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Executive Summary
Imagine the following scenario: a load of parts is processed in an atmosphere furnace, only for certain parts to emerge with slight distortion. As a result, they must undergo post-treatment steps, such as grinding, to ensure they have the desired part geometry.

While, to a certain extent, this is a typical part of the heat treatment process, having to repeatedly perform excessive post-processing operations can end up affecting the bottom line over the long term. Heat treatment is a manufacturing process that adds value to the parts produced. Yet once you begin to add in post-treatment steps, the manufacturing costs associated with heat treatment begin to rise. If the ultimate goal is to stay competitive by finding ways to control and reduce costs, then the first priority is finding ways to improve part quality.

When working with atmosphere furnaces, refining all possible aspects of the carburizing and quenching processes is the most effective way to maximize part quality and reduce distortion. In addition, reducing distortion means there is less need for post-processing, which keeps the costs associated with heat treatment to a minimum. This means you can rely on repeatable, quality heat treatment – all while maintaining competitive manufacturing costs.

In this paper, we will discuss best practices for refining the carburizing and quenching processes so you can meet these goals. This includes the benefits of establishing temperature and gassing uniformity, utilizing modern atmosphere controls and quenching systems and applying other process best practices.

Introduction
Carburizing and quenching are two common, and often essential, processes performed in atmosphere heat-treating systems. These processes have similar aims: to carburize parts uniformly and to produce a uniform quench in oil – all with minimal part distortion.

One of the primary goals for companies that produce parts is to reduce overall manufacturing costs by minimizing part distortion during heat treatment. After all, if there is less part distortion then the part is less likely to need extensive post-treatment steps, such as cleaning, blasting, straightening and/or grinding. With less post-processing comes less manufacturing costs associated with the heat treatment process.

The cost for heat treatment – a manufacturing step that adds value to the parts produced – is only a fraction of the total production costs: typically less than five percent. Plus without heat treatment, a part expensively manufactured by melting, hot rolling/forging, annealing, rough machining, teeth cutting or grinding is essentially useless and of little to no value.
Once you add in all further post-treatment steps inherent with or caused by heat treatment, though, this percentage increases to roughly 15 percent of the cost per part. Which is why, if you are to maintain competitive overall manufacturing costs, minimizing part distortion – and thus all the steps and costs associated with post-processing – should be a primary goal.

Which brings us to the main challenge: what is the best way to minimize part distortion when processing parts in an atmosphere furnace? This takes us back to carburizing and quenching, for which several factors influence whether these processes result in distortion-free parts. The goal, then, is to understand how these processes work, which factors most influence and affect part distortion and how you can refine these processes for optimum results – all with the ultimate goal of sustaining competitive manufacturing costs.

Attaining Ideal Carburizing Conditions
If you are to positively influence the quality of parts produced (i.e., reduce part distortion), the first step is achieving ideal carburizing conditions. Doing so can lead to more uniform case depths and carburizing of the surface layers, which are key components of ensuring parts emerge without distortion.

While there are currently two industrial carburizing processes – gas carburizing in atmosphere furnaces and low-pressure carburizing in vacuum furnaces – both have the same aim: to carburize all parts in a load uniformly, to the same surface carbon (C) content and to the same case depth.

Atmosphere carburizing runs a series of different process steps. Knowledge of these steps is necessary for achieving repeatable work and uniform carburizing:

1. **Gas reactions**: generation of the carburizing gas components in the atmosphere
2. **Convective gassing**: transport of the carbon-containing molecules in the gaseous phase to the component
3. **Diffusion transport**: transport of the carbon-containing molecules through the boundary layer (v=0) at the component surface
4. **Dissociation and adsorption**: dissociation of the molecules at the component surface
5. **Absorption**: taking up of the carbon by the component surface
6. **Diffusion**: transport of the carbon into the component

### ATLAS: Integral Quench Batch Atmosphere Furnace

The ATLAS atmosphere line delivers advanced features and streamlined design. Capable of running multiple processes, it also integrates into existing furnace lines and fits into existing pits. Other features include:

#### Efficient Burners
Recon® III Burners increase thermal efficiency up to 75 percent by utilizing the heat from the exhaust gases to preheat the combustion air and reducing time to recovery of the hot zone temperature. Distinguished by low noise levels, high durability, low maintenance and easy installation, these burners provide ideal heating while optimizing gas consumption and achieving maximum energy efficiency.

#### Advanced Quenching Systems
Ipsen’s SuperQuench® and TurboQuench™ oil-quenching systems reduce distortion, improve properties of steel and consistently achieve uniform surface and core hardening. These systems feature a variable-speed agitation system that produces a uniform and adjustable flow of oil throughout the load and allows the oil flow to be adjusted based on section size, material and load density. They can also tackle even the most challenging alloys by reducing the hardness spread and increasing the overall throughput.
Meeting those conditions, however, also comes with challenges. The first step is ensuring that temperature and gassing uniformity, flow over components and fast reaction kinetics occur evenly throughout the treatment chamber.

