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Case Hardening:
HPGQ, Oil or Salt?

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In order for manufacturers and heat treaters to make an informed decision on what case-hardening equipment to purchase, they must have more than a theoretical knowledge of the processes they may be considering. They must also be aware of the practical implications affecting their individual circumstances.

Case hardening can be defined as the process of increasing the surface hardness and strength of a steel or alloy by carburizing or differentially heating (induction) the part's surface followed by quenching, leaving a more ductile core. Once a part's surface carbon and case depth have been achieved, however, the quenching process will determine the ultimate depth of hardness.

To answer these and other equipment- and process-related issues, the following will present this writer's historical observations on how said equipment affects the ultimate case depth.
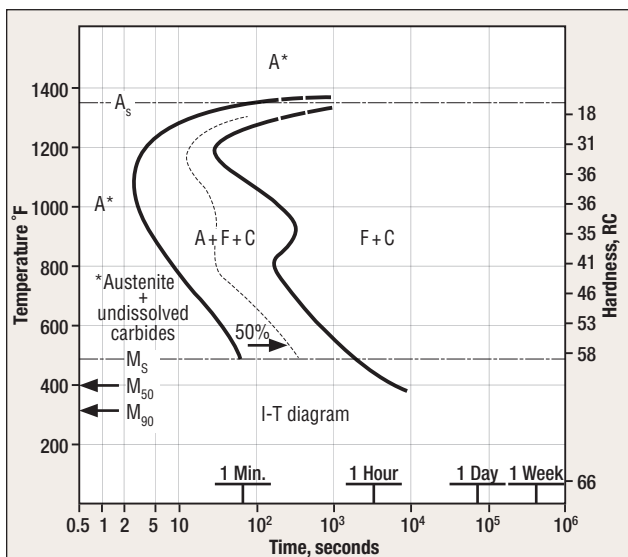
Two Microstructures

There really are only two microstructures desired from quenching ferrous alloys: martensite and bainite. In each case the TTT (time-temperature-transformation, Fig. 1) and the CCT (critical-cooling-transformation, Fig. 2) graphs dictate the ratio of each phase achieved versus temperature and time. The TTT graph typically displays the transformation product during isothermal cooling (i.e., rapid cooling) followed by holding at a specific temperature and time to form the desired microstructure. Bainite is the case in point, but martensite is

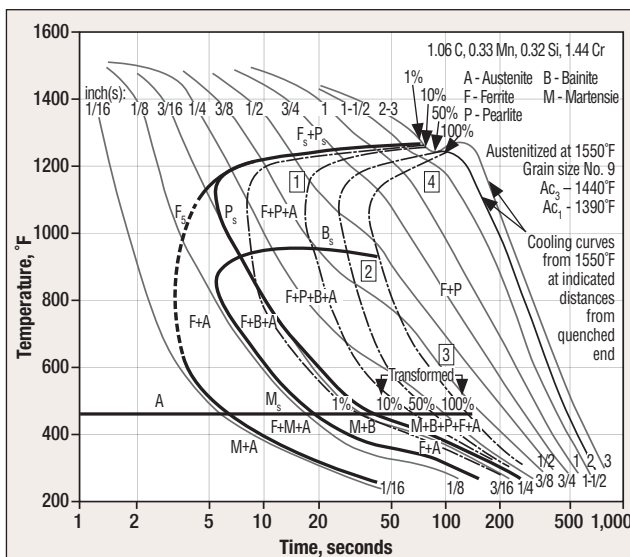Fig. 1. TTT diagram for 52100 steel austenitized at 1550°F

Fig. 2. CCT diagram for 52100 steel austenitized at 1550°F

formed by achieving a sufficiently fast cooling rate to avoid the pearlite nose and pass through the M_S point, as shown on the CCT diagram. It is true, however, that bainite can form in the core in larger parts and also in the carburized case of smaller parts if quenched too slowly.

LPC/HPGQ and Automotive

It's no secret that suppliers of LPC (low-pressure carburizing) and HPGQ (high-pressure gas quench) equipment have been trumpeting their success in penetrating the automotive captive heat-treat market. The reasons for this development are primarily twofold.

1. LPC, or vacuum carburizing, is a faster process when the total case depth does not exceed about 0.070 inch (1.75 mm).
2. HPGQ, due to its convection-only heat-transfer mechanism, reduces distortion in drivetrain components.

