PROS AND CONS OF VARIOUS AUTOMOTIVE MATERIALS AND HARDENING PROCESSES

Automotive designers and heat treaters have many choices when it comes to the materials and processes that will meet their overall needs.

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Typical automotive parts made of austempered ductile iron. From left, turbo charger housing, exhaust manifold, and ring and pinion set. Courtesy of Wikimedia Commons/Panoha and zircotec.com.

Automotive heat treating has benefited from significant developments in recent years due to the need for high production and predictive process automation (PPA) to improve efficiency. Four major goals of automotive component heat treating include:

- Reduce distortion in low mass transmission gears.
- Choose materials that reduce vehicle weight to improve fossil fuel economy.
- Reduce fossil fuel emissions like CO_2, CO, and particulate matter.
- Improve the range of hybrid and electric vehicles.

Each heat treating and/or quenching process provides unique solutions for automobile designers and plant engineers. However, it is likely there is no single process or material that provides all the answers. There are advantages and disadvantages of quenching media options such as oil and press quenching and high pressure gas quenching (HPGQ), austempering (salt) for steel, austempering ductile iron (ADI), and the use of aluminum alloys versus other materials. This article discusses how OEMs and heat treaters can take advantage of particular hardening processes.

Challenges facing auto designers include reducing emissions produced during acceleration to cruising speed and decreasing overall vehicle weight. Two methods for reducing weight include shrinking the overall unit size and adopting lighter (less dense) materials. Auto manufacturers in Europe and the U.S. each face their own unique challenges because consumers desire different car models, which affects the size and utility of product offerings. Thus, it is necessary to not only manufacture vehicles that meet government standards, but also produce vehicles that consumers will purchase.

CONSUMER PURCHASING STATISTICS

Per the Car Sales Statistics report on January 29, 2018, by Henk Bekker, in Europe the VW Golf was again the leading vehicle sold in 2017 with 445,206 units. In the U.S., SUVs and crossovers were segment leaders, with 3.53 million sold in 2017. Light trucks or pickups totaled 2,988,856 units. Overall, 17,134,700 vehicles of all kinds were sold the in the U.S. in 2017. For clarification, crossover SUVs are sport utility vehicles based on an automobile platform, while SUVs are truck-based. Considering that SUVs and light trucks on average weigh more than passenger cars, they require on average a higher proportion of weight reduction to meet their respective efficiency criteria.

Meeting the 2025 CAFE standards in the U.S. will be a challenge due to the weight of the vehicles: Americans love their trucks. With the deadline just around the corner, improving mileage by weight reduction alone seems impossible. Therefore, a new generation of engines, transmissions, and hybrid technology will likely need to play a major role. However, electric and hybrid vehicles have not impressed the American consumer to date.

2016 VEHICLE SALES IN U.S. AND EUROPE

Best-selling cars in Europe, 2016:

- VW Golf 491,681
- Renault (Clio) 310,944
- VW Polo 307,462
- Ford Fiesta 298,999

Best-selling vehicles in the U.S., 2016:

- Ford F-Series 820,799 (half-ton pickup truck)
- Chevrolet Silverado 574,876 (half-ton pickup truck)
- Dodge RAM Trucks 489,418 (half-ton pickup truck)
- Toyota Camry 388,616
- Honda Civic 366,927
- Toyota Corolla 360,483
- Honda CR-V 357,335 (crossover SUV)
- Toyota RAV4 352,139 (crossover SUV)

COUNTRIES ADOPT AUTOMOBILE FUEL STANDARDS

A decade ago, the EU entered into a series of voluntary agreements known as the European Union Automotive Fuel Economy Policy with associations of automobile manufacturers that sell vehicles in the European market to reduce CO_2 tailpipe emissions. These agreements applied to each manufacturer's new vehicle fleet and set an industrywide target of 140 g CO_2/km (100 km per 6 L or 39 mpg). The original agreement with the European Automobile Manufacturers Association (ACEA) had an initial compliance date of 2008, while the Asian manufacturers (represented by South Korean and Japanese associations KAMA and JAMA) had to comply by 2009.

