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Advanced materials for future IC engines

The key to achieving successful designs for new eco-friendly IC engines lies in advanced materials – often involving innovative metallurgical processes

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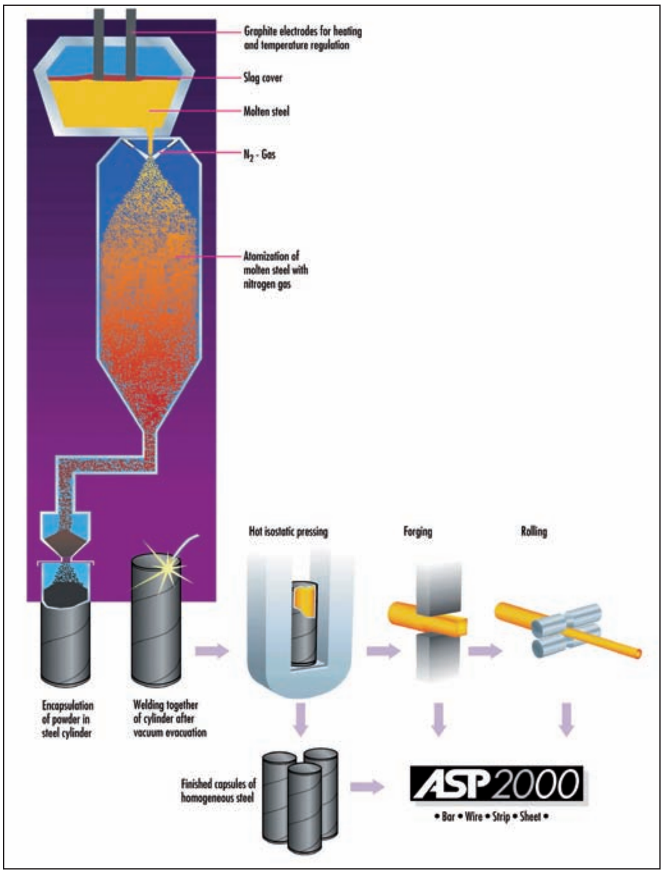
It is most likely that IC engines will still power cars, trucks, trains, and ships, exclusively or in combination with electric engines, for a few more decades. But for this to happen, IC engine technology will have to evolve, and the multiple innovative designs that will emerge will require innovation in the field of materials, and particularly steels.

What will be the drivers for IC engine innovation? A first driver is performance, and in particular performance that focuses on the environment. The necessary technological changes to meet the increasingly stringent environmental regulations – emissions and pollutants control, use of biofuels, downsizing, or even novel IC engine designs – will call for materials that can cope with increasingly aggressive operating conditions.

In addition to this trend, there are specific markets where reliability, safety, or performance will be key to the success of powertrains such as heavy-duty diesels and racing engines.



The innovative ASP process, first established in 1972 by Erasteel, consists of gas atomization of metallic powders followed by hot isostatic compaction

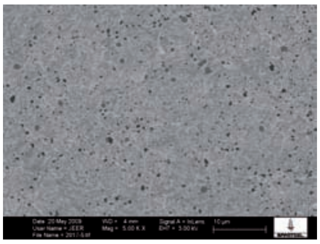
IC engines are mature systems in a very competitive market, but cost is – and will continue to be – the other major driver. The recent raw material price surge has shown how highly alloyed grades could negatively impact product cost. Cost reduction can be achieved through optimization to reduce the content of expensive elements or through the use of alloyed grades that enable engineers to avoid using expensive PVD coatings.

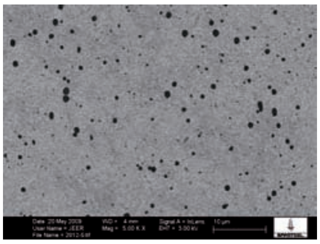
Although in most cases these contradictory drivers – cost and performance – must be taken into account, advanced alloys can still be relevant solutions, with advanced not only meaning optimized grades/compositions but also state-of-the-art metallurgical manufacturing processes.

Does this mean that new grades/processes need to be developed each time the standard material toolbox is not sufficient? There is no easy answer to such a question. From a steel supplier's perspective, grade innovation strongly depends on volumes. Applications with large volumes can justify specific grade developments. This is typically the case for valves or light-duty engine parts where yearly volumes reach several thousand tons. In such cases material development is done through partnerships between suppliers and OEMs, and sometimes even with exclusivity agreements. For smaller volume applications, the approach is different and the designer must often go to great lengths to source existing materials. Grade development can to some extent still be triggered but this becomes generic and the supplier in this case must spend time targeting several markets. Historical examples of such material transfers include: high-speed steels for diesel injection parts, originally designed for cutting tool/cold work markets; martensitic stainless steels for gasoline injection parts, developed for bearings or knives; or Ni-based alloys for exhaust line parts, originally developed for aerospace.

