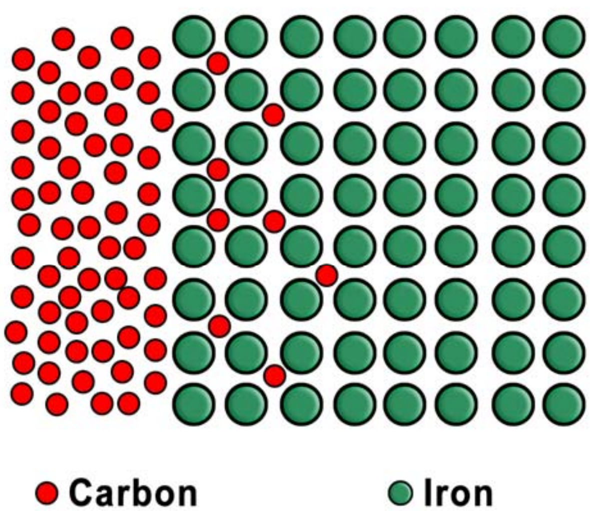


Figure 1. Hardening is caused mainly by the diffusion of Carbon into the lattice.

To predict the carbon profile correctly, the calculation has to take into account that there are two different types of diffusion taking place. First, there is a carbon transfer from the atmosphere into the near surface and second, the inner diffusion once the carbon is dissolved in the steel.

Carbon Transfer

The mass flow of carbon (J) from the atmosphere into the steel is governed by the following equation:

$$J = \beta * (C_{atm} - C_S)$$

where C_{atm} is the actual carbon potential measured in the atmosphere and C_S is the carbon content in the surface. The driving force for diffusion is the difference in carbon concentrations between atmosphere and steel multiplied by the carbon transfer coefficient Beta. Beta is dependent on temperature and the partial pressures of hydrogen and carbon monoxide in the atmosphere.

Figure 2 shows a typical curve representing Beta as a function of the atmosphere at a given temperature of 1652°F (900°C). The plot shows a theoretical maximum at 50% H_2 and 50% CO. The more practical maximum is reached by using pure methanol which cracks to 33% CO and 66% H_2.

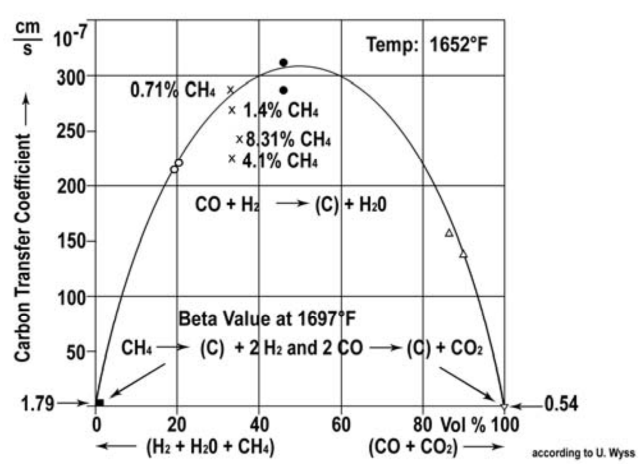


Figure 2. The carbon transfer coefficient reaches a theoretical maximum at 50% CO and 50% H2 at 1652ºF (900°C).

Inner Diffusion

The diffusion of carbon within the steel can be described by Fick's Law.

$$J = -D * \frac{dC}{dX}$$

The diffusion coefficient D is dependent on temperature and the carbon content already reached in the steel part. The higher the temperature and the higher the carbon content in the steel, the faster the diffusion speed.

This reason this process "speeds up" is due to the lattice opening more when heated and from having carbon atoms inside, essentially pushing the lattice open.

As an example the diffusion speed increases by a factor of 10 when increasing the temperature from 1742°F (950°C) to 1922°F (1050°C).