However, automakers did not meet the voluntary target and the European Commission (EC) has now set mandatory targets. In June 2007, the Council of Environment Ministers formally adopted a resolution to approve the shift to mandatory standards and an integrated approach to achieve 120 g CO_2/km (100 km per 5.2 L or 45.6 mpg), with automakers achieving 130 g CO_2/km (100 km per 5.6 L or 42 mpg) through technical improvements and the remaining 10 g CO_2/km coming from complementary measures. The full EC strategy to reduce CO_2 emissions from cars and vans is available online, as is the regulation[1].

In the U.S., the CAFE (corporate average fuel economy) standard was adopted in 1975, and was primarily targeted to improve fuel mileage for automobiles in the wake of the Middle East oil crisis of 1970. As time passed, political pressures also mandated the reduction of greenhouse gases (GHGs) such as CO_2 and NOx (nitrogen oxides).

EXISTING MODIFICATIONS

Attempts to reduce fuel consumption were adopted over the decades, including decreasing the number of cylinders to reduce engine block mass. Probably the most significant and successful solution to date (and perhaps the most cost effective) has been the integration of turbochargers to four and six-cylinder gasoline and diesel engines combined with six, seven, eight, and even nine and 10-speed transmissions. This approach also has limits, especially as fuel economy standards are applied to larger passenger vehicles and half-ton pickup trucks.

Where light trucks are concerned, one OEM substituted aluminum for steel body panels with a reported weight savings of 500 to 700 lb (227 to 318 kg). However, body panels are just one of many components that are candidates for potential weight reduction, including suspension parts, transmission and transfer cases, and structural and space frame components, some of which will be fabrications, castings, and forgings. In every case, the tradeoff between mass and strength must be considered, as well as the potential for reducing post-heat treat processing.

MATERIALS AND PROCESSING

Six materials with suitable strength-to-weight ratios used in automotive construction today include magnesium, carbon composites, cast gray and ductile irons, aluminum, and steel. Each material is used for a specific performance characteristic:

Magnesium has been slowly gaining acceptance for use in automotive applications. Its low density and machinability makes it an ideal candidate for transmission, differential, and transfer cases. However, it lacks aluminum's overall strength, making it unsuitable for engine blocks and similarly stressed applications. It also requires a protective coating to reduce corrosion, whereas aluminum has very good oxidation resistance. Probably the biggest advantage of magnesium is its availability, although it is not inexpensive to refine. It is not found in the pure state, but can be refined from several materials including dolomite and magnesite ore, sea water, and salt brines, which contain about 10% magnesium chloride. Ocean water contains about 0.13% magnesium[2].

Carbon fiber reinforced polymer (CFRP) has one of the most advantageous strength-to-weight ratios of any engineered material. However, it is not as easily recycled as aluminum and wrought and cast ferrous alloys, and there has been much research to make recycling more cost effective. Most virgin woven poly fiber is produced in Japan and is used for aerospace applications and expensive automobiles. The aerospace industry produces about 35% CFRP scrap, which is used in many under-hood automotive applications, because the chopped recycled fiber material does not have the structural strength offered by virgin long-fiber polymers for chassis and body panel applications[3]. Although heat is used to manufacture raw carbon fiber, it does not play a significant role in making the final product.

One of the major obstacles facing CFRP is the end-of-life (EOP) products stated in ELV Directive 2000/53/EC. This directive issued a 2015 target applicable to Europe and Japan that 95% of an automobile ready for the scrap yard must be recoverable and recyclable. Today, it is accepted that approximately 75% of an automobile is made of ferrous and nonferrous metals and the remaining 25% is made of toxic materials.