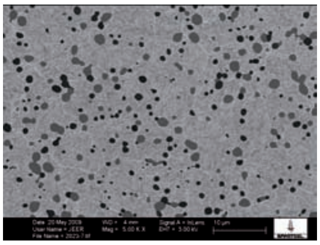
Melt size influences the critical volume for grade development. For continuously cast grades, the key figures are in the hundreds of tons, while in air-melted ingot cast steels, some tenths of tons are to be considered. Special melting processes such as VIM/VAR remelting (typical for aerospace or Formula 1) or powder metallurgy have lower critical masses (of up to 10 tons).

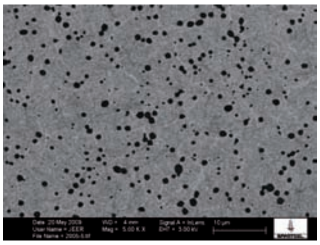
To find the right grades and treatments for the multiple parts of innovative engines, suppliers with experience of a range of materials are extremely valuable, as they have the ability to guide the designer through the materials jungle and provide valuable feedback during development or early market launch. One such example represents one of the most challenging areas for engineers: diesel injection. Advanced steels/surface treatments are used in pumps and injectors,

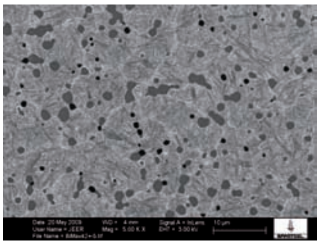




All: Carburizing grades are now used because they are cost-effective, suitable for mass production in the automotive industry, and also provide a deep depth







which are often the most severely loaded parts of the system. To meet emission requirements, temperatures of the system have increased to 400°C and more, and pressure has also increased to 3,000 bar and more. Numerous families of grades that are either hardened or case hardened/nitrided, cover a wide range of automotive applications including carburizing steels, nitriding steels, tool/high-speed steels (conventional or PM) and martensitic stainless steels (conventional or PM).

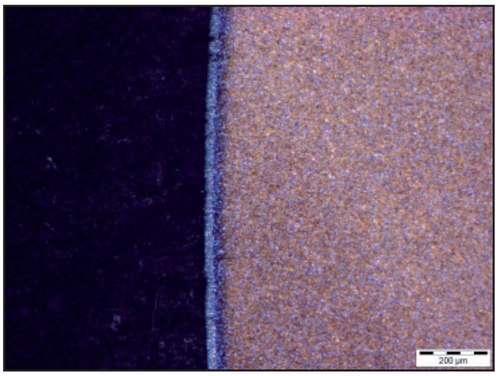
Carburizing grades are used because they are cost-effective, suitable for mass production, and provide a deep case depth. Carbon contents range between 0.15-0.2% and 0.4-0.7%, with various amounts of Si, Ni, Mo, and Cr being added.

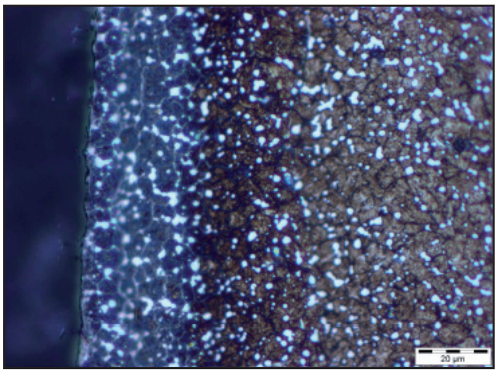
A common handicap for these grades is temperature resistance, which does not exceed 200°C (between 150°C and 250°C). They tend to soften, which restricts the choice of PVD coatings that can be applied. A special grade called FND has been developed by Aubert & Duval, which enables an extra operating temperature of 100°C. This is achieved mainly through additions of Si and Mo. The slightly increased Ni content improves hardenability, enabling gas quenching and therefore limiting distortion. Another possible solution is CX13VD, a martensitic stainless steel with 11.5 w% Cr. Its mechanical properties are close to FND, but after carburizing it displays corrosion resistance up to 58 HRC. In very specific designs, the carburized part can be locally removed at annealed state by machining to fully use the corrosion resistance of the grade. Both grades are tempered typically at 250°C, and easily up to around 200°C.

