A perfect combo for production of diesel fuel-injector components.

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Low-pressure (vacuum) carburizing and high-pressure gas quenching techniques have become a widely used case hardening process for precision and sophisticated components. Out of many successful applications, the most recognized components are probably transmission gears and the parts used for diesel fuel injectors. This is because this process provides cleaner surfaces, less distortion, higher fatigue strength, and better wear resistance than conventional gas carburizing and oil quenching, if material hardenability is designed into the product.

The industry trend
In the past, such critical precision components were typically heat treated either by nitriding, (atmospheric) carburizing with press quenching, or induction hardening. Since the late 1990’s, low-pressure carburizing (LPC) and high-pressure gas quenching (HPGQ) techniques have evolved into a successful alternative for heat treating these components. This new heat treat process offers lower cost than nitriding or atmosphere carburizing with press quenching, yet better quality than induction hardening for complex components.

Thanks to improvements in product quality and process consistency, low-pressure carburizing plus high-pressure gas quenching has become the standard process for diesel fuel injectors and premium transmission gears in Europe. This influenced North American manufacturers such as Caterpillar Inc., which in 1999 led the way and started to vacuum carburize and 20-bar gas quench their diesel fuel injector components. Since then, industry leaders like Siemens VDO and Robert Bosch have adopted this technology for their latest family of diesel fuel injectors used in heavy-duty, mid-duty, and light-duty engines.

LPC + HPGQ benefits
In the automotive power train sector, the diesel engine has increasingly become an important power source for premium passenger cars. Recently in Europe, cars equipped with diesel engines have taken nearly 50% of the market share due to the new engine’s impressive performance, for such reasons as higher torque and better fuel economy. Yet, the new diesel car runs as clean and as quietly
as a gasoline car. The diesel fuel injector, the heart of the engine, is the primary contributor to performance.

Compared to gasoline, diesel fuel is more difficult to ignite. As such, the fuel injector must first generate ultrahigh fuel pressure of up to 2000 bar, vs. less than 15 bar for a typical gasoline injector, and then inject a precise quantity of high-pressure fuel into the combustion chamber to reach the desirable fuel atomization for clean and efficient combustion. This is why the diesel fuel injector is known as one of the most technically challenging automotive systems.

New fuel injectors manufactured by Siemens VDO represent the latest in fuel injection technology (Fig. 1). Not surprisingly, this injector plays an important role in the new International 6.0 L, generation II engine, which powers the diesel version Ford F350 trucks and Excursion SUVs. The injector performs three functions: the pumping function to create high-pressure fuel, the metering function to control the quantity of injection, and the injection function to inject sufficiently atomized fuel to create the proper fuel-air mix (Fig. 2).

Key characteristics
To consistently perform all three functions, most of the fuel-contacting components must have the following characteristics:

- Lower heat treat distortion and precise finish. The injector has very tight clearance between the many mating components (≤ 4 μm) in order to create high fuel pressure. In addition, the injector delivers a pilot fuel injection and a main fuel injection in very short time (a few ms) to reduce the noise and to improve combustion efficiency. As such, all high-pressure, fuel-contacting components must be heat treated with the lowest possible distortion, and then precisely finished to submicron tolerances.
- Superior fatigue strength and excellent wear resistance. Many components need to withstand high cyclical stress from the fuel pressure change in each cycle (7 bar to 2000 bar) for the life of the component up to 7 × 10^6 cycles. In addition, these components must offer excellent wear resistance for up to 500,000 miles to overcome the sliding wear, fretting, and fuel cavitation erosion. To fulfill such challenging requirements, the components must be case hardened to create superior fatigue strength and wear resistance.
- Greater surface cleanliness. All components must meet a stringent cleanliness specification to avoid accelerated wear or nozzle spray hole plugging from the micro-particles, surface scale, or contamination.

