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Gas carburizing is a cost-effective hardening solution for gears but there are several factors to consider in making the decision.

An overview of heat treatment techniques

Editor's note ›› This is the second in a five-part series.

In this second segment of my series on heat-treating techniques, I will discuss the pros and cons of gas carburizing.

Carburizing is a thermochemical process in which carbon is diffused into the surface of low carbon steels to increase the carbon content to sufficient levels so that the surface will respond to heat treatment and produce a hard, wear-resistant layer.

The process of gas carburizing the component is held in a furnace containing an atmosphere of methane or propane with a neutral carrier gas, usually a mixture of N_2, CO, CO_2, H_2, and CH_4. At the carburizing temperature, methane (or propane) decomposes at the component surface to atomic carbon and hydrogen, with the carbon diffusing into the surface of the component to be heat treated. In most cases, the carburizing atmosphere is created from methane or propane, and is produced in a special device (the endothermic generator) by gases partially oxidated with air. The reaction for methane is: $2CH_4 + O_2 (+N_2) => 2CO + 4H_2 (+N_2)$ and similar for propane. The atmosphere consists mainly of: CO, H2, and N2, while the main C carrier is CO (reaction $2CO => C + CO_2$), while CO_2, H_2O, O_2, and CH_4 are residual gases. The carburizing atmosphere is delivered to a furnace from the endothermic generator (not directly), and methane or propane is injected directly into the furnace in small amounts to compensate for the carbon absorbed by steel.

Methanol is the only agent which can create the carburizing atmosphere directly in a furnace, which decomposes accordingly: $CH_3OH => CO + 2H_2$. The temperature is typically 925°C and carburizing times range from five to six hours for a 1 (mm) depth case to as much as 90 hours for a 4 (mm) case. The quenching medium is usually oil, but can be water, brine, caustic soda, or polymer, and neutral gas under high pressure.

INTENT OF CARBURIZING HEAT TREATMENT

Carburizing, or carburization, is a heat-treatment process in which iron or steel absorbs carbon while the metal is heated in the presence of a carbon-bearing material, such as charcoal or carbon monoxide. The intent is to make the metal harder and, in the case of gears, drive carbon into a surface layer (thickness and carbon density are a function of the process and process variables).

The application of force to a gear or bearing is accomplished through a same contact patch created from the theoretical point or line contact as a function of the geometry. The local deflection that causes an actual contact area to be formed is due to the local deflection of the material in the contact patch to change from a curvilinear surface profile to essentially a flat surface. The relationship in the contact patch between the two bodies in contact is complex and a function of material properties, hardness level, and sliding velocity, etc. However, the main component of the von Mises surface stress is compressive.

Thus, by inducing proper stress in the surface of a part (gear or bearing, etc.) the resultant compressive stress induced by an external applied force must first negate the induced tensile stress, go through a neutral stress, and then into compressive stress. This works well in the loaded contact region of a gear or bearing and on the root of the non-loaded side of the gear tooth. There are many similarities in terms of the effect to shot peening the root of a gear tooth (however, shot peening is a localized effect, i.e. just the root of the tooth) and the overall effect of heat treating.

To be complete, the difference between von Mises stress and principal stress is that the maximum principal stresses are the components of stresses when the basis of other stress tensors are zero (all vector representations of stress as a function of the summation of all applied forces are zero) and define the stress concentrated in a specific region. Von Mises stress, on the other hand, is a scalar quantity obtained from the stresses acting on any structure. In essence, it is the maximum non-vector point stress, if we think of a discretized representation of the loaded body. Maximum von Mises stress criterion is based on the von Mises-Hencky theory, also known as the Shear-energy theory or the maximum distortion energy theory.

METHODOLOGY OF CARBURIZING

There are three main methods of carburizing: gas carburizing, liquid carburizing, and pack carburizing. The gas carburizing process is a surface chemistry process, which improves the case depth hardness of a component by diffusing carbon into the surface layer to improve wear and fatigue resistance based on immersing the part in a gaseous carbon-rich environment at an elevated temperature. Liquid carburizing involves placing parts in a bath of a molten carbon-containing material, often a metal cyanide.

Finally, pack carburizing is a process which involves placing steel items into a furnace in close proximity to high-carbon items. These high-carbon items include everything from carbon powder to cast-iron particles, and more. After you've inserted these items, they will be heated with the use of carbon monoxide

I will focus on gas carburizing, a process that involves placing the parts in a furnace maintained with a methane-rich gaseous atmosphere, for the remainder of this article.

Gas carburizing has become the most effective and widely used method for carburizing steel parts in large quantities, even though it is a complex process (and thus potentially more expensive). Gas carburizing is conceptually the same as pack carburizing, except that carbon monoxide (CO) gas is supplied to a heated furnace and the reduction reaction of carbon deposition takes place on the surface of the part. This process overcomes most of the problems of pack carburizing.