**Solution #1: Temperature Uniformity**

A uniform temperature is one of the first, and most essential, steps for ensuring parts emerge with an ideal carburizing depth and thus higher quality. So how do you ensure a uniform temperature?

To start, it depends on the atmosphere equipment you’re using. In efficient batch atmosphere furnaces, such as the ATLAS, temperature uniformity of at least ±13 ºF (±7 ºC) is maintained in the heat chamber. Upon completion of the heating phases, all components in the austenitic phase are at the same temperature. This is an essential first step if parts are to emerge with the desired case depth.

Efficient burners (e.g., Ipsen’s Recon® III Burners) can also enhance the heating and temperature uniformity of batch furnaces. These burners are single-ended recuperative tubes (SERT) fitted with special ceramic inner tubes. They can increase thermal efficiency up to 75 percent, as well as provide reliable performance.

While advanced furnace designs and construction from high-quality materials can help result in furnaces with tight uniformity, proper furnace maintenance is also critical for maintaining temperature uniformity. For example, cleanup cycles should be performed on a weekly or monthly basis, depending on soot buildup. This helps remove the soot formation, which can reduce the life of heating elements and cause temperature fluctuations.

Just as important is taking the time to inspect the furnace lining to verify it is in good condition as damage can result in heat loss. You should also regularly tune the burners within a tight temperature range to maintain temperature uniformity throughout the furnace.

Finally, regular performance of temperature uniformity surveys (TUS) can help identify any reductions in temperature uniformity. A TUS should be performed before first using the furnace, as well as periodically (at least every six months) and after any major repair work. These steps are all essential for preserving temperature uniformity throughout the furnace’s life span.

**Solution #2: Gassing Uniformity**

Maintaining temperature uniformity, however, is not possible without also improving the gas flow over components. You must have a well-planned circulation system to achieve excellent flow around components and, thus, maintain the temperature uniformity.

The positive convective properties, which result in excellent temperature uniformity within the load area, also result in improved heat transfer to the load and homogenous process atmosphere. Figure 1 portrays how the combination of minimum temperature deviation within the load area and the homogenous process atmosphere results in minimized case depth deviations throughout the load.

Continuous introduction of the carrier gas and controlled addition of the enriching gas also result in a furnace atmosphere capable of producing carburized parts with the specified percent of surface carbon and to a specified case depth with highly repeatable results (Figure 2).
One of the challenges associated with gassing uniformity is effectively managing the introduction of gases. Intuitive controls software, such as Ipsen’s Carb-o-Prof® system, can assist in maintaining balance by regulating, documenting and archiving the carburizing processes in atmosphere furnaces. No matter the case – if your power goes out or some other unforeseen event occurs – the software is able to adapt the process to the changing circumstances, preventing the potential waste of parts and resources. It also helps ensure the parts emerge with the desired case depth and uniformity.

Uniform Carburizing Results

Understanding how to optimize the carburizing process is one of the first steps in solving the question: “How do I reduce part distortion?” The next step is applying these best practices. After doing so, a sample piece exhibited signs of reduced distortion.

More specifically, with supervision and the use of Carb-o-Prof software – which monitors and controls uniformity of the C-level within the atmosphere – a tolerance of ±0.05 percent C for the workpiece surface carbon content was maintained. This consistency of the atmosphere’s carburizing effect resulted in uniform carburizing of the surface layer, as shown in Figure 3.
In the end, uniform carburizing of the surface layer translates to less part distortion, which in turn, results in less need for any post-processing steps to correct the effects of distortion. The outcome is less manufacturing costs associated with the heat treatment process – thus meeting the ultimate goal (and challenge) of producing parts.

Maintaining Quenching Flexibility

When it comes to the quenching process, experience shows there is a significant potential for optimizing it and producing uniform parts. Yet to do so, you must first meet the three goals for distortion-optimized quenching:

1. Uniform heat extraction over the whole surface of the part
2. Uniform heat extraction on every part within one load
3. Material- and part-adapted timing to control the quench intensity

The Carb-o-Prof® controls software computes and executes complete carburizing and quenching cycles, as well as other heat treatment processes. It provides the flexibility needed to measure and analyze your equipment and processes with ease. You can use this analysis to adjust equipment settings and parameters to enhance your process, improving part quality.

Recipe Database
Programmed with hundreds of available recipes, the database allows the most important recipe information to be registered via a quick, simple input. Faulty inputs are prevented by appropriately limiting the input range, thus maintaining a safe operation and avoiding excessive consumption.

Simulation with C-Profile Optimization
The simulation function computes the materials’ expected carbon profile according to entered parameters and displays the results as a table and graph. This gives you the ability to review the process results for a specific load immediately after generating the potential recipe – all without having to do the actual run or wasting valuable parts, time and resources.