HPGQ Evolution

Many heat treaters are aware that vacuum carburizing (LPC) has evolved into a mainstream process, but they perhaps have not kept up to date with the HPGQ process. The very early combination of LPC and helium HPGQ in Europe was found to be the best solution for carburizing and quenching critical parts for early CVTs (continuously variable transmissions). However, as the CVT concept lost favor with U.S. automakers, application for the process was directed to the then-developing six-speed automatic transmissions.

Consequently, as the cost of helium recycling systems, compressors and their associated maintenance became too expensive, nitrogen began to again emerge as a component of the more favored and less costly HPGQ process. When load sizes approach full capacity of 2,200 pounds (1,000 kg), however, 20-bar helium (many times) cannot be avoided.

As a result of the reduced cooling rate of nitrogen, higher-alloy steel, lighter gears and smaller load sizes became a necessity. Figure 3 is a table showing the coefficient of quench severity for various media with 20-bar nitrogen and 20-bar helium indicated for an approximate comparison.

Nitrogen vs. Helium

It should be noted that the quench severity for 20-bar nitrogen is for comparison purposes only (Fig. 3) because it is basically unrealistic to have a fan/motor with the required gas velocity to accommodate a 2,200-pounds (1,000-kg) load. The density of helium is 0.011 pounds/ft^3 (0.17 kg/m^3) and 0.079 pounds/ft^3 (1.2 kg/m^3) for nitrogen. For a plenum chamber sized for a 2,200-pound load, 20-bar helium requires two 200-HP fan motors compared to over 2,800 horsepower (2,072 kW) for 20-bar nitrogen due to the gas-density difference alone. Obviously, if 10-bar nitrogen is specified as the quenching media, the load and plenum chamber must be extremely small to accommodate a reasonably sized fan/motor combination, likely a single layer of parts occupying perhaps 2-3 square feet (0.185-0.28 m^2).

Although HPGQ has become popular to reduce distortion, keep in mind that the core hardness of the applicable

"H" factors – coefficient of severity of quench			
Agitation	**Cooling medium**		
	Oil	**Water**	**Brine**
None (20-bar N₂)	0.25 – 0.30 (0.20)	0.9 – 1.0	2.0
Mild (20-bar He)	0.30 – 0.35 (0.35)	1.0 – 1.1	2.0 – 2.2
Moderate	0.35 – 0.40	1.2 – 1.3	
Good	0.4 – 0.5	1.4 – 1.5	
Strong (approx. 150 fps velocity)	0.5 – 0.8	1.6 – 2.0	
Violent	0.8 – 1.1	4.0	5.0

Fig. 3. For comparison, the 20-bar nitrogen and 20-bar helium coefficients are generalized. Load size and configuration will impact the ultimate quench capability.

- Plain-carbon steels containing 0.50-1.00% C and a minimum of 0.60% Mn
- High-carbon steels containing more than 0.90% C and possibly a little less than 0.60% Mn
- Certain carbon steels (such as 1041) with a carbon content of less than 0.50% but with manganese content in the range from 1.00-1.65%
- Certain low-alloy steels (such as the series 5100) containing more than 0.30% C; the series 1300 and 4000 steels with carbon contents in excess of 0.40% and other steels such as 4140, 6145 and 9440

Fig. 4. Steels suitable for austempering[2]

hardenability steels cannot match that of oil quenching for the equivalent quantity and part mass and overall load size.

Commercial Heat Treaters and Integral-Quench Batch Furnaces

Endo carburizing and oil quenching are the overwhelming choice of commercial heat treaters due to the inherent flexibility of the IQBF (integral-quench batch furnace). Carburizing and oil quenching with cold and hot oil can harden the widest range of ferrous alloys. Also, with the continuing development of nonmetallic hot-zone components, IQBF will have the capability to process the new high-temperature grain-size-restricted microalloyed steels.

Off-road and heavy-truck drivetrains and large railroad bearings are just a few parts that must be oil quenched. When care is taken to properly assemble the load, HPGQ can reduce distortion in appropriately sized steel parts, but not even under the best of conditions can HPGQ produce the very low distortion in large drivetrain components that can be achieved with oil press quenching.

Quenching Basics

Eliminating distortion during quenching has and will continue to be the Holy Grail of case hardening. In every quenching process (including HPGQ) the objective is to reduce the boundary layer surrounding the part surface. The boundary layer is the naturally formed static fluid that is in immediate contact with the part's surface.