Carburizing is carried out at a temperature where the steel is austenitic, typically in the temperature range 820 to 950 °C (1,510 to 1,740 °F), and which requires a controlled furnace atmosphere at slight overpressure that transfers carbon from the atmosphere to the steel surface. "Case hardening" is sometimes alternatively used to more clearly describe the fact that the process includes both hardening and tempering.

OUTCOME OF GAS CARBURIZING

The highest hardness of a hardened steel having a martensitic microstructure is obtained when its carbon content is high, around 0.8 percent carbon by weight. Steels with such high carbon content are hard, but also brittle, and therefore not well-suited to be used as gears or bearings. Any component that experiences dynamic bending and tensile stresses during operation are candidates for carburizing. A carbon content as high as 1 percent carbon by weight makes the steel difficult to machine as in cutting, turning, or drilling. The case with increased carbon concentration is typically 0.1–1.5 mm (0.004–0.060 inches) thick. The core of the part maintains its low carbon concentration and corresponding lower hardness.

The issue of machinability can be mitigated by using a low carbon content steel during machining the part to a form near the finished dimensional requirements. The part at this point will be a little "bigger"; it will have enough stock such that as it distorts during heat treatment, there will be enough excess material to be post-heat treatment (PHT) machined to its final required form and dimensions.

The low carbon content in the steel before heat treatment ensures good machinability and then, after carburizing, the finished part will have enhanced material performance due to the hard case caused by the high surface carbon concentration, and with a softer core, which in combination of properties will assure good wear and fatigue resistance.

Carburizing depth is defined by the requirements of the gear or bearing during service. The requirements for the case depth and hardness ratio between surface and core are also a function of the operational requirements and design parameters set by the service factors for the gear or bearing. Proper case-depth requirements are determined by the surface load, wear conditions, and static and bending fatigue stresses that the finished part will be subjected to in its service life. A limiting factor is typically the cost of the required process time, which increases in a parabolic manner as carburizing depth increases.

When it comes to carburizing depth — or case depth — this is defined as the depth from the surface to the point corresponding to a specified carbon concentration. The case depth is typically defined as the gradient where the carbon concentration is approximately 0.35 percent carbon by weight. Case depth depends on several factors and the interaction of time at temperature and carbon concentration in the atmosphere. The longer the part is at temperature and the atmosphere is stable at the defined carbon concentration, the greater the case depth. Increasing the temperature (and keeping all other parameters constant) and carbon will diffuse deeper and faster into the surface of the part.

PITFALLS OF THE GAS CARBURIZING PROCESS

It is essential that the furnace atmosphere is evenly mixed and circulated so that all part surfaces will experience the same carburizing effect with respect to final carbon content and case depth. Thus, it becomes critical to maintain an even flow, both in terms of velocity of the moving gaseous mixture and the concentration and uniformity (not homogeneity) of the various gaseous components as they move through the furnace. If either of these parameters are 'off,' then the resultant effect of the heat-treatment process will not be uniform throughout the part load or even throughout the part itself.

Beyond the issues outlined above (which are addressed by good maintenance procedures and process control, which can be monitored in real-time, and the system adjusted in real-time), there is the issue of effectiveness of the entire process. A good deal of work continues to develop new techniques (processes) that generate better parts.

Many techniques are reliant on the inherent ability of the equipment used. One technique that produces similar final parts but takes less time in the furnace is that of carbon pulsing. Details can be researched and are well described, but at a high level the carbon concentration is dynamic (not static) and varies from an over-concentration to less than the required amount that would normally be necessary to achieve the final case hardness. This technique provides a means to create a very high carbon concentration atmosphere without the adverse outcome of soot formation. Another interesting technology is to use gas jets to drive mixture into the atmosphere and create the uniformity required for good heat-treatment results, without the need for the typical fan-driven atmosphere velocity profile. Another technique is to use propane as the carbon generating agent, and to use ammonia as a cracking catalyst to separate the molecular components. Purity, consistency, and concentration all become more manageable and can be fine-tuned to provide more specific results. And there are other techniques.

NEXT IN THE SERIES

The other two common case carburizing techniques — liquid and pack carburizing — can be used to provide surface hardness and case depth according to the part design requirements. However, using pack carburizing involves a process wherein steel items are loaded into a furnace in close proximity to high-carbon items. These high-carbon items include everything from carbon powder, to cast iron particles, and more. The atmosphere in the furnace is then maintained as simple carbon monoxide and without the need to maintain a constant and uniform atmosphere velocity. However, pack carburizing is dirtier than atmosphere carburizing. Shallow case depths are also not recommended, and the case depth is not consistent. Carbon potential is not as easily controlled compared to normal gas carburizing. The uniformity of carbon potential in the atmosphere is a function, and very sensitive to, the packing of the carbon material.

Finally, liquid carburizing generates the carbon potential through the use of a molten salt composed mainly of sodium cyanide (NaCN) and barium chloride ($BaCl_2$). Liquid carburizing has issues in terms of reduced ductility of the steel as a function of the process and the process requires longer heating and cooling times.

Liquid carburizing makes steel less ductile because it reduces the amount of free ferrite, which is capable of deforming without fracturing, in the final part.

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