C-Profile Control
Using pre-specified target parameters, such as surface carbon content, carburizing depth and/or core carbon content, it defines a target carbon-content curve in the shape of a smooth S-form. As a result, parts within the same load are consistent in both case depth and hardness, and this performance is repeated load after load.
To meet these goals, it is first important to understand the quenching process and resulting challenges. The first part of the quenching process uses a maximum oil flow so that a quick vapor film breakdown occurs and a high heat extraction is realized in the nucleate boiling phase – all of which prevents the production of ferrite and perlite.

The second part of the quenching cycle reduces the cooling rates to allow temperature homogenization between the surface and core before martensitic transformation starts. This equalizes thermal and transformational stresses, resulting in less distortion.

Much like the carburizing process, quenching also has its unique challenges. For example, the quenching process can sometimes lead to the vapor phase, commonly known as the Leidenfrost effect. This phenomenon occurs when a liquid – which is in near contact with a mass significantly hotter than the liquid’s boiling point – forms an insulating vapor film that keeps the liquid from boiling rapidly. As the vapor film randomly breaks down, the nucleate boiling phase starts and is characterized by a high cooling rate followed by the final stage: the convection phase.

With the Leidenfrost effect’s ability to reduce the flow of heat between the quench oil and the part, this often leads to residual stresses and part distortion. Older quench systems for batch atmosphere furnaces also pose a unique challenge with their lack of flexibility when it comes to varying the quench intensity.

While this might not have a strong effect on the final quality of simple parts, it does make it difficult to reach an equal flow of oil around parts with complex geometries. As these challenges conflict with the goals for distortion-optimized quenching, it is imperative to find ways to overcome them.

**Solution #1: Uniform Oil Flow**

With the development of newer, more advanced atmosphere furnaces comes technology that can help produce a uniform oil quench, as well as adapt the quenching intensity to the needs of different components (e.g., hardenability and minimized distortion). By adapting the quenching intensity, you can also increase production of quality components without worrying about affecting overall manufacturing costs.

Modern oil quenching systems, like Ipsen’s SuperQuench® and TurboQuench™, have an all-encompassing agitation system that allows them to produce a uniform oil flow through the load section, as well as utilize an adjustable oil flow speed. This helps overcome the challenges posed by older systems, as well as makes it possible to achieve uniform heat extraction across complex part geometries.

Having the right controls software also makes it easy run complex quench cycles. Users can define the temperature, duration, intensity and flow direction of the quench cycle within the software. Figure 4 illustrates how, compared to a conventional oil bath, these quenching systems optimize performance and produce quality components.
Solution #2: Ideal Heat Extraction

As mentioned, one of the challenges posed by the quenching process is the Leidenfrost effect. You can prevent the difficulties associated with this vapor phase by using non-evaporable media like salt or gas. Their cooling rate in the upper temperature region, however, is usually not sufficient for low-alloyed or carbon steels. Therefore, the objective must be to optimize the oil quenching in such a way that it reproduces an ideal cooling curve.

Assuming the usage of a high-performance quench oil – as is normal in sealed quench furnaces today – a high oil flow velocity best achieves a high, uniform cooling rate on the entire surface area of a part. This speeds up the breakdown of the vapor film in areas of less flow, producing a faster, more uniform quench. This, in turn, helps result in more uniform parts.

Higher oil velocities can also considerably improve the uniformity of heat extraction. Depending on the thickness of the part and the hardenability of the respective steel, the influence of the flow velocity can result in further quality improvement of the part.

Uniform Hardening Results

Through application of best practices and newer quenching techniques, we were able to achieve more uniform hardening of parts with an improved microstructure and reduced distortion.

By utilizing the agitators’ timing control within the SuperQuench® and TurboQuench™ systems, the cooling curve can reach results closer to the ideal cooling curve, as seen in Figure 5. This feature increases the efficiency and flexibility of oil quench systems and makes hardening of low-alloyed materials and thicker cross-sections possible.
Figure 5 – Representation of an ideal cooling curve with a high cooling rate to start and a cooling rate reduction when entering the martensitic phase

With the achievement of uniform heat extraction across every part in a load – including those with complex geometries – as well as the ability to adapt the quench intensity to the part and material, the goal of minimized part distortion can be realized. Much like with carburizing, this leads to less post-processing after heat treatment and contributes to competitive manufacturing costs.

Conclusion

Refining the carburizing and quenching processes provides a solution to the challenge of reducing part distortion among loads heat treated in an atmosphere furnace. This includes achieving uniformity of temperature and gassing, optimizing the flow over components and aiming for ideal quench speeds and heat extraction.

Of course, following best practices is for naught if the atmosphere technologies and systems used are not capable of providing the needed flexibility and process refinement. You must rely on a combination of process knowledge and modern technologies if you are to successfully reduce part distortion while achieving competitive manufacturing costs via heat treatment.