Obviously, the quench fluid – liquid or gas – that is not near the part surface will reach a higher velocity proportional to the energy producing the velocity. Thus, the objective of agitation

in a liquid or with a fan is to disturb the boundary layer and increase the heat transfer. When using a liquid (e.g., immersion in oil), the density of the fluid reduces the boundary layer except where a gaseous vapor-film barrier forms. Agitation or gas velocity is required to break down the boundary layer, allowing cooled gas or heated oil to mix with the cooler volume in the quench tank.

Gas-to-Water Heat Exchangers

Pressurized gas in HPGQ increases the fluid density. Therefore, the higher the gas density, the greater is the contribution to the convection heat-transfer coefficient (h_c). The thermal conductivity of the gas, heat capacity (C_p) and absolute viscosity complete the parameters required to determine the effectiveness of the HPGQ process. In HPGQ, the water-cooled heat exchanger provides the mechanism by which heat is removed from the quench chamber.

As the increased gas density improves the heat-transfer coefficient at the part's surface, it does likewise in the copper-finned heat exchanger. Heat exchangers are sized to transfer the heat energy to the water and eliminate all possibility of steam formation.

For an HPGQ heat exchanger to be most effective, it has to remove as much heat from the gas in each successive pass as possible. This leads to the surface area and fin design of the device. At the beginning of HPGQ, for example, the gas entering the heat exchanger from the load may be 1000°F (538°C) and leaving after one pass through the heat exchanger might be 900°F (482°C). So, the most critical portion of the cooling cycle is when the temperature difference between the incoming water and gas is small, thus reducing the heat transfer. This is also the portion of the cycle where the fan motors consume the maximum horsepower.

Oil Quench Tank Cooling

Oil quench tanks are sized to reduce the temperature rise of the oil. Typically, the temperature rise is maintained at 50°F, and this takes place gradually over approximately 10 minutes during the immersion time. For example, if a 3,000-pound (1,361-kg) load at 1550°F (843°C) is quenched into 3,500 gallons (13,250 liters), the oil will rise 52°F in 10 minutes. Oil quench tanks also have air-to-oil heat exchangers, but they are designed to remove heat over time before the next load will be quenched.

Bainite and Austempering

Although austempering may not strictly fall under the case-hardening category, it does exhibit similar characteristics in larger components. Lower bainite forms in the surface region with upper bainite in the core. In the 1920s, Davenport and Bain discovered what has been named bainite as a phase, which develops isothermally after rapid cooling to and holding above the M_S point.

They also identified two primary forms: the softer upper bainite and harder lower bainite. For decades, austempering has

been the process employed to form bainite by quenching steel in hot salt and isothermally holding it at a temperature below the pearlite nose and above the M_S point. The quantity and type of alloying elements in the steel determine the length of time required to form bainite.

The pearlite- and bainite-forming regions overlap in low-carbon steels, thus making the bainite-start temperature difficult to determine. This is not so with high-carbon steels. Elevated carbon lowers the bainite temperature much as it does for martensite, forming the harder lower bainite. Because of the desire to find the Holy Grail of case hardening, austempering has seen a resurgence in its popularity. However, bainite still has one major obstacle: it lacks martensite-like hardness.

But maybe it doesn't. Closer examination of Figure 1 shows that 52100 steel has an M_S temperature of 480°F (249°C) and the expected hardness is slightly above 58 HRC after soaking for approximately 30 minutes. Since no tempering is required, that time is also saved. Figure 4 shows steels that are suitable for austempering.

Bainite Provides Reduced and Predictable Growth

The major benefit of bainite is toughness and ductility. As such, the process of austempering has never found the need to change that basic primus. However, the other major benefit of bainite is uniform dimensional growth. Martensite forms instantly when the temperature cools below the M_S point but ceases if the temperature stops dropping. So, the rate that martensite forms changes on even a single part, and that causes distortion. Austempering in salt, on the other hand, holds the temperature precisely at the bainite-forming range, so austenite transforms to bainite. How fast the process begins initially is up for discussion as is how the process proceeds.[1]

Not disputed is that, once initiated, the bainite formation proceeds at a rate commensurate with the alloy content. But does it proceed by displacive or diffusion-controlled mechanism as detailed in the referenced source? Be that as it may, when quenched in salt and held at the proper temperature, lower bainite will form in steel, resulting in half of the volume expansion of martensite. And when the carbon concentration is higher, as in 52100, it is possible for bainite to approach the hardness levels of tempered martensite. ▣

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