To fulfill all these requirements, engineers traditionally choose nitriding or atmosphere carburizing with intensive post-heat-treat finishing. Nitriding offers less heat treat distortion along with superior fatigue and wear resistance, but requires a more expensive alloy steel to resist the tempering effect associated with nitriding. This option also adds cost in the heat treat process due to a longer cycle time.

On the other hand, atmosphere carburizing with oil quenching usually generates more distortion, a light surface scale, and lower fatigue strength from the presence of intergranular oxidation (IGO) or shallow case on certain areas of a complex contour. Today, however, low-pressure vacuum carburizing and high-pressure gas quenching offers a superior alternative to meet such requirements because it balances the cost and enhanced mechanical properties. In brief, the new LPC plus HPQG costs less than nitriding, while generating less distortion with higher fatigue strength than the atmosphere carburizing oil quench process.

To take advantage of this new technology, Siemens engineers made the strategic decision to partner with ALD Vacuum Technologies, specifying that the process be carried out in low-pressure carburizing furnaces with 20-bar He or N₂ gas quenching capability (Fig. 3). Siemens also made the decision to outsource the heat treatment of all important injector components. Currently six vacuum carburizing furnaces are in production, and three more units are being installed in ALD Thermal Treatment’s state-of-the-art vacuum carburizing facility, which operates in an air-conditioned and nearly zero-emission environment as a “clean and quality focused” shop. The facility is designed to meet current and future demands in terms of both volume and quality, as well as servicing other commercial customers.

Critical components’ makeup
In the new Siemens injector, most of the critical components are made of SAE 8620 or 18NiCr8 carburizing steels. These components (Fig. 4) must meet the following metallurgical and quality requirements:

- Surface hardness of 76–81 HRN 30 with a uniform effective case depth of 0.2–0.5 mm (0.0078–0.0197 in.) through all required surfaces including small fuel passages
- Carburized case microstructure: uniform tempered fine martensitic structure
- Clean surface with no scale or other visual foreign substance
- Other requirements include no visual retained austenite, no intergranular oxidation (IGO), and no visual carbide network.

Considering the cylindrical injector body as the example (upper left part in Fig. 4), process capability for surface hardness was studied with a 30 piece random sample lot selected from throughout the load. Results indicated that the low-pressure carburizing with
20-bar N₂ gas quenching produced very consistent surface hardness, with a standard deviation of 0.4, and process capability of \( C_{pk} = 1.7 \) against the specification (Fig. 5).

In addition, case depth was measured at three locations (external surface, internal hole, and thin wall) for each injector body. Three injector bodies were selected from top, middle, and bottom of the load. The results indicate that the case depth among the three samples was consistent (Fig. 6). The majority of the case depth variation was from the same part between thin wall and thick wall, which is less than 0.05 mm (0.0019 in.).

Metallographic examination of the carburized injector body (Fig. 7) revealed uniform case depth through the external surfaces and small fuel passage (< 1 mm or 0.04 in. dia.). Only low-pressure carburizing allows such consistently tight uniformity of a complex contour and small deep holes repeatedly under full production conditions.

Carburized case microstructure showed desirable martensitic structure, but without IGO network, carbide, or retained austenite (Fig. 8). Because of the accurately controlled process gas and computerized parameter control software, the low-pressure carburizing process became more scientific and accurate. Consequently, it generated the most desirable carburized case microstructure and mechanical properties.

In addition to the superior metallurgical and mechanical properties, low-pressure carburizing with 20-bar N₂ gas quench also produced very clean injector bodies (Fig. 4), which not only minimized the number of post-heat-treat washing processes, but also reduced the quality problems related to the component cleanliness.