Gray cast iron has been the material of choice for automobile engine blocks for decades, primarily due to its low cost and adequate strength for gasoline, but not diesel, engines. Due to its lack of as-cast strength and the fact that it is not typically hardened by heat treatment, it has limited application for stressed components. As for heat treatment, gray iron is rarely heat treated to increase hardness, but it does receive treatments such as annealing and normalizing to enhance machinability. Stress relieving after welding is also common. Gray cast iron automotive components include engine blocks, brake rotors, constant-velocity joint housings, exhaust manifolds, transmission cases, and cylinder heads.

Aluminum is more expensive to manufacture than steel, but it has an attractive strength-to-weight ratio and therefore has continued to see more application in automobiles and trucks. Much of it is recycled and it also requires different forming and coating techniques. The 2*xxx*, 6*xxx*, and 7*xxx* series grades are hardenable by solution treating, rapid water quench, and natural and artificial (heat) aging. As such, the 6*xxx* series is finding application in vehicle structural and body panels. A less tangible effect of material selection is sound conduction. For example, a material can have ideal properties but transmit undesirable sound and vibration to the passenger cabin.

Plain-carbon and alloy steels have the highest percentage of application in cars and trucks simply due to their wide range of strength-to-weight relationships through diverse heat treating options. High-strength low-alloy (HSLA) grades have been used for years in the substructures of U.S. cars and trucks. The more recent use of higher hardenability alloy steel has been directed to drivetrain components, such as transmission and differential gears, where the goal is to reduce gear mass. This has resulted in the growth of using high pressure gas quenching (HPGQ) and improved distortion control. The growth of HPGQ is primarily due to increased distortion control required for more precise, less massive gearing in multispeed transmissions. In addition, OEMs realize that improving the hardenability, even at increased cost, can reduce or eliminate post-heat treating machining, grinding, and straightening. One of the original growth drivers for HPGQ was the use and recovery of helium. However, as the capital cost and maintenance of compressors has increased, nitrogen is making a comeback. Nitrogen forces users to improve the hardenability of steels, because the horsepower for the fan motors required to equal the quench capacity of helium would have to be increased to impractical levels.

Ductile iron (DI), specifically austempered ductile iron (ADI), has been around for decades, but it never gained mainstream acceptance compared with steel and aluminum. One reason, in this author's opinion, is the negative perception of heat treating in salt. However, today's salts are much more EPA-friendly than those used in the past for carburizing and cyaniding. Austempering salts consist of a 50-50 mixture of sodium nitrite and sodium nitrate compounds. A significant quantity is recycled by recovering salts from post-wash solutions. Similar to steel, alloying elements play a significant role in ADI to produce properties that increase hot strength and improve tensile strength and hardness.

A fundamental misunderstanding still exists regarding the microstructure formed when DI is quenched in hot salt compared with austempered steel and ferrous alloys. Years ago, investigators were credited with identifying the ferrite/Fe_3C/austenite microstructure as *ausferrite* or *upper bainite,* as some have called it, when DI is isothermally held above the martensite start (M_s) temperature, but not long enough to form bainite. Further, they reportedly discovered that the carbon-enriched stable austenite formed is different from what some called retained, or metastable, austenite. Lawrynowicz[4] indicated that ausferrite is a mixture of ferrite and high-carbon austenite, and forms at austempering salt temperatures (Fig. 1). He further noted that bainite will not form unless the DI is held at temperature for very long times, much longer than is perhaps practical for normal production.

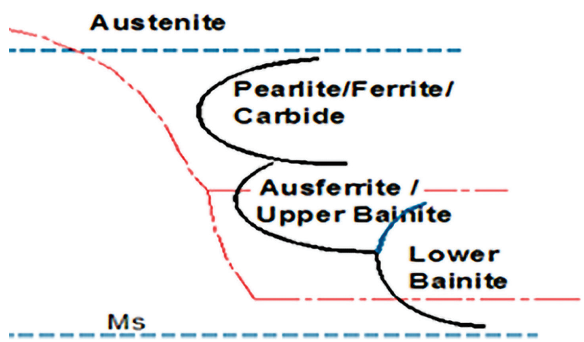

Fig. 1 — Ausferrite is a mixture of ferrite and high carbon austenite formed at austempering salt temperatures. Bainite will not form unless the ductile iron is held at temperature for a very long time[4].