Carbon Content and Hardness

When quenching a heated steel part, the widened austenitic structure will go back to the ferritic structure. If the cooling is fast enough to prevent diffusion of the carbon back out of the lattice, the carbon will prevent the lattice from returning to its ferritic structure. The result is that the lattice is forced into a distorted ferritic structure called martensite. The maximum hardness that can be reached is dependent on the amount of carbon within the martensitic structure (Figure 3).

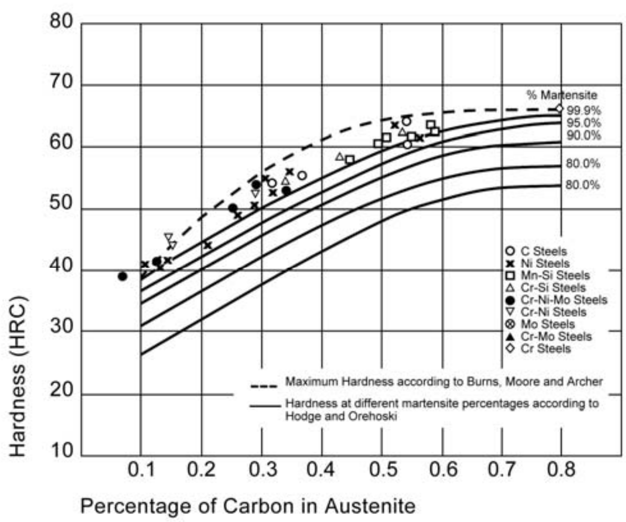


Figure 3. Carbon increases hardness up to a point – after that retained austenite degrades hardness.

Interestingly, amounts of carbon higher than approximately 0.75 to 0.80 wt% result in decreasing hardness. This is because, at these high carbon levels, not all austenite is transferred to martensite. The so-called retained austenite can only be transferred to martensite by deep cooling after quenching.

The hardness curve that can be obtained - meaning the height of the curve at higher depths - is not only dependent on the amount of carbon dissolved at the according depth, it is also dependent on the velocity of the cooling within higher depths.

The values influencing the velocity are dependent on the size of the part (bigger parts will cool down more slowly and therefore have lower internal hardness), the alloying elements that have a high influence (Figure 4), austenitic grain size and, of course, the quenching conditions. For example, water will quench more rapidly than oil or salt.

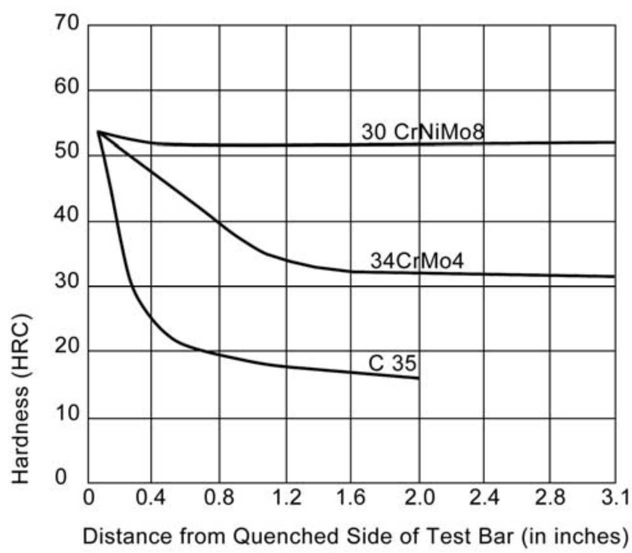


Figure 4. Alloying has a substantial impact on internal hardenability.

REQUIREMENTS FOR A MODERN CONTROLLER

A modern controller should be able to take these influences into account when predicting the carbon profile and the hardness curve which will be obtained when running the desired process. Moreover it should calculate the amount of carbon needed to obtain the required case-hardened depth for the specific part when processed in a specific installation.

The following paragraph will show an example how to fulfill these requirements based on a United Process Controls' instrument.

Material Data

A material database (Figure 5) within the instrument's memory holds the content of the different alloying elements for the steels to be treated.