**Less distortion: a plus**

Siemens views distortion reduction as another major benefit of LPC and HPGQ. Unfortunately, distortion is the inherent result of high-temperature heat treating. As such, the distortion can be minimized, but not eliminated. Normally, distortion is affected by the following variables:

- Pre-heat-treated material condition, geometry, and residual stresses from machining
- How parts are racked in the heat treat fixture
- Heating and austenitizing parameters: temperature and time

Quenching related thermal stresses and phase transformation related to volume change

Typically, low-pressure carburizing with high-pressure gas quenching minimizes the influence of the last two
variables. In other words, because low-pressure carburizing reduces the cycle time for the same case depth, it reduces the warpage due to creep at high temperature. However, the more influential factor is gas quenching, which removes heat from the workpiece more uniformly compared to oil quenching, due to the absence of an oil vapor blanket. This contributes to reduced distortion more than vacuum carburizing itself.

The dimensional change or distortion of the injector body was determined by measuring its overall length before and after the heat treat process. To eliminate other variables, 50 injector body samples were randomly picked from the same machining batch, which were then split into two groups: one for atmosphere carburizing with oil quench and one for low-pressure carburizing with 20-bar N₂ gas quench. After heat treating (Fig. 9) the atmosphere heat treated group of 25 samples showed an average length growth of 59.6 μm with a standard deviation of 3.7 μm, yet the low-pressure carburized group of 25 samples showed length growth of only 28.4 μm with a standard deviation of 3.5 μm. The reduction of 52% in length growth is primarily the result of gas quenching and vacuum carburizing. Such distortion reduction provides a great opportunity to reduce stock removal after heat treat and to make near-finished components, both of which reduce cost and dimension related quality problems.

Fig. 7 — SEM photo at 10X showed a uniform case through the small fuel passage and the external surface.

Fig. 8 — SEM photo at 2000X showed uniform martensitic structure in the carburized case without any retained austenite, IGO network, or carbide.

Fig. 9 — LPC and HPGQ treated injector bodies showed less distortion (growth) than atmosphere carburized, oil quenched counterparts, a definite dimensional control advantage for this critical application.
LPC + GQ choices

What should be considered when choosing low-pressure carburizing and gas quenching? Although low-pressure carburizing and gas quenching offers many benefits and advantages, engineers who choose this process for their products must understand that material hardenability needs to be carefully calculated in order to gain most or all of the benefits. This is because most of the currently used materials, for example, SAE 8620, SAE 5120, etc. were developed for oil quenching, which may still be necessary for large cross-section parts. However, these materials could be a challenge for high-pressure gas quenching, even using 20-bar He gas.

Normally, engineers consider such factors as product metallurgical requirements, product geometry, quench media, and total cost in the course of the material hardenability calculation and material selection. For Siemens injector components, the SAE 8620 is sufficient to gain all the benefits from low-pressure carburizing and gas quenching, yet not sacrifice the metallurgical quality. But for other products, engineers may want to use their current materials. This raises a frequently asked question: Why not use oil-quenching in combination with low-pressure carburizing, so that material hardenability is not an issue. This can be done, but product quality will not see the benefits of improved distortion reduction, and there will be little cost savings from the post-heat-treat machining processes.

Another factor to consider when using LPC and HPGQ technology is pre-heat treatment surface cleanliness. This usually is a critical concern. The low-pressure carburizing process generally requires a clean and residue free surface for proper carburizing under vacuum. If foreign material residue is present, it forms a tight thin film that prevents carbon atoms from penetrating into the surface, resulting in inconsistent carburizing results. It appears that vacuum carburizing is more sensitive than atmosphere carburizing in this regard because the latter allows formation of a porous oxide film during heating allowing carbon atoms to pass through the porous layer and react with the metal surface.

Conclusions

Diesel fuel injector systems are required to meet many tough challenges within the automotive industry. To fulfill these requirements, its components must be heat treated to superior fatigue strength and wear resistance, yet with also the highest possible precision and cleanliness. Low-pressure carburizing and high-pressure gas quenching offers exactly these characteristics but at a lower cost than nitriding or press quenching. This synergy has made low-pressure carburizing and high-pressure gas quenching technology the best choice for the latest family of diesel fuel injectors.