Accelerated cooling for sinter-hardening

The success of sinter-hardening depends on the cooling rates achieved in the forced-convection zone. Accelerated cooling rates can provide the opportunity to reduce raw material costs by using leaner alloy steels, in addition to increasing production rates.

Benefits to our customers

- Reduction in powder raw material cost (cheaper alloys)
- Increased flexibility in manufacturing
- Reduction of dimensional distortions
  - Due to reduced hardenability
  - As compared to heat treated parts
- Potential for shorter furnace footprint
  - Belt savings
  - Less maintenance
  - Space savings
- Increased throughput (stacking)
- Enables larger parts to be sinter-hardened instead of heat treated

Sinter-hardening is a well established commercial technology combining sintering and forced-convection gas quenching of martensitic steels in one continuously processing furnace. It is valued for its cleanliness and process integration that, eventually, translate into reduced operating and capital costs. However, the quenching rates of the atmospheric pressure forced-convection cooling systems used in typical sintering furnaces are limited if compared to the conventional oil bath quenching, and this creates an issue when considering sinter-hardening of lower-cost, lean-alloyed, powder metallurgy (PM) steels. Consequently, new and more effective convection cooling systems are required for maximizing martensitic transformation during quenching by increasing the cooling rate.
CR is a function of heat transfer coefficient and $\Delta T$ between the cooled part and the cooling medium:

$$CR \sim \frac{dQ}{dt} = h \frac{A}{dt} \Delta T$$

where: CR – cooling rate, K/s; Q – heat, J; t – time, s; h – heat transfer coeff., J/(m² K); A – surface area, m²; and T – temperature, K.

For $CR_2 > CR_1$, the hardenability of steel can be reduced; i.e., the extent of steel alloying can be less. Hence, $CR_2$ may allow for a complete martensitic quenching of lean-alloyed, less costly steels.

Shown in Figure 1, above, is the typical sinter-hardening temperature profile. If cooling rate, CR, is increased, less alloying (C, Mn, Mo, Ni, Cr, Si, Cu, Mn, ...) is needed to obtain martensitic transformation, even though the critical cooling rate for martensitic transformation of lean-alloyed steels is higher. So increasing CR is desired. Figure 1 shows the part temperature profile within a sinter-harden furnace.

Fundamentally, the CR increase is possible by making the coolant temperature lower, making the interface heat transfer coefficient higher, and increasing the contact area, A.

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This illustrates that the cooling rates and the LIN jet quenching method match that of the oil bath quenching within the temperature range important for the austenite-to-martensite transformation. The multi-jet mimics a convective cooling unit.
By using cryogenic nitrogen, we can increase $\Delta T$ by direct-jetting liquid nitrogen (LIN) onto the part surface. We can increase $h$, and even if the contact area $A$ between the cryogenic jet and the part surface isn't larger than conventional, the overall heat transfer, $dQ/dt$, and CR will increase enough to transform lean-alloyed steels to martensite.

Industrial-scale cryogenic jet cooling tests were carried out using a large sinter-hardening furnace built by Abbott Furnace Co. and equipped with a Varicool blower-driven convective cooling unit. Manifolds with LIN spray-jetting nozzles were installed inside the Varicool on the entry side, not far from the end of the sintering zone, Figure 3. As planned, the jets expanding inside the furnace were reaching the belt surface without excessive evaporation.

The gears were loaded on a 36-inch-wide (0.91 m) belt of the furnace to the production capacity of about 500 lbs/hr (227 kg/hr). With the stainless steel mesh belt and the ceramic support plates for the sintered gears moving at 6 in/min (2.5 mm/s), the total mass of hot material entering the convective cooling unit was estimated to reach 1000 lbs/hr (454 kg/hr). Preliminary evaluations of the heat-and-mass balances inside the cooling unit equipped with LIN jetting system, performed using Fluent CFD, Figure 4, have shown that sufficiently rapid quenching could be obtained when the LIN spray is directed toward the gears and the mesh belt, and carried out concurrently with the normal operation of the Varicool unit recirculating N$_2$-10 vol % H$_2$ atmosphere across the water-cooled heat exchanger.

Resultant as-quenched hardness was comparably high (see Table 1 below), suggesting a complete or a nearly complete martenistic transformation. A starkly different transformation response for the convective cooling with and without LIN impingement was observed. Earlier industrial sinter-hardening tests, carried out in the same furnace and using the same loaded belt procedure, have shown that the average gear hardness measured for the lean alloy parts was only 21–33 HRC, less than the 36–38 HRC threshold required for these industrial gear parts.

### Table 1: Apparent HRC Hardness Values

<table>
<thead>
<tr>
<th></th>
<th>Conventional Convective Cooling Unit</th>
<th>Heat Treated$^1$</th>
<th>LIN Cooling Unit$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current Alloy</td>
<td>33</td>
<td>44</td>
<td>45</td>
</tr>
<tr>
<td>Lean Alloy #1</td>
<td>24</td>
<td>40</td>
<td>44</td>
</tr>
<tr>
<td>Lean Alloy #2</td>
<td>21</td>
<td>39</td>
<td>42</td>
</tr>
</tbody>
</table>

$^1$ Oil quenched by external heat treating shop, external to PM facility.

$^2$ Dimensional stability (ID and OD) of the LIN-cooled parts were within the same tolerances as the current production.
This presents typical microstructures of the gears quenched using LIN cooling. The gears have a good degree of sinter, and their microstructures are predominately martensitic. Etched using 2% nital/4% picral.

To summarize, recorded cooling rates, apparent hardness values, and the steel microstructures show that the direct cryogenic impingement, applied inside a concurrently operating conventional, blower-driven convection cooling unit, can produce good quality lean-alloy parts, even with production-scale loading. The extent of the transformation was found to be excellent by the industrial norms and comparable to that of oil bath quenching, but without the thermal distortions associated with the latter. Industrial implementation of this new sinter-hardening method requires retrofitting or replacing existing convection cooling units. Shorter belt furnace cooling zones can also be used with this method, and smaller, conventional sintering furnaces can be adopted for sinter-hardening operations.

For more information:
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