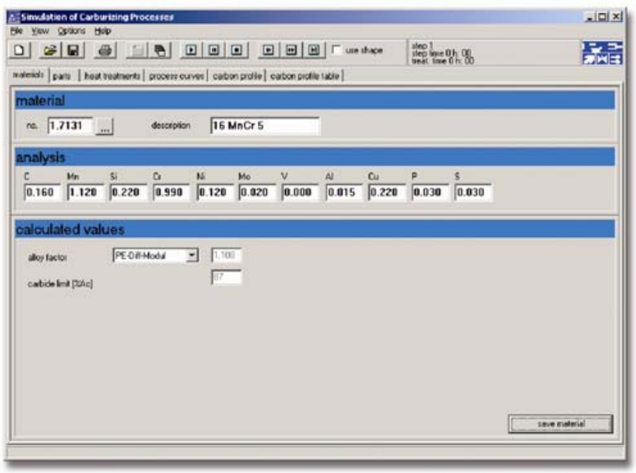


Figure 5. Materials data is used for calculating carbide limits.

Dependent on the weight percentage of the alloying elements, the alloying factor and the carbide limit are calculated. The alloying factor describes the amount of carbon which can be obtained in the surface at a specific carbon potential in the atmosphere.

The relation follows the equation:

C_S [wt%] = alloy factor * CP

The instrument is able to calculate according to the formulas developed by Neumann, Gunnarson and Grabke.

The carbide limit gives the amount of carbon soluble in the steel as a percentage of the soot limit at a specific temperature. If carbon exceeds this level it will result in carbide formation.

C_{Smax} = carbide limit * soot limit

Parts Data

In the advanced controller, parts are described by the material, the part shape and some additional data as shown in Figure 6.

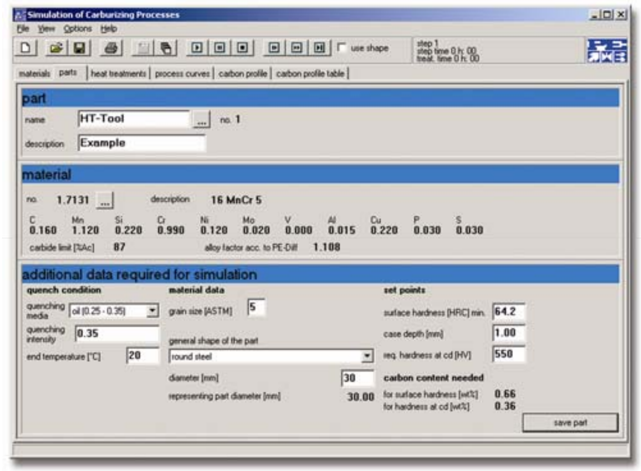


Figure 6. Part shape, quenching conditions and grain size are used to determine carbon needed for case depth in real-time during the carburizing process.

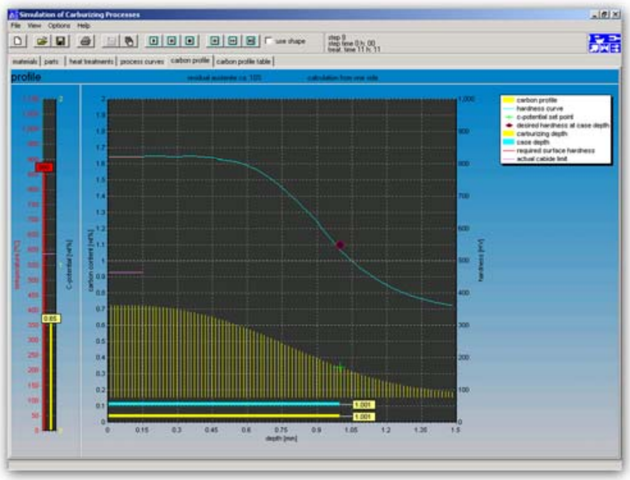
The quenching condition, the grain size and the general shape and diameter are used to calculate the amount of carbon needed at the specified case depth. This value will be utilized for the carburizing depth used in the diffusion program.