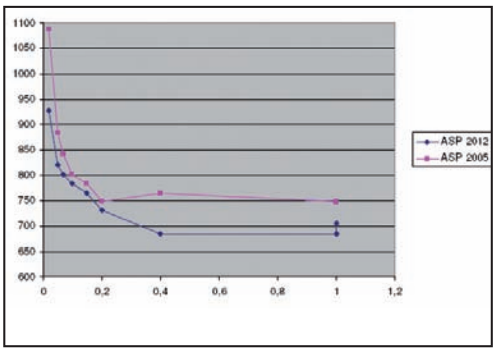
At the other end of the range, ASP grades, hardened or nitrided, are very interesting materials for engineers to look at when resistance is needed and temperature requirements exceed 350°C, and tool steels/nitriding steels cannot cope. ASP is an industrial process established in 1972 with the trade name of Erasteel. It consists of gas atomization of metallic powders followed by hot isostatic compaction.

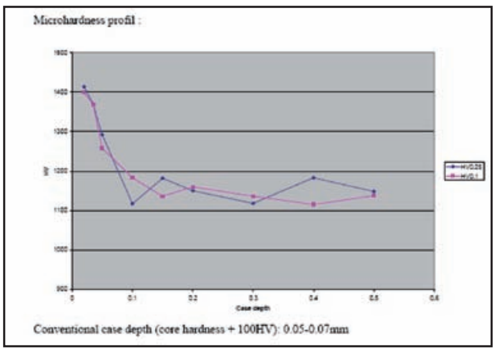
The ASP process brings major microstructural benefits for alloyed steels, typically high-speed steels that include high amounts of carbon and carbide forming alloying elements such as W, Mo, and V: ASP 2023, 2030, 2060 are most popular for cutting and cold work tools. But continuous improvements in cleanliness have recently opened up the components markets for a range of ASP grades: ASP 2012, ASP 2017, ASP 2005, ASP 2004, and Bimax 42 are all very interesting candidates with increasing levels of carbides. As a result of all this development, it becomes clear that the ASP process can be used for classes of alloys other than HSS/TS, and is also suitable for martensitic stainless steels and superalloys.

The main microstructural benefits of the ASP process are the drastic reduction of carbide size to a very few microns – up to 10 times less than for ingot cast material – and the isotropy and lack of macrosegregation, even for large sizes. In addition, this process enables the exploration of compositions that cannot be ingot cast. All ASP grades consist of a steel matrix, but different amounts and types of carbides provide different property combinations, such as









The above illustrations show it is possible to achieve 1,400 HV for components made of Bimax42. Such a high level provides automotive engineers with a cost-effective alternative to ceramics in terms of hardness levels and overall wear resistance

hardness, impact resistance, and abrasion resistance. The very high cleanliness levels are achieved through process development and control based on investigations involving destructive testing such as ultrasonic testing, LOM/ automated SEM analysis, and fatigue testing, and allow for a generic resistance to brittle and fatigue failure. The average cleanliness is comparable to remelted steels. These general features give ASP grades several exciting key characteristics for engine designers.

Most ASP grades can be tempered at high temperatures, typically 560°C for PM high-speed steels, and this makes them stable at up to 500°C for hundreds of hours. In some cases, ASP grades can even be pushed up to 600°C if temperature excursions are not so frequent.

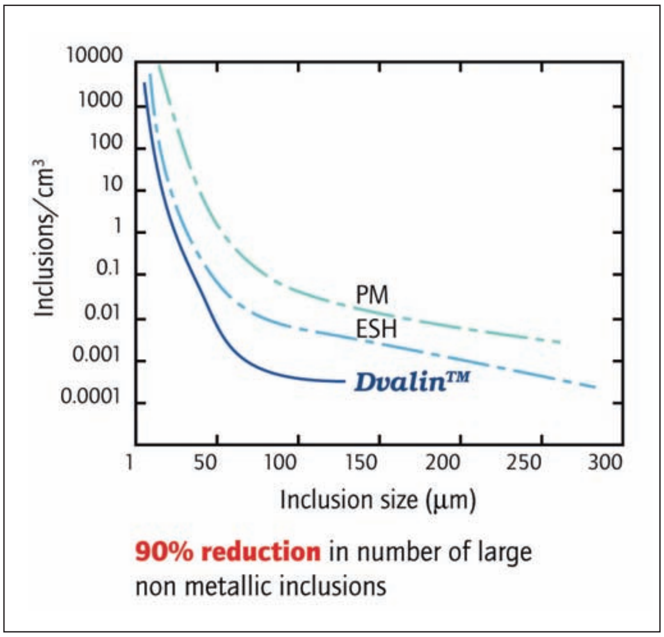
Wear resistance – particularly abrasion and erosion resistance – is achieved through overall high hardness and the amount/ size and types of carbides. The hardest are the MC carbides, which are rich in V, followed by the M6C carbides, rich in Mo and W, and finally MxCry carbides found in the stainless grades or in most Cr alloyed tool steels. Chromium carbides can be hard enough for less abrasive environments.