Fig. 2 — Universal batch quench austemper furnace (914 × 1829 × 1422 mm) used at Zanardi Fonderie S.p.A. to study heat treated properties of cast iron and austempered ductile iron. Three chambers enable transferring product to a salt-quench tank under a protective atmosphere.

Austenite is not retained as some have indicated, because the parts would never have cooled below the M_s temperature. Carbon in the austenite is high enough to lower the M_s temperature well below room temperature. Some proposed that this microstructure contributes to the hardening effect when the part is subjected to strain or stress, producing the shear or deformation required to change from face centered cubic (fcc) austenitic lattice to body centered tetragonal (bct) martensitic lattice.

Zanardi Fonderie S.p.A.[5] compared the properties of cast iron and ADI parts treated in a universal batch quench austemper (UBQA) furnace (Fig. 2). Fig. 3 shows a suspension arm made of austempered ductile iron compared to a pearlitic-ferritic cast iron version. Both weight savings and strength are gained by using austempered ductile iron versus pearlitic-ferritic cast iron. In addition to strength, DI is inherently quieter than steel alternatives due to the presence of graphite. Fig. 4 shows the relative damping of ductile iron and steel[6].

CONCLUSION

Several weight reduction options exist when it comes to the materials and processes available to designers and heat treaters for automotive applications. However, remaining challenges include whether the choice for weight reduction can be cost effective in vehicle pricing, and whether the selected process can be integrated cost effectively into the predictive process automation methodology of the manufacturer.

From a heat treating perspective, controlling distortion is a primary goal in reducing manufacturing cost. Because steel and ductile iron offer the greatest potential for achieving an appropriate strength and wear resistance parameter, austempering with its predictable, uniform growth seems

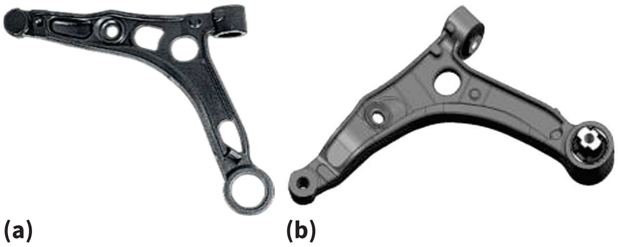

Fig. 3 — (a) Austempered ductile iron (ISO 17804/JS/900-S) suspension arm provides weight savings (5.9 kg machined weight versus 8 kg) and strength (600 MPa yield, 900 MPa tensile, 8% elong. versus 370 MPa, 590 tensile, and 10% elong.) over the (b) GH 60-38-10 pearlitic-ferritic cast iron version.

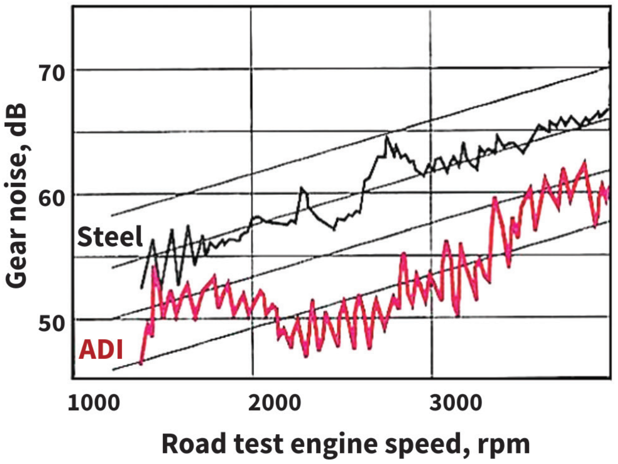

Fig. 4 — Relative damping of ductile iron and steel.

poised to satisfy weight-related obstacles. The one remaining issue with austempering—the "Holy Grail of bainite"—is hardness. Additional research in microalloying ADI and steel would solve that major hurdle. ~HTPro

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