The Recipe

The recipe is built by several stages. In each stage, the user can select various types of setpoints for both temperature and atmosphere. The atmosphere control, in particular, provides enhanced process-control opportunities. A soot control enables the carbon potential to be held below a specified percentage of the soot limit throughout heating up or cooling down.

The so-called "auto mode" is a combination of soot-limit control and carbide-limit control holding the carbon potential at a maximum throughout the boost stage to enable a maximum carbon diffusion into the part while preventing carbide building.

When reaching a specified percentage of the desired depth, the atmosphere control switches to a control of the surface carbon of the part. When optimizing the recipe, it is possible to define this point in a way to provide a perfect s-shaped carbon profile (Figure 7) with a near-to-horizontal hardness curve as shown.



BENEFITS OF A MODERN CONTROLLER

Beside the ability to obtain the process target values by entering the desired specifications of the parts, by calculating the relation between the real conditions and the carbon content needed in either the case depth or surface, the built-in atmosphere control enables lower process times and therefore better productivity and cost-savings.

Productivity

Figure 8 shows the same part treated to a case depth of 1 mm at 1652°F (900°C) in the same equipment. The only difference is the atmosphere control used. The first window shows a traditional process with two stages, boost and diffuse, the second used the auto-control facility.

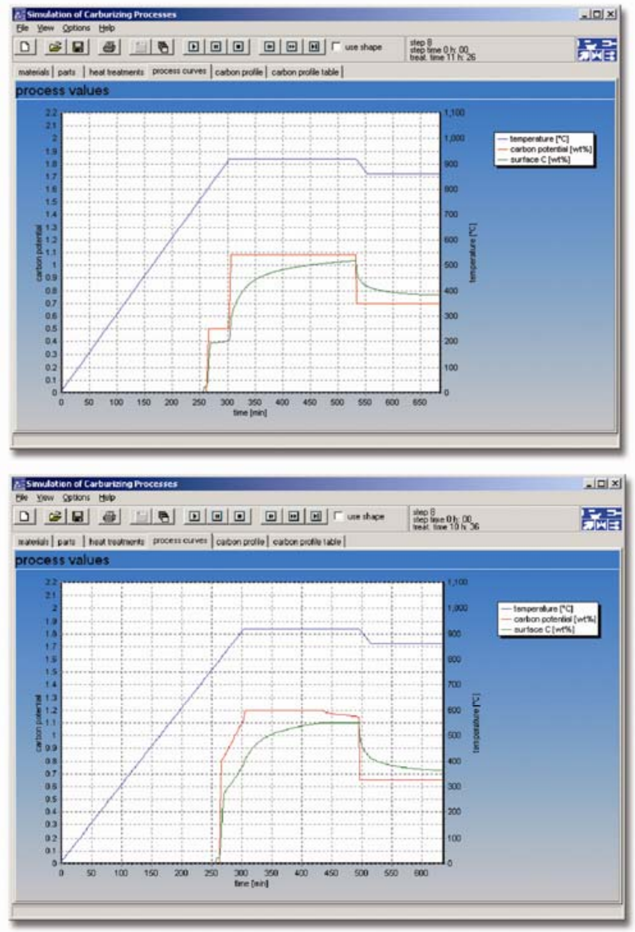


Figure 8. The auto-boost stage (bottom graph) with its maximum carbon diffusion controlled to a value just below the carbide limit shortens the process time by nearly one hour compared to traditional carbon control (top).

The auto-boost stage - with its maximum carbon diffusion controlled to a value just below the carbide limit - shortens the process time by nearly one hour, which represents 10% of the total runtime.

Reliability

Another great advantage when using a modern controller is the ability to control the heat-treatment process to the required values, even when there are recipe differences for either temperature or atmosphere. A temperature that will not come up to the desired setpoint simply causes an increase in process time. The controller will take it into account automatically.

CONCLUSION

Modern control instruments conclusively improve the reliability and productivity of heat-treatment equipment. When equipped with a modern and user-friendly graphical interface, the handling can be learned more or less intuitively. Together, these advantages result in better parts in less time and a rapid return on investment.