The ASP process enables an outstanding combination of high hardness and impact resistance to be achieved, typically above 53-4 HRC, and a very high strength – ASP grades are the strongest metallic alloys of all on the market.

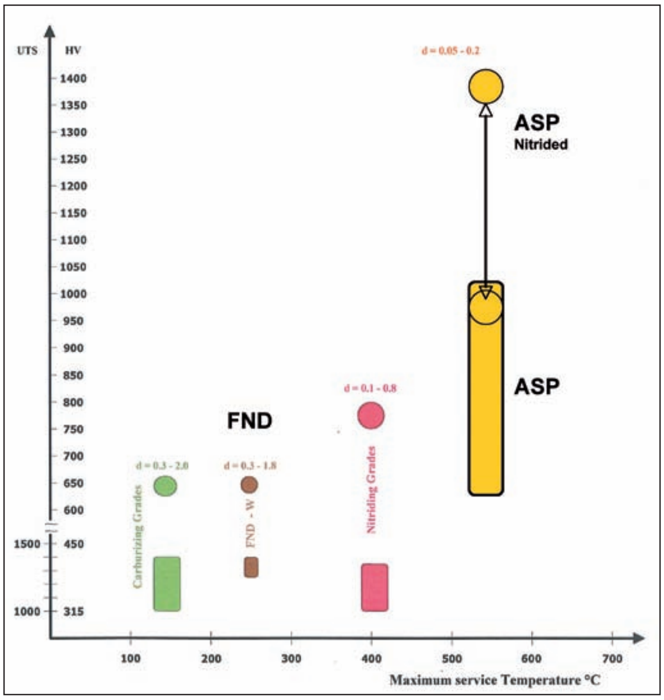
One of the most interesting properties is fatigue resistance. The small carbide size together with the high cleanliness level give exceptional fatigue resistance at a high number of cycles. Typical fatigue resistance in rotating bending at 20 million cycles ranges between 1,100MPa and 1,450MPa, depending on the grade and the heat treatment. It must be emphasized, however, that the experience of using such grades in such applications is relatively new; more work needs to be done to quantify and improve the reliability of cleanliness for PM grades. Using the potential of these materials for brittle fracture or fatigue sets very high requirements on surface finish. The potential is there and component testing should determine whether these materials are suitable for any given application.

An unexplored property is the specific modulus. Grades with a significant volume fraction of carbides, particularly V carbides, can display a fairly high Young's modulus for a moderate density, giving specific moduli E/ϱ up to 25% higher than high-performance construction steels. This gives ideas for decreasing component weight for motorsport applications in particular.

Another way to use these materials for applications such as rollers is to use nitriding.



The graph above highlights the reduction in the number of large non-metallic inclusions



The graph above illustrates the temperature level advantages to the ASP process

Nitriding of ASP steels is not a very easy process to control, as the white layer formed is brittle and the case is shallow, typically 50µm. However, if performed according to the best practices, it enables 1,100-1,200 HV and high compressive stresses to be easily reached, which improves the component's lifespan. It is even possible to achieve 1,400 HV for components made of Bimax42, providing a cost-effective alternative to ceramics in terms of hardness and wear resistance levels.

PM MSS can be considered when corrosion resistance and serious mechanical properties at certain temperatures are needed. Two grades are available today: APZ10 and RWL34, a PM version of martensitic steel 618. An advantage of the PM structure is that it limits the extension and intensity of the local Cr depletion around phases such as carbides, hence decreasing the risk of pitting. There are enough carbides to provide good abrasion resistance, and this enables the range to expand.

It is important to note that all applications and grades do not require or profit from the specifics of powder metallurgy. Particularly in the field of stainless steels, many exciting properties can be achieved with other melting techniques.

Gasoline injection is a field that is not as demanding in terms of mechanical properties as diesel injection, but this powertrain area has its own challenges in terms of corrosion resistance in connection with the use of flexfuels.

A very successful grade is N-Alloyed X15TN, which is closely related to the XD15NW grade that was developed for aerospace bearings. Its composition enables it to reach 59 HRC and it can be tempered at low (180°C) and high (500°C) tempering temperatures. It has an outstanding corrosion resistance and almost outperforms the high-temperature tempering grade 440°C. The trick is the limitation of carbon content and the addition of N. This mixture, in combination with a very sophisticated remelting process control and a very strict conversion scheme, provides exceptional homogeneity for this kind of grade, as well a strictly bound inclusion content ensuring exceptional reliability.

Such examples of material development for the automotive industry show how advanced materials – often involving advanced metallurgical processes – can be key to achieving successful designs at controlled cost for the new environmentally friendly IC engines of the future, thereby creating value for engine developers, suppliers, OEMs, and for society as a